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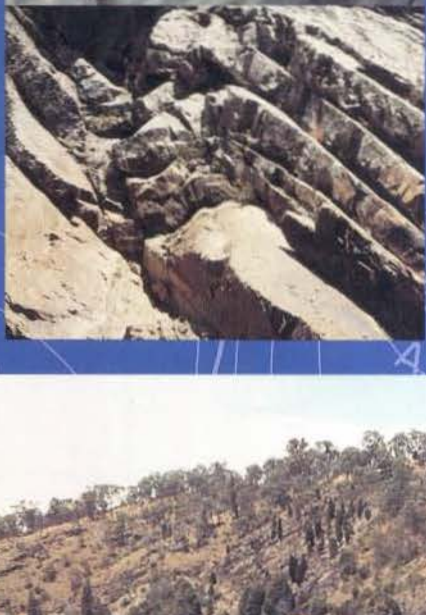

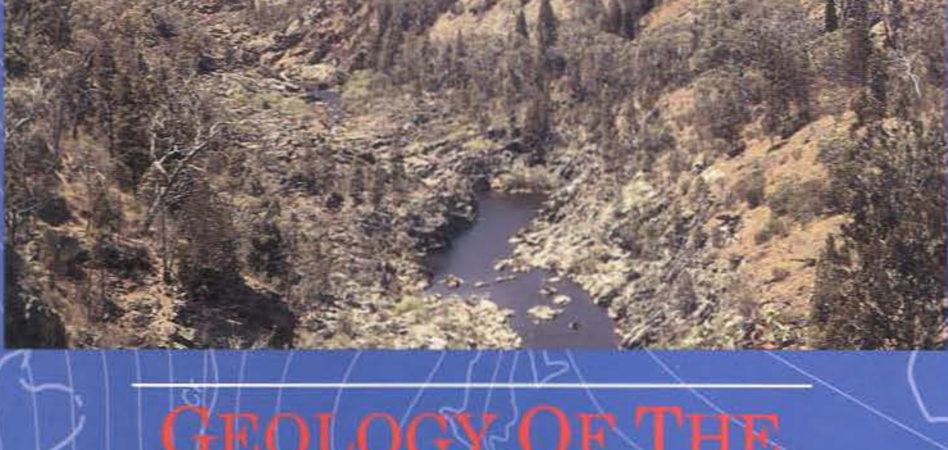

GEOLOGY OF THE CANBERRA 1:100 000 SHEET AREA

DEPARTMENT OF PRIMARY INDUSTRIES & ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

BULLETIN 233

Geology of the Canberra 1:100 000 Sheet area, New South Wales and Australian Capital Territory

by
Robert S. Abell

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Cover: Molonglo Gorge (and railway line), 3 km northeast of Queanbeyan. The gorge was formed during the early Tertiary when uplift of the Cullarin Block east of the Queanbeyan Fault caused the Molonglo River to cut down and across folded north-striking quartz-turbidite sediments of Late Ordovician age (Pittman Formation). The small photos show crenulation folds, flute casts in overturned beds, and open folds. The outcrops are best viewed during periods of low flow in the Molonglo River.

Frontispiece: Red Rocks Gorge, Murrumbidgee River, 4 km southeast of Kambah Pool. The river here is incised into the Late Silurian Laidlaw Volcanics. The brownish orange surficial weathering has etched out the columnar jointing in the volcanics; this contrasts with the bluish-grey fresh rock in the river bed.

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MAP (separate, in wallet)

Canberra 1:100 000 Geological Sheet

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Abstract

The Canberra 1:100 000 Geological Sheet covers about 2500 km^2 of hilly, upland terrain in the Australian Capital Territory and southeastern New South Wales. The bedrock comprises Ordovician to Silurian sediments and acid volcanics which have been invaded by several generations of Siluro–Devonian acid and basic intrusions. Crustal evolution was from an oceanic environment characterised by turbidites in the Ordovician to a shallow-marine shelf and emerging terrestrial conditions in the Silurian represented by sediments and widespread pyroclastic flows. The sequence has been folded, faulted, and weakly metamorphosed by a series of mid Palaeozoic earth movements which have given a strong meridional trend to the geological structure. The region has been stable since the Carboniferous, apart from minor fault movements and intracratonic sedimentation associated with Cainozoic epeirogenic uplift.

Summary

The Canberra 1:100 000 Geological Sheet covers about 2500 km^2 between latitudes 35° 00′ and 35° 30′ S and longitudes 149° 00′ and 149° 30′ E in the southern part of the Lachlan Fold Belt in New South Wales and the Australian Capital Territory. The Palaeozoic bedrock (sedimentary, volcanic, and plutonic, and regionally metamorphosed to a low grade) occurs in four major fault-bounded north-trending blocks, from west to east, the Canberra, Cullarin, Captains Flat and Rocky Pic Blocks.

The Ordovician, now exposed mainly in the Cullarin Block, is represented by deep-water sediments — distal turbidites and graptolitic black shales — derived from a southerly landmass. These strata were deformed at the end of the Ordovician largely by gravity-collapse folding associated with uplift of the Wagga Metamorphic Belt west of the Sheet area.

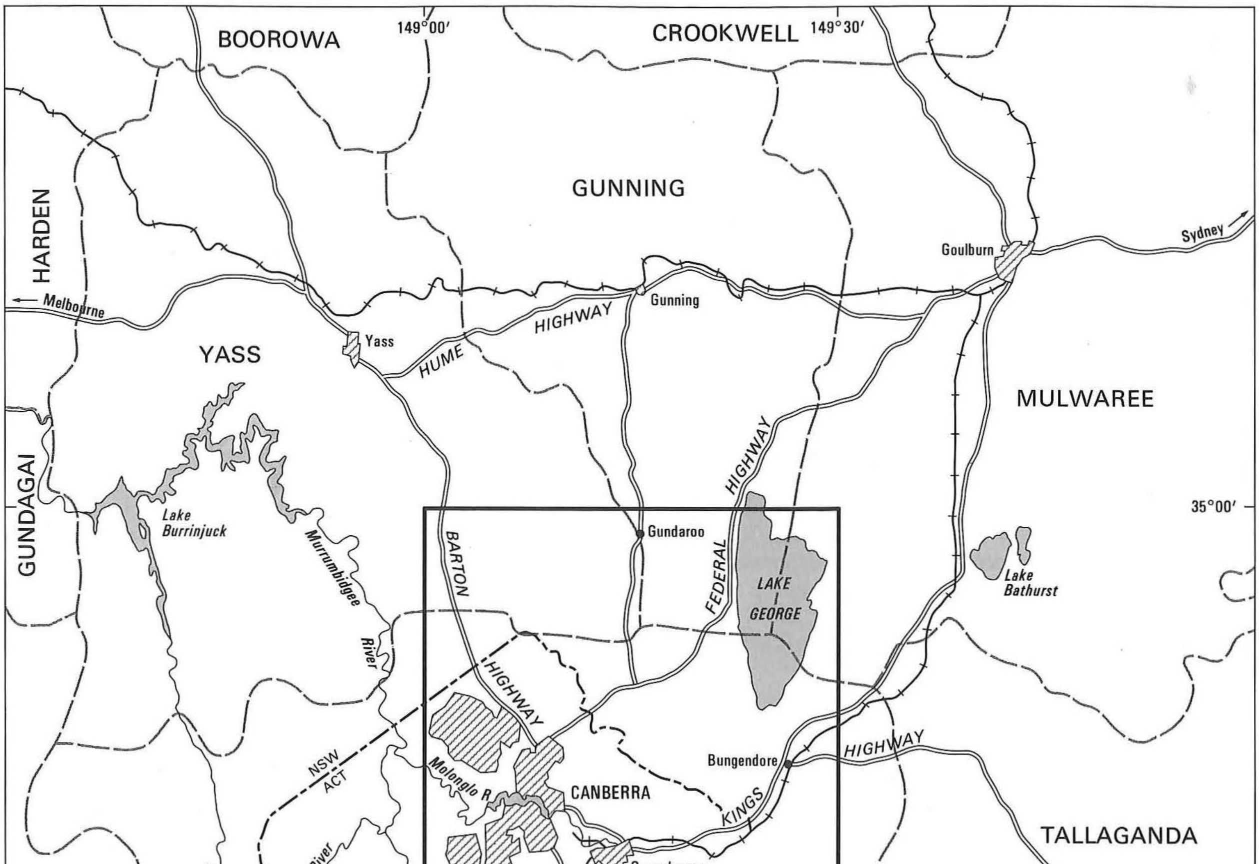
In the Early Silurian a proximal quartz-turbidite sequence derived from deformed Ordovician strata in the west was deposited disconformably on the north-trending Canberra–Yass Shelf (proto Canberra Block). Further uplift and an increase in the regional metamorphic grade to upper greenschist facies occurred at about the Llandovery/Wenlock boundary. These events were followed in the late Wenlock and early Ludlow by deposition of shallow-marine-shelf sediments and predominantly S-type felsic pyroclastic flows. At the end of the Silurian a phase of warping brought acid volcanism to a close on the Canberra–Yass Shelf, and comagmatic S and I type granitoids and acid porphyry intruded the volcanic piles.

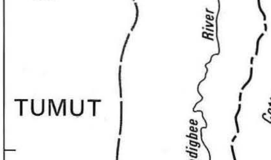
The Captains Flat Graben (proto Captains Flat Block, and part of the 'Ngunawal basin' of Bain & others, 1987) formed in the Late Silurian (Ludlow). Its strata are characterised by shale, felsic I-type primary volcanics and secondary volcaniclastics, minor basalt, and local development of proximal quartz turbidites. Evidence for an extensional regime is provided by meridional intrusions of tholeiitic dolerite and gabbro. East of the Captains Flat Graben, along the western margin of the Capertee High (regional term), I-type acid volcanics, tholeiitic basalt and proximal quartz turbidites are coeval with the volcano-sedimentary sequence in the Graben. At the end of the Silurian, sedimentation in the Captains Flat Graben was halted by mild tectonism and uplift, followed by the intrusion of I-type granitoids and east-trending dolerite dykes.

Widespread tectonism in the mid Devonian affected all Palaeozoic rocks. In the Captains Flat Block prolonged east–west compression formed tight meridional isoclinal folds and a strong cleavage-foliation. In the Canberra Block, the deformation formed more open northeast and northwest trending folds. East of the Whiskers Fault this deformation was associated with upper greenschist–lower amphibolite facies regional metamorphism. In the Late Devonian–Early Carboniferous there was movement along meridional reverse faults and later conjugate faults.

The region was stable during the late Palaeozoic and Mesozoic and an extensive peneplain developed. Epeirogenic uplift commenced in the early Tertiary, but alkali basalt flows, extruded over much of the Lachlan Fold Belt in the Tertiary, are absent from the Canberra area. During the Miocene, rejuvenation of older meridional faults allowed continental sediments to accumulate in local cratonic basins, e.g. Lake George. Unconsolidated Quaternary sediments are restricted mainly to alluvium along major drainage lines and colluvium on hillslopes.

Known metalliferous deposits are small and uneconomic. They include gold associated with the I-type Sutton Granodiorite and base metals related to Late Silurian acid volcanics. The major currently exploited mineral resource is construction materials — sand, gravel, crushed rock, and brick shale.





YASS	GUNNING	GOULBURN
BRINDA-BELLA	CANBERRA	BRAID-WOOD
TANTAN-GARA	MICHEL-AGO	ARALUEN

INDEX TO ADJOINING 1 : 100 000 MAPS

Canberra 1:100 000 Sheet area
State/Territory boundary
Shire boundary

Fig. 1. Locality map.

Introduction

The Canberra 1:100 000 Geological Sheet covers an area of about 2500 km^2 in the Southern Tablelands of New South Wales and the Australian Capital Territory. It forms the north-central part of the Canberra 1:250 000 Sheet area (SI/55–16) and is bounded by latitudes 35° 00′ S and 35° 30′ S and longitudes 149° 00′ E and 149° 30′ E. About one-third of CANBERRA* lies within the ACT and the rest is in New South Wales (Fig. 1).

This First Edition of the Canberra 1:100 000 Geological Sheet is primarily designed to provide updated geological controls for resources exploration, urban development, and education in the ACT and surrounding areas of New South Wales. Also, the rationalisation of the local stratigraphy that it embodies will assist in preparation of a Third Edition of the Canberra 1:250 000 Geological Sheet and in a wider context contribute to our knowledge of the regional geology of the Lachlan Fold Belt.

Work on the Sheet began in early 1976. Compilation of previous work and field checking were completed by late 1980, with the production of a series of 1:50 000 field compilation sheets (Abell, 1981). The text of this Bulletin is based on information available up to the end of 1988.

All map references are to the Australian metric map grid, as included in the geological map. The Sheet area is in part covered by 1:25 000 scale colour aerial photography flown in 1968 by the Division of National Mapping (now AUSLIG). Revised radiometric dates given in the text use the decay constant proposed by Steiger & Jager (1977). The geologic time scale used follows that of Harland & others (1982). The size limits for sediments are based on the Wentworth scale as tabled in Pettijohn (1957, p. 19).

Access and population distribution

Access to the surrounding area from Canberra is provided by the Federal Highway northeast to Goulburn, the Barton Highway northwest to Yass, the Monaro Highway south to Cooma, and the Kings Highway east to Braidwood and the coast (Fig. 1). The valley and gorge cut by the Molonglo River across the Cullarin Tableland afford a major trunk route from Canberra to the east by means of the Kings Highway and the Canberra–Goulburn railway. A branch line joins Canberra to Cooma via Queanbeyan. An extensive system of secondary roads has developed over much of the area in recent times as a response to increased urban growth of Canberra and Queanbeyan and flourishing smallholding developments along the NSW/ACT border. The area is well served by numerous property tracks and fire trails which open up the remoter parts such as the Googong Reservoir foreshore areas, Bradleys Creek catchment and the Lake George Range. Gates on many of these tracks are locked, and access to the public is restricted. Permission to enter can be sought from the relevant administrative organisation or property owner.

The most important population centres are the cities of Canberra (approx. 280 000) and Queanbeyan (approx. 25 000), and the township of Bungendore (approx. 1000). Smaller centres of population are at Hall, Gundaroo, Sutton, and Hoskinstown.

Climate

A warm-temperate continental climate over the Canberra region is typified by hot summers and cold winters with altitude moderating summer temperatures and lowering winter temperatures. The proximity of Canberra to the coast (120 km) means that southeasterly humid onshore sea breezes may reach inland to bring temporarily cooler or more humid conditions during summer months. General aspects of the Canberra climate are covered by McAlpine & Yapp (1969) and the Division of National Mapping (1986).

The mean yearly rainfall across CANBERRA ranges from 600–800 mm. There is little seasonality of rainfall and the mean number of rain days per year is 100. An isohyetal map (Fig. 2) based on rainfall data supplied by the Bureau of Meteorology up to 1980 shows an orographic variation in rainfall that gradually diminishes eastwards across the Canberra Plain on the leeside of the Brindabella Ranges (which are 15 km west of Canberra). Progressive urbanisation of Canberra and Queanbeyan has led in recent times to an expansion of the rainfall gauging network so that local rain shadow zones can now be detected on the eastern side of scarps and ridges, the two most notable being east of the escarpment west of the Murrumbidgee River and the Ainslie–Majura ridge. A small area of high rainfall (>750 mm) over west Canberra is due to impedance by local monadnock topography at Mount Taylor, Mount Stromlo, and Black Mountain. A local ridge of high rainfall (>700 mm) coincides with the Lake George Range. Low rainfall (<600 mm) at Hoskinstown and Queanbeyan may be a rain-shadow effect due to the westward expansion of coastal climatic influences across the Eastern Highlands during summer months and the local effects of the Ballallaba and Queanbeyan escarpments. Snow may fall during winter months but is rare below 500 m. Snowfalls occur in Canberra on average 1–3 times per year; falls are light and snow rarely lies for more than a few hours. Fogs and early morning mists in low-lying parts are most common in winter and result from nocturnal cold air drainage.

The annual mean ranges of temperature are determined largely by elevation. Mean monthly temperature ranges are 12–28°C in summer and 1–11°C in winter. Canberra has a relatively high incidence of frosts, with a mean of 77 frost days per year, and an annual mean of 7 hours of sunshine per day. There is a high frequency of northwesterly winds over the greater part of the year, with cold winter winds blowing off the alpine regions in the southwest, whereas in summer humid east to southeast sea breezes may extend inland from January to March.

Vegetation

The vegetation contains both native and introduced species. Vegetation type ranges from natural sclerophyll open forests and woodlands dominated by one or more eucalypt species to savannah grassland with patches of recent pine plantation. Natural vegetation patterns have been greatly disturbed since settlement more than 100 years ago through land clearing, grazing, burning and urbanisation. Some of the land has recovered through secondary regrowth and suburban 'greening' from new plantings. Further detail on vegetation patterns is available in Story (1969), Burbidge & Gray (1970) and the National Capital Development Commission (1984).

Warm-temperate dry sclerophyll forest and eucalypt woodland is found where rainfall exceeds 650 mm on slopes with a northerly or westerly aspect at elevations above 700 m. Typical forms are scribbly gum (*Eucalyptus rossi*), white brittle gum (*E. mannifera*), red stringy bark (*E. macrorhyncha*), and peppermint (*E. dives*). Along the Lake George range patches of grasstrees (*Xanthorrhoea australis*) occur at GR

* The names of 1:100 000 Sheet areas are printed in capitals.

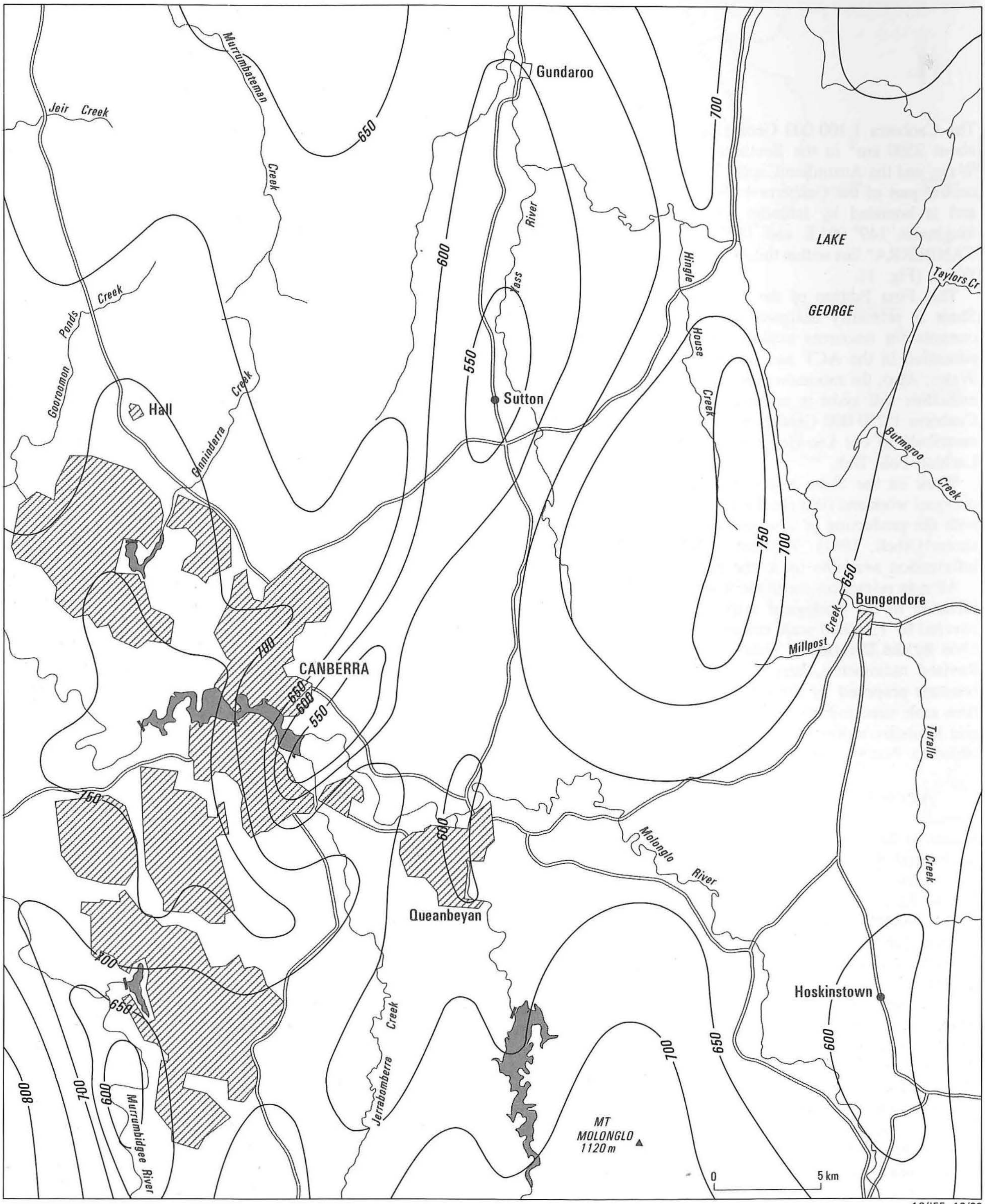


Fig. 2. Rainfall distribution.

169/087. Some of the dry schlerophyll forest has been cleared for pine plantations (*Pinus radiata*) at Mount Stromlo and Kowen. Small stands of pine have been planted to combat gully erosion and as wind breaks on properties. Open savannah woodland comprising scattered eucalypts and grassland is common around the Canberra plain, Bungendore and Hoskinstown. In this environment typical woodland trees are yellow box (*E. mellidora*), red box (*E. polyanthemos*), red gum (*E. blakelyi*) and apple box (*E. bridgesiana*).

Open savannah grassland dominated by spear grass (*Stipa* sp.) and kangaroo grass (*Themida australis*) is confined to low-lying areas with poorly drained soils. Much of this grassland has now been overtaken by urbanisation or replaced by crops. The most extensive development of this vegetational alliance is along floodplains of the Molonglo River, and at Lake George, Tuggeranong and Lanyon.

Minor but specialised vegetation communities such as the river oak (*Casuarina cunninghamiana*) develop along creeks, but in areas cleared for agricultural and pastoral use this native species has been largely replaced by the European weeping willow (*Salix babylonica*).

Soils

The genesis, classification and distribution of soils in the area has its antecedence in the geomorphological studies of Van Dijk (1959) and Woodyer & Van Dijk (1961). These authors argued for a multicyclic landscape model (K cycles) induced by climatic fluctuations to explain the soil patterns in the Canberra region. However, it is more probable that soil development is conditioned by more diverse factors such as parent material, climate, vegetation cover, landscape form and time. The distribution of soils within a 25 km radius of Canberra is summarised in the soil-landscape studies of Walker (1978) and Sleeman & Walker (1979). Soil associations have also assisted in the classification of terrain for engineering purposes (Grant, 1976). The accelerated growth in soils knowledge in recent decades has been embodied in the soil resources map orientated to land management compiled by the Division of National Mapping (1980).

The soils on CANBERRA can be broadly grouped as lithosols (skeletal soils), podzols, and alluvial soils.

Lithosols are thin stony or gravelly soils which lack pedological differentiation. They form on steep slopes and ridges where there is extensive rock outcrop and erosion is dominant. *Podzols* are duplex soils with pronounced texture-contrast profiles. They are widespread and develop best in gently undulating terrain. The older and more mature podzols may reach up to 2 m in thickness. They are red and brown clayey soils with some hardpan layering of iron. The profiles show some degree of pedological differentiation into A and B horizons. Leaching is strongly evident. The podzols are thickest in low-lying areas such as the Canberra and Bungendore Plains.

Alluvial soils occur in the lowest-lying areas, just above river level. They are loams, and show little or no profile development. They appear to reflect depositional rather than pedological processes. Layers of dark-grey organic clays are indicative of swampy conditions. Soil-forming processes may be active in older alluvial terraces away from drainage lines.

Generally there is poor correlation between soil type and parent rock. In a few instances, colour aerial photography can pick out patches of terra rossa soils on limestone and calc-silicate outcrops at Nobby Hill and Red Hill ridge and interbedded calcareous and volcanic rocks southwest of Harman Naval Base. Local krasnozems have formed over basic rocks along the Lake George Range and at Red Hill northeast of Bungendore (MR 250/082).

Land use

Partly because of the limitations imposed by climate, relief, and soils, sheep and cattle grazing is the major land use. It is estimated that about 65% of CANBERRA can be designated as pasture suitable for grazing and cultivation (grass, wheat, and fodder crops) with 15% largely higher ground taken up by natural hardwood forest and eucalypt woodland. Encroaching urbanisation has put severe pressure on the availability of rural land. Urban development accounts for about 10% of land use and with the continuing growth of Canberra there is now strong competition for land for smallholdings along the NSW/ACT border, and for recreational and water resource needs. About 6% of the area is taken up by natural or artificial lakes (Lake George, Lake Burley Griffin, Lake Ginninderra, and the Googong and Tuggeranong reservoirs). As a source of softwood to assist the building industry, pine plantations at Stromlo and Kowen account for about 3% of land use. Light industrial plant at Fyshwick, Mitchell, Hume, and Queanbeyan fulfil the service requirements of local urban communities, while manufactured products requiring heavy industry are brought into the area by road and rail from Sydney and Melbourne. Quarrying is orientated towards the construction industry and currently there is no mining activity.

Geomorphology

The Canberra Sheet area forms part of the Southern Tablelands of New South Wales. Relief is moderate, with physiographic features ranging from uplands and dissected tablelands to mature plains with wide valleys and perched alluvial basins. Undulating terrain in the northwest with isolated hills and ridges at elevations of 550–650 m rises gradually southeastwards to rugged terrain reaching locally over 1000 m; the highest point is 1120 m at Mount Molonglo (MR 108/718). The general northwest direction of the main drainage results from the position of the mapped area immediately west of the Main Divide. Most streams tend to either follow or cut sharply across the meridional tectonic grain of the underlying geology. The country is drained largely by the Molonglo and Yass drainage basins. Streams in these basins flow towards the Murrumbidgee River, which acts as a local base level. Lake George is the centre of a local basin of internal drainage.

Geomorphic units

Towards the end of the Mesozoic the Canberra region was part of a moderately dissected landscape with some uplands to the south. The present scenery originated by differential uplift of parts of this Mesozoic terrain along fault lines during the Cainozoic. The consequent rejuvenation of streams and selective erosion of rock types formed the present relief. Plains and uplands (tablelands) are the two main terrain types recognised on CANBERRA. Boundaries between them are largely fault-controlled (Fig. 3).

— *Plains* are characterised by: low-lying undulating terrain (in parts dissected); elevations of 550–750 m; residual hills and ridges; deep weathering profiles and soil development.

— *Uplands* are characterised by: broad, meridionally oriented ranges (sometimes planated) and valleys which are assumed to be dissected relics of an original Mesozoic upland; elevations from 750–1100 m; stripped weathering profiles with poor soil development.

Because of the marked structural (fault) control on physiography, the major physiographic units (Canberra Plain, Bungendore Plain, Mount Kelly Upland, Cullarin Tableland, and Rocky Pic Upland) correspond throughout much of the Sheet area with the major structural geological blocks (see Fig. 26).

Canberra Plain

Most of the western half of the Sheet area is taken up by the Canberra Plain (Strusz, 1971; Owen & Wyborn, 1979), at 550–650 m elevation. The subdued relief is almost entirely controlled by the resistance to erosion of different rock types. The undulating terrain largely reflects the softness of the underlying shale and siltstone of the Canberra Formation and interbedded sediments in the Deakin Volcanics. Monadnocks are formed by resistant rocks such as dacite, e.g. Mount Taylor (856 m) and

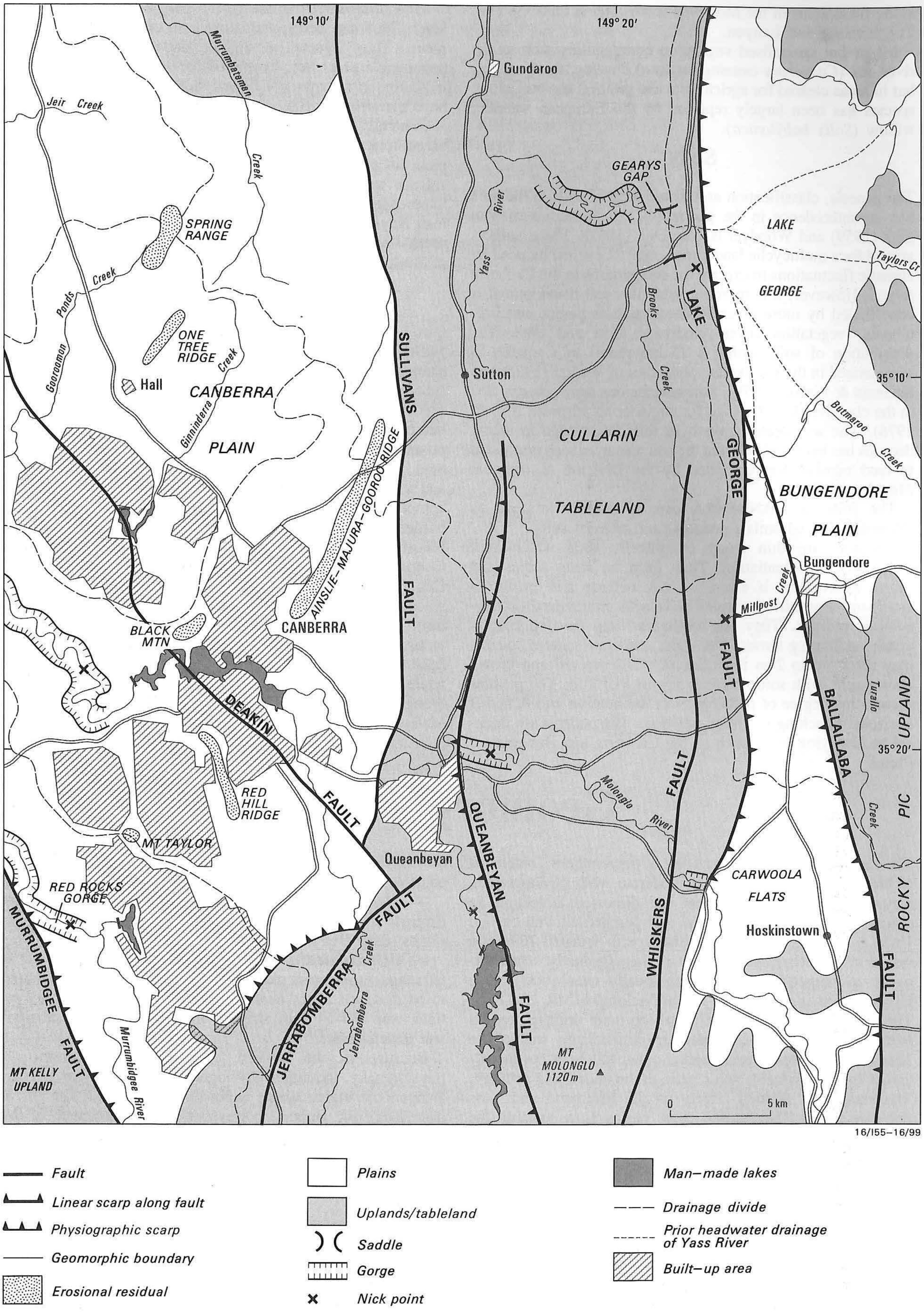


Fig. 3. Geomorphology (semi-diagrammatic).

Spring Range (886 m), while other erosional residuals are formed by the indurated quartz-rich sandstone of Black Mountain (812 m), the volcanic rocks along the Ainslie–Majura–Gooroo ridge, and hard metamorphic rocks along the Red Hill ridge (Ollier & Brown, 1975). The plain is interrupted by the incised drainage of the Murrumbidgee and Molonglo Rivers west of Canberra. Here, incision into resistant volcanic rocks has produced valley-in-valley profiles with rock-floored channels 40–60 m below the level of broad gently-sloping outer valleys. Earlier episodes of river incision are preserved as the remains of high-level gravels along the Murrumbidgee River below Pine Island and rock terraces at Red Rocks Gorge. The relatively low base level of the Molonglo River suggests there has been capture of the headwater streams of the Ginninderra and Yass drainage basins. The Canberra Plain is essentially a downfaulted area bounded on the west by the Murrumbidgee Fault and broadly on the east by the Sullivans Fault (which has only slight topographic expression). Southwest of Queanbeyan, an apparently non-fault-controlled physiographic boundary separates the mature Canberra Plain from the upland areas along a scarp of resistant volcanic rock.

Bungendore Plain

The narrow Bungendore Plain at 700–750 m is at a higher elevation than the Canberra Plain. It is a downfaulted area bounded on the west by the prominent escarpment of the Lake George Range. It is a matter of debate whether this escarpment results from Cainozoic faulting or differential erosion of exhumed relief following Palaeozoic faulting (Taylor, 1907; Garretty, 1937; Jennings & others 1964; Ollier, 1978; Abell, 1985a). To the east the boundary with the Rocky Pic Upland is partly gradational and partly coincident with a topographic break along the north-northwest-striking Ballallaba Fault. A low watershed 10 km south of Bungendore divides the Bungendore Plain into the Lake George drainage basin and the Carwoola Flats, which are drained by the Molonglo River.

The Lake George basin is a local tectonic depression representing a base level of internal drainage (Abell, 1985a). The basin margin is defined by the topographically subdued watershed of the Great Divide in the east (just east of the Sheet area) and the Lake George Range in the west. Within the basin, relief ranges from 680–900 m above sea level. The gently undulating terrain slopes gradually west towards Lake George; granitic rocks form monadnocks at Governors Hill (902 m) and Gibraltar Hill (897 m). The bed of the lake, at an elevation of ~673 m, is essentially flat (variations in the bottom topography are depicted in an early contour map produced by the NSW Public Works Department, 1903). Streams in the Lake George basin occupy wide, open valleys in their upper reaches before meandering towards Lake George across alluvial plains. Turallo Creek is locally controlled in its higher reaches by meridional structures in the underlying geology. Only minor creeks enter the basin from the Lake George Range, the most important being Millpost Creek. The Lake George Range is a wall-like escarpment reaching over 200 m above the lake bed; the Range gives way gradually to more subdued topography south of the Bungendore–Gundaroo road. Gearys Gap is a broad saddle which at its lowest point forms a shallow V-shaped notch about 500 m wide, 30–40 m above the lake bed. Still higher, and extending about 4 km along the scarp, a wider depression contains relict fluvial deposits of quartz gravel. The lower notch may have been a Late Quaternary overflow point for Lake George when it was 37 m deep (Coventry, 1976), whilst the higher depression is the remains of the old Yass River valley prior to its truncation by faulting (Taylor, 1907; Ollier, 1978). Changes in direction of the Lake George escarpment are related to processes and rates of westward scarp retreat from a meridional fault zone passing beneath a cover of unconsolidated sediment in Lake George and environs. The curvature (in plan) and steepening of the escarpment adjacent to Lake George is attributed to lake-shore abrasion at times of high lake levels in the Late Quaternary (Jennings, 1972; Coventry, 1976). A nick point on a small creek south of 'The Grove' homestead (MR 167/113) at an elevation of 716 m may be associated with Late Quaternary slope trimming. About 4 km northwest of Bungendore the scarp changes direction by 30° and trends south towards Carwoola Flats. This section has not been steepened by lake shore erosion and the terrain is more mature and rounded. The slight curvature of the scarp is probably due to headward erosion by Millpost Creek. A nick point on this creek at an elevation of 760 m may be related to mid-Tertiary fault-line rejuvenation.

The Carwoola Flats represent a local base level for the Molonglo River. This lowland area at an elevation of ~740 m is a narrow floodplain with terrace development which widens out into an embayment with incipient drainage north of 'Carwoola' homestead. The diminished expression of the Lake George escarpment and the absence of a nick point in the Molonglo River where it leaves the Carwoola Flats at MR 160/808, suggest only minor reactivation of the Lake George Fault. The flood plain is otherwise limited by clusters of rounded hills southwest of Hoskinstown.

Mount Kelly Upland

The Mount Kelly Upland is mainly on BRINDABELLA (Owen & Wyborn, 1979). On CANBERRA it is represented along the Bullen Range (800–900 m) by Ordovician metasediments and resistant granite of the Murrumbidgee Batholith. It is bounded by a prominent escarpment along the Murrumbidgee Fault.

Cullarin Tableland

The Cullarin Tableland — part of the Tinderry–Gourock Highlands of Strusz (1971) — is a dissected plateau which slopes gradually northwards from elevations of 1000 m to elevations of 750 m. It is bounded to the west by the Sullivans Fault, although in the south this boundary extends well to the west of the Jerrabomberra Fault. The eastern boundary is taken as the Lake George Fault. Drainage modifications west of the Lake George Range relate to Cainozoic faulting and block tilting. Brooks Creek west of Gearys Gap was once part of a much enlarged Yass River headwater system subsequently truncated by uplift on the western side of the Lake George Fault. Brooks Creek currently maintains an entrenched westward course across the Cullarin Tableland and joins the Yass River south of Gundaroo. Gearys Gap, the site of the original course of Brooks Creek, remains as a wind gap. Brooks Creek has incised its course and extended its catchment southwards parallel to the Lake George escarpment. It now has a prominent right-angled bend about 2 km northwest of Gearys Gap. On the other hand the Molonglo River has eroded its bed to keep pace with uplift. The antecedent course of the river occupies an incised valley where it crosses the Cullarin Tableland. Gorges have formed where the river leaves the Bungendore Plain and where it enters the Canberra Plain. Dissected hills formed mainly from volcanic rock close off the Canberra Plain between Queanbeyan and Tharwa. Youthful relief is indicated by the entrenched Queanbeyan River and nick points in tributary creeks where they cross the Queanbeyan Fault, and also on Jerrabomberra Creek before it flows across the Canberra Plain.

Rocky Pic Upland

The Rocky Pic Upland in the east of the Sheet area consists of hills and low meridional ridges bordered to the west by a low escarpment along the Ballallaba Fault. Streams draining this upland flow westwards from the crest of the Main Divide to join the Molonglo River or northwards into the closed Lake George drainage basin.

Landscape evolution

Andrews (1910), Taylor (1911), and Woolnough (1927) attributed relief features in southeast Australia to polycyclic erosion of an extensive Miocene peneplain uplifted by intermittent epeirogenesis and block faulting in the Late Tertiary. In descriptions of the physiography of the Shoalhaven River valley and the Monaro, Craft (1932, 1933a and 1933b) argued for greater stability in the landscape and demonstrated that Tertiary basalts could be used to interpret a landform history extending back over a long period. Identification of pre-basaltic surfaces in the landscape showed the existence of dissected and undulating relief that had evolved through warping and cycles of fluvial activity. The oldest part of the landscape (the Monaro land surface) at about 1000 m was considered to be Late Palaeozoic or Early Mesozoic in age, with younger surfaces recognised at lower levels. Subsequently Van Dijk (1959) and Woodyer & Van Dijk (1961) attempted long-range correlation of Craft's erosion cycles in the Shoalhaven valley by identifying four pediplanated land surfaces in the Molonglo and Yass river valleys. In the Canberra region remnants of Craft's Monaro land surface have been equated with continuity of level of landforms at altitudes of about 1000 m (Browne, 1969). However, the hills, ranges and low-lying undulating topography on CANBERRA cannot be consistently equated with any specific land surfaces. Uplift histories and erosion rates may differ in adjacent areas and some surfaces may be local base levels determined only by the effects of faulting and erodibility of the rocks.

The regional landscape in southeastern Australia is essentially a plateau that was uplifted when Tasman Sea rifting occurred about 80 Ma ago. Further modifications have been affected by faulting and volcanic activity. The plateau has also been differentially eroded by ancient drainage lines that have become increasingly adjusted to the meridional structures in Palaeozoic bedrock. However, in the Canberra region there was renewed movement along meridional faults in the Miocene to give local rifting and rejuvenated landscapes with linear escarpments, incised drainage and stream capture. The interpretation by Öpik (1958) that Canberra landforms reflect survival of an Early Palaeozoic landscape is therefore untenable (Jennings, 1972; Ollier & Brown, 1975). Renewed landscape dissection on CANBERRA in the mid Tertiary is also evidenced by the Early Miocene age (22–18 Ma) of nearby basalts which occur as small remnants on watersheds (Wellman & Mcdougall, 1974) or are displaced by faults (Wyborn & Owen, 1986). Other evidence of landforms dating from the Miocene is provided by a sequence of Late Miocene–Pleistocene sediments which overlie a deep weathering profile of mid Tertiary age in the fault-angled depression of the Lake George basin.

Previous investigations

Geological interest in the Canberra Sheet area began about the mid-19th century when The Rev. W.B. Clarke, travelling through the Southern Tablelands of New South Wales, collected some of the first Silurian fossils found in Australia from shales (now assigned to the Canberra Formation) exposed in the Duntroon area (de Koninck, 1898; Etheridge & Mitchell, 1916; Mitchell & Dun, 1920). After these early reconnaissance expeditions geological work became largely economic in emphasis, following a suggestion in 1852 by Clarke (1860) that the Gundaroo–Sutton district would be a prospective area for gold. This eventually led to a minor gold rush to the Bywong area in the late 19th century, reported on by Carne (1896). The physiography of the Canberra region was considered at an early stage largely through curiosity aroused by Lake George (Russell, 1886) and the prominent meridional scarp on the western side of the lake. Federation, when proclaimed in 1901, led to the establishment of the ACT and Canberra as the national capital of Australia; these new developments prompted more detailed geological studies in the Canberra district (Taylor, 1910; Pittman, 1911; Mahoney & Taylor, 1913; Taylor, 1914). After these early investigations little was accomplished in the Sheet area for the next 35 years except for geological mapping east of Lake George (Garretty, 1936). However, the post World War II urban growth of Canberra created a need to update geological controls in the local region (Öpik, 1958). These investigations provided a stratigraphic synthesis and geological history for the Palaeozoic rocks which is embodied in the First and Second Editions of the Canberra 1:250 000 Geological Sheet (Joplin & others, 1953; Best & others, 1964; Strusz, 1971).

Since the early 1960s there has been an explosion of geoscience information dealing with CANBERRA. University theses, mining and mineral exploration activities (unpublished reports held by the Department of Minerals & Energy, Sydney), and detailed mapping in support of engineering geology investigations (held mostly in the BMR *Records* series) formed the basis of the First-Edition Canberra 1:50 000 geological map (Strusz & Henderson, 1971). Since 1971, geological mapping has concentrated on clarifying the stratigraphy of the volcano-sedimentary rocks of the Canberra Block. Petrographic and chemical methods for delineating Late Silurian volcanic units on BRINDABELLA (Owen & Wyborn, 1979) were successfully applied to volcanic rocks on CANBERRA in the late 1970s. This led to a more comprehensive Second Edition of the Canberra 1:50 000 geological map (Henderson, 1980) and a better understanding of Late Silurian sequences on BRAIDWOOD, MICHELAGO, and ARALUEN.

Stratigraphy

A major purpose of the most recent mapping was to rationalise the lithostratigraphic nomenclature for the Sheet area. It was found initially that over 60 named units had been or were in current use. In many cases the units had been granted formal status only by virtue of publication. Most lithostratigraphic units had descriptive detail but none had been systematically defined on CANBERRA, although some had already been defined on MICHELAGO, BRAIDWOOD and ARALUEN. Where these units extend onto CANBERRA, supplementary information has been used to refine their definitions. The lithostratigraphic nomenclature and definition of units follow as far as possible the guidelines set out by Staines (1985).

Undefined or invalid units are printed in quotation marks.

Geologically, the Sheet area can be conveniently divided into four major structural elements, with a strong meridional tectonic 'grain': the Canberra Block (Owen & Wybom, 1979), the Cullarin Block, the Captains Flat Block, and the Rocky Pic Block (Fig. 26). The Canberra Block, in the west, consists essentially of Silurian volcanic and sedimentary rocks; the Cullarin Block is formed from an Ordovician turbidite succession; the Captains Flat Block, like the Canberra Block, contains a Silurian volcano-sedimentary succession; and the Rocky Pic Block, at the eastern edge of the area, has both Ordovician and Silurian components. Granitoid and other intrusions occur in all four blocks.

Pre-Ordovician

The oldest rocks exposed on CANBERRA are Ordovician. There is conjecture as to the nature, composition and age of the rocks that may underlie the Ordovician. According to Crook & others (1973) the southern part of the Monaro Trough is underlain by oceanic crust with an age 'probably not older than early Cambrian'. In a later paper Crook (1980) outlines evidence for a more widely occurring oceanic substrate beneath the Palaeozoic in the Tasman Geosyncline. Alternatively, the complexity of the crustal geology can be inferred from the distribution of S and I-type granitoids derived respectively from the partial melting of crystalline metasedimentary basement and mantle-derived igneous basement (Chappell & White, 1974). According to White & others (1976) the chemical data on S and I-type granitoids in the Berridale area suggest a crystalline basement of continental-type crust underlying the Ordovician turbidite sequence. From an analysis of major elements, Wybom & others (1979) have deduced that a plagioclase-rich sedimentary layer of supposedly late Precambrian to Cambrian age underlies the Ordovician quartz-rich greywackes in the Lachlan Fold Belt and was the source of the S-type granitoids. Geophysical evidence (Finlayson & others, 1979) also indicates a complexly layered pre-Ordovician base, as the velocity/depth structure deduced from explosion seismic profiles across the Lachlan Fold Belt shows considerable vertical and lateral inhomogeneity in the continental crust. Although the prevailing view at present is that continental Precambrian crust underlies the Ordovician, there is no direct evidence yet for the nature of this basement, and the underlying crust may be of a transitional nature or perhaps partly oceanic and partly continental (Cas & others, 1980).

Ordovician

Quartz-rich turbidites of Ordovician age form most of the rock outcrop on CANBERRA. The outcrop belts coincide with fault-bounded meridional blocks which were once part of an extensive depositional basin, the Monaro Basin, also termed Monaro Slope & Basin by Scheibner (1973) (see also series of palaeogeographic sketches at right-hand edge of map sheet), that developed east of the Molong Volcanic Arc (Owen & Wybom, 1979). The sequence comprises interbedded sandstone, siltstone and shale, typical of a turbidite fan complex and now deformed and metamorphosed. Black siliceous shale beds are relatively common, but chert is rare. Turbidity current structures include graded bedding, sole markings, plane laminations, small-scale cross-bedding and various slump structures; most beds show elements of the Bouma sequence (Bouma, 1962).

These Ordovician rocks range in age from Darriwilian or older to early Bolindian, i.e. from Middle to Late Ordovician (~470–440 Ma). The base of the sequence is not exposed and the sequence is overlain disconformably by Early Silurian sediments and with marked angular discordance by later Silurian sediments and volcanics. The Ordovician rocks in the Canberra region consist of a number of lithologically similar units, e.g. Pittman Formation, Birkenburn beds, etc. These units have similar lithostratigraphic positions, have approximately the same age based on the sparse faunas so far recovered in the black shale beds, and belong to a widespread suite of thick distal turbidite deposits. Regional correlations for Ordovician lithostratigraphic units are given by Webby (1981).

Adaminaby beds (Oa)

The Adaminaby beds have been described in detail on MICHELAGO (Richardson, 1979) and BRINDABELLA (Owen & Wybom, 1979) where they crop out over an extensive area. On CANBERRA, the beds form a wedge-shaped outcrop area about about 2 km wide near Kambah Pool, at the southeast end of a narrow belt extending on to CANBERRA from BRINDABELLA. The belt forms part of the Canberra Block (Fig. 26).

The beds are marine turbidite sediments. The best exposures are in creek sections in hills à few kilometres north of 'Freshford' homestead (MR844/765). The sequence has been hornfelsed by the Murrumbidgee Batholith, forming resistant outcrops along the Bullen Range. A sedimentary raft in a marginal intrusion of the batholith at MR 821/703 is a probable correlative of the Adaminaby beds. The thickness of the beds is unknown because of faulted boundaries with other units.

Neither the base nor the top is exposed. The eastern contact with the Laidlaw Volcanics is along the Murrumbidgee Fault; the western contact with the Murrumbidgee Batholith is both faulted and intrusive. However, on BRINDABELLA, the Adaminaby beds have been mapped as unconformable beneath the Early Silurian Tidbinbilla Quartzite and Late Silurian Paddys River Volcanics. From the graptolite faunas on BRINDABELLA the age of the beds is late Eastonian to early Bolindian (i.e. ~455–450 Ma old). On the basis of similarities in lithology, facies development, age, and relationships with other stratigraphic units, the Adaminaby beds are considered a correlative of the Pittman Formation.

Pittman Formation (Op)

Derivation of name. Defined and named by Öpik (1954, 1958) in creeks (including Etheridge Creek) in Pittman Valley, between Black Mountain and Mount Painter, southeast of the Canberra suburb of Aranda.

Nomenclature. Öpik (1954, 1958) named the Pittman Formation and Acton Shale for Late Ordovician sediments around Canberra. In the Cullarin Block, Phillips (1956) named Ordovician sediments in the Queanbeyan area as the 'Murriara Formation'; this name was retained by Moore (1957) to cover a northward extension of these rocks between Queanbeyan and Sutton. Farther east, Glasson (1957) introduced the 'Beverly

Beds' and 'Railway Slates' to describe Ordovician flysch and black slate beds west of Captains Flat, a terminology that was formalised by Glasson & Paine (1965). Oldershaw (1964, unpublished) named similar Ordovician rocks between Captains Flat and Hoskinstown the 'Foxlow beds', with the 'Bullongong Shale' as a member introduced for the black graptolitic slates. These Ordovician units of Oldershaw were extended northwards to the Farrar–Hoskinstown area by Wilson (1964). This informal and unpublished but by then apparently accepted terminology led Stauffer & others (1964) to extend Oldershaw's stratigraphy over an even wider area by naming the Ordovician east of Queanbeyan the 'Foxlow beds', in anticipation of formalisation of the name by Oldershaw (1965) in his published report on the Captains Flat area.

The introduction of the 'Foxlow beds' and 'Bullongong Shale Member' by Oldershaw unnecessarily complicated stratigraphic terminology in the Captains Flat area. In retrospect, there was no need for these names, as opportunity already existed to extend and define the informal stratigraphy of Glasson (1957). Contrary to Richardson (1979), the arguments are compelling enough to support Glasson & Paine's published stratigraphy (1965) as having precedence over that of Oldershaw (1965). However, since neither Glasson nor Oldershaw defined or even nominated type areas, it is recommended where appropriate on CANBERRA that the name 'Foxlow beds' be discarded or otherwise treated as synonymous with the Pittman Formation as introduced by Öpik (1954).

Distribution. On CANBERRA the Pittman Formation crops out over the full length of the Cullarin Block. In the northern part of the block the formation reaches an outcrop width of 25 km, narrowing to 7 km at the southern edge of the Sheet area. On the Canberra Block a faulted wedge-shaped inlier tapering northward occurs in the east Belconnen area of Canberra. A small triangular outcrop of Ordovician rocks extending onto CANBERRA from MICHELAGO immediately west of 'Foxlow' homestead (MR 215/698) is also assigned to the Pittman Formation. The eastern limit of the Pittman Formation on CANBERRA is taken to be along the line of the Whiskers and Lake George Faults where the formation has been juxtaposed with Late Silurian rocks of the Captains Flat and Rocky Pic Blocks.

Reference sections. The type section designated by Öpik (1958, table 1) in the bed of Etheridge Creek is at approx. MR 906/957. This section, with a measured thickness of 52 m and a total estimated thickness of about 73 m, has now deteriorated badly with overgrowth of vegetation, logs dumped in the creek to avert gully erosion and disposal of industrial waste; only the more resistant sandstone and chert beds can be located with confidence. Considering the condition of the section, the limited range of lithologies represented and the lack of boundary relationships, this section now has little more than reference status. According to Öpik (1958), the section is representative of the middle part of the Pittman Formation, corresponding to the upper half of the Middle Ordovician. Nicoll (1980) recovered a small conodont fauna of *Pygodus serrus* and *Periodon aculeatus* from bed 14, which indicates that the lower part of Öpik's section is middle to late Llanvirn in age. To supplement the information at Etheridge Creek, brief descriptions are given below for other reference sections in the Pittman Formation.

Outcrops of fresh, resistant Ordovician rocks assigned to the Pittman Formation are exposed in the Molonglo Gorge, northeast of Queanbeyan (front cover). The section extends for some 2 km upstream from a recreational area at MR 044/878 (elev. 580 m) at the foot of the Queanbeyan Fault escarpment to the Blue Tiles barbecue area at MR 066/872 (elev. 680 m). The section is also well exposed in the railway cutting on the south side of the gorge. The almost continuous section comprises a strongly folded turbidite sequence of interbedded sandstone, siltstone and shale. Turbidity current deposition is indicated by a wide assortment of sedimentary structures such as graded bedding, sole markings and small-scale current bedding. Further detail on the section is given in Owen (1987).

On the southern side of a road cutting at the eastern end of Ginninderra Drive at approx. MR 915/980, a weathered sequence of sandstone and shale is exposed over a length of 440 m. Thick sandstone–shale interbeds at the western end of the section give way in the middle to easterly dipping beds of brown shale and leached dark-grey siliceous shale. The grey shale has yielded conodonts of an age similar to that of the Pittman Formation in Etheridge Creek (R. Nicoll, pers. comm., 1982). Throughout the length of the section, sandstone units appear to have been repeated by folding, disrupted by faults or detached through slumping.

A turbidite sequence with meridional strike crops out along the incised downstream portion of Brooks Creek where it crosses the Cullarin Block. The exposed straight-line length of the section is about 6 km. The sediments are intruded by small bodies of quartz-feldspar porphyry. Open folds are well displayed in the western and middle portions of the section.

Lithology. The Pittman Formation consists of quartz-rich sandstone, siltstone and shale with minor occurrences of black shale, chert and impure calcareous sandstone. No volcanic debris has been recorded. The sequence has been regionally metamorphosed to quartzite, phyllite, psammitic and pelitic schist, local beds of calc-silicate rock and narrow zones of knotted schist. Spotted and biotite hornfelses occur in a zone of contact metamorphism around the Sutton Granodiorite.

For descriptive purposes the turbidite deposits are subdivided into beds of proximal aspect, beginning with Bouma divisions A and B, in which thickly bedded sandstone grades up into thinner beds of siltstone and shale, and more common beds of distal aspect, beginning with Bouma's division C, showing thinly bedded rhythmic alternations of fine-grained sandstone, siltstone and shale. These subdivisions are gradational and are not mappable field units.

The sandstones consist of a framework assemblage of variably sorted sub-rounded clasts of quartz, with subordinate amounts of feldspar, rock fragments and detrital mica. Monocrystalline and polycrystalline varieties of quartz occur, and most grains are strained. Where the rock has been deformed, the quartz clasts have been flattened and aligned along shear planes; in some places augen have developed. Feldspar clasts consist of plagioclase with albitic twinning, and grey untwinned or perthitic potash feldspar. Rounded rock fragments up to 2 mm consist mainly of shale and quartzite. Mica occurs mainly as detrital laths of muscovite up to 3 mm long. The framework clasts are set in a fine-grained matrix of phyllosilicates (biotite, muscovite and chlorite), quartz, feldspar, opaque iron oxide, and rounded grains of accessory tourmaline (some reaching 1 mm in diameter) and zircon. The matrix has responded to deformation by alignment of muscovite laths along cleavage planes. The low percentage of rock fragments is evident in modal analyses for sandstones assigned to the Pittman Formation in the Gundaroo–Nanima area by Smith (1964). In other parts of the Cullarin Block the sandstone grades towards arkose. The angularity and poor bimodality of the framework quartz, and the feldspar and clay matrix, indicate that the sandstones are texturally immature and represent a first-cycle turbidite deposit.

Argillaceous sediments interbedded with the sandstones vary from pale-grey when fresh to pale-brown when weathered. Sedimentary banding is represented by laminae; rare sedimentary structures are indefinite cross laminations and contorted bedding. The sediments show a lepidoblastic texture comprising augen of quartz and feldspar set in a fine-grained matrix of biotite and muscovite (now altered to chlorite and sericite). Accessory minerals are opaque iron oxides and traces of detrital tourmaline and zircon.

Radiolarian chert beds occur towards the top of the Pittman

Formation. They have been described in the Canberra district (Öpik, 1958) and the Gundaroo–Nanima area (Smith, 1964), and at a few localities along the eastern margin of the Cullarin Block (Stauffer, 1964). The cherts are discontinuous, grading laterally into argillite beds, and are stratigraphically associated with black siliceous shale beds. They are laminated with a weak colour banding varying from pale grey or green to white. The thickness of individual beds is usually 5 cm but may range up to a metre or more. The cherts are composed of cryptocrystalline quartz with accessory muscovite and black iron oxide. Small, rounded bodies of recrystallised quartz up to 0.5 mm in diameter are replacements of radiolaria. The chert beds are probably products of chemically precipitated silica in a deep-water pelagic environment.

Boundary relationships. The base of the Pittman Formation is not exposed on CANBERRA. Originally Öpik (1958) regarded the Pittman Formation as unconformable on the Black Mountain Sandstone and conformable beneath the Acton Shale. From detailed mapping of boundary relationships in the Black Mountain area, Strusz & Henderson (1971) and Crook & others (1973) deduced the presence of an unconformity from the discordance in bedding and fold attitudes between the Pittman Formation and the Early Silurian State Circle Shale. More recently, Henderson (1980) has identified this boundary as a disconformity in the north Belconnen area of Canberra and Jerrabomberra Hill near Queanbeyan. A slight unconformity is inferred from the discordance in dip between the Pittman Formation and the Early Silurian Murrumbateman Creek Formation in the Gundaroo–Nanima area. On MICHELAGO, Richardson (1979) shows that the upper part of the 'Foxlow beds' (Pittman Formation) progressively cuts out southwards to Colinton Hill, where the Early Silurian Ryrie Formation is in unconformable contact with siliceous black shale.

Unconformable contacts with high angular discordance can be demonstrated between the Pittman Formation and later Silurian rocks. At Acton in central Canberra, Henderson (1979a) described the Canberra Formation (late Early Silurian) as resting unconformably on the Pittman Formation with high angular discordance in a temporary exposure uncovered during the construction of the Molonglo Parkway. Photographic evidence exists for an unconformity described by Richardson (1979) from a site on Burra Creek now covered by the headwaters of Googong Reservoir, where the Cappannana Formation (Late Silurian) discordantly overlies the Pittman Formation. In the Captains Flat Block the Rutledge Quartzite (basal member of the Late Silurian Copper Creek Shale) rests with apparent unconformity on the Pittman Formation at Rutledge Hill and Grose Meadow Hill (MR 168/701 and MR 204/722). Apart from these unconformable relationships, it is more usual for the Pittman Formation to be in contact with Silurian sedimentary and volcanic rocks along meridional faults developed at the margin of the Cullarin and Rocky Pic Blocks.

Thickness. According to Henderson (1981), the Pittman Formation is estimated to have a thickness in excess of 800 m in the Canberra district. Further north, a substantial increase to 2650 m is reported by Smith (1964) in the Gundaroo–Nanima area. Oldershaw (1965) records a thickness >1200 m for the 'Foxlow beds' (regarded in this study as a continuation of the Pittman Formation) in the Captains Flat area. Accurate measurement is prevented by strong folding, faulting and stratigraphic complexity. A realistic estimate of total thickness is not possible since much of the Pittman Formation is a present-day erosion surface and the base of the formation has yet to be defined.

Environment of deposition. The sedimentological features of the Pittman Formation suggest turbidity flow deposition in a marine basin far removed from source areas. The high proportion of B, C, D and E units of the composite Bouma profile, the fine grainsize of the massive sandstone beds and the proximality index (Crook & others, 1973) are indicative of the more distal elements of the submarine fan model of Walker (1984, fig. 15). Graptolite and radiolarian fossils in black shales and cherts indicate pelagic conditions occurred near the top of the Pittman Formation. Sedimentary structures show sediment flow patterns with a northerly transport direction, supporting suggestions made by Owen & Wyborn (1979) and Cas & others (1980) for a sediment source to the south (i.e. what is now the Antarctic region).

Age. According to Öpik (1958), the Pittman Formation in the Canberra district is Middle Ordovician, ranging in age from Darriwilian to Gisbornian. The lowest graptolite horizon identified by Öpik contained *Phyllograptus anna*, *Trigonograptus ensiformis*, *Pterograptus*, *Didymograptus*, *Isograptus* and *Hallograptus*, corresponding to Zone 5 of the British Ordovician sequence, i.e. late Arenig, equivalent to the earliest Darriwilian.

Near the top of the formation a different assemblage was recorded, including *Dicellograptus sextens* and *D. divaricatus salopiensis*, indicating a Gisbornian age. Öpik's upper age limit was restricted by the Acton Shale Member, which he regarded as a distinct unit conformably overlying the Pittman Formation. Subsequently, Smith (1964) and later Strusz & Henderson (1971) showed that the black siliceous shale beds in the Gundaroo–Nanima area and in Belconnen were overlain by sandstone similar to that of the Pittman Formation. With the redefinition of the Acton Shale as a member of the Pittman Formation, the upper age of the formation can now be extended to the early Bolindian (Webby, 1981).

The available fossil evidence also indicates a hiatus of 5–10 million years at about the Ordovician/Early Silurian boundary. The earliest known graptolites in the Early Silurian State Circle Shale belong to zones 22 and 23 of the British Early Silurian, zones 16–21 (Rhuddanian, Idwian and lower Fronian Stages) not being represented. However, the actual gap in sedimentation may be smaller because strata which may in future yield fossil remains occur above the known graptolite horizons near the top of the Pittman Formation in the Canberra district (Henderson, 1980).

Correlation. The Pittman Formation is the only formal stratigraphic name that can be applied to the Ordovician on CANBERRA. This unit represents part of Packham's (1969) Late Ordovician quartz-rich greywacke association which is widespread in New South Wales. This study also supports views expressed by Phillips (1956) and Smith (1964) that the Ordovician sequence in the Cullarin Block is similar to the Pittman Formation in the Canberra City area. Since the Pittman Formation has an age and range of rock types similar to those seen in Ordovician outcrops at the western and eastern margins of the Sheet area it is also a probable correlative of the Adaminaby and Birkenburn beds. Furthermore, Hughes (1971) and Holloway (1972) describe Eastonian graptolites from black shales in the 'Jerrawa beds', suggesting a northward continuation of the Pittman Formation into the Yass area.

Acton Shale Member (Oua)

Derivation of name. After the suburb of Acton, Canberra, ACT.

Nomenclature. Öpik (1958) regarded his Acton Shale as a distinct formation conformably overlying the Pittman Formation. From detailed mapping of the Pittman Formation in the Belconnen area of Canberra, Strusz & Henderson (1971) were able to redefine the Acton Shale as a member high in the Pittman Formation. In the Gundaroo–Nanima area, Smith (1964) followed Öpik's interpretation by mapping an assemblage of chert, black siliceous shale and sandstone conformably overlying the Pittman Formation, which he informally called 'Picaree Formation'; the base of this unit was taken 'at the first persistent black slate band'. The 'Picaree Formation' subsequently became formalised when published on the Second

Edition of the Canberra 1:250 000 Geological Sheet (Best & others, 1964). Since this unit has never been properly defined and the black siliceous shale contained within it is a probable continuation of the Acton Shale Member, continued use of the name is not recommended.

Distribution. Black graptolite-bearing shale beds in the Pittman Formation crop out at widely-spaced locations across CANBERRA. In many places these rocks are resistant enough to form low ridges extending along strike for up to 8 km in the Queanbeyan area, and distinctive enough to form marker horizons outlining minor fold structures in the Gundaroo–Nanima area (Smith, 1964) and the Canberra district (Henderson, 1980). A common distribution of this black shale lithology is as a series of disconnected linear outcrops along the western margin of the fault-bounded Cullarin Block. A few scattered outcrops correlated with the Acton Shale Member occur in the Lake George Range between Gearys Gap and the Bungendore–Gundaroo road. The most prominent is a linear exposure on top of the escarpment extending 2.5 km north of Forrest View Estate.

Type locality. The original type locality given by Öpik (1954, 1958) was the old racecourse at Acton, the site of which is now mostly inundated by Lake Burley Griffin. At this locality Öpik described the Acton Shale as a siliceous black shale over 60 m thick, conformably overlying the Pittman Formation. Poorly preserved but abundant graptolites, rare brachiopods, conodonts and sponge spicules indicated an Eastonian age for this unit. Exposures of the Acton Shale Member in this vicinity have been restricted further by the construction and landscaping of the Molonglo Parkway. All that now remains are scattered outcrops along an old track on a hillside immediately south of the ANU Staff Centre (MR 923/925). At this new type locality (Owen, 1987), the Acton Shale Member is exposed as a low rubbly outcrop of thinly laminated siliceous black shale which has weathered to light-grey or buff. The dip is 20° to the east and bedding is distinct. Fossils are not clearly evident.

Supplementary reference localities for the Acton Shale Member in the Canberra district are the few isolated outcrops on ridges east of Aranda suburb (Owen, 1987), along a northeast-trending ridge from Belconnen Naval Station to Gungahlin Hill and in the vicinity of Lake Ginninderra (Henderson, 1980). Exposures of black siliceous shale also occur in a quarry near the Gundaroo–Murrumbateman road at MR 937/215, and in the vicinity of Picaree Hill (MR 963/231).

Lithology. The Acton Shale Member is a thinly-laminated siliceous shale which is pale-black where fresh and a patchy whitish-grey where weathered. A strong cleavage normally parallel to the bedding imparts a strong fissility to the shale. Graptolites are preserved on bedding planes as black carbonaceous films on fresh surfaces, and white micaceous or rust-coloured films of iron oxide on weathered surfaces. The shales consist largely of cryptocrystalline quartz, fine sericite laths and black carbonaceous matter aligned sub-parallel to the cleavage; pyrite is the main accessory. Banding in the rock is caused by quartz and phyllosilicate-rich layers alternating with carbon-rich layers. Shearing has also recrystallised and segregated the quartz into augen and discontinuous layers. A chemical analysis of these rocks given in Smith (1964) shows that silica accounts for 80 percent. This analysis confirms the results given by Joplin (1945) for similar rocks in the Canberra region and at other localities in New South Wales.

Boundary relationships. The Acton Shale Member is conformable within the upper part of the Pittman Formation. An apparently unconformable relationship exists with the Silurian where steeply dipping black siliceous shale is overlain with disrupted contact by the Colinton Volcanics along the old Cooma road south of Queanbeyan (MR 024/800). Along the same road 1.3 km to the south (MR 018/789) a discordant, near-vertical contact can also be observed between the same rock units (Henderson, 1981).

Thickness. Henderson (1981) estimates a thickness of up to 60 m in the Canberra district. The thickness of other black siliceous shale beds in the Pittman Formation that are probable correlatives of the Acton Shale has been estimated at up to 60 m in the Gundaroo–Nanima area (Smith, 1964), at least 30 m near Queanbeyan (Phillips, 1956) and up to 200 m in the Googong area (Goldsmith & Evans, 1980).

Environment of deposition. The black siliceous shales appear to be associated with the more distal elements of the submarine fan model proposed by Walker (1984). According to Smith (1964) black shales are the products of local deposition in a reducing environment in sea-floor depressions. This view was followed by Crook & others (1973) who described similar rocks as accumulating 'in depressions between adjacent submarine fans in areas inaccessible from all but the finest terrigenous material'. It is probable that the black shales were deposited in association with distal outer fans on the abyssal plain or locally within proximal zones such as inner fan levées or abandoned feeder channels. Small pulsatory earth movements would cause slumping and higher energy conditions for turbidity currents to locally shed fine clastic quartz, derived from surrounding turbidites, into these low-energy environments. The abundance of graptolites in these sediments is taken to mean that the low-energy reducing conditions were a local environment favourable for their preservation. Overall, the thickness of these black shales and their apparent confinement to one broad stratigraphic level may denote condensed sequences associated with a period of relative quiescence in turbidite deposition in the Late Ordovician. The volcanic ash origin proposed by Joplin (1945) is not supported, since acid volcanicity at this time is unknown in the region. The terrigenous dust origin of Öpik (1958) is unlikely since there is no evidence to support these shales as being remnants of a once widespread blanket of deposition.

Age. Öpik (1958) concluded from graptolites collected from the Acton Shale in the Canberra district that the age of this unit ranges from Gisbornian to Bolindian. The stratigraphic range of key graptolite species (Webby 1981, fig. 2), when applied to Öpik's graptolite listings, gives the following details:

Pleurograptus linearis — Eastonian–Bolindian
Dicranograptus hians — Eastonian
Dicellograptus elegans — Eastonian
Climacograptus tubuliferus — Eastonian–Bolindian
Climacograptus hastatus — Bolindian
Climacograptus bicornis — Gisbornian
Dicranograptus nicholsoni — Gisbornian–Eastonian

It is evident from this graptolite assemblage that some species are long-ranging forms. Hence the only certain conclusion is that the Acton Shale Member is Late Ordovician (post-Darriwilian) in age.

Correlation. The black siliceous shale beds at the top of the Pittman Formation were probably deposited at one broad stratigraphic interval. The Gisbornian to Bolindian age range duplicated for graptolite assemblages in black shales in the Gundaroo–Nanima area (Sherrard, 1952; Smith, 1964) and the Queanbeyan area (Phillips, 1956) suggest these shales are probable correlatives of the Acton Shale Member.

The age range of other occurrences scattered across the Cullarin Block, e.g. old Cooma road at MR 024/800 (Stauffer, 1964), Googong reservoir catchment and Lake George Range, has not been established. However, on the occurrence of graptolites and lithological similarities, these are regarded as coeval with the Acton Shale Member.

Birkenburn beds (Ob)

Nomenclature. The Birkenburn beds have been defined on BRAIDWOOD by Felton & Huleatt (1977), with supplementary information in the Tarago area provided by Henry (1978). This stratigraphic unit has been retained on CANBERRA, for the quartz turbidite sequence exposed along the eastern margin of the Sheet area. Read (1961) originally named the Ordovician rocks between Bungendore and Hoskinstown the 'Turallo Creek beds'. For the same sequence in the same area Wilson (1964) used the term 'Foxlow beds' since this name was to be used for the Ordovician sequence around Captains Flat by Oldershaw (1965). For simplicity, and since there is doubt as to the validity of the 'Foxlow beds' in the Captains Flat area, the term Birkenburn beds is retained.

The upper part of the Birkenburn beds contains a distinctive black shale unit. Oldershaw (1965) originally mapped it as the 'Bullongong Shale Member' of the 'Foxlow beds', a terminology also accepted by Wilson (1964). However, Richardson (1979) regarded the term 'Bullongong Shale Member' as invalid on the grounds that it was not possible to designate a member from within a named unit of beds. For the purpose of this study, this unit will be called the 'Bullongong Shale' and will be regarded as informal until such time as it may be named as a member within a formation as part of a more acceptable regional stratigraphic scheme for the Ordovician in southeastern Australia.

Distribution. The Birkenburn beds crop out as a meridional belt with an average width of 5 km stretching from Bungendore to the southern edge of the sheet, and thence southwestwards to MICHELAGO (although on MICHELAGO they are named 'Foxlow beds' by Richerdson, 1979). An exposure on the eastern shore of Lake George is regarded as an extension of the Birkenburn beds from BRAIDWOOD. Interbedded phyllite and quartzite intersected by drillholes through a cover of Cainozoic sediments represent a northward extension of these beds beneath the Lake George basin (Abell, 1985a). Similarly, micaceous sandstone, shale and black siliceous slate beds were proved beneath alluvium at the northeastern end of Lake George by Jododex (Aust.) Pty Ltd as part of their drilling program at Exploration Licence (E.L.) 386, west of Woodlawn Mine.

Description. The Birkenburn beds are a sequence of quartz-rich sandstone, siltstone and shale with minor black siliceous shale. The sequence has been regionally metamorphosed in part to biotite-grade psammitic and pelitic schist. The thickness of the beds on CANBERRA is unknown because of complex tectonics, but Felton & Huleatt (1977) suggested about 3000 m on BRAIDWOOD. Wyborn & Owen (1986) measured 3600 m of continuous section on ARALUEN.

Quartz sandstone units are well displayed on the eastern side of Lake George in an old cliff line north of Rocky Point, at approx. MR 257/152. The 2 km long section shows thinly bedded turbidite units up to 0.5 m thick, consisting of laminated and cross-bedded pale-grey sandstone grading up into bluish-grey siltstone and shale (Pl. 1 and 2). Sedimentary structures include well preserved sole markings, and ball-and-pillow structure. These graded turbidites correspond with the B, C, (D), and E divisions of the Bouma sequence (Bouma, 1962). The sandstones consist of a framework assemblage of poorly sorted, sub-rounded, recrystallised quartz with subordinate feldspar and detrital muscovite. Rock deformation is indicated by quartz clasts that are strained and weakly aligned parallel to the cleavage. Feldspar clasts consist of plagioclase with albitic twinning and perthitic potash feldspar. A fine-grained matrix (up to 30% of the rock) consists of muscovite, biotite, quartz and feldspar with accessory opaques and rounded grains of tourmaline, zircon, apatite and sphene. The matrix has responded to deformation by alignment of phyllosilicates along cleavage planes. Such a sequence may have been deposited by slow-moving turbidity currents in the more distal parts of an oceanic basin.

The 'Bullongong Shale' within the upper part of the Birkenburn beds crops out along the western margin of the Rocky Pic Block, where it is overlain by the Rutledge Quartzite Member. The black siliceous shale forms a distinctive marker bed less than 60 m thick, striking southwards from Yandyguinula Creek for about 4 km. The best exposures occur in that creek at MR 249/738 and in a cutting on the Rossi road at MR 247/736. These outcrops are also taken to be the same unit as the black graptolitic shales exposed at Captains Flat railway station (Oldershaw, 1965). The field character and petrology of this rock unit is similar to that given for the Acton Shale Member of the Pittman Formation.

Age and correlation. On CANBERRA, poor exposure obscures the boundary relationships of the Birkenburn beds. From the lists of graptolites given in Oldershaw (1965), Felton & Huleatt (1977), and Richardson (1979), the Birkenburn beds are Middle to Late Ordovician. On the range of lithologies mapped it would appear that they may be a correlative of the Pittman Formation. The late Gisbornian to early Eastonian age of graptolites from the 'Bullongong Shale' suggests a correlation with the Acton Shale Member (Webby, 1981) and possibly the Merigan Black Shale (late Eastonian to early Bolindian age) on BRAIDWOOD.

Silurian (Llandovery)

The known distribution of Llandovery rocks on CANBERRA is confined to local outcrops in and to the north of the City. Their present-day confinement to the downfaulted Canberra Block has prevented their total removal by post-Palaeozoic erosion and they now remain exposed as folded inliers north of the Deakin Fault. Llandovery sediments are represented by a sequence consisting of shale which passes upward gradationally into quartz-rich sandstone. Unconformities define the lower and upper parts of this sequence.

Quality of exposure and predominance of sandstone in the sequence determines the number of mappable stratigraphic units. At most localities in the Canberra area these rocks are well enough exposed to enable them to be mapped as two formations: the State Circle Shale and Black Mountain Sandstone. In the Murrumbateman Creek area this division is not attempted. The Llandovery rocks there have not been accurately dated and as they cannot be readily demarcated into lower shale and upper sandstone units they are mapped in their entirety as the Murrumbateman Creek Formation. The State Circle Shale and Black Mountain Sandstone may be correlated broadly with the Tidbinbilla Quartzite (Owen & Wyborn, 1979), the Ryrie Formation (Richardson, 1979) and the Mundoonan Sandstone (Crook & others, 1973) on the basis that they display a lithofacies typifying turbidite deposition and monograptid fossils of Llandovery age.

State Circle Shale (Slc)

Derivation of name. Öpik (1954, 1958) named the State Circle Shale after the State Circle road cutting, Canberra, ACT.

Nomenclature. Öpik (1954, 1958) introduced the name for beds of shale and minor sandstone of Llandovery age outcropping in central Canberra and on the flanks of Black Mountain. Subsequently, Strusz & Henderson (1971) and Henderson (1980, 1981) considered the nomenclature valid and extended its use to describe shaly sequences of Llandovery age in northeast Belconnen and Jerrabomberra Hill.

Distribution. The State Circle Shale crops out poorly over CANBERRA. Around Black Mountain, Jerrabomberra Hill and northeast Belconnen the formation can only be recognised as narrow discontinuous weathered outcrops of laminated dark-grey shale flanking hills of resistant quartz-rich sandstone. Urban development in the ACT has temporarily exposed the State Circle Shale in road cuts and trenches, and over the years has enabled its distribution in central Canberra to be more accurately known (Henderson, 1980; 1981).

Type locality. The original type locality designated for the State Circle Shale was the northwestern road cutting on State Circle near the South African Embassy, at MR 927/909 (Öpik, 1958; Strusz & Henderson, 1971). The formation as described by Öpik comprised about 60 m of non-calcareous sandy shale and black shale with beds of fine-grained sandstone. Upper and lower boundary relationships were not exposed.

Öpik's type locality is now partly obscured by a retaining wall and covered with shrubs. Near this locality an excellent reference section for the formation is exposed in a cutting in the northeastern part of State Circle between Commonwealth Avenue and Kings Avenue. Here the State Circle Shale consists of buff-coloured laminated siltstone and shale with fine sandstone beds contorted by slumping. The late Llandovery age of the sequence is indicated by the graptolite *Monograptus exiguus* found during excavations just behind the cutting at the southern end of Commonwealth Avenue (Henderson, 1973; Strusz & Jenkins, 1982). This reference section has been retained as a geological monument; further details are given in Owen (1987).

Lithology. The State Circle Shale consists of a lower unit of massive pale-grey siltstone and mudstone and an upper unit of strongly laminated shale. According to Henderson (1980, 1981) the lower beds are exposed on Black Mountain Peninsula and were temporarily exposed in trench excavations in northeast Belconnen. A mudstone at a similar stratigraphic level with a thickness of >70 m was encountered in BMR drillhole C5 at the southern foot of Black Mountain (Henderson, 1978a). The upper part of the State Circle Shale is characterised by strongly laminated dark greenish-grey shale alternating with silty bands up to 1 cm thick. Sandstone beds are rare in the formation but appear with increasing frequency as the overlying Black Mountain Sandstone is approached.

The formation is weathered and outcrop samples are unsuitable for petrographic analysis. Thin-section descriptions by Joplin *in* Bofinger & others (1970) were taken from fresh drill core samples of State Circle Shale obtained in a 64 m deep bore drilled on Camp Hill (Henderson, 1969). Major-element chemistry, rare earths and other trace elements identified from samples taken from this drill core are given in Nance & Taylor (1976).

Boundary relationships. From the evidence available to him Öpik (1958) thought the State Circle Shale was conformable on the Camp Hill Sandstone and overlapped onto the Black Mountain Sandstone and Pittman Formation; the upper boundary was considered conformable with the 'Canberra Group'. Subsequently Strusz & Henderson (1971) reappraised these relationships and showed that the State Circle Shale is overlain conformably by the Black Mountain Sandstone and unconformably by the Camp Hill Sandstone. The base of the formation is not exposed.

The upper boundary of the State Circle Shale is gradational with the Black Mountain Sandstone. In the bed of an erosion gully on the south side of Black Mountain (MR 908/933), shale and siltstone of the State Circle Shale grade upslope to interbedded sandstone and shale typical of the Black Mountain Sandstone (Strusz & Henderson, 1971). Mapping does not support the existence of a fault separating the State Circle Shale and Black Mountain Sandstone, as proposed by Öpik (1958). At this locality the base of the State Circle Shale is not exposed but Crook & others (1973) have shown that from discordance in bedding attitudes with the Pittman Formation the existence of an unconformity may be inferred. Crook & others (1973) have also described an upper gradational contact with concordant dips between the State Circle Shale and Black Mountain Sandstone in creeks on the north side of a hill near 'Ginninderra' homestead, approx. MR 905/030. On the east side of Jerrabomberra Hill, massive and laminated siltstone and mudstone assigned by Henderson (1980, 1981) to the State Circle Shale dip conformably west beneath Black Mountain Sandstone at the southern end of an abandoned brick shale pit. Although the basal contact of the State Circle Shale is not exposed, the discordance in dip with the Pittman Formation suggests an unconformity.

In the State Circle road cut, the State Circle Shale is overlain unconformably by the Camp Hill Sandstone Member — the basal unit of the Canberra Formation. The unconformity is folded and displaced by numerous faults. Selective Tertiary weathering has penetrated down faults to form liesegang rings, and along the unconformity to form a pallid layer up to 50 cm thick of weathered shale with small iron concretions. The same relationship, though no longer exposed, also exists in the Ginninderra area (Henderson, 1980; 1981).

Thickness. The greatest known thickness is 113 m as logged in BMR drillhole C5 (Henderson, 1978a). However, the average maximum thickness may be closer to 200 m (Strusz & Henderson, 1971).

Environment of deposition. Based on the fauna, the gradational boundary with the Black Mountain Sandstone and the lack of sedimentary structures, the unit probably accumulated as a deep-water marine turbidite deposit remote from sources of terrigenous sediment (Crook & others, 1973).

Age and correlation. Except for graptolites, fossils are rare in the State Circle Shale. The presence of such monograptids as *M. turriculatus*, *M. spiralis* and *M. exiguus* collected and identified by Öpik (1954, 1958) from the central Canberra area places the age of the formation in the upper part of the Llandovery (Fronian Stage), about the middle of the Early Silurian. Confirmatory evidence of the late Llandovery age of the State Circle Shale was provided by Strusz & Jenkins (1982) who found *M. exiguus* in siltstone from below the unconformity exposed in test pits on Camp Hill. A Rb–Sr age of 445 ± 7 Ma (revised to 435 ± 7 Ma) obtained by Bofinger & others (1970) broadly confirms the Llandovery age of the State Circle Shale.

The State Circle Shale may correlate with the lower part of the Ryrie Formation (Gungoandra Siltstone) on MICHELAGO and the lowermost beds of the Murrumbateman Creek Formation.

Black Mountain Sandstone (Slb)

Derivation of name. Öpik (1954, 1958) named the Black Mountain Sandstone after Black Mountain, Canberra, ACT.

Nomenclature. Thick beds of buff-coloured sandstone on Black Mountain were first mapped by Pittman (1911) in his early account of the geology of the site of the future city of Canberra, and were more fully described by Öpik (1954, 1958). However, there was disagreement about the nature of the lower boundary and age of the Black Mountain Sandstone. Pittman thought the sandstone was conformable on a shale–limestone sequence (the present Canberra Formation) east of Black Mountain, while Öpik (1958, p.7) stated 'the lower contact is eliminated by faults'. Since the formation lies conformably on the State Circle Shale (Strusz & Henderson, 1971; Crook & others, 1973), the nomenclature is considered valid and has been extended to describe other sandstone sequences of Early Silurian age in the Canberra area.

Distribution. At Black Mountain and Jerrabomberra Hill the formation is thick enough to crop out as erosional residuals of quartz-rich sandstone surrounded by low-lying ground consisting predominantly of shale. A narrow belt of Black Mountain Sandstone in the Ginninderra area contains a higher proportion of shale, and forms a low ridge striking southwest over an outcrop length of about 2 km. A few exposures occur northwest of Capital Hill at approx. MR 924/912.

Type locality. Öpik (1958) designated the type locality as Black Mountain but did not mention a specific section. He described the Black Mountain Sandstone at this locality as a fine-grained quartzose sandstone with several shale interbeds in the lower 60 m; the thickness was estimated at <460 m.

An ideal reference section for the Black Mountain Sandstone is in cuttings along the access road to the summit of Black Mountain. Here the formation is exposed as a sequence of grey fine-to-medium-grained quartz sandstone with subordinate grey shale interbeds showing a wide range of sedimentary structures typical of a proximal turbidite deposit. Part of the reference section has been retained as a geological monument; further details are given in Owen (1987).

Lithology. The greater part of the Black Mountain Sandstone is a grey, thickly bedded, sometimes massive medium-grained sandstone in which siltstone and shale interbeds become more frequent lower in the sequence. The range of observed sedimentary structures includes small-scale plane, cross and convolute laminations, load casts and occasional flute moulds and ripple markings (Crook & others, 1973); slump units and sole markings are displayed in a disused quarry on the east face of Black Mountain at MR 912/945 (Öpik, 1958, fig. 9). Graded bedding is poorly expressed, shale clasts (a few cm in diameter) commonly occur at the base of sandstone beds and sometimes shale breccias are interbedded with sandstone.

Similar sandstone sequences are exposed on Capital Hill (Henderson, 1973; 1982) and at Jerrabomberra Hill (Phillips, 1956; Henderson, 1980; 1981). In a cutting on the Barton Highway north of Ginninderra Creek (MR 904/027) the Black Mountain Sandstone contains a higher proportion of shale, and occasional shale breccia beds. The sequence dips steeply, and graded units show the beds are locally overturned to form a tight northeast-trending syncline (Crook & others, 1973; Owen, 1987).

The sandstones consist of a framework assemblage of rounded quartz clasts and subangular rock fragments set in a fine-grained matrix rich in subangular quartz, phyllosilicates and accessory zircon and tourmaline. Feldspar is absent. The framework quartz commonly reaches up to 1 mm in diameter and is both monocrystalline and polycrystalline; some quartz has inclusions of muscovite, biotite and a needle-shaped mineral. Rock fragments reach up to 2 mm and comprise detrital chert, shale and fine-grained sandstone often rich in phyllosilicates. All quartz grains show varying degrees of undulose extinction, sutured boundaries and other marginal recrystallisation features relating to post-depositional tectonics. Haematite, a product of weathering, may rim quartz grains and also occurs in void space. A QFR diagram for the Black Mountain Sandstone is given in Crook & Powell (1976). The common occurrence of argillaceous rock fragments and the feldspar-free nature of the detritus suggests that the sandstone may have been derived mainly by recycling of Ordovician turbidite sediments. The poor sorting and bimodality of the quartz suggest a turbidite sequence of mixed source. The rounding of the larger quartz grains may be a function of abraded bed load in the turbidite flow units while the smaller angular quartz grains were carried in suspension for longer distances.

Boundary relationships. Neither the base nor the top of the Black Mountain Sandstone are exposed. At its base it is thought to have a gradational and conformable contact with the State Circle Shale, mapped in a creek at the southern foot of Black Mountain (Strusz & Henderson 1971). At Ginninderra a conformable contact with the State Circle Shale has been mapped by Crook & others (1973).

Phillips (1956) identified a massive grey to white quartzite at Jerrabomberra Hill as the Black Mountain Sandstone. Following Öpik's stratigraphic interpretation of the Canberra area she regarded the quartzite as an Ordovician inlier. A more plausible field relationship places the Black Mountain Sandstone as resting conformably on the State Circle Shale as an Early Silurian outlier folded into a north-plunging synclinorium (Strusz & Henderson, 1971). At Capital Hill the base of the Black Mountain Sandstone is not exposed but a conformable relationship was deduced by Henderson (1973) from the close association of the two formations and their similar bedding attitudes.

Before the new Parliament House was built the uppermost beds of the Black Mountain Sandstone were exposed on Capital Hill. Here Öpik (1958, figs. 4 and 5) shows the Camp Hill Sandstone resting with a high angular unconformity on the Black Mountain Sandstone. Close by, at State Circle, the same unconformable boundary has cut down to lower stratigraphic levels in the Early Silurian sequence, as the Camp Hill Sandstone rests unconformably on the State Circle Shale, cutting out the Black Mountain Sandstone. This relationship suggests that, following early Wenlock tectonism (D_{1b}), there was appreciable erosion, with local removal of the Black Mountain Sandstone. The Camp Hill Sandstone also rests unconformably on the Black Mountain Sandstone in the Barton Highway cutting. Elsewhere the formation is in fault contact with the Pittman and Canberra Formations.

Thickness. The full thickness cannot be accurately estimated as the top and bottom of the formation are not exposed. Crook & others (1973) give a thickness of >800 m, while Henderson (1981) estimates an exposed thickness of >450 m.

Environment of deposition. The rock types and variety of sedimentary structures suggest the Black Mountain Sandstone was deposited as part of a submarine turbidite fan complex typical of the models discussed in Walker (1984). The thick sandstone beds and a proximality index of up to 70% (Crook & others 1973) suggest the formation probably represents the mid-fan environment of a prograding submarine fan that was deposited by eastward-flowing turbidity currents into a rapidly shallowing but tectonically disturbed marine basin.

Age and correlation. Fossils are unknown in the Black Mountain Sandstone. Öpik (1954; 1958) interpreted the Black Mountain Sandstone as pre-Darriwilian (i.e. pre mid-Ordovician) and therefore older than the Pittman Formation. At the southern foot of Black Mountain *Monograptus exiguus* was collected (Strusz & Henderson, 1971) from mudstone beds of State Circle Shale dipping north towards Black Mountain. In gullies above the road, similar mudstones interbedded with sandstones (but lacking graptolites) pass up gradationally into thickly bedded Black Mountain Sandstone (Strusz & Henderson, 1971; Crook & others, 1973). Until fossils are found or a definite boundary with the State Circle Shale is exposed, the available evidence can only support a late Llandovery age for the Black Mountain Sandstone.

On a similarity of lithofacies the Black Mountain Sandstone is probably coeval with the Tidbinbilla Quartzite (BRINDABELLA), the Mundoonan Sandstone (YASS), the uppermost beds of the Ryrie Formation (MICHELAGO), and the Murrumbateman Creek Formation.

Murrumbateman Creek Formation (Slm)

Derivation of name. After Murrumbateman Creek, a tributary of the Yass River. The name derives from the thesis work of Smith (1964).

Nomenclature. First publication of the name was by Best & others (1964) in the Second Edition of the Canberra 1:250 000

Geological Sheet. Smith (1964) originally described the Murrumbateman Creek Formation as slate with fine-to-medium-grained sandstone. The base was unconformable on Late Ordovician slate and arenite and the top conformable with the 'Westmead Park Formation'. An indeterminate mixed shelly/graptolite fauna was taken to indicate a 'mid Silurian' (Wenlock) age for the formation. Henderson (1978b) adopted Smith's nomenclature but regarded the formation as Early Silurian in age. He described a lower sequence of massive siltstone, mudstone and minor quartz sandstone unconformable on Ordovician sediments. The upper part comprised micaceous and feldspathic sandstone and minor siltstone and shale unconformably overlain by quartz sandstone at the base of the 'Westmead Park Formation'. Henderson's description and stratigraphic relationships are taken as valid and used to define the Murrumbateman Creek Formation as a formal lithostratigraphic unit.

Distribution. The Murrumbateman Creek Formation crops out in a broad north-northeast-trending triangular belt about 10 km west of Gundaroo, north of Canberra. The southern limits of the formation reach 'Wantagong' homestead (MR 934/152) whilst the northern limits extend about 1 km north of the Gundaroo–Murrumbateman road.

Type area. A type section for the Murrumbateman Creek Formation is not designated owing to lack of exposure and poor age control. Smith (1964) specified a type area in the vicinity of 'Glencoe' homestead (MR 937/181) but the rocks in this area have now been assigned to the Canberra Formation. The type area adopted for the formation is in low hills and creeks east of Murrumbateman Creek and along the Gundaroo–Murrumbateman road. Here poorly laminated mudstone and siltstone pass gradationally upwards into a sequence dominated by thick beds of sandstone. The succession has been deformed into tight southwest-trending folds.

Lithology. The formation consists predominantly of shale with sandstone interbeds which become thicker and more frequent towards the top. The shale is usually buff-coloured with bedding laminations poorly preserved owing to superimposed cleavage and moderately deep weathering. The mineralogy consists of quartz, sericite, chlorite and opaques (weathered to haematite).

The sandstone beds range from 0.5 to 5.0 m thick and form flaggy and relatively resistant outcrops. Bedding where seen is often emphasised by variations in colour caused by weathering along matrix-rich bands. Sedimentary structures were not observed. The sandstone consists of a poorly sorted assemblage of subrounded quartz clasts reaching up to 0.5 mm in diameter and angular rock fragments of shale, siltstone and arenite set in a matrix of subangular quartz, detrital muscovite and accessory tourmaline, zircon and opaques. A modal analysis and QFR classification for the sandstones is given in Smith (1964). Petrographically they average about 60% quartz, little or no feldspar, 25% matrix, and rock fragments rarely exceeding 6%. The poorly sorted texture, bimodal quartz, rock fragments and mineralogical composition suggest correlation with the Black Mountain Sandstone.

Boundary relationships. Boundary relationships are obscured by the continuity of fold structures and disruption by northeast-trending faults. The base of the formation is not exposed. Sherrard (1952) could not find any evidence for an unconformity between Ordovician and Silurian rocks in the Nanima–Bedulluck district. Her section along the Gundaroo–Murrumbateman road shows a folded and apparently conformable boundary. Smith (1964) mapped an outlier of weathered buff-coloured siltstone float about 1 km southeast of 'Glenlee' homestead (MR 933/227) resting on siliceous black slate of the Pittman Formation. Although the float was unfossiliferous he declared that it belonged to the Murrumbateman Creek Formation and therefore represented the best evidence for an Ordovician/Silurian unconformity. Nevertheless the discordancy in dip and similar lithostratigraphic relationships for Early Silurian rocks elsewhere on CANBERRA suggest the Murrumbateman Creek Formation is unconformable on the Pittman Formation.

The upper boundary of the formation is not exposed. The present investigation confirms the mapping of Henderson (1978b) northeast of 'Wantagong' homestead where a basal sandstone unit of the Canberra Formation is in apparent unconformity with the Murrumbateman Creek Formation. This sandstone unit defines the nose of a major shallow-plunging anticlinorium trending southwest and also cross-cuts tightly folded and steeply plunging sandstone beds in the upper part of the Murrumbateman Creek Formation. A small remnant of the Canberra Formation occurs as an outlier on the Murrumbateman Creek Formation at MR 960/172 (Henderson, 1978b).

Thickness. Smith (1964) gave an estimate of 900 m. Sparse outcrop and complex structure suggest this may be a minimum.

Environment of deposition. The mixed shale–sandstone lithology and the lack of sedimentary structures and fossils suggest the Murrumbateman Creek Formation was deposited as a series of turbidite units towards the distal edge of a submarine fan complex, as outlined in Walker (1984).

Age and correlation. The fossil localities in the Murrumbateman Creek Formation as originally defined by Smith (1964) now fall within the boundaries of the Canberra Formation. The Early Silurian age of the Murrumbateman Creek Formation is based largely on its stratigraphic position and lithological correlation with other proven localities of Early Silurian rocks elsewhere on CANBERRA. Henderson (1978b) suggests an Early Silurian age for the Murrumbateman Creek Formation because of the presence of laminated shale lithologically similar to the Early Silurian State Circle Shale at Ginninderra and Black Mountain. As the formation becomes more sandstone-rich and proximal towards the top of the sequence it begins to grade into lithologies typical of the Black Mountain Sandstone.

Silurian (Wenlock to Ludlow)

The present day distribution of Wenlock to Ludlow sedimentary and volcanic rocks on CANBERRA is confined in the west to the Canberra Block and in the east to the Captains Flat Block and a small part of the Rocky Pic Block.

For the Canberra Block the stratigraphy of this Silurian sequence is well understood, since the rocks are only mildly deformed. Further east, in the Captains Flat Block, the stratigraphic sequence is less clear owing to intense deformation and severe faulting. At the margins of the blocks the Silurian rocks are mostly faulted against Ordovician and Llandovery sediments, although there are unconformities at several localities. The younger Silurian sedimentary rocks differ sufficiently from the Ordovician and Llandovery formations to mark a major change in the depositional environment.

Canberra Block

The Wenlock and Ludlow rocks of the Canberra Block lie in a broad zone in the western half of the Sheet area which narrows southwards towards MICHELAGO, and widens northwards onto YASS. The sequence was deposited on the Canberra–Yass Shelf, and on CANBERRA is represented by shallow-marine shelf sediments and a thick pile of subaerial acid volcanics ranging in age from late Wenlock to early Ludlow.

The oldest unit of this shelf sequence is the Canberra Formation, which consists of mudstone and siltstone with subordinate limestone and sandstone. Towards the top of the formation the first evidence of Silurian volcanism is given by sporadic development of thin ignimbrite flows, tuffs, and volcaniclastic beds.

Many difficulties beset a reconstruction of the nature and stratigraphic setting of early Palaeozoic volcanism on the Canberra–Yass Shelf. Evidently, there was a gradual eastward migration of Silurian volcanism across the Shelf. Alternating phases of eruption and quiescence in close proximity to shallow-marine environments gave local unconformities, interfingering volcanic flows and sedimentary lenses of limited depositional extent. The volcano-sedimentary sequence was deposited over a relatively short period of about 5–10 Ma. Unfortunately the detailed stratigraphy is obscured by lack of diagnostic fossils and marker lithologies, and by complex tectonics. Devitrification, recrystallisation and low-grade regional metamorphism have also contributed to lithological homogeneity by masking the original depositional character of the volcanic units.

Most continental volcanic rocks form constructional topographic features that are quickly modified or destroyed by erosion. The present volcanic topography of the Canberra Block results initially from a prolonged period of weathering and erosion in the Mesozoic, subsequently interrupted by uplift episodes in the Cainozoic, which imposed new cycles of weathering and erosion on the earlier palaeotopography. It is hardly surprising that the resulting thick weathering profiles and poor lithology–morphology relationships now evident in the present-day topography provide only limited assistance to the mapping of volcanic units and even less information on the disposition and character of the early Palaeozoic volcanic environment. The present volcanic topography reflects differential erosion between the more resistant volcanic rocks and the softer volcaniclastic and epiclastic interbeds. Upland country is characterised by the erosional remnants of massive volcanic units which form isolated bouldery hills, ridges and, in a few cases, poorly developed dip and scarp features. Where a significantly higher proportion of softer volcaniclastic and epiclastic beds occur within the volcanic sequence, low-lying undulating country is interspersed with upland.

The textures and thickness variation of intercalated sedimentary beds provide some evidence of the depositional nature of the volcanic environment. However, uncertainties exist in the interpretation of volcaniclastic material as either products of erosion of older volcanics or primary eruptive materials active during sedimentation. Although the ignimbritic rocks are unequivocally continental in origin, the presence of interbedded shales and occasional limestones suggests a proximal marine environment. However, the volcanic sequence in the Canberra Block rarely shows evidence of thick subaqueous mass flow deposits such as the Early Devonian Merrions Tuff from the Hill End Trough (Cas, 1978) and the Kowmung Volcaniclastics in the Yerranderie area of NSW (Cas & others, 1981).

The sharp cross-cutting nature of many igneous rock contacts led Sherrard (1952), Öpik (1958), Strusz (1971), and Strusz & Henderson (1971) to consider and in some instances confirm that many of the acid porphyry rocks were intrusive. However, cross-cutting contact phenomena can occur just as commonly in extrusive rocks. Sharp and irregular contacts may occur where volcanic units have been deposited over undulating topography. Careful observation and interpretation is needed in areas where felsic volcanic flows are closely allied with high-level felsic porphyry intrusions. Layering in volcanic rocks is synonymous with stratification in sediments and is therefore regarded as a primary depositional structure. Where displayed in the field it is usually a widely-spaced regular banding better emphasised in weathered than in fresh outcrops. Layering may result from compositional variation, changes in grain and crystal size and alignment of fragmental material. It is most pronounced where thin ignimbrite flows are interbedded with volcaniclastic and marine sediments and where compositional change is affected by faster cooling rates near the upper and lower parts of flows. The attitude of the layering suggests the volcanic sequence is a succession of warped sheets. However, close to zones of intense deformation, e.g. adjacent to the Sullivans Fault, the layering is folded and often obscured by an intense foliation.

Most present-day studies are directed to modern and Cainozoic ignimbritic eruptions where there is good exposure and the rocks are unaffected by long periods of weathering, tectonism and other alteration processes. Many of the physical characteristics observed in 'young' ignimbrites are now rarely preserved in the older Palaeozoic volcanic terranes. The Palaeozoic volcanic stratigraphy of the Canberra Block has recently undergone major revisions, largely on petrological and chemical criteria developed for the intrusive and volcanic rocks on BRINDABELLA (Owen & Wyborn, 1979). Elements of the volcano-stratigraphic sequence established on BRINDABELLA can now be traced onto CANBERRA and YASS (Wyborn & others, 1981; Wyborn & others, 1982). The acid extrusive rocks of the Canberra Block are now divided into two cogenetic volcanic suites — the Hawkins Suite and the Laidlaw Suite. Each suite contains several formations which are capable of stratigraphic definition.

Canberra Formation (Smc)

Nomenclature. Öpik (1954, 1958) used the name 'Canberra Group' as comprising three formations: the 'Turner Mudstone', 'Riverside Formation', and 'City Hill Shale' with 'Acton Limestone Member'. He stated the group had conformable boundaries with the underlying State Circle Shale and overlying 'St Johns Church beds'. The Group was redefined by Strusz & Henderson (1971) to include the underlying Camp Hill Sandstone and overlying 'St Johns Church beds'. This redefinition was consequent mainly on the discovery during more detailed mapping that the State Circle Shale unconformably underlies the Camp Hill Sandstone, rather than being conformable between the Camp Hill Sandstone and 'Turner Mudstone', as mapped by Öpik (1958).

Subsequent mapping and drilling are now sufficiently detailed that it can be argued that lithological distinctions between the five formations within the group are insufficient to justify their separate existence. It is proposed that the status of the 'Canberra Group' be downgraded to Canberra Formation, and that the Camp Hill Sandstone be retained as a member of that Formation. In addition, the Narrabundah Ashstone, regarded by Öpik (1958) as being the final phase of volcanism in the Mount Ainslie Volcanics, is now included as a member high within the Canberra Formation (Owen & Cas, 1980; Henderson, 1981).

Öpik (1954, 1958) introduced the name 'Fairbairn Group' (with four constituent formations) to describe interbedded sandstone, shale, limestone and tuff cropping out in the Fyshwick area in eastern Canberra. Moore (1957) gave the name 'Gladefield Volcanics' to the volcanic sequence conformably overlying the 'Fairbairn Group'. The 'Gladefield Volcanics' are lithologically similar to the Mount Ainslie Volcanics, which are also conformable on the Canberra Formation. Since these volcanic units are synonymous it follows that the 'Fairbairn Group' and Canberra Formation are time equivalents. As these units are also lithologically comparable and do not contain distinct faunal differences it is recommended that the name 'Fairbairn Group' be discarded.

The 'Westmead Park Formation', cropping out in the north of the ACT and beyond in New South Wales, was named by Smith (1964) and later was formalised on the Canberra 1:250 000 Geological Sheet (2nd edition) as a sedimentary sequence similar in lithology to the Canberra Formation. Mapping by Hohnen (1974) and Henderson (1978b) established that this unit extends as far south as Belconnen and occupies a similar stratigraphic position to the Canberra Formation. The unit lies unconformably on Early Silurian (Llandovery) sediments and passes conformably upwards into the Mount Ainslie Volcanics. The 'Westmead Park Formation' comprises mudstone and siltstone with minor sandstone, limestone and calc-silicate hornfels; acid volcanic tuffs termed the 'Glenesk Volcanics' (Smith, 1964) occur near the top of the sequence. Since recent mapping has established outcrop continuity and lithological and faunal similarities between the two units, it is recommended that the term 'Westmead Park Formation' be discarded in favour of Canberra Formation.

On the western outskirts of Queanbeyan, mudstone with interbedded thin sandstone and a lens of limestone overlying the Camp Hill Sandstone were mapped by Phillips (1956) as the 'Bouchon Beds' and 'Brun Shale'. These beds are probably lateral time-equivalents of lower portions of the Canberra Formation.

Distribution. The Canberra Formation crops out over much of the inner city area of Canberra and extends along the valley of Sullivans Creek to the ACT–NSW border. In New South Wales, the formation extends a further 15 km north, as far as 'Glencoe' homestead and around Nobby Hill. To the east there are poorer exposures in the Fyshwick and Queanbeyan areas. In the Woolshed Creek valley the Canberra Formation has been mapped in continuity as far as the Federal Highway (Ollier & Brown, 1975). The subsurface presence of the Canberra Formation has yet to be proved south of the Deakin Fault.

Type locality. A fully representative type section is not available; there are no longer suitable exposures because of the rapid urbanisation of the Canberra City area. All of the outcrops mentioned by Öpik (1958) as type areas for units of

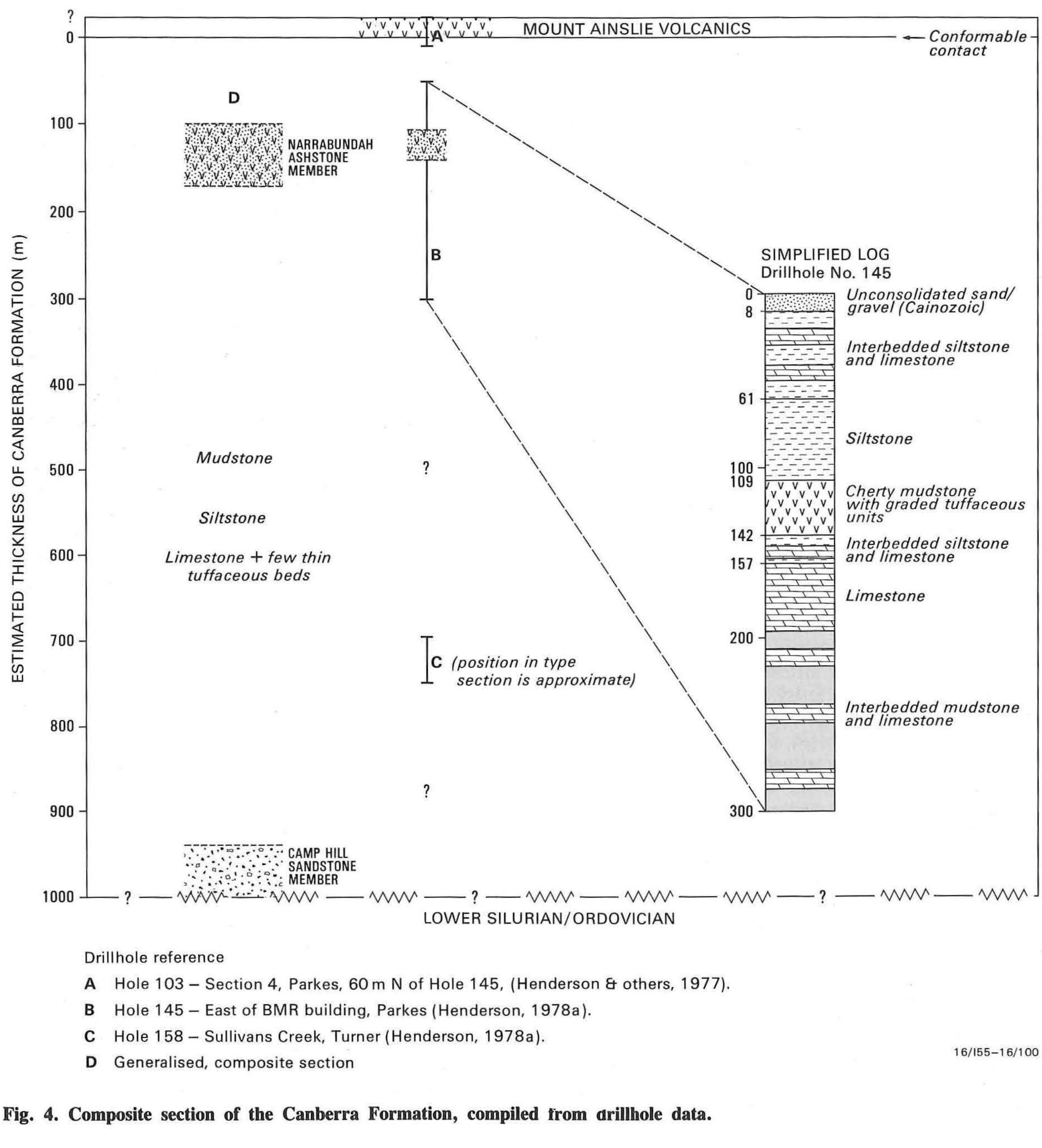


Fig. 4. Composite section of the Canberra Formation, compiled from drillhole data.

his 'Canberra Group' and also included by Strusz & Henderson (1971) in their version of an enlarged 'Canberra Group', have been built over or otherwise obscured. The only exception is the Camp Hill Sandstone exposed in the outer State Circle road cut on the southwest side of Camp Hill.

It is therefore proposed that the core from BMR stratigraphic hole C 145 (approx. MR 945/923; drilled to a depth of 300 m) be treated as representative of the Canberra Formation. The hole was continuously cored, and the core is kept at the BMR Core & Cuttings Laboratory, Fyshwick. A detailed log, from which Figure 4 was partly constructed, is given in Henderson (1978a). The top of this drillhole is at a level only a short interval beneath the base of the Mount Ainslie Volcanics, the contact being exposed in another hole (C 103) a few metres to the north. As Figure 4 shows, the reference section covers less than one-third of the estimated thickness of the Canberra Formation. The only available material representative of the lower part of the formation is given by Henderson (1978a) in a detailed log of almost 50 m of core from hole C 158 drilled near Sullivans Creek (MR 930/946).

A representative section for the Canberra Formation north of the ACT border occurs west of 'Kia-Ora' homestead (MR 988/144). Here, Smith (1964) describes an easterly dipping sedimentary sequence of mudstone, siltstone and limestone which passes gradationally upwards into ashstone and dacitic tuff. The sequence is partly contact-metamorphosed and in places strongly cleaved.

Lithology. The Canberra Formation consists of mudstone and siltstone with minor sandstone and limestone. Siltstone and sandstone with a significant component of volcanogenic detritus become increasingly common towards the top of the sequence. Primary volcanic rocks such as dacitic welded tuff also appear at these stratigraphic levels, e.g. at Crace Hill (MR 942/994) and more commonly north of the ACT border near 'Westmead Park' homestead (MR 976/126) and north of 'Emohruo' homestead (MR 918/146). The sediments have been patchily contact-metamorphosed to calc-silicate and pelitic hornfels.

Mudstone and siltstone underlie much of the low-lying ground in the Canberra city area. Fresh outcrops are scarce but grey, banded and strongly cleaved fossiliferous mudstone can be seen in the bed of Woolshed Creek (MR 980/915) (Owen, 1987) and in a drainage ditch along Antill Street (MR 971/990). There is also a good exposure, albeit weathered, in a cutting just below the Archbishop's house on the northern approach to Commonwealth Avenue Bridge. These sediments weather readily into yellow, pale-brown and purple ferruginous colours which locally contain liesegang rings. Characteristically, bedding is denoted by shallow-dipping widely spaced partings which are displayed as solution holes and channels by the weathering of thin calcareous bands, fossils or diagenetic nodules. Bedding is overshadowed by a prominent closely spaced cleavage which dips at much higher angles (70°–90°). Good examples of this relationship are displayed in a cutting on the Barton Highway opposite the CSIRO Divison of Wildlife offices, at MR 932/995. In thin-section the sediments consist of a fine-grained granular mosaic of subangular quartz, opaque iron oxide, and thin laths of muscovite often aligned parallel to the bedding. A patchy development of late calcite is common as a replacement mineral in fossil casts. Graded bedding is indicated by quartz-rich siltstone layers which pass into sericite-rich mudstone over a thickness of a few centimetres. A few grains of accessory plagioclase, zircon and tourmaline occur in the quartz-rich layers.

Outcrops of limestone (Smc_2) are known from widely-spaced localities in the Canberra Formation. Evidence from building site excavations and drilling in the Canberra City area indicates limestone is more widespread than hitherto recognised; it is present at several stratigraphic levels. Most of the limestone outcrops in the Canberra Formation have at some stage been examined and quarried for lime and as a source of building materials. Pittman (1911) was the first to refer briefly to them, and Mahoney & Taylor (1913) followed with detailed descriptions of most localities. Carne & Jones (1919) also referred to limestones in the Canberra area, but their descriptions relied heavily on Mahoney & Taylor's data.

A limestone lens on the eastern edge of the Acton Peninsula (MR 925/927) was originally described as the 'Acton Limestone deposit' by Mahoney & Taylor (1913), and subsequently by Öpik (1954; 1958) as the 'Acton Limestone', a member of his 'Canberra Group'. Strusz & Henderson (1971) suggest that as the limestone lens is relatively small, a formal name is not required. It was included as such in the Canberra Formation by Henderson (1981).

A detailed description of a limestone deposit about 1 km northeast of 'Gungaderra' homestead (MR 967/041) is given by Noakes & Perry (1952).

These limestones form discontinuous oval outcrops, massive or well-bedded, and are enclosed conformably by calcareous mudstone and siltstone. A ferruginous red–brown terra rossa soil often outlines the extent of outcrop. Fresh limestone varies from white to dark-grey. Solution grooves (rillenkarren) are a common weathering feature. The weathered surfaces of most of the limestones show a crinoid–coral–brachiopod fauna; where tectonism has been severe the fossils have been boudinaged and drawn out parallel to the cleavage. Outcrop thickness commonly ranges up to 30 m; however, core logged from stratigraphic drillhole C 145 shows that limestone beds can reach nearly 40 m in thickness. Strike length normally reaches about 100 m but in the vicinity of the rifle ranges at the head of Woolshed Creek a prominent limestone crops out over a strike length of about 2 km. The limited thickness and strike length of the limestones has precluded large-scale solution-cavity (cave) development.

The limestone has a framework of coarse calcitic fossil material consisting of crinoid, coral, bryozoan, shelly and possibly algal clasts, in places tectonically aligned, set in a recrystallised matrix of fine micritic calcite with accessory quartz and muscovite. Locally the micritic matrix has been replaced by a granular mosaic of pale-yellow, rhombic crystals of secondary dolomite. Thin stylolitic seams are denoted by concentrations of chloritic and ferruginous matter. Stylolites normally occur against clasts, but are also pronounced within the micritic matrix where they may define boundaries between calcite and dolomite. Following Folk (1974) the limestones are classified as biomicrites. The presence of magnesium, confirming the existence of dolomite, is indicated by partial chemical analyses of limestones from selected localities in the Canberra Formation (Mahoney & Taylor, 1913; Carne & Jones, 1919). More detailed chemical analyses (including boron) from three locations in a discontinuous limestone unit near the top of the Canberra Formation are given in Table 1. Smith (1964) mentions dolomitic beds in limestone northwest of 'Westmead Park' homestead.

The delicate preservation of the fossil material in the limestones suggests they accumulated as biostromal banks of low relief in a low-energy environment. Clastic material was cemented by a calcareous mud which at a later stage was partially replaced by dolomite. The dolomite was derived probably by the migration of magnesium-rich fluids during diagenesis, metamorphism and tectonism of the surrounding shales; however, a hydrothermal source for magnesium could be from Late Silurian volcanics which are interbedded in the sequence and also overlie the Canberra Formation.

Volcanic rocks in the Canberra Formation consist mainly of thin dacitic ignimbrite flows, with minor agglomerate, tuff and ashstone (Smc_4). It is difficult to trace individual lithologies in the field owing to poor exposure and complex fold and fault patterns. The best exposures of these rocks are in the headwaters of Ginninderra catchment and near 'Kia-Ora' homestead

Table 1. Canberra Formation: major and trace element analyses

Sample no.	*76460009*	*76460138*	*76460301*	*76460303*	*76460304*
Rock type	*albitised dacitic ignimbrite*	*albitised dacitic ignimbrite*	*limestone*	*limestone*	*limestone*
Grid ref.	*977128*	*924098*	*999995*	*984018*	*977982*
%					
SiO_2	68.49	67.13	4.90	2.72	2.35
TiO_2	0.54	0.60	0.06	0.04	0.04
Al_2O_3	14.66	14.52	1.10	0.91	0.94
Fe_2O_3	1.42	0.78	0.36	0.29	0.06
FeO	2.95	3.75	0.08	0.12	0.23
MnO	0.04	0.04	0.02	0.05	0.02
MgO	2.25	3.41	0.79	1.73	0.78
CaO	0.49	0.54	50.80	51.20	52.80
Na_2O	5.75	3.85	0.08	0.09	0.08
K_2O	0.25	2.03	0.26	0.25	0.23
P_2O_5	0.12	0.16	0.01	0.01	0.01
H_2O+	2.56	2.70	0.48	0.43	0.34
H_2O-	0.10	0.02	0.12	0.11	0.13
CO_2	0.05	0.28	40.5	41.60	41.80
Rest	0.11	0.14	—	—	—
Total	99.78	99.95	99.7	99.6	99.80
ppm					
B	—	—	10	20	5
Ba	60	300			
Rb	12	70			
Sr	150	120			
Pb	15	<2			
Th	16	20			
U	4	6			
Zr	195	180			
Nb	10	10			
Y	32	30			
La	50	30			
Ce	80	90			
V	100	100			
Cr	30	50			
Co	15	15			
Ni	5	20			
Cu	10	12			
Zn	50	38			

(MR 989/143) where they form low hills with rubbly outcrops, or low ridges which are in places resistant enough to define minor fold structures. The dacitic ignimbrite flows are normally massive, and the volcaniclastic rocks commonly show a rudimentary banding which indicates they are conformable within the sedimentary sequence.

North of 'Emohruo' homestead, acid volcanic rocks near the top of the Canberra Formation were named the 'Glenesk Volcanics' by Smith (1964). The name was subsequently published as the 'Glenesk Formation' by Best & others (1964) on the 2nd Edition of the Canberra 1:250 000 Geological Sheet. The 'Glenesk Volcanics' consist of dacitic tuff with minor tuffaceous shale and agglomerate. Like other volcanic beds near the top of the Canberra Formation this unit has limited extent but shows petrological affinities to the Mount Ainslie Volcanics. Since Smith neither mapped the entire unit nor proposed a type locality or section, it is recommended that this stratigraphic nomenclature be discarded. Other noteworthy outcrops of volcaniclastic rocks in the Canberra Formation include a well-bedded northeasterly-striking fine-grained unit at the base of the northwestern slope of Nobby Hill (MR 986/150) and agglomeratic tuff beds in the vicinity of Oak Hill (MR 957/089).

The dacitic ignimbrites consist of corroded phenocrysts of angular to rounded monocrystalline quartz, albitic plagioclase altered to calcite and sericite, and rounded felsic rock fragments. There are also biotite, strongly altered to light-green pleochroic chlorite, and opaques with the occasional growth of secondary quartz along prismatic cleavage planes. The phenocrysts are set in a fine-grained felsic groundmass containing accessory calcite, opaque iron oxides, zircon and apatite. Potash feldspar is absent. Locally the groundmass structure may be partially destroyed by the growth of spherulites (plumose radial aggregates of quartz and feldspar enclosed by an outer layer of secondary quartz). In some instances, spherulites have grown around small phenocrysts of quartz and plagioclase; this is attributed to devitrification during cooling of the ignimbrite flows. The whole-rock analyses for these dacitic tuffs (Table 1) show a similar chemistry to the overlying Mount Ainslie Volcanics.

In the dacitic volcaniclastics the framework consists of a poorly sorted assemblage of angular quartz and altered albitic plagioclase clasts with felsic volcanic, argillaceous and calcareous rock fragments set in a sandy, commonly calcareous matrix. Biotite is much reduced and potash feldspar is absent. Over the interval of 108–134 m in drillhole C 145 (Fig. 4), tuffaceous layers contain poorly sorted clasts of angular quartz, albitic plagioclase, chloritised and ferruginised biotite aligned parallel to the bedding, and siltstone fragments. The phenoclastic mineralogy and presence of accessory garnet and cordierite suggest that these volcanic beds are allied to the S-type Hawkins Volcanic Suite. Volcaniclastic beds showing evidence of reworking occur over the interval 38–41.5 m. Here thin tuffaceous beds in calcareous siltstone are indicated by the layered concentration of well-sorted, rounded monocrystalline quartz, calcite and calcareous rock fragments up to 3 mm. Plagioclase and biotite are only accessories.

Patches of calc-silicate hornfels conformably bedded with shale, siltstone and acid volcanic rock occur within the Canberra Formation. The main outcrop belt stretches from Oak Hill north-northeast towards the vicinity of Nobby Hill. Beds of calcareous hornfels and marble occur on the western side of the Ainslie–Majura ridge at approx. MR 974/993. Similar rocks ('Molonglo Ford Hornfels') were described by Öpik (1958) on the northern side of the light industrial area, Fyshwick. Banding measurements in some outcrops of hornfels to the north of Nobby Hill define small southerly-plunging anticlines.

Boundary relationships. The Canberra Formation rests with variable angular discordance on Ordovician and Early Silurian (Llandovery) rocks. In a temporary excavation on the Australian National University campus, Crook & others (1973) noted that the Camp Hill Sandstone Member, the basal member of the Canberra Formation, rested unconformably on the Pittman Formation. Henderson (1979a) described a similar but weathered contact between the same units in a road cutting along Parkes Way (MR 925/930) (now obscured by a concrete retaining wall). In the outer State Circle road cut, mildly folded Camp Hill Sandstone rests with marked unconformity on the State Circle Shale (Strusz & Henderson, 1971). At the former summit of Capital Hill (removed during excavation for the new Parliament House) the Camp Hill Sandstone was unconformable on the Black Mountain Sandstone (Öpik, 1958, figs. 4–7; Henderson, 1982). In a cutting on the Barton Highway (MR 904/026), Crook & others (1973) mapped a shale-clast breccia assigned to the Camp Hill Sandstone, resting with high angular discordance on Black Mountain Sandstone. Northeast of 'Wantagong' homestead Henderson (1978b) mapped a sandstone unit at the base of the Canberra Formation apparently resting unconformably on the Murrumbateman Creek Formation.

The top of the Canberra Formation is marked by a conformable contact with the Mount Ainslie Volcanics. Volcaniclastic sediments and ignimbrite flows increase in abundance towards the top of the Canberra Formation, and the upper boundary is therefore placed at the highest mappable marine sedimentary bed. Boundary relationships at the top of the Canberra Formation can be seen on the western slopes of Mount Majura where fossiliferous mudstone passes upwards through a sequence of dacitic tuff, limestone and siltstone to dacite of the Mount Ainslie Volcanics (Henderson, 1981).

Thickness. A minimum thickness of 300 m is given for the Canberra Formation from stratigraphic data obtained from drillhole C 145 (Henderson, 1978a). For the central Canberra area, Henderson (1981) gives a thickness estimate of >1000 m. In the Gundaroo–Nanima area, Smith (1964) indicates an approximate thickness of 1800 m for units of his 'Westmead Park Formation', measured on the western limb of a syncline. Strusz & Henderson (1971) quote a minimum estimated thickness of 240 m for the 'Fairbairn Group' in the vicinity of Fyshwick and Canberra Airport. The considerable variation in thickness estimates for the Canberra Formation is largely due to repetition of lithological units by folding, faults with indeterminate displacement and poor outcrop. The uncertainty of thickness estimates is further complicated by the abrupt termination of the Canberra Formation southwards by the Deakin Fault and eastwards by the Sullivans Fault.

Environment of deposition. The early depositional phase of the Canberra Formation is characterised by shelf sediments indicative of shallow-marine conditions. The poor development of sandstone interbeds and sedimentary structures in the sequence suggest a low-energy environment mostly below wave base. An eastward transgression of volcanic activity across the shallow marine basin is suggested by the increase of volcanic beds near the top of the Canberra Formation. Stable and quiescent intervals between volcanic pulses are indicated by the close association of limestones with volcanic rocks and reworked tuffaceous deposits in littoral zones.

Age and correlation. Stratigraphic relationships indicate that the Canberra Formation is of approximately late Wenlock age (Strusz, 1983). The Canberra Formation also contains a fairly abundant though poorly preserved shelly marine fauna. Accounts of the fauna ranging in age from late Wenlock to early Ludlow are given in Sherrard (1952), Strusz (*in* Pickett, 1982) and Strusz (1983; 1985).

Based principally on a small conodont fauna, Link (1970) concluded that Öpik's 'Riverside Formation of the Canberra Group' was early to middle Ludlovian in age. The fauna retrieved from limestones in site excavations in the northern Canberra suburb of Braddon was identified by Link & Druce (*in* Strusz & Henderson, 1971) as *Kockelella variabilis*, *Spathognathodus inclinatus inclinatus* and varieties of panderodids. However, the Ludlovian age for this fauna is questionable on the following grounds:

- The Ludlow age and correlation of units of the 'Canberra Group' (Link 1970, 1971a) was disputed by Öpik (1971) who questioned the validity and status of *Kockelella variabilis* as a species suitable for stratigraphic use.
- According to Barrick & Klapper (1976), the stratigraphic range for *K. variabilis* is uncertain. Their conodont studies on the Late Llandovery–Wenlock Clarita Formation in Oklahoma, USA, indicate that the *K. variabilis* zone is an equivalent of the *'Ozarkodina' crassa* zone. The age range of this *'O.' crassa* zone is still doubtful although it appears to span upper Wenlock to lower Ludlow.
- Supportive but by no means conclusive evidence is from the association of the conodont fauna with halysitid corals. These distinctive tabulate corals are widely distributed in the Canberra Formation. Their known distribution in the Australian Silurian is overwhelmingly pre-Ludlow.

The identity of the *K. variabilis* collected from the site at Lonsdale Street, Braddon, could not be confirmed in 1979, as the specimens were missing from the BMR palaeontological collection. To test the conclusions of Link (1970), limestone outcrops in the Canberra Formation were sampled for conodonts with R.S. Nicoll during 1979. Tabulated results of the sampling program are given in Table 2; from them it may be concluded that:

- Conodonts are most common in a discontinuous limestone bed, near the top of the Canberra Formation, which crops out in the vicinity of Woolshed Creek and on the western slopes of the Ainslie–Majura ridge.
- Preservation of conodonts is poor. According to R.S. Nicoll (pers. comm., 1982) the bulk of the specimens are cone fragments of indeterminate species of *Panderodus*. A few cones were identified as *Pseudoneotodus bicornis* from sample 303E and from core in drillhole C 282. *Kockelella* cf. *K. ranuliformis* was identified in sample 304C. According to Barrick & Klapper (1976) these conodont species first appear in the Wenlock zone of *K. ranuliformis* and persist through the *K. amsdemi* and *K. stauros* zones before dying out in the Ludlow *K. variabilis* zone.
- *K. variabilis* was not identified from any of the sample locations, including the NRMA building site, which is closest to the Lonsdale Street site in Braddon from which the species was originally recorded (Strusz & Henderson, 1971).

Age control is not good enough to make specific correlations with Late Silurian sedimentary units on BRINDABELLA, but the stratigraphic position and probable late Wenlockian age of the Paddys River Volcanics (and their close proximity to Canberra) suggest correlation in part with volcanic units near the top of the Canberra Formation (Owen & Cas, 1980). At this stage there is no evidence in support of a direct stratigraphic correlation of the Canberra Formation with Late Silurian sequences in the Captains Flat and Rocky Pic Blocks. The Wenlock age now considered most likely for the Canberra Formation requires that the Ludlow age given for this formation in regional stratigraphic correlation charts (Crook & others, 1973; Talent & others, 1975; Richardson, 1979) should be amended.

Camp Hill Sandstone Member (Smc_1)

Derivation of name. The Camp Hill Sandstone as described by Öpik (1954, 1958) was named after Camp Hill (MR 934/909) in Canberra, ACT.

Nomenclature. Öpik (1954, 1958) named the Camp Hill Sandstone as a formation lying conformably beneath the State Circle Shale (and 'Canberra Group') and unconformably above the Black Mountain Sandstone. A revision of the position of the State Circle Shale by Strusz & Henderson (1971) and Strusz & Jenkins (1982) led to a redefinition of the 'Canberra Group' to include the Camp Hill Sandstone as its basal unit. Following the change from 'Canberra Group' to Canberra Formation (p. 15), the Camp Hill Sandstone is now redefined as a Member at the base of that Formation.

Distribution. Scattered outcrops occur in the central Canberra and Ginninderra areas (Henderson, 1980; 1981), west of Queanbeyan and extending north of the Molonglo River to Fairbairn RAAF Base (Phillips, 1956; Moore, 1957) and in the Murrumbateman Creek catchment (Henderson, 1978b).

Type locality. The type locality given by Öpik (1958) was at Camp Hill behind Old Parliament House. The exposure is now much better in the deep road cutting on State Circle on the southwest side of Camp Hill (MR 934/908). Here, the unit is exposed as gently folded beds resting with marked unconformity on State Circle Shale (Llandovery). The sequence consists of a thin basal gritstone about 10 cm thick overlain by thinly bedded multi-coloured sandstone and siltstone; the top is not exposed.

Lithology. The Camp Hill Sandstone Member comprises well-bedded sandstone and siltstone with thin shale partings. The lower part of the unit normally consists of a thin bed of coarse-grained quartz sandstone (grit), but Crook & others (1973) noted a sedimentary breccia containing clasts derived from the nearby State Circle Shale in a cutting on the Barton Highway at MR 904/027. Pale-grey fine-to-medium-grained

Table 2. Occurrence of conodonts in limestone, Canberra Formation

Canberra Hospital											
Sample no.	283A	283B									Total
Processed weight (kg)	4.4	5.1									9.5
Conodonts (cone elements)	—	—									—
Gungaderra											
Sample no.	284A	284B	284C	284D	284E	284F	284G	284H	284I	284J	
Processed weight (kg)	4.3	5.1	4.6	5.4	4.6	4.6	5.2	4.9	4.5	5.4	48.6
Conondonts (cone elements)	1	6	—	8	6	—	—	—	2	—	23
Woolshed Creek											
Sample no.	301A	301B	301C	301D	301E	301F	301G	301H			
Processed weight (kg)	5.5	4.9	3.0	5.4	5.1	5.2	5.2	5.1			39.4
Conodonts (cone elements)	—	10	5-	3-	3	13	4	10			48
Canberra Park											
Sample no.	303A	303B	303C	303D	303E						
Processed weight (kg)	5.1	4.7	4.9	4.9	4.6	5.5					24.8
Conodonts (cone elements)	27	22	17	45	59						170
West Slope, Mt Majura											
Sample no.	304A	304B	304C	304D	304E						
Processed weight (kg)	4.7	4.6	5.0	5.0	4.6						23.9
Conodonts (cone elements)	5	12	12	11	13						53
BMR drillhole (C280), NRMA building site											
Sample depth (m)		6.0–6.5		6.6–7.0							
Processed weight (kg)		3.1		2.5							5.6
Conodonts (cone elements)		8		5							13
BMR drillhole (C281), NRMA building site											
Sample depth (m)		2.5–3.0		7.05–7.5		8.75–9.2		10.0–10.5			
Processed weight (kg)		2.7		2.0		2.6		2.8			10.1
Conodonts (cone elements)		5		14		1		—			20
BMR Drillhole (C282), NRMA building site											
Sample depth (m)		1.5–2.9(a)		5.8–6.7(b)		8.1–8.5					
Processed weight (kg)		1.6		3.9		2.6					8.1
Conodonts (cone elements)		3		15		1					19
BMR drillhole (C282) NRMA building site											
Sample depth (m)		4.5–5.3		7.2–7.8							
Processed weight (kg)		4.1		3.2							7.3
Conodonts (cone elements)		2		6							8

(a) *Pseudoneotodus bicornis*
(b) *Kockelella* cf. *K. ranuliformis*

Total weight 177.3 kg
Total cone elements 354

laminated sandstone is well exposed in a quarry at MR 004/875. At this quarry the sandstone beds range up to 50 cm thick with shale partings <10 cm thick. At 'Wantagong' homestead (MR 935/150) a thickly bedded sandstone defines the nose of a southwesterly plunging anticline. This sandstone, which is faulted in places, can be traced more or less continuously northeast as a marker bed defining the base of the Canberra Formation (Henderson, 1978b).

The sandstones are well sorted and composed almost entirely of subangular, recrystallised grains of quartz with subordinate amounts of micaceous siltstone and cherty rock fragments; the only obvious accessory is sporadic tourmaline. The high quartz content, lack of matrix and absence of feldspar suggest a mature sandstone derived locally from Early Silurian quartz turbidite deposits.

Boundary relationships. The Camp Hill Sandstone Member overlies the Ordovician Pittman Formation and the Silurian State Circle Shale and Black Mountain Sandstone (Strusz & Henderson, 1971; Crook & others, 1973; Henderson, 1979a) with a major unconformity. Within the Murrumbateman Creek catchment the unit is inferred to rest unconformably on steeply plunging sandstone beds of the Murrumbateman Creek Formation (Henderson, 1978b). The Camp Hill Sandstone Member passes gradually upwards into the interbedded mudstone, siltstone and lenticular limestone which form the greater part of the Canberra Formation. The top of the member is taken arbitrarily at the level where mudstone predominates over sandstone.

Thickness. Öpik (1958) estimated a thickness of 12 m on Camp Hill. Subsequent geological investigations around the type locality however have shown it to be up to 60 m (Henderson, 1981); near 'Wantagong' homestead the unit may reach 100 m. Presumably, being the basal transgressive member of the Canberra Formation, the Camp Hill Sandstone was deposited on an irregular land surface; this would give rise to the apparent sudden variations in thickness and even non-deposition in some areas (e.g. the Westlake Outlier of Öpik, 1958).

Environment of deposition. The textural characteristics of the sandstone and occasional cross-laminations and ripple marks suggest a shallow-marine depositional environment. The presence of thin gritstone beds at the base of the unit suggests that a land surface of moderate topography may have existed locally in the Canberra region during the late Wenlock.

Age. Fossils are normally sparse and poorly preserved. According to Strusz (1975) the most fossiliferous exposure of the Camp Hill Sandstone Member so far encountered was just above the unconformity on Capital Hill (now covered by the new Parliament House). At this site, Öpik (1958) collected the pentamerid brachiopod *Rhipidium* which, according to Berry &

Boucot (1970), establishes an age which is not younger than late Wenlock for this unit. Sandstones in the quarry at MR 004/875 are known to be fossiliferous and might provide further evidence for the age of the Camp Hill Sandstone Member in this area.

Narrabundah Ashstone Member (Smn)

Derivation of name. The Narrabundah Ashstone Member, as described by Öpik (1954, 1958), was named after the Canberra suburb of Narrabundah.

Nomenclature. Öpik (1954, 1958) interpreted the 'Narrabundah Ashstone' to be the final eruptive phase of the Mount Ainslie Volcanics, which he considered lay unconformably on Silurian sedimentary rocks and were thus of Early Devonian age. Temporary excavations for the Googong pipeline near the type area of Narrabundah showed this unit to be interbedded in the upper part of the Canberra Formation (Henderson, 1978c), and therefore one of the oldest rather than youngest of the felsic volcanic units in the Late Silurian (Owen & Cas, 1980). The 'Narrabundah Ashstone' is now regarded as having member status within the Canberra Formation.

Distribution. The unit has limited lateral extent. Apart from a few scattered outcrops its distribution is known mainly from drillholes and trench excavations in the Fyshwick–Narrabundah area, Pialligo, and between Kings Avenue and the suburb of Reid.

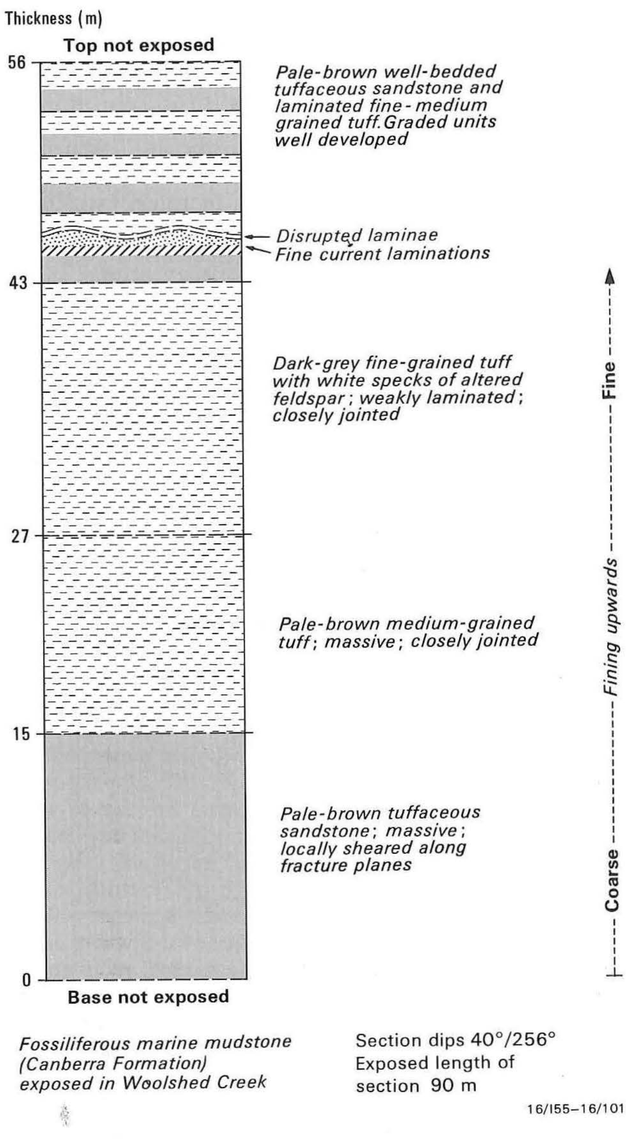


Fig. 5. Representative section of the Narrabundah Ashstone Member at Woolshed Creek.

Type locality. Designated by Öpik (1958) as a quarry (now disused) adjacent to Jerrabomberra Creek (MR 962/876 — access from Goyder Street). In the quarry only about 3 m of apparently flat-lying massive tuff remains exposed. However, in 1979 a BMR stratigraphic drillhole (C 284) penetrated 30 m of hard pale-grey fine-to-medium-grained tuff below the floor of the quarry (Henderson, 1983).

A representative section of the Narrabundah Ashstone Member is exposed in a road cutting in Fairbairn Avenue immediately west of Woolshed Creek bridge (MR 978/915). This section, which is figured in Henderson (1981, p. 9), shows a westerly-dipping sequence of volcaniclastic rocks. While the upper and lower contacts of the section are not seen, almost the full thickness must be exposed since it is clearly conformable within marine mudstone beds of the Canberra Formation which outcrop in the adjacent Woolshed Creek. An annotated diagrammatic section is given in Figure 5.

Lithology. The unit comprises strongly-jointed generally massive tuffaceous sandstone, and fine-to-medium-grained tuff. The variation in lithology can be examined in the cutting on Fairbairn Avenue (see Fig. 5). The tuffaceous sandstone is pale-brown, and bedding (where present) is a function of grainsize difference; graded units are present. The tuffs are grey where fresh but pale-brown where weathered; bedding is indicated by thin cherty laminations, which may be locally convoluted.

In thin-section the mineralogy is consistently displayed by clasts of angular quartz, sub-rounded altered albitic plagioclase, and siltstone rock fragments. Spindly and stubby prismatic laths of chloritised and ferruginous biotite with a preferred alignment parallel to bedding suggest a waterlain volcanic deposit. Similar mineralogical and textural features were noted in volcanic beds in the Canberra Formation intersected between 108 and 134 m in drillhole C 145.

Boundary relationships. The Narrabundah Ashstone Member is a conformable unit within the Canberra Formation. In the Narrabundah–Fyshwick area the unit is estimated to lie about 100 m below the top of the Canberra Formation (Henderson, 1980).

Thickness. The greatest known thickness, of 56 m, was measured in the section exposed on Fairbairn Avenue. Henderson (1981) estimates a thickness of up to 70 m.

Environment of deposition. Öpik (1958) originally suggested the unit was an ashfall deposit. However, the graded nature of the tuff beds with occasional convolute and fine current laminations displayed in the Fairbairn Avenue cutting support the view of Owen & Cas (1980) that the Narrabundah Ashstone Member was a volcaniclastic submarine mass-flow deposit laid down by turbidity currents in locally deeper parts of the Canberra–Yass Shelf.

Age and correlation. The Narrabundah Ashstone Member is unfossiliferous. As it is a member of the Canberra Formation its Wenlock age is based on fossil and stratigraphic evidence already given for the Canberra Formation.

The Narrabundah Ashstone Member is probably coeval with other Silurian volcanic beds near the top of the Canberra Formation.

Hawkins Volcanic Suite

The Hawkins Volcanic Suite is a petrographically and chemically related group of volcanic rocks of probably late Wenlock age which extends from the immediate vicinity of Canberra northwards onto YASS. Wyborn & others (1981) show that the Hawkins Volcanic Suite is characterised by an S-type phenocryst mineralogy of quartz + plagioclase (normally altered to albite) + biotite + cordierite + hypersthene ± accessory garnet. The relatively high iron-oxide content (4–5%) of the Suite is reflected in the red-brown colouring of the weathered rocks and overlying soils and the whole-rock analyses. Wyborn & Chappell (1986) also demonstrate that the Hawkins Volcanic Suite shows chemical and mineralogical similarities to S-type plutonic rocks. An internal stratigraphy recognisable within the Suite is depicted in Figure 6.

The Mount Ainslie Volcanics are the oldest formation. They consist of a subaerial sequence of dacitic ignimbrite with interbedded tuff and agglomerate; beds of marine shale occur near the base. The Mount Ainslie Volcanics rest conformably on the Canberra Formation and are overlain by the Mount Painter Volcanics north of the Deakin Fault.

The Walker Volcanics are a formation with uncertain affinities. They consist of multicoloured dacitic ignimbrite and several sedimentary lenses of limestone and shale. They are in fault contact with the Mount Painter Volcanics but are otherwise considered to represent a separate centre of volcanism west of CANBERRA.

The Mount Painter Volcanics, originally interpreted as a sill (Öpik, 1958), are now recognised as having features typical of an ignimbrite. They are the youngest formation of the Hawkins Volcanic Suite and represent the termination of the first phase of Silurian (Wenlock) volcanism on CANBERRA.

Mount Ainslie Volcanics (Sma)

Derivation. Öpik (1958) named the 'Ainslie Volcanics' after Mount Ainslie (843 m), a prominent wooded hill and recreational area (MR 962/947) in central Canberra. To avoid confusion with the suburb of Ainslie the name has been modified to Mount Ainslie Volcanics.

Nomenclature. Pittman (1911) recognised the volcanic nature of the porphyries in the Mount Ainslie area. Mahoney & Taylor (1913) examined a wider area and named them the 'Ainslie Series'. Öpik (1954, 1958) used the name 'Ainslie Volcanics' to describe acid to dacitic pyroclastics and lavas composing the Mount Ainslie–Mount Majura–Gooroo Hill ridge. The unit was regarded by Öpik as Early Devonian and from the discordance in dip he interpreted it as resting unconformably on the 'Canberra Group' and in turn as being overlain unconformably by the 'Narrabundah Ashstone'. However, it is now known that the 'Narrabundah Ashstone' is a member of the Canberra Formation and therefore the oldest named volcanic unit on CANBERRA (see p. 21).

Problems with Öpik's nomenclature became apparent when Moore (1957) mapped the 'Gladefield Volcanics' as a sequence of deformed felsic volcanic rocks adjacent to the Sullivans Fault. He interpreted the unit as lying conformably on the 'Fairbairn Group'. Ollier & Brown (1975) mapped similar bedding dips in the 'Ainslie Volcanics' and underlying 'Canberra Group' and concluded that these two units were also conformable and that the Mount Ainslie Volcanics were the oldest rather than the youngest volcanic formation on CANBERRA. To simplify the terminology, it is proposed that the name 'Gladefield Volcanics' be discarded since the stratigraphic position and lithological, petrological and chemical affinities of the 'Gladefield Volcanics' show they are a foliated equivalent of the Mount Ainslie Volcanics, resting conformably on the Canberra Formation.

A felsite originally mapped by Pittman (1911) near Mount Pleasant (MR 955/917) was named the 'Mount Pleasant Rhyolite' by Öpik (1958) and subsequently the 'Mount Pleasant Porphyry' (Strusz, 1971). Öpik (1958) recognised these rocks as a suite of altered acid volcanics forming part of the 'St Johns Church beds', the unit occurring as a Silurian inlier within his 'Ainslie Volcanics'. Outcrops of cream 'rhyolite' shown interbedded with the Mount Ainslie Volcanics on the Second Edition of the Canberra 1:50 000 Geological Sheet (Henderson, 1980) are probably the unnamed equivalent of the 'Mount Pleasant Porphyry'. There is little evidence in support of the retention of the 'Mount Pleasant Porphyry' as a member of the Mount Ainslie Volcanics. Instead, these rocks are now regarded as a zone of local hydrothermal alteration within the volcanic sequence (Sma_2).

Distribution. The outcrop pattern of the Mount Ainslie Volcanics is largely a reflection of structure. Differential erosion along broad anticlines and synclines in Silurian rocks north of the Deakin Fault has left the formation exposed as three major north-northeast trending belts. The most prominent is the Mount Ainslie–Mount Majura–Gooroo Hill ridge, an erosional residual with a synclinal structure, standing above softer sediments of the Canberra Formation. A narrow belt of foliated volcanics forms a line of low hills east of Majura Road and continues southwards to form more subdued country south of Fyshwick. Volcanic rocks between Hall and Nanima Hill (MR 887/244) give sufficient topographic relief in the Spring Range area for the base of the Mount Ainslie Volcanics to be mapped on the western limb of a major anticlinorial structure in the Canberra Formation. South of the Deakin Fault the Mount

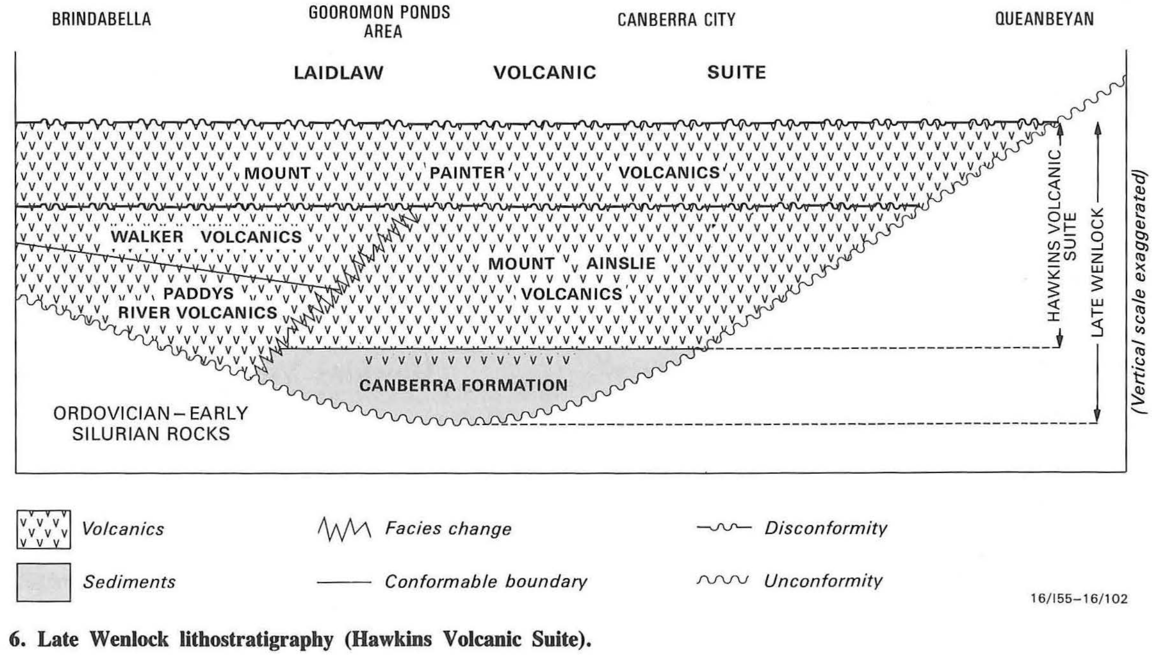


Fig. 6. Late Wenlock lithostratigraphy (Hawkins Volcanic Suite).

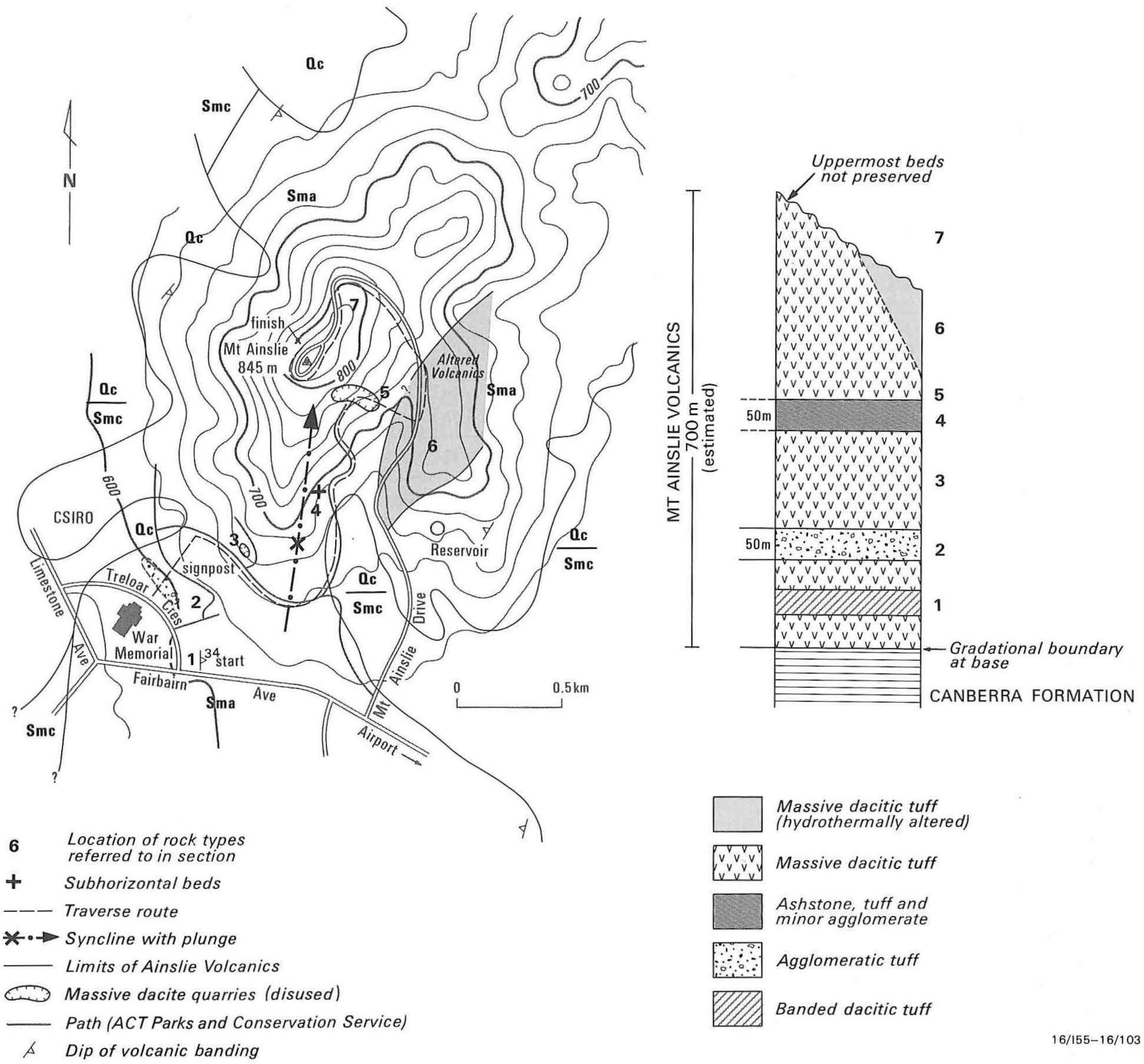


Fig. 7. Type locality and schematic section, Mount Ainslie Volcanics.

Ainslie Volcanics do not outcrop and have yet to be proved by drilling.

Type locality. Öpik (1958) designated acid to dacitic pyroclastics and lavas along the Mount Ainslie–Mount Majura–Gooroo Hill ridge as the type locality for the 'Ainslie Volcanics', but did not give a type section. Instead, a panoramic section near the base of the western slopes of Mount Ainslie (Öpik 1958, fig. 36) depicts the stratigraphic relationships of his rock units.

The type locality now designated for the Mount Ainslie Volcanics comprises the outcrops on the southern slopes of Mount Ainslie (Fig. 7). The schematic section at the type locality is interpretative because of discontinuity of outcrop. Relationships between the units are inferred from stratigraphic superposition, the older ones being exposed on the lower slopes of Mount Ainslie. The section consists predominantly of bluish-grey massive dacitic tuff with poorly outcropping interbedded lenses of dacitic agglomerate and ashstone. The thickness is estimated at about 700 m. The base is not exposed, but west of the Australian War Memorial the boundary can be inferred at a small topographic break where the more resistant massive volcanics overlie the softer sedimentary Canberra Formation. Measured dips on the flanks of Mount Ainslie indicate the volcanic sequence is folded into a broad syncline plunging north. In cuttings about half way up Mount Ainslie Drive, massive dacitic tuff has been hydrothermally altered to a white leached rock of rhyolitic composition with associated iron oxide mineralisation along joint planes.

Lithology and petrography. A degree of lithological variation near the base of the Mount Ainslie Volcanics is evidenced by banded dacitic tuff, dacitic agglomerate and thin shale beds. At the top, the formation is more uniform, with the common rock type a medium-grained massive dacitic tuff which forms much of the ridge and hill country north of Canberra. The tuff has been foliated locally near major faults.

Massive discontinuous beds of dacitic agglomerate locally characterise the lower portion of the Mount Ainslie Volcanics. On the lower slopes of Mount Ainslie near the War Memorial (Fig. 7), bouldery outcrops of agglomerate are composed of subangular clasts of greyish dacitic tuff up to 10 cm across and subordinate amounts of lithic clasts set in a tuffaceous matrix. Similar but less well-exposed agglomerates occur in the vicinity of Old Joe (MR 994/031) and in a railway cutting a few hundred metres northwest of Harman Naval Base (MR 994/867). Limestone clasts have been found in an 'agglomerate' north of 'Emohruo' homestead at MR 911/156. The local

Table 3. Mount Ainslie Volcanics: major and trace element analyses (dacitic ignimbrites)

Sample no.	*74840012*	*74840079*	*74840080*	*74840081*	*74840082*	*74840083*	*74840084*	*75360009*	*75360012*
Grid ref.	*949942*	*951923*	*008953*	*985982*	*984985*	*012018*	*012018*	*012015*	*893179*
%									
SiO_2	66.80	66.16	64.55	63.94	64.94	49.35	67.94	67.54	66.32
TiO_2	0.59	0.57	0.62	0.59	0.59	0.51	0.58	0.66	0.61
Al_2O_3	14.28	14.50	14.50	14.57	14.46	12.04	14.75	15.25	14.39
Fe_2O_3	0.79	0.13	1.01	0.29	0.36	3.97	0.36	0.96	1.51
FeO	3.42	4.17	3.57	4.58	4.76	12.25	3.64	3.20	3.75
MnO	0.04	0.05	0.07	0.15	0.11	0.19	0.07	0.06	0.08
MgO	2.15	2.29	2.21	2.80	2.65	10.10	2.41	2.03	2.42
CaO	2.61	1.57	3.30	2.18	3.62	0.27	0.42	0.30	2.95
Na_2O	2.05	3.95	1.97	0.68	1.40	0.22	6.62	7.10	1.91
K_2O	3.80	3.06	3.71	5.23	3.03	0.11	0.23	0.41	2.92
P_2O_5	0.11	0.07	0.07	0.07	0.07	0.05	0.06	0.12	0.14
H_2O+	1.94	2.04	2.32	2.96	2.53	6.77	1.76	1.70	1.98
H_2O-	0.55	0.90	1.50	1.55	0.75	0.05	0.05	0.05	0.20
Rest	0.23	0.19	0.27	0.24	0.34	0.20	0.12	0.15	0.22
Total	99.42	99.73	99.95	99.97	99.74	96.19	99.07	99.54	99.43
ppm									
Ba	580	600	1250	740	1800	60	70	340	580
Rb	160	105	80	150	190	8	6	15	145
Sr	140	180	200	190	85	12	150	200	160
Pb	330	16	<2	12	65	22	<2	6	150
Th	18	14	16	14	14	16	14	16	22
U	4	4	4	<4	<4	4	<4	4	4
Zr	180	165	175	185	160	130	180	190	210
Nb	6	6	4	6	6	<2	6	10	<4
Y	25	30	30	30	25	40	20	25	25
La	50	60	60	40	50	30	60	60	50
Ce	80	70	90	80	70	80	80	90	100
V	155	135	155	170	170	350	135	110	135
Cr	75	65	60	90	95	35	85	60	80
Co	14	8	8	12	8	60	6	10	8
Ni	14	14	2	12	20	20	22	28	20
Cu	32	38	16	24	28	470	10	10	26
Zn	57	35	75	205	84	100	33	27	84

extent and lack of bedding in this rock type suggest it may be a pyroclastic debris flow. Thin beds of cleaved brown shale (Sma$_1$) crop out along the western belt of the formation; the most persistent horizons form a series of discontinuous outcrops between Hall and Nanima Hill.

Massive dacitic ignimbrite is often exposed as sloping rock surfaces. On lower ground, tors are more common where weathering has been able to penetrate vertical joints. Fresh outcrops are uncommon and are best found in road cuttings and quarry sections where the rock is bluish-grey beneath a thin creamy-brown weathering skin. Field specimens are not strongly porphyritic, but phenocrystic quartz, greenish feldspar, cordierite and rare garnet can be recognised, while there is patchy dissemination of pyrite and chalcopyrite, notably in a cutting on the Federal Highway west of Ginns Gap (approx. MR 984/006).

Typical specimens of Mount Ainslie Volcanics are characterised by strong alteration of the phenocrysts and groundmass. Quartz occurs as large embayed, sometimes fractured, crystals or as smaller angular clasts. Plagioclase feldspar (up to An$_{30}$) with corroded and diffuse crystal outlines is mostly altered to albite, sericite and calcite; zoning is rare but can be recognised in the fresher crystals. The mafics are intensely altered: a few fresh pleochroic brown biotite crystals survive, but cordierite and hypersthene have been totally altered to chlorite, epidote, opaques and sphene. Prismatic laths of altered biotite can be readily identified through an alteration mineral assemblage of pale-green chlorite, opaque iron oxide and sphene. Cordierite is present as irregular pale-green fragments with rare crystal outlines; clear pale-green chlorite is the main alteration product and may rim and preserve strongly sericitised cores. Orthopyroxene occurs as brown stubby crystals sometimes showing eight-sided cross-sections; pseudomorphing chlorite and epidote have more or less destroyed the cleavage. Diffuse felsic rock fragments in which the mafic minerals have been strongly altered to chlorite, calcite, epidote, sphene and opaques may be distinguished from mafic minerals by their less holocrystalline texture. A few lithic fragments of limestone and siltstone also occur. The groundmass is cryptocrystalline; a variable grainsize relates to patchy devitrification and recrystallisation of a quartz–feldspar mosaic containing sericite, calcite and chlorite. The groundmass may also show relict shard texture, eutaxitic flow layering, disseminated pyrite, accessory zircon and rare garnet.

Massive dacitic tuff becomes progressively more foliated towards the Sullivans Fault. The field occurrence of the foliated tuffs is as elongate knife-edged outcrops having a strong alignment with the strike of the foliation. In the Federal Highway Quarry (MR 012/015) fresh exposures of strongly foliated and jointed greenish-grey dacitic tuff show dark-grey streaks of chlorite aligned subparallel with the foliation. A shallow-dipping banding defining minor fold structures is preserved in creek sections west of 'Gladefield' homestead (MR 007/951) and in Doughboy Creek.

Differences in the thin-section mineralogy and texture of the foliated rocks compared with the massive variety are attributable to shearing. Phenocrysts of quartz are more strongly strained and fractured, while those of plagioclase still retain their general outline but are totally altered to sericite. Except for a few kinked remnants of altered biotite, the mafics have been reduced to chlorite and drawn out parallel to the foliation. The strongly sheared cryptocrystalline groundmass is composed largely of sericite, calcite, quartz and pyrite. Locally, pressure fringes have developed in quartz phenocrysts and

Table 3 (continued)

Sample no. *Grid ref.*	*75360013* *896180*	*75360014* *869032*	*75360019* *960950*	*76460021* *012015*	*76460060* *018915*	*76460140* *902175*	*76460141* *897180*
%							
SiO_2	66.82	64.07	63.20	65.88	61.47	67.49	66.74
TiO_2	0.57	0.56	0.61	0.60	0.53	0.63	0.57
Al_2O_3	14.37	13.98	14.92	14.34	14.54	14.68	13.83
Fe_2O_3	1.24	1.98	1.87	0.99	1.39	0.88	1.79
FeO	3.40	3.05	4.55	4.15	4.20	3.67	2.81
MnO	0.07	0.07	0.03	0.04	0.08	0.07	0.07
MgO	2.96	3.32	4.15	3.15	3.30	1.79	2.58
CaO	1.11	1.79	0.34	0.25	3.34	2.39	2.45
Na_2O	3.20	2.69	5.88	3.05	2.10	2.02	1.83
K_2O	3.19	3.55	0.08	3.69	2.80	3.69	3.88
P_2O_5	0.15	0.13	0.12	0.15	0.11	0.17	0.17
H_2O+	2.42	2.83	3.18	2.63	3.60	1.69	2.40
H_2O-	0.02	0.13	0.06	<0.02	0.08	0.04	0.07
CO_2	0.03	1.25	0.05	0.05	2.45	0.10	0.62
Rest	0.20	0.18	0.12	0.29	0.15	0.18	0.20
Total	100.02	99.58	99.16	99.26	100.14	99.49	100.01
ppm							
Ba	580	560	50	1650	410	470	510
Rb	135	150	6	95	130	180	180
Sr	110	100	110	120	65	140	140
Pb	22	10	4	3	2	24	22
Th	12	14	4	14	6	26	22
U	—	—	12	4	<4	8	8
Zr	190	150	160	200	130	180	180
Nb	—	10	—	14	12	6	<4
Y	40	25	20	28	22	30	30
La	60	50	40	30	30	30	30
Ce	120	70	80	90	60	110	110
V	95	100	200	100	150	100	110
Cr	120	95	100	45	70	60	80
Co	12	10	14	20	25	15	15
Ni	30	30	18	15	15	25	30
Cu	20	6	44	9	50	24	66
Zn	67	77	23	25	40	61	62

quartz-rich portions of the groundmass adjacent to large rigid crystals of pyrite. The curved quartz fibres (Spry, 1969) indicate some quartz phenocryst rotation during deformation. The pyrite predates the shearing episode.

Whole-rock analyses of the volcanic rocks are listed in Table 3.

Boundary relationships. The conformity of bedding dips in the Mount Ainslie area indicates that the Mount Ainslie Volcanics overlie the Canberra Formation conformably (Ollier & Brown, 1975). In a broad sense they have a gradational contact with the Canberra Formation, the base being mapped at a topographic break corresponding with the bottom of the first persistent dacitic ignimbrite. In detail however the contact is more complex. A contact observed by Henderson (pers. comm., 1982) in a temporary building excavation at the Russell Defence Offices showed clasts of sediment caught up in a basal dacitic ignimbrite. At another site, on the corner of Constitution Avenue and Cresswell Street, Campbell, the basal ignimbrite has a sharp, steeply dipping contact with mudstone of the Canberra Formation.

The upper boundary with overlying volcanic units on CANBERRA is obscure. The topmost beds have been eroded along the Mount Ainslie–Mount Majura–Gooroo Hill ridge. A contact with the overlying Mount Painter Volcanics is not exposed, but where this boundary has been mapped between Hall and Nanima Hill, it is only arbitrarily differentiated on petrographic and chemical criteria. Since stratigraphic relationships with the Walker Volcanics are indefinite, a disconformity may exist at the upper boundary of the Mount Ainslie Volcanics north of the Deakin Fault.

Thickness. Estimates of thickness are complicated by folding and faulting. Henderson (1981) gives a minimum thickness of 700 m in the Canberra area. The unit probably thickens westwards, but estimates depend largely on accurate mapping of the upper boundary with the Mount Painter Volcanics.

Environment of deposition. Shale, agglomerate and other volcaniclastic units interbedded with dacitic ignimbrites suggest that the early volcanic units were deposited from eruptive centres marginal to a shallow-marine shelf. Deposition of younger, massive, dacitic ignimbrites indicate the establishment of a subaerial environment, which appears to have transgressed eastwards across the Canberra–Yass Shelf.

Age and correlation. Originally Öpik (1958) gave an Early Devonian age for the Mount Ainslie Volcanics based on an inferred unconformity with the underlying Silurian sequence. However, a probable late Wenlock age can now be deduced from fossil assemblages in the underlying Canberra Formation (Strusz, 1983; 1985). Other evidence in support of this age is provided by Wenlock trilobites and brachiopods collected from sedimentary beds in the possibly coeval Walker Volcanics (Chatterton & Campbell, 1980; Strusz, 1982b).

A suggestion that the Mount Ainslie Volcanics correlate with the Mount Painter and Deakin Volcanics (Ollier & Brown, 1975) is not supported on grounds of stratigraphic superposition and differences in petrography and geochemistry. According to Owen & Cas (1980) the Mount Ainslie Volcanics are a probable correlative of the Paddys River Volcanics on BRINDABELLA. This correlation is supported on the following grounds:

— the units are the oldest members of the Hawkins Volcanic Suite in their respective Sheet areas.

— each contains a similar lithological grouping of interbedded marine sediments in basal volcanic units passing up into subaerial dacitic ignimbrites.
— the chemistry of each unit shows similar silicate and elemental variation.

On petrographic and geochemical grounds the Mount Ainslie Volcanics are a probable correlative of the Walker Volcanics. Alternatively, the apparent absence of the Walker Volcanics in the volcanic stratigraphy north of the Deakin Fault suggests this formation may represent a separate centre of volcanic activity synchronous with that of the Mount Ainslie Volcanics.

Walker Volcanics (Smw)

This stratigraphic unit has been defined on BRINDABELLA by Owen & Wyborn (1979) where it forms a wedge-shaped outcrop tapering eastwards onto CANBERRA. The Walker Volcanics have an approximate outcrop area of 30 km^2 and underlie the lower Molonglo River catchment south of Belconnen. On CANBERRA the best exposures are in the river about 3 km downstream from Coppins Crossing (MR 822/950). The designated type section is in the Murrumbidgee River (on BRINDABELLA) 50 m downstream from the causeway at Uriarra Crossing (Owen & Wyborn, 1979).

Lithology and petrography. The Walker Volcanics comprise mainly purple and greenish-grey massive and banded dacitic ignimbrite. The multi-coloured appearance of the formation is similar to that of the Deakin Volcanics. Interbedded lenses of fossiliferous limestone and shale (Smw_1) crop out 2 km northwest of Coppins Crossing (MR 835/943) and near The Pinnacle (MR 856/943).

The best exposures of the sediments are at the former locality where these sediments once formed a continuous lens within the Walker Volcanics, although their outcrop pattern has been disrupted by faulting and folding. At the base of the section there is an impersistent cherty shale bed resting with an irregular contact on felsic volcanics. The best exposed sediments are fossiliferous, dark-grey nodular limestone with a maximum thickness of 15 m. A return to volcanic activity at the top of the section is indicated by beds of calcareous and tuffaceous shale.

A detailed description of the petrography and chemistry of the volcanic rocks on BRINDABELLA is given by Owen & Wyborn (1979). The volcanic rocks examined on CANBERRA show quartz, albitised plagioclase, rare garnet and altered orthopyroxene and cordierite. Biotite is often altered to pseudomorphs of muscovite and opaque minerals. Nevertheless the presence of cordierite indicates that the Walker Volcanics belong to the S-type Hawkins Volcanic Suite. Chemical analyses for this unit on CANBERRA are listed in Table 4.

Thickness. On CANBERRA accurate thickness estimates are impossible since boundaries are almost invariably faulted. Henderson (1980) estimated a thickness in excess of 1500 m south of Belconnen. The banding in the Walker Volcanics dips consistently westwards onto BRINDABELLA and, as folding appears to be minor, the thickness probably exceeds 2000 m.

Environment of deposition. The dominance of ignimbrite flows indicates that the Walker Volcanics accumulated subaerially. Proximity to a marine environment is indicated by the deposition of autochthonous limestone and clastic sediments during quiescent periods.

Age and correlation. A probable late Wenlock age has been established for the Walker Volcanics based on the identification of a shelly marine fauna of trilobites and brachiopods in sediments along the Molonglo River valley below Coppins Crossing (Chatterton & Campbell, 1980; Strusz, 1980; 1982a & b) and stratigraphic relationships with the better controlled Yass sequence (Strusz, 1982b). The limestones have also yielded conodonts although the forms were insufficiently diagnostic to date the sediments. R. Nicoll (pers. comm., 1982) reports a fairly abundant assemblage of panderodid cones from The Pinnacle area but the retrieval of only a few indeterminate cone fragments from below Coppins Crossing. Near the top of the Walker Volcanics a coral–brachiopod fauna of probable late Wenlockian age occurs in bioclastic limestone near Uriarra Crossing (Strusz, 1975).

Table 4. Walker Volcanics: major and trace element analyses (dacitic ignimbrites)

Sample no.	*75360003*	*77360025*
Grid ref.	*840942*	*830948*
%		
SiO_2	68.16	68.57
TiO_2	0.54	0.55
Al_2O_3	14.11	13.87
Fe_2O_3	2.59	1.02
FeO	1.65	3.09
MnO	0.05	0.05
MgO	1.49	2.90
CaO	1.37	0.32
Na_2O	2.65	2.56
K_2O	4.38	3.47
P_2O_5	0.13	0.14
H_2O+	1.85	3.28
H_2O-	0.23	0.20
CO_2	0.65	0.20
Rest	0.20	0.13
Total	100.05	100.35
ppm		
Ba	620	280
Rb	240	140
Sr	80	24
Pb	18	9
Th	18	16
U	4	6
Zr	190	200
Nb	<4	<4
Y	30	32
La	60	30
Ce	100	70
V	110	75
Cr	50	<10
Co	6	12
Ni	10	18
Cu	6	15
Zn	72	90

The precise stratigraphic position of the Walker Volcanics on CANBERRA is uncertain, since almost all contacts are faulted. However, the balance of evidence suggests they are equivalent in age to the Mount Ainslie Volcanics but older than the Mount Painter Volcanics.

The Walker Volcanics are separated from the Mount Painter Volcanics by the Winslade Fault. However, the Second Edition of the Canberra–Queanbeyan 1: 50 000 scale map (Henderson, 1980) shows an outlying remnant of the Mount Painter Volcanics resting on the Walker Volcanics near the Molonglo River (MR 845/924).

According to Sufni Hakim (1985), on BRINDABELLA the Walker Volcanics are overlain unconformably by the Mount Painter Volcanics in the Fairlight area. Both units are in turn overlain by the early Ludlow Tarpaulin Creek Ashstone which is the basal member of the Uriarra Volcanics (Owen & Wyborn, 1979; Sufni Hakim, 1985).

Mount Painter Volcanics (Smp)

Derivation. Öpik (1954, 1958) named the 'Mount Painter Porphyry' after Mount Painter (MR 876/950), a hill immediately south of the Canberra suburb of Cook.

Nomenclature. The name 'Mount Painter Porphyry' was based largely on Öpik's conclusion that this unit is a sill. The evidence is summarised below:

- — massive and uniform lithologic composition
- — contains igneous and sedimentary xenoliths
- — little affected by tectonic stress
- — apparent intrusive contacts with the 'Red Hill Group' (Deakin Volcanics and Yarralumla Formation).

Since Öpik's work, stratigraphic and petrographic studies have resolved that the unit is extrusive (a crystal tuff) and arguments in support of an intrusive origin cannot be sustained. Therefore the unit has now been renamed the Mount Painter Volcanics.

Distribution. The present outcrop occupies two belts which have been displaced along the Deakin Fault. A folded southeast-trending belt extends from Coppins Crossing towards Narrabundah and Jerrabomberra Creek. North of the Deakin Fault the Mount Painter Volcanics extend from Gooromon Ponds Creek northwards onto the YASS and GUNNING Sheets.

Type locality. Öpik (1958) designated Mount Painter as the type locality for his 'Mount Painter Porphyry'. At this locality he described the rocks as a 'dark massive porphyry with numerous xenoliths of sedimentary and igneous origin, amongst them fragments of vein quartz. Garnet was present in places'. The thickness of the unit was estimated to be 200 m.

It is recommended that the type locality for the Mount Painter Volcanics be extended to encompass a square area of pastureland and pine plantation bounded to the north by the Winslade and Deakin faults and to the south by the Molonglo River and Lake Burley Griffin. Within this area the formation is exposed as boulders and tors on and around the southern flanks of Mount Painter and in a series of rapids in the Molonglo River at MR 857/923. The volcanic rock is a massive, bluish-grey dacitic crystal tuff with phenocrysts of quartz (up to 1 cm across), plagioclase, altered biotite and accessory almandine garnet. The extrusive nature of the tuff is indicated by the local development of agglomerate containing predominantly lithic clasts (up to 20 cm across) in exposures north of 'Kallenia River' homestead (not named on map) at approx. MR 864/941 and compacted pumice clasts in boulders on the roadside 200 m north of Coppins Crossing (MR 854/934). The top and bottom of the formation are not exposed.

Lithology and petrography. The Mount Painter Volcanics consist of dark bluish-grey dacitic ignimbrite with prominent quartz and feldspar phenocrysts and minor interbeds of tuffaceous sandstone and siltstone (Smp_1). The ignimbrite is characteristically exposed on rocky knolls as boulders and tors, e.g. Narrabundah Tors (MR 943/872). The unit is generally massive but layering has been observed in outcrops northwest of Hall. A north-trending foliation occurs locally in dacitic outcrops near the intersection of Hindmarsh Drive and the Monaro Highway. Fiamme occur in a large boulder at the eastern end of a cutting in Hindmarsh Drive (MR 937/864). Certain lithologic and mineralogic features combine to make the Mount Painter Volcanics a distinctive field unit:

- — poorly sorted texture and heterogeneous composition owing largely to the presence of lithic xenoliths, dacitic autoliths, and pumice clasts;
- — a high phenocrystic content of up to 80%;
- — common occurrence of red almandine garnet, for example in volcanic exposures at Narrabundah Tors.

Lithic xenoliths consist mainly of subangular to rounded bodies of pelitic hornfels and quartzite showing occasional relict bedding; a few rounded xenoliths of garnetiferous schist occur at approx. MR 864/117. Vein-quartz fragments represent xenoliths of contrasting origin. The average maximum size of lithic and quartz fragments from 23 outcrop areas of the Mount Painter Volcanics south of the Deakin Fault was determined by measuring the long diameters of about 200 such fragments. Fragment size ranged from 5 to 30 cm, but the measurements did not provide any discernible trends in size distribution and did not indicate the position or direction of an eruptive source. Autoliths of coarsely crystalline dacite (Pl. 3) are generally more abundant than lithic xenoliths. They are usually rounded or ellipsoidal, ranging up to 30 cm. They probably represent remnant vent material incorporated into the pyroclastic flow at the time of eruption. Areas of brecciated jasper up to 10 m long occur in outcrops of dacitic ignimbrite in the Molonglo River (MR 857/923) and as extensive float on low hills abutting the river on its northern bank. The brecciated jasper was probably formed by movement of hot iron-rich fluids through the ignimbrite flow as it cooled; pyrite is also developed in the brecciated zones.

Volcaniclastic sediments form only a minor component of the Mount Painter Volcanics. In the Gooromon Ponds area, the ignimbrite sequence contains thin westerly-dipping reworked tuff and volcaniclastic shale which outcrop in a drainage ditch near a disused quarry at Ahchow Hill east of the Barton Highway (MR 869/141). Similar sediments have been mapped in dacitic ignimbrite south of the Deakin Fault, but are of limited extent. The top of the Mount Painter Volcanics is marked by a pale-brown tuff and ashstone up to 30 m thick (Smp_2). These are exposed best in creeks northwest of 'Callum Brae' homestead (MR 954/847), and also reappear near the suburb of Lyons ('Lyons Ashstone') and can be traced with difficulty north-northwest towards the Molonglo River. These beds are taken to be the final eruptive phase of the Mount Painter Volcanics.

The petrography of the dacitic ignimbrite is dominated by large angular clasts and rounded, embayed crystals of quartz. Smaller crystals of plagioclase (An_{45-55}) are also rounded and fragmented and show alteration patches of muscovite and calcite; zoned crystals are rare. Mafics consist mainly of euhedral laths of biotite normally altered to chlorite and opaques; their recognition is based on the preservation of a strong prismatic cleavage and basal hexagonal sections. Locally fresh biotite occurs in outcrops about a kilometre north of Lake Springfield (MR 890/167). Anhedral to subhedral crystals of cordierite are usually altered to pale-green chlorite; some crystals contain inclusions of quartz, biotite and plagioclase. Xenocrysts of almandine garnet up to 10 mm occur in an accessory capacity to the extent of about one grain per slide. The recognition of orthopyroxene is based on crystal shape; it has been replaced by chlorite. Felsic lithic and flattened crystal-rich pumice fragments are present. Accessories usually associated with secondary alteration are epidote, zircon and apatite. The groundmass texture is cryptocrystalline (quartz-feldspar mosaic) and eutaxitic layering is common.

The Mount Painter Volcanics are strongly S-type in character as indicated by the presence of cordierite, xenocrysts of garnet and fragments of vein quartz. Chemical analyses for this unit on CANBERRA are listed in Table 5. Based on the criteria outlined by Wyborn & others (1981), the geochemistry of the volcanics and composition of the lithic fragments suggest the Mount Painter Volcanics were derived from a mature aluminium-rich pelitic sequence.

Boundary relationships. The base of the Mount Painter Volcanics is not exposed. Along the Molonglo River a partly fault-bounded outlier of the Mount Painter Volcanics appears to rest on the Walker Volcanics (MR 845/924); elsewhere the formation is downthrown against the Walker Volcanics along the Winslade Fault. Where volcaniclastic sediments at the top of the Mount Painter Volcanics thin out north of Hindmarsh Drive, it is probable that the formation is disconformably overlain by the transgressive Yarralumla Formation. Evidence

Table 5. Mount Painter Volcanics: major and trace element analyses (dacitic ignimbrites)

Sample no. *Grid ref.*	*75360001* *883923*	*74840003* *875954*	*74840004* *876951*	*74840085* *956865*	*74840086* *943873*	*74840088* *938864*	*75360011* *862190*	*76460109* *943873*	*77460253* *876927*
%									
SiO_2	65.49	66.40	67.15	65.65	66.52	65.03	65.55	66.65	68.28
TiO_2	0.63	0.57	0.54	0.59	0.57	0.58	0.59	0.65	0.59
Al_2O_3	14.11	13.80	13.74	14.13	14.06	13.88	13.62	14.20	13.82
Fe_2O_3	0.95	0.81	0.98	0.30	0.40	0.46	1.17	0.47	0.59
FeO	4.30	4.47	4.34	4.52	4.20	4.20	4.40	4.70	4.00
MnO	0.08	0.08	0.09	0.10	0.07	0.10	0.12	0.08	0.09
MgO	1.49	2.92	3.09	3.09	2.80	2.80	2.96	2.85	1.67
CaO	3.63	2.09	2.39	1.74	1.52	2.06	1.46	2.47	3.16
Na_2O	1.67	1.73	1.82	2.10	1.92	1.36	2.52	1.85	1.76
K_2O	3.57	3.38	2.81	3.86	4.27	4.67	3.05	3.15	3.47
P_2O_5	0.15	0.11	0.11	0.06	0.07	0.07	0.13	0.15	0.18
H_2O+	2.16	2.41	2.69	2.75	2.44	2.78	2.85	2.45	1.71
H_2O-	0.10	0.11	0.13	0.13	0.08	0.10	0.07	0.03	0.17
CO_2	0.80	0.05	0.15	0.75	0.40	1.40	0.95	0.10	0.52
Rest	0.22	0.19	0.20	0.20	0.21	0.19	0.19	0.18	—
Total	99.35	99.12	100.22	99.97	99.52	99.52	99.63	99.99	100.19
ppm									
Ba	640	580	500	620	640	640	500	470	470
Rb	165	150	130	170	160	200	135	140	160
Sr	150	130	130	100	80	44	95	120	150
Pb	22	14	20	12	6	12	50	22	22
Th	16	16	16	12	14	16	16	12	18
U	6	4	<4	4	<4	4	<4	4	4
Zr	200	190	185	175	175	195	180	203	200
Nb	<4	4	8	4	4	6	<4	12	6
Y	25	20	20	25	25	30	25	28	30
La	70	40	60	50	60	60	50	50	40
Ce	100	80	70	80	80	80	100	100	90
V	110	135	130	145	170	180	120	120	110
Cr	95	—	80	85	80	85	80	60	50
Co	12	20	16	2	4	<2	10	20	15
Ni	40	24	20	22	36	28	28	50	20
Cu	24	28	66	30	22	30	54	25	28
Zn	96	104	84	114	71	104	75	90	64

for a disconformity is better in areas where the Mount Painter Volcanics are overlain by the Deakin Volcanics.

North of Gooromon Ponds Creek, a lower boundary, of uncertain nature, has been mapped with the Mount Ainslie Volcanics. The top here is partly faulted and appears to be conformable with the Yass Formation but where the latter thins southwards the Mount Painter Volcanics are disconformably, or even possibly unconformably, overlain by the Deakin Volcanics.

Thickness. In the Gooromon Ponds Creek area, where the top and bottom boundaries of the Mount Painter Volcanics have been mapped, the thickness is estimated at 1000 m. South of the Deakin Fault accurate estimates of thickness are difficult to make since most contacts are faulted. A minimum estimate of 220 m is based on differences in topographic elevation, but the Mount Painter Volcanics in this area are folded and Henderson (1981) estimates a thickness exceeding 1000 m. The formation appears to thin out towards Jerrabomberra Creek.

Environment of deposition. The Mount Painter Volcanics represent the termination of the first phase (Wenlock) of Silurian volcanism in the Canberra region. The rarity of volcaniclastic and marine sediments within the unit suggests a major subaerial ignimbritic eruption spanning a short period of time, with few quiescent intervals. The abundance of fragmented phenocrysts, lithic xenoliths and autoliths suggests that the Mount Painter Volcanics originated by progressive energy build-up at depth, which culminated in a paroxysmal explosive event that deposited the unit as one thick ignimbrite cooling unit.

Age and correlation. The probable late Wenlock age of the Mount Painter Volcanics is stratigraphically based on the Wenlock age deduced for the underlying Walker Volcanics and the early Ludlow age of the overlying Yarralumla and Yass Formations. The volcanogenic sediments contained within and at the top of the Mount Painter Volcanics are unfossiliferous.

A Rb/Sr isochron age of 438 ± 4 Ma (revised to 425 ± 4 Ma) was obtained by Bofinger & others (1970) on volcanic rocks named the 'Mount Painter Porphyry'and 'Stromlo Volcanics' from what was then a stratigraphically poorly known area west of Canberra. Mapping in this area now shows that only two of Bofinger's samples (GA 2814 and GA 2815) used for dating fall within the newly-mapped boundaries of the Mount Painter Volcanics. In a review of these geochronological data W. Compston (pers. comm., 1982) notes these samples have a $^{87}Rb/^{86}Sr$ ratio that is too small and therefore unlikely to provide useful age control.

A calculated mean age of 397 ± 6 Ma based on a total rock–biotite join was obtained by Amdel (GS 6227/82) on a specimen from north of Lake Springfield (approx. MR 880/174). This is mid Early Devonian, and thus younger than the stratigraphically-based Wenlockian age for the Mount Painter Volcanics. The kinked crystals of biotite, strained quartz phenocrysts and alteration of some of the xenocrystic phases suggest this date may refer to a later tectonic and metamorphic event. A specimen of Hawkins Suite volcanics from YASS (MR 623/623) that contained unaltered biotite, cordierite and orthopyroxene was dated by Amdel (G 6821/87) on a biotite–orthopyroxene pair by the Rb/Sr method at 427 ± 5 Ma (Wenlockian). A K/Ar age determination on biotite from the source rock gave an anomalously old age of 453 ± 2 Ma.

The Mount Painter Volcanics are the youngest formation of the S-type Hawkins Volcanic Suite on CANBERRA. A correlation does not appear feasible with the stratigraphic sequence in the Captains Flat and Rocky Pic Blocks as the volcanic rocks in these areas are not 'S' type and are somewhat younger. Mapping on CANBERRA shows the formation extends northwards onto YASS (Owen & Cas, 1980). Further elucidation of its stratigraphy and regional correlation must await subdivision of the Hawkins Volcanic Suite on YASS and the adjoining sheet to the north (BOOROWA).

Laidlaw Volcanic Suite

The Laidlaw Volcanic Suite is a petrologically and chemically related group of mainly volcanic rocks of early Ludlow age. The suite is well exposed southwest of Canberra and is extensively developed northwestwards onto BRINDABELLA and YASS (Wyborn & others, 1981) and southwards onto MICHELAGO (Henderson, 1990). The Laidlaw Volcanic Suite is characterised by a phenocryst assemblage of quartz + plagioclase (often unalbitised and strongly zoned, with cores of labradorite) + sanidine + biotite + hypersthene. Garnet and cordierite are never found, whereas allanite is a common accessory. Chemically the suite has features in common with certain S-type granitoids (Wyborn & others, 1981). An internal stratigraphy recognisable within the suite is depicted in Figure 8.

The shallow-marine sedimentary Yarralumla Formation and Yass Formation are the oldest stratigraphic units included in the Laidlaw Volcanic Suite. The Yarralumla Formation is a clastic shallow-marine unit disconformably overlying the Mount Painter Volcanics. It is also partly representative of an important and possibly extensive marine transgression at the base of the Ludlow. The Yarralumla Formation is probably coeval with the Yass Formation further north and the Cappanana Formation south of Queanbeyan, although these three formations are not (now) in outcrop continuity.

The Deakin Volcanics are the oldest volcanic formation, resting with apparent conformity on the Yarralumla Formation and Yass Formation but disconformably on the Mount Painter Volcanics. The Deakin Volcanics are a heterogeneous sequence of rhyodacitic ignimbrite, tuff and local waterlain sediments; many horizons show a reddish-purple alteration reminiscent of the Walker Volcanics. The Mugga Mugga Porphyry Member is a lava at the base of the Deakin Volcanics.

The Laidlaw Volcanics are a sequence of rhyodacitic ignimbrites with minor volcanogenic sandstone and shale. They conformably overlie the Yass Formation, but further south they appear to lap disconformably onto the Deakin Volcanics; basal units of the Laidlaw Volcanics and Deakin Volcanics are probably facies equivalents (Wyborn & others, 1982). On YASS, the top of the Laidlaw Volcanics grades upwards into the marine Silverdale Formation, but on CANBERRA these topmost beds are not exposed.

The Colinton Volcanics have uncertain affinities. On CANBERRA they consist of foliated dacitic ignimbrite with thin sedimentary lenses, conformably overlying the Cappanana Formation but in fault contact with the Deakin Volcanics. The Colinton Volcanics may represent a separate volcanic centre in the eastern part of the Canberra–Yass Shelf. They have some petrological and chemical affinities with the Laidlaw Suite.

Yass Formation (Sy)

Nomenclature. Following the terminology of Owen & Wyborn (1979) the term Yass Formation is retained. Member units — the O'Briens Creek Sandstone and Cliftonwood Limestone (Link, 1970) — are not differentiated on CANBERRA.

Distribution. On CANBERRA the Yass Formation crops out as a south-southeast trending wedge of sediments which thin and terminate 2 km north of Gooroomon Ponds Creek, 7 km north-northwest of Hall. The formation extends onto the northeast corner of BRINDABELLA and finds its most extensive development on YASS. A 3 x 0.5 km strip of sediments in the Belconnen area (Henderson, 1980) is also tentatively mapped as Yass Formation.

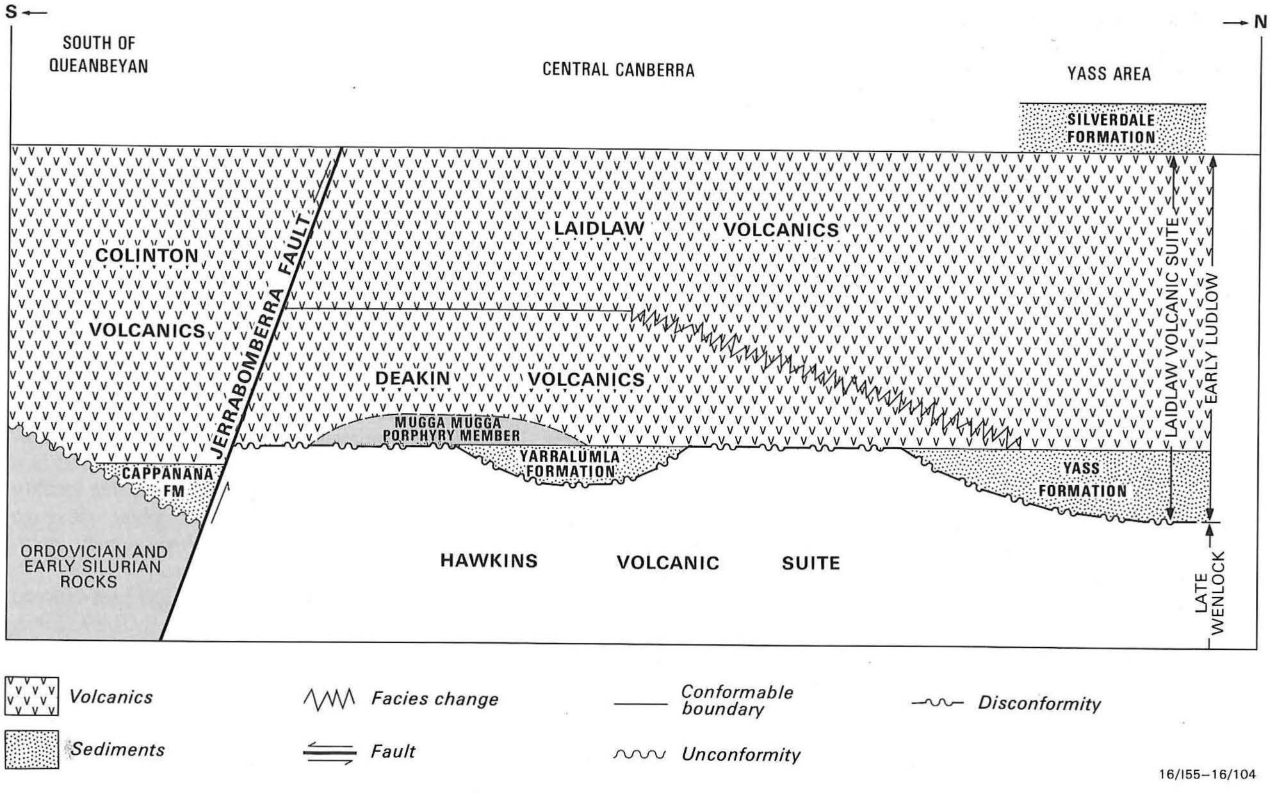


Fig. 8. Early Ludlovian lithostratigraphy (Laidlaw Volcanic Suite), Canberra Block.

Description. Outcrops of westerly dipping shale and limestone along the Barton Highway northwest of Hall were briefly described by Carne & Jones (1919) and Sherrard (1952). More detailed mapping now shows that the Yass Formation in this area consists of a poorly exposed sequence of calcareous and tuffaceous shale and sandstone with minor interbeds of limestone (Sy_1) passing upwards into volcaniclastic siltstone and sandstone with rare detrital garnet. Henderson (1978a) provides detail on the lower portion of the lithological sequence in BMR stratigraphic hole C.155 at MR 848/162.

Boundary relationships. The Yass Formation is partly faulted, but otherwise is in apparent conformity with underlying felsic ignimbritic rocks of the Mount Painter Volcanics. On a ridge a few hundred metres west of the Barton Highway the uppermost beds of the Yass Formation appear to pass up conformably into the massive purple and grey dacitic porphyry of the Deakin Volcanics and massive dark-grey dacitic tuff of the Laidlaw Volcanics.

Thickness. Stratigraphic drillhole C.155 failed to reach the base of the Yass Formation at 240 m (Henderson, 1983). Since the hole was sited stratigraphically about 100 m below the top of the formation (Henderson, 1978a) a minimum thickness for the Yass Formation at that site is 320 m. The unit thickens northwest of this site and onto BRINDABELLA and YASS.

Environment of deposition. The calcareous sediments and shelly fossils suggest a shallow-water marine environment. The influx of volcaniclastic sediments near the top represents a gradual change to a subaerial volcanic environment. The presence of detrital garnet in the volcaniclastic sediments suggests that at least locally the Yass Formation was derived from units in the underlying Hawkins Volcanic Suite.

Age and correlation. Fossil listings for the Yass Formation on CANBERRA are given in Strusz (1975). On faunal evidence the age of the Yass Formation is now reasonably well established as being earliest Ludlow, since the topmost portion of the formation corresponds with the conodont zone of *Neoprioniodus excavatus* (Link & Druce, 1972). The age of the Yass Formation is also stratigraphically constrained by the early Ludlow age placed on the overlying Laidlaw Volcanics by Wyborn & others (1982).

Continuity of outcrop northwards and similar stratigraphic relationships with the Hawkins and Laidlaw volcanic suites on YASS (Cramsie & others, 1978) enable these sediments on CANBERRA to be identified with the Yass Formation. Although outcrop is not continuous, lithological and faunal similarities indicate correlation with a small strip of Late Silurian sediments beneath the Deakin Volcanics in the Belconnen area (Henderson, 1980) and with the Yarralumla Formation.

Yarralumla Formation (Suy)

Derivation. Öpik (1958) named the Yarralumla Formation after the Canberra suburb of Yarralumla.

Nomenclature. In the Yarralumla–Red Hill area of Canberra, Öpik (1958) interpreted the Yarralumla Formation as conformable on the Deakin Volcanics. Since the distribution of these two units was limited to a small area and by poor exposure, Öpik included them within the larger framework of the 'Red Hill Group'. The relationship of this stratigraphy to other rock units in the Yarralumla–Red Hill area is depicted in Öpik (1958, figs. 31 and 32). The interpretation of the geology was also unneccessarily complicated by Öpik's failure to recognise the 'Mount Painter Porphyry' and 'Mugga Mugga Porphyry' as extrusive. Areas west of Öpik's mapping were investigated for the First Edition of the 1:50 000 scale map of Canberra City (Strusz & Henderson, 1971). These authors retained the 'Red Hill Group' but reinterpreted Öpik's stratigraphy to make the Yarralumla Formation a unit enclosed within the lower part of the Deakin Volcanics. Since that time, further investigations in the Canberra area (Owen & Cas, 1980; Henderson, 1981) have established a volcanic stratigraphy that discards the 'Red Hill Group' and now identifies the Yarralumla Formation as a stratigraphically distinct unit below the Deakin Volcanics.

Type locality. Öpik (1958) designated the type locality as the suburb of Yarralumla, in and around the old Commonwealth brick pits (MR 900/905). It is easier and safer to examine the outcrops here than it was before the quarry was landscaped into a recreational area. Exposed at this locality are well-bedded, olive-green calcareous mudstone and siltstone with minor tuffaceous sandstone and dark-grey cherty limestone. The bedding is denoted by major partings, sometimes accentuated by fossiliferous horizons, spaced up to a few metres apart or on a smaller scale as laminations and graded tuffaceous units up to 2 cm thick. The sequence is folded into open symmetrical anticlines with a shallow plunge southwards. A spaced, almost vertical cleavage is axial planar to the folds and also forms a well defined lineation where it intersects the bedding. The brachiopod fauna is described in Strusz (1984) and the encrinurids in Strusz (1980). Other forms are favositid and heliolitid tabulate corals and the microcrinoid, *Pisocrinus*. Fossils are distorted and flattened in the plane of the cleavage and along bedding plane partings. Neither the top nor the bottom of the formation are exposed.

Distribution. The Yarralumla Formation occurs in two main outcrop belts; one extends from Red Hill ridge to Lake Burley Griffin and the other from Woden Valley towards the Molonglo River. There has been some lateral displacement of the two belts by faulting. The sigmoidal outcrop pattern indicates deformation along north-northwest trending fold axes.

Lithology and petrography. The formation consists of a clastic sequence of calcareous and tuffaceous mudstone and siltstone with minor interbeds of limestone and quartz sandstone. Airfall tuff and a few rhyodacitic units were also deposited coevally with the marine sequence.

Interbedded blue–grey limestone, calcareous siltstone and tuff supporting patchy terra rossa soils are exposed on and around the northern side of Red Hill ridge. Brief descriptions of these rocks are given in Pittman (1911), Mahoney & Taylor (1913) and Owen (1987). The assemblage has been locally contact-metamorphosed to calc-silicate hornfels and marble. The hornfels is well exposed in an abandoned quarry southeast of the Red Hill Kiosk. The massive varieties of hornfels comprise a microcrystalline mosaic of quartz, epidote, calcite and black iron ore; vugs of coarsely crystalline quartz, calcite and epidote may represent remnant fossil moulds. Bedded hornfels contains pale-green cherty laminations made up of a cryptocrystalline mosaic of quartz and epidote. These laminations are often disrupted and displaced by thin veinlets of secondary calcite and epidote. Coarser layers of graded sandy relict tuff 1 cm thick comprise subrounded clasts of quartz, altered plagioclase and a few rock fragments set in a matrix of epidote, calcite and quartz. Partial chemical analyses for calcareous rocks in the Red Hill area are listed in Pittman (1911) and Mahoney & Taylor (1913).

Fresh, laminated olive-green mudstone and siltstone containing graded beds of tuff up to 5 cm thick are well exposed in a disused brickpit at Deakin Oval (MR 914/898). At this locality two anticlines show a widely spaced axial plane cleavage which intersects and disrupts the bedding. A prominent lineation defines a southward plunge to the folds.

Quartz sandstone is sporadically exposed. The best outcrop is in Yarralumla Creek adjacent to Yarra Glen (MR 897/896). At this locality a pale-grey quartz sandstone weathered to shades of brown and purple shows current bedding (Pl. 4). Another exposure occurs in the Molonglo River beneath the Tuggeranong Parkway bridge (GR 875/901).

Boundary relationships. The lower contact with the Mount Painter Volcanics is not exposed. The Second Edition of the Canberra 1:50 000 Geological Sheet (Henderson, 1980) shows the contact to be faulted north of Red Hill ridge but apparently conformable west of the suburbs of Lyons and Curtin. However, this contact may be unconformable in the Red Hill and Woden Valley areas since the Yarralumla Formation appears to transgress the uppermost beds of the Mount Painter Volcanics (Smp_2).

The upper contact with the Deakin Volcanics is complex. On the western side of Red Hill ridge the Yarralumla Formation is abruptly overlain by the Mugga Mugga Porphyry Member (basal member of the Deakin Volcanics). Bedding dips within both units suggest they are conformable. The Mugga Mugga Porphyry Member dies out to the northwest, leaving the Yarralumla Formation to pass gradationally up into the basal sediments and bedded volcanic units of the Deakin Volcanics. At this boundary the top of the Formation is arbitrarily taken as the base of the first volcanic unit in the Deakin Volcanics.

Thickness. Henderson (1981) gives a thickness ranging from 100–300 m. Rapid variation in thickness is probable since the formation thins out to the northwest and southeast; thickening and repetition of rock units by folding and faulting is also suggested by the outcrop distribution.

Environment of deposition. The shallow-water marine transgression represented by the Yarralumla Formation is indicated by limestone and fine clastic sediments containing a shelly fauna of brachiopods, trilobites and corals. Local current-bedded quartz sandstone, probably derived from adjacent volcanic terrain, suggests deltaic environments were temporarily established at the basin margin. The overall marine environment indicates a temporary waning of volcanic energy at the end of the Wenlockian. However, the coeval deposition of some volcaniclastic sediments suggests sporadic volcanism at centres marginal to the site of marine deposition.

Age and correlation. Fine-grained calcareous sediments and limestones in the Yarralumla Formation yield a varied shelly marine fauna. Fossil types listed in Öpik (1958) and Strusz (1975, 1984) are in accord with an early Ludlovian age (*crassa* Zone) for the Yarralumla Formation. An upper age limit for the formation is also constrained by the contact-metamorphism along Red Hill ridge. The metamorphism is attributed to a tonalite intrusion which has given a Ludlovian radiometric date of 417 ± 8 Ma.

Originally Öpik (1958) correlated the Yarralumla Formation with the Silurian sequence at Yass, in particular with the Barrendella Shale, later shown to be of middle Ludlow age (Link & Druce, 1972). The Yarralumla Formation has also been correlated with the Yass Formation (Owen & Cas, 1980), although the two formations are not in outcrop continuity. The early Ludlovian age of the marine transgression represented by these two units is constrained by the conodont zonation scheme for Ludlovian sediments in the Yass basin (Link & Druce, 1972).

Deakin Volcanics (Sud)

Derivation. Named by Öpik (1958) from the Canberra suburb of Deakin.

Nomenclature. Originally Öpik (1958) regarded the Deakin Volcanics as the lower of the two formations in the 'Red Hill Group', the other being the Yarralumla Formation. His recognition that the Deakin Volcanics extended to the west and south of Canberra subsequently led Strusz & Henderson (1971) to redefine the 'Red Hill Group' as comprising the Deakin Volcanics, which enclosed the Yarralumla Formation in their lower part. As Figure 9 shows, Owen & Cas (1980), followed by Henderson (1981), abandoned the 'Red Hill Group' and referred that portion of the Deakin Volcanics below the Yarralumla Formation to the Mount Painter Volcanics. This left the Deakin Volcanics as the oldest volcanic formation in the Laidlaw Suite resting with apparent conformity on the Yarralumla Formation. The only named member of the Deakin Volcanics is the Mugga Mugga Porphyry Member, considered by Öpik (1958) to be a sill, but now reinterpreted as a lava defining in part the base of the Deakin Volcanics.

Distribution. The Deakin Volcanics crop out extensively over the southern part of the Canberra Block, especially in the Weston Creek, Tuggeranong and Lanyon areas. Southwards, the formation wedges out onto MICHELAGO, largely by fault contact with the Colinton Volcanics. The Deakin Volcanics are poorly exposed in the West Belconnen area, but northwards there are better exposures west of Gooroomon Ponds Creek, where the formation can be traced onto BRINDABELLA.

Type locality. Öpik (1958) originally designated the suburb of Deakin as the type locality for the Deakin Volcanics. As prominent marker rocks he cited purple tuffs and rhyolites in the Red Hill quarry (now filled in).

The newly designated type locality is the cutting along the Tuggeranong Parkway between Hindmarsh Drive and the Cotter road overpass, where the Deakin Volcanics are almost continuously exposed over a distance of about 2 km. Roadcuts on either side of the Tuggeranong Parkway about 0.5 km south

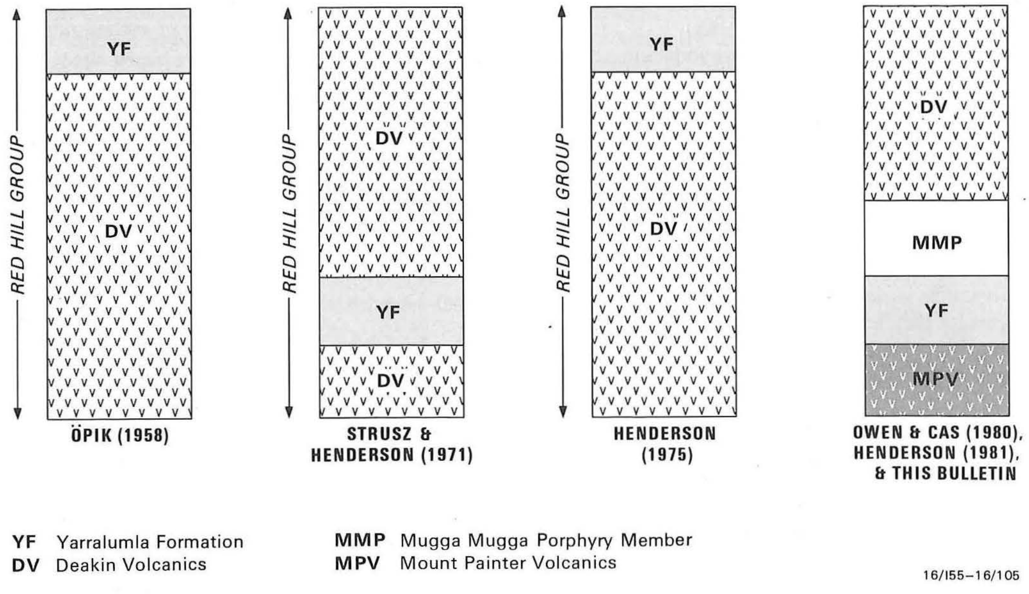


Fig. 9. Deakin Volcanics: evolution of stratigraphic understanding.

of the Cotter road overpass expose the basal portion of the Deakin Volcanics as a weathered southwest-dipping sequence of interbedded rhyodacitic ignimbrite and sandstone, siltstone and shale. Southwards the section passes up into a considerable thickness of massive and locally banded rhyodacitic ignimbrite. The top and bottom of the formation are not exposed, but the lowest rhyodacitic unit in the section cannot be far above a contact with the marine Yarralumla Formation. The minimum thickness of the Deakin Volcanics exposed in this section is estimated as 400 m. The schematic section in Figure 10 is based on a detailed examination of the western roadcut in 1982, supplemented by descriptions given in Crook & Powell (1976) and Owen (1987).

Lithology and petrography. Compared with other volcanic formations in the Canberra Block, the Deakin Volcanics have a multicoloured appearance in the field and a relatively high proportion of interbedded volcaniclastic and sedimentary units.

On the First and Second Editions of the Canberra 1:50 000 Geological Sheet (Strusz & Henderson, 1971; Henderson, 1980), the Deakin Volcanics were subdivided into numerous lithological units. Because it was found to be difficult to trace these units in the field during the present mapping, an alternative scheme (presented here) depicts the Deakin Volcanics as comprising two main lithological groups:

- Rhyodacitic ignimbrite and lava (including the Mugga Mugga Porphyry Member) often with phenocrysts of pink potash feldspar.
- Volcaniclastic and waterlaid epiclastic sediments comprising tuff, tuffaceous shale and minor tuffaceous quartz sandstone.

The best outcrops of rhyodacitic ignimbrite occur in a range of hills stretching northwest from Mount Rob Roy (MR 929/698) to Pemberton hill (MR 964/783). These rocks were incorrectly mapped as 'Tuggeranong Granite' on the Second Edition of the Canberra 1:250 000 Geological Sheet (Best & others, 1964).

The harder rhyodacitic units of the Deakin Volcanics form low bouldery hills and ridges and also rugged hills between Mount Rob Roy and Pemberton. On high ground these rocks may also form extensive bare rock surfaces where the thin soil cover has been stripped. However, much of the terrain is gently undulating, confirming that the formation contains a high proportion of softer tuffaceous sediment. Between Tuggeranong Pine Plantation and Jerrabomberra Creek, some geomorphological expression is given by a fairly prominent escarpment where southward-dipping beds of resistant rhyodacitic ignimbrite overlie softer volcaniclastic rocks.

The multicoloured appearance of the rhyodacitic units in shades of purple, red and green appears to relate to weathering and oxidation. M.J. Rickard (unpublished report) has ascribed colour variation in these rocks outcropping north of the abandoned Tuggeranong railway station (MR 945/767) to red haematitic pigment and possibly green clay minerals (var. celadonite) in the groundmass. On Tuggeranong Parkway at approx. MR 877/872, greyish spheroids averaging 1 cm in diameter are patchily developed within the volcanics (Pl. 5). The spheroids occur as isolated bodies or as coalescent groups with crude alignment parallel to the volcanic layering. They do not show spherulitic or concentric structure but contain inclusions of quartz and biotite phenocrysts. They may represent secondary alteration associated with devitrification of a glassy volcanic matrix.

Banding is prominent in many of the ignimbritic and lava units. The strike and dip pattern suggests the Deakin Volcanics have been gently folded along NNW-trending axes. The most representative exposure of these rocks is in a 2 km section of Jerrabomberra Creek. Just below a weir at MR 992/803 the base of the section starts at fresh rhyodacitic ignimbrite showing eutaxitic layering and autoliths of coarsely porphyritic rhyodacite. Upstream, to the south, this unit passes gradually up into shallow southeast-dipping beds of pale-purple and reddish-brown rhyodacitic ignimbrite. The section is terminated at a faulted contact with pale-green foliated dacitic ignimbrite of the Colinton Volcanics at approx. MR 994/793. An intraformational volcanic conglomerate is exposed in a large roadcut on the Monaro Highway at MR 938/771. Zones a few metres thick at the top of two volcanic units consist of rounded rhyodacite clasts up to 50 cm across in a matrix of layered red ash and tuff.

A typical rhyodacitic ignimbrite consists of a poorly sorted framework of quartz, feldspar, biotite and volcanic rock fragments in a cryptocrystalline quartzofeldspathic groundmass. Quartz occurs as embayed and fragmented phenocrysts up to 3 mm. Albitic plagioclase has a diffuse outline and is strongly altered to sericite. Some crystals are zoned and rimmed by potash feldspar. Phenocrysts and fragments of sanidine are present in about 75% of the sections examined; the sanidine is recognised from its brown turbid appearance under ordinary light, and pale-grey colouring, perthitic twinning and alteration to calcite under crossed polarisers. Biotite occurs as prismatic laths and basal sections. It is usually altered to green chlorite, epidote, sphene and opaques. Bent, spindly, pyroclastic fragments of biotite almost totally altered to black iron oxide

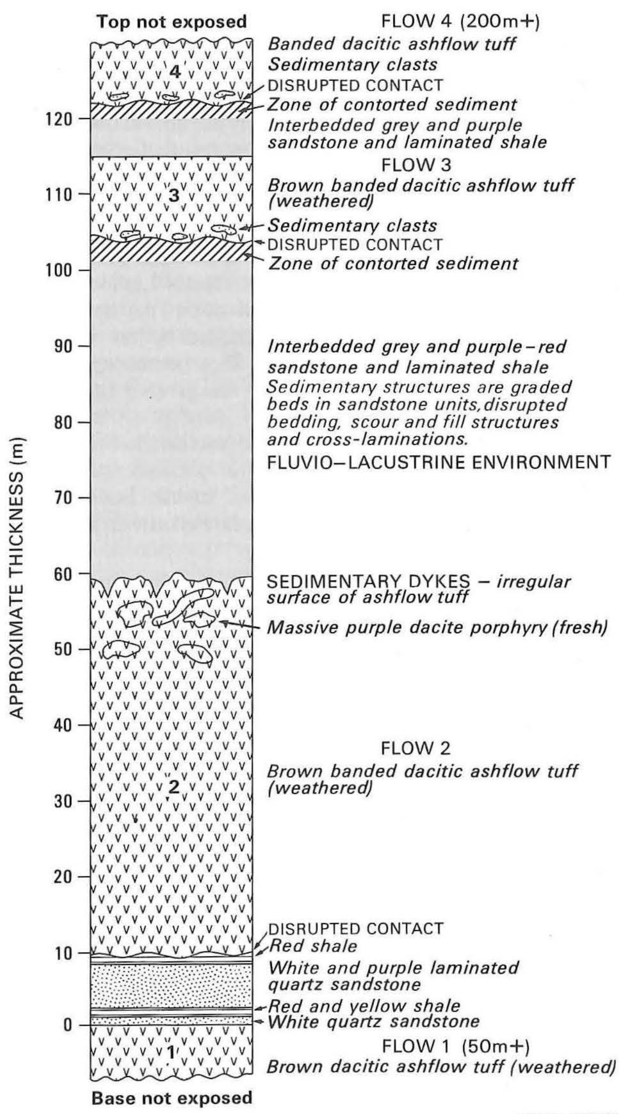


Fig. 10. Basal rock units of the Deakin Volcanics exposed in cuttings along the Tuggeranong Parkway.

characterise these volcanics and may be cleavage fragments of larger biotite laths disrupted during extrusion of the ignimbrite. Orthopyroxene, altered to pale-green chlorite, is accessory. Angular fragments of felsic volcanic rock consist of devitrified glass and altered porphyry and pumice. The devitrified glassy matrix is a cryptocrystalline mosaic of quartz, feldspar, sericite and epidote, locally spherulitic. Accessories are zircon, apatite and calcite. Eutaxitic layering and relict shard texture may be present.

Chemical analyses for this group of rocks are given in Table 6.

The airfall pyroclastics and waterlaid volcanogenic sediments are poorly exposed and form much of the low-lying topography. The most prominent belt of these rock types consists of bedded tuff, tuffaceous sandstone, shale and ash-stone near the base of the Deakin Volcanics (Sud_1). A common rock type is tuff: a good example is exposed in a road cutting on the Monaro Highway, 1 km south of its junction with Isabella Drive (MR 946/787). There, a bedded but poorly sorted rhyodacitic tuff contains subangular clasts up to 8 cm in size of pink, purple and green dacitic porphyry and pale-green shale. Where rock fragments are sufficiently numerous, agglomerate develops in some beds. The exposure is without graded or current-bedded units. Dark-brown volcanic accretionary lapilli (volcanic pisoliths) averaging 5 mm in diameter occur on a bedding plane at the southern end of the cutting. Thickly bedded units of similar rocks are also well exposed in cuttings along the Queanbeyan–Cooma railway line at approx. MR 941/767 and in the vicinity of Mount Wanniassa (MR 920/813).

Beds of tuffaceous quartz sandstone (Sud_2) are locally developed in the Deakin Volcanics. In addition to the type locality along the Tuggeranong Parkway, these rocks crop out in creek sections in hills east of Lanyon Station. Grey, purple and brown tuffaceous sandstone is the commonest rock type, displaying rounded quartz clasts in hand specimen. Seen in thin-section, the quartz clasts reach a size of 3 mm and form a well-sorted framework. Relict embayments in the grains suggest a derivation from quartz phenocrysts in nearby volcanic rocks. Rock fragments consist of rounded volcanic clasts of devitrified glass and altered porphyry and subrounded lithic clasts of shale and siltstone. Rare subrounded grains of plagioclase also occur and the even rarer presence of garnet suggests the Hawkins Volcanic Suite was in part a provenance for these sandstones. A fine-grained matrix which often constitutes less then 25% of the rock comprises angular quartz grains, muscovite and secondary calcite. A banding in the rock is defined by brown hematitic replacement of the matrix. The lack of feldspar and the low percentage of matrix indicate a submature sandstone. The rounded and well-sorted framework clasts suggest littoral abrasion and perhaps deposition in a local deltaic environment.

Calcareous sediments are rare in the Deakin Volcanics, but a thin bed of calcareous tuff at approx. MR 989/822 contains a poorly sorted framework of angular clasts of limestone, quartz, plagioclase and devitrified volcanic glass in a calcite-rich matrix. Beds of polymict volcanic conglomerate containing volcanic clasts and a few cobbles of limestone (some fossiliferous) occur in a cutting on the Queanbeyan–Cooma railway line (MR 955/764).

Boundary relationships. In the central Canberra area the base of the Deakin Volcanics is formed by the Mugga Mugga Porphyry Member which passes laterally into a sequence of dacitic tuff and tuffaceous sandstone and shale. These basal units appear to overlie the Yarralumla Formation conformably, but overlap disconformably onto the Mount Painter Volcanics. In the Gooroomon Ponds Creek area, the Yass Formation is overlain in part by the Deakin Volcanics, apparently conformably. North of quarries in the Gooromon Ponds Creek area the Deakin Volcanics thin out, and the Laidlaw Volcanics directly overlie the Yass Formation.

At the top, the Deakin Volcanics appear to pass conformably up into massive grey ignimbritic tuff of the Laidlaw Volcanics. Contacts between the two formations are not exposed but their field characteristics are sufficiently distinct for an approximate boundary to be mapped.

Thickness. An accurate estimate of thickness for the Deakin Volcanics is hampered by folding and faulted contacts with older volcanic units. In the Weston Creek area, where the top and bottom of the formation have been mapped, Henderson (1981) estimated a thickness of 1000 m. The Deakin Volcanics are thickest in the Tuggeranong area where they appear to reach 1500 m but from there they thin rapidly southwards onto MICHELAGO. The Formation also thins out northwards towards the Gooroomon Ponds Creek area and dies out completely north of 'Ginnagulla' homestead (MR 852/139).

Environment of deposition. The depositional environment of the Deakin Volcanics is complex. The Formation represents a renewed phase of volcanic activity on the Canberra–Yass Shelf. The older volcanic flows are interbedded with shale, sandstone and minor calcareous sediments which show that shallow-marine conditions persisted into early Deakin Volcanics time. However, the predominance of ignimbrites and airfall tuffs higher in the sequence indicates the eventual establishment of subaerial conditions.

Age and correlation. The Deakin Volcanics do not contain diagnostic fossils, and alteration and weathering make the formation unsuitable for radiometric dating. The stratigraphic age is constrained by the early Ludlovian age of the underlying Yass Formation (Link & Druce, 1972), the Yarralumla Formation (Strusz, 1984), and overlying Laidlaw Volcanics (Wyborn & others, 1982).

The Deakin Volcanics do not correlate directly with any other volcanic unit in the Canberra Block. However, they are petrologically and chemically similar to the Colinton Volcanics on MICHELAGO (Henderson, 1990) and may be coeval with basal units of the Laidlaw Volcanics in the Yass area (Wyborn & others, 1982). It is probable that the Deakin Volcanics represent a separate centre of volcanic activity based on the Mugga Mugga Porphyry Member.

Mugga Mugga Porphyry Member (Sum)

Derivation. This unit was first described, but not formally named or defined, by Pittman (1911). He described it as 'an extensive "massif" of quartz porphyry ... typically developed in the mountain known as Mugga Mugga'. The name is derived from Mount Mugga Mugga (813 m, MR 932/855).

Nomenclature. Pittman (1911) interpreted quartz porphyry outcropping on Mount Mugga Mugga as intrusive into Late Silurian strata but did not name it. Mahoney & Taylor (1913) described the porphyry as an extrusive dacitic tuff and placed it within a broadly based stratigraphic unit termed the 'Mugga Series'. Öpik (1954, 1958) first named the unit as the 'Mugga Mugga Porphyry' and supported Pittman's interpretation by describing the porphyry as an intrusive stock. His argument was based largely on the existence of pendants of metamorphosed Yarralumla Formation presumably in the saddle between Red Hill and Mugga Mugga ridge (Öpik, 1958, fig. 32). He also discounted Mahoney & Taylor's conclusion by suggesting that they were referring to volcanic rocks adjacent to the 'Mugga Mugga Porphyry'. Further evidence in support of an extrusive origin was provided by Oldershaw (1966) and Vanden Broek (1971) who observed flow banding and gave petrographic evidence that the porphyry could be a welded tuff or lava flow. However, the intrusive origin for the 'Mugga Mugga Porphyry' still continued to receive support. Strusz (1971) and Strusz & Henderson (1971) gave a Late Silurian age to the unit and believed it intruded the 'Mount Painter Porphyry' and the 'Red Hill Group'. Ollier & Brown (1975) regarded it as intrusive because of the character of the

Table 6. Deakin Volcanics: major and trace element analyses (rhyodacitic ignimbrites)

Sample no.	*75360002*	*74840013*	*74840090*	*74840091*	*75840013*	*75840014*	*75840015*	*75840016*	*75360006*
Grid ref.	*866895*	*918856*	*905857*	*915832*	*(a)864853*	*(a)863873*	*(a)863870*	*(a)862875*	*882849*
%									
SiO_2	69.25	69.94	70.28	69.58	69.78	71.84	72.99	69.34	69.65
TiO_2	0.47	0.48	0.42	0.45	0.47	0.22	0.23	0.46	0.47
Al_2O_3	14.08	14.10	14.03	14.41	14.23	12.93	13.33	14.44	14.46
Fe_2O_3	1.57	2.03	1.36	1.87	0.68	1.39	0.53	1.14	1.95
FeO	1.80	1.34	1.77	1.51	2.25	0.55	0.90	1.95	1.55
MnO	0.07	0.08	0.06	0.09	0.09	0.04	0.03	0.05	0.06
MgO	1.81	1.29	1.00	1.35	2.22	0.59	0.49	1.36	1.45
CaO	2.10	3.14	3.16	3.12	2.16	2.49	1.73	2.63	2.67
Na_2O	3.62	2.22	2.37	2.56	2.43	0.75	1.12	1.61	2.59
K_2O	2.26	3.83	3.72	3.10	3.75	4.12	3.78	3.72	3.77
P_2O_5	0.11	0.10	0.05	0.05	0.11	0.06	0.06	0.10	0.11
H_2O+	1.54	0.93	1.06	1.23	1.64	2.23	2.47	2.14	1.25
H_2O-	0.10	0.09	0.08	0.07	0.08	0.47	0.51	0.32	0.11
CO_2	0.05	0.05	0.40	0.10	0.15	1.95	1.60	0.35	0.05
Rest	0.21	0.19	0.19	0.19	0.21	0.16	0.16	0.20	0.20
Total	99.04	99.81	99.95	99.68	100.25	99.79	99.93	99.81	100.34
ppm									
Ba	840	620	640	560	740	620	540	660	660
Rb	85	170	190	130	140	240	210	210	165
Sr	220	190	190	190	180	80	100	180	200
Pb	16	22	20	140	40	36	34	55	26
Th	18	18	18	20	16	18	18	18	16
U	6	4	4	<4	6	6	8	6	6
Zr	160	170	165	180	185	115	125	175	170
Nb	<4	4	6	4	<4	<4	<4	<4	<4
Y	30	25	30	25	30	30	30	30	35
La	50	60	40	70	50	40	60	50	70
Ce	80	90·	80	90	100	80	100	90	120
V	80	100	100	70	100	35	50	100	90
Cr	35	40	15	25	35	15	15	20	25
Co	4	2	<2	6	2	.862	<2	<2	4
Ni	14	8	12	<2	12	2	14	12	10
Cu	10	14	20	12	22	20	14	22	8
Zn	66	66	71	51	91	45	50	62	59

(a) Tuggeranong tunnel

phenocrysts and its homogeneity. It is now accepted, however, on a large body of field and petrographic evidence, that the Mugga Mugga Porphyry Member is a phenocryst-rich lava, distinctive enough to be mapped as having member status at the base of the Deakin Volcanics (Owen & Cas, 1980; Henderson, 1981).

Distribution. The unit outcrops over a strike length of about 10 km. Weathered and faulted exposures occur south of Deakin, and it is well exposed along Mugga Mugga ridge. The porphyry strikes east-southeast across Jerrabomberra Creek, where it abuts the Deakin Fault.

Type locality. Öpik (1954, 1958) gave the type locality as Mugga Mugga ridge where he described the unit as 'a medium-grained, dark, massive porphyry'. The designated type locality for the Mugga Mugga Porphyry Member is the large active quarry at the summit of Mount Mugga Mugga about 0.5 km south of Hindmarsh Drive (Owen, 1987). The site exposes about 90 m of well jointed, massive, blue–grey rhyodacite containing phenocrysts of quartz, plagioclase, pink potash feldspar and altered biotite. A faint flow-banding dipping 20° southwest is locally visible. Other reference localities are in a nearby quarry on Mugga Lane (MR 937/843) and on the northern side of a road cutting near the top of Hindmarsh Drive (MR 927/862).

Lithology and petrography. The Mugga Mugga Porphyry Member is a compact blue and mauve-grey porphyritic rhyodacite with minor tuffaceous siltstone and shale (Sm_1). The porphyry has, in many places, weathered to residual boulders that rest on strongly jointed bedrock. The unit is very uniform in appearance but in outcrops on Mugga Mugga ridge and in the Mugga Lane (south) quarry (MR 937/843) a well-marked flow banding dips 20–30° southwest. The rock is cut by veins up to 5 mm thick of calcite, light-green epidote and deep-red hematite.

The fresh porphyry consists of phenocrysts of clear glassy quartz, grey plagioclase, lesser amounts of pink potash feldspar up to 5 mm across, and flakes of altered black biotite set in a dense fine-grained glassy groundmass. In thin-section, phenocrysts of quartz are usually corroded and embayed and there are occasional smaller angular fragments. Plagioclase (An_{45-55}) occurs as zoned euhedral phenocrysts altered in various degrees to sericite and calcite. Sanidine forms faintly brown-coloured phenocrysts. The main mafic is tabular laths, wisps and basal sections of biotite strongly altered to pale-green chlorite and hematitic iron oxide. Accessories are sphene, zircon, apatite and epidote. The groundmass is a devitrified glass consisting of a cryptocrystalline and spherulitic mosaic of quartz and feldspar.

Secondary introduction of calcite, hematite and locally saccharoidal galena (Gilligan, 1975) into the Mugga Mugga Porphyry Member in the quarries is attributed to a tonalite intrusion exposed on the north side of the access road leading to the Federal Golf Course. This intrusion may have brecciated the porphyry, allowing entry of calcium-enriched hydrothermal fluids from calcareous rocks in the underlying Yarralumla Formation.

Chemical analyses for the Mugga Mugga Porphyry Member are listed in Table 7.

Boundary relationships. The unit has no exposed contacts with other formations. It appears to overlie the Yarralumla

Table 6 continued

Sample no. *Grid ref.*	*75360007* *879876*	*75360010* *840087*	*75360017* *850013*	*75360018* *853011*	*75360020* *940790*	*76460093* *992802*	*76460095* *994794*	*76460102* *955778*	*76460103* *950772*
%									
SiO_2	69.13	69.98	75.62	67.54	72.22	74.15	76.32	72.71	76.04
TiO_2	0.45	0.42	0.10	0.57	0.32	0.29	0.11	0.25	0.13
Al_2O_3	14.23	14.06	12.74	13.95	13.32	12.68	12.87	13.58	13.35
Fe_2O_3	1.59	2.47	0.88	3.28	2.64	1.08	1.00	1.17	1.21
FeO	2.00	0.80	0.40	0.90	0.20	1.16	0.17	0.07	0.15
MnO	0.06	0.05	0.04	0.06	0.03	0.07	0.04	0.07	0.04
MgO	1.40	1.44	0.41	1.80	0.46	0.73	0.29	0.64	0.37
CaO	2.51	1.23	1.01	1.75	1.25	1.35	0.30	1.10	0.23
Na_2O	2.98	3.53	2.62	2.00	2.77	1.97	2.55	3.20	2.10
K_2O	3.32	3.88	5.00	4.83	3.93	4.53	5.22	4.65	4.55
P_2O_5	0.11	0.11	0.04	0.14	0.09	0.11	0.05	0.09	0.05
H_2O+	1.53	1.52	0.81	1.90	1.35	1.26	0.85	1.08	1.61
H_2O-	0.09	0.10	0.01	0.16	0.17	0.12	0.09	0.12	0.19
CO_2	0.15	0.50	0.10	0.35	0.65	0.10	0.05	0.40	<0.05
Rest	0.20	0.18	0.12	0.24	0.18	0.16	0.10	0.15	0.14
Total	99.75	100.27	99.90	99.47	99.58	99.76	100.01	100.28	100.16
ppm									
Ba	700	660	280	900	620	540	220	440	290
Rb	140	175	250	240	180	180	250	220	230
Sr	210	115	90	135	135	130	85	100	65
Pb	24	44	34	20	24	22	28	30	55
Th	18	16	10	6	4	18	18	18	20
U	<4	4	24	14	18	4	8	<4	8
Zr	180	170	85	200	150	125	80	120	95
Nb	<4	<4	—	—	—	6	10	8	10
Y	30	30	50	35	35	36	40	40	120
La	50	70	50	70	50	30	20	40	80
Ce	110	110	90	110	110	90	50	90	100
V	100	35	25	95	70	50	15	40	25
Cr	30	20	10	40	20	15	5	10	5
Co	8	4	—	12	6	10	9	15	8
Ni	16	8	6	36	2	5	<5	<5	<5
Cu	16	6	6	16	8	60	15	30	15
Zn	58	53	38	70	38	50	20	40	40

Formation conformably but overlaps southeast to lie disconformably on the Mount Painter Volcanics. The dip and strike of the flow-banding suggest the porphyry is conformable with higher units in the Deakin Volcanics.

Thickness. Henderson (1981) gives a thickness of up to 300 m. From the outcrop pattern the unit apparently thickens eastwards towards the Deakin Fault. Near the Mugga Lane quarries, where the layering is well developed, the thickness is estimated to reach up to 600 m.

Environment of deposition. The large euhedral phenocrysts of quartz and feldspar, lack of rock fragments and the presence of layering suggest the Mugga Mugga Porphyry Member is a lava rather than an ignimbrite. It is evident that extrusion was largely subaerial but locally it may have flowed into the sea since the porphyry at its northwest extremity lies between shallow-marine sequences at the top of the Yarralumla Formation and at the base of the Deakin Volcanics.

Age. The Mugga Mugga Porphyry Member is a unit of local extent representing the first signs of a new phase of volcanism at the base of the Laidlaw Volcanic Suite. An early Ludlovian age is given by its stratigraphic position above the Yarralumla Formation and at the base of the Deakin Volcanics.

In terms of absolute age, Bofinger & others (1970) originally dated the porphyry at 423 ± 9 Ma, now revised to 414 ± 9 Ma, an age numerically younger than the Laidlaw Volcanics dated as 421 ± 2 Ma by Wyborn & others (1982). The age difference may be explained by the Federal Golf Course Tonalite which post-dates the Mugga Mugga Porphyry Member. This intrusion caused the contact metamorphism on Red Hill ridge and in the process re-set the isotopic chemistry of the Mugga Mugga Porphyry Member. This interpretation is supported by W. Compston (pers.comm., 1982) who provided the following comment on the revised age of the Mugga Mugga Porphyry Member:

'Bofinger et al. (1970) analysed 7 Mugga Porphyry samples by Rb-Sr, and displayed the data for 6 of these on their Sr evolution diagram, fig. 2 (the 7th sample is calcite which lies at ~zero $^{87}Rb/^{86}Sr$ and defines the initial $^{87}Sr/^{86}Sr$ of the isochron at .7112). Bofinger et al. noted the presence of excess scatter in the "isochron" (MSWD of 5.05), and made the explicit assumption that this was due to small variations between samples in the initial $^{87}Sr/^{86}Sr$. They also made the implicit assumption that all samples had the same age, i.e. that their Rb–Sr chemistry was established at the same time.

'The recent reinterpretation of the Porphyry as a metamorphosed acid volcanic rather than a deuterically-altered sill makes the above age determination much less conclusive. It should be noted (1) that the 3 particular samples in Bofinger et al. having high Rb/Sr, and thereby controlling the slope of the isochron, all have low Sr content in comparison both with the others and with "normal" igneous rocks, and (2) that two of these are vein material which is now interpreted as probably originating from a newly discovered nearby tonalite. Therefore, an alternative interpretation of the excess scatter, that all the samples do not have the same ages, can be supported. Because of (1) and (2), it follows that the age given by Bofinger et al. (1970) for the Mugga Porphyry (423 ± 9 Ma, recalculated to 414 ± 9 Ma using ^{87}Rb at 1.42×10^{-11}/yr) is the age of secondary veining or secondary alteration accompanied by Sr loss, which may be somewhat later than the original formation as volcanics.

'Another method of interpretation is to link the secondary calcite sample 2808C with the two vein samples 2801 and

Table 6 continued

Sample no.	*76460104*	*7360023*	*77360024*
Grid ref.	*932746*	*866905*	*866902*
%			
SiO_2	71.30	69.94	65.50
TiO_2	0.23	0.48	0.62
Al_2O_3	14.91	13.95	14.67
Fe_2O_3	1.96	1.36	0.86
FeO	0.22	2.09	2.82
MnO	0.04	0.07	0.04
MgO	0.98	1.42	1.14
CaO	0.41	2.62	1.21
Na_2O	1.67	2.28	0.34
K_2O	5.50	3.42	8.83
P_2O_5	0.09	0.13	0.18
H_2O+	1.80	1.87	2.12
H_2O-	0.38	0.15	0.22
CO_2	<0.05	0.10	0.60
Rest	0.14	0.19	0.24
Total	99.63	100.07	99.39
ppm			
Ba	300	680	940
Rb	320	130	360
Sr	100	210	55
Pb	32	22	40
Th	22	20	18
U	10	4	4
Zr	125	180	210
Nb	14	4	4
Y	38	34	32
La	40	40	20
Ce	80	90	70
V	40	65	85
Cr	5	<10	12
Co	15	5	10
Ni	<5	8	22
Cu	25	32	32
Zn	30	55	90

2808A and the low Sr sample 2808B, to obtain 3 model Rb-Sr ages for the secondary material. The results are 418, 403 and 407 Ma, averaging 409 ± 4 Ma (σ mean). The 409 Ma value is a little less than the biotite ages (417 ± 8 Ma Rb–Sr, 422 ± 6 Ma K–Ar) cited for the intrusive tonalite. The significance of this difference is not known at the present time.

'The remaining 3 samples, which are more normal geochemically (2198, 2808F, 2808G), do not define an isochron that has usable precision, as their range in $^{87}Rb/^{86}Sr$ is too small. The data do not therefore provide any estimate for the original age of the volcanics'.

Laidlaw Volcanics (Sul)

Derivation. From Laidlaw Trig Station (541 m), about 1 km west of Yass (MR 738/429 on YASS).

Nomenclature. The nomenclatural history of the Laidlaw Volcanics is discussed in detail in Owen & Wyborn (1979). This report follows their proposal that the name be restricted to the volcanic sequence above the Yass Formation and below the Euralie Limestone at the base of the Silverdale Formation.

Distribution. On CANBERRA the main outcrop area of the Laidlaw Volcanics is a broad belt up to 7 km wide, extending south from Mount Stromlo and Weston Creek to the edge of the Sheet area. In this area, the formation is truncated westwards by the Murrumbidgee Fault and northwards by a splay of the Winslade Fault. Southwards, the Laidlaw Volcanics thin towards MICHELAGO. Other smaller tongue-shaped areas in west Belconnen and south of 'Jeir' homestead thicken onto BRINDABELLA.

Type section. A review of the Laidlaw Volcanics around Yass indicates that a type section can be established over a 3.2 km stretch of the Yass River downstream from its confluence with Jones (Bango) Creek. Along this section of the Yass River, Jenkins (1878) alluded to acid porphyries separating the 'Yass and Hume Beds'. Shearsby (1912) interpreted his 'No.3 porphyry' overlying the 'Yass Beds' as a volcanic sequence of massive quartz porphyry and bedded tuff. Later, Mann (1921) named these rocks 'Laidlaw Porphyry' and interpreted them as a sill intruding the 'Yass and Hume Beds'. Sherrard (1936) was less confident and interpreted the 'Laidlaw porphyry' as only partly intrusive into bedded fine-to-medium-grained acid tuff. According to Pickett (1982), the type section of the Willow Bridge Tuff (a member unit of the Laidlaw Formation) is also along this section of the Yass River. As the nomenclature outlined by Owen & Wyborn (1979) shows the Laidlaw Volcanics are synonymous with the Willow Bridge Tuff, it follows that this locality can also be designated the type section for the Laidlaw Volcanics.

The lower boundary of the type section commences half a kilometre below a weir at the confluence of Jones (Bango) Creek and the Yass River. Here a shallow westerly-dipping sequence of limestone and shale of the Yass Formation (Cliftonwood Limestone Member) passes gradationally up through bedded tuff into the Laidlaw Volcanics. The volcanic rocks are readily accessible and crop out continuously in a small gorge in the Yass River over a distance of about 2.5 km. They comprise several units of massive grey rhyodacitic tuff and porphyry, some of which are rich in pink potash feldspar phenocrysts; layering with variable dip and strike develops locally. The section terminates at MR 722/430 where the Laidlaw Volcanics pass conformably up through a sequence of

Table 7. Mugga Mugga Porphyry Member: major and trace element analyses (rhyodacites)

Sample no.	*76460100*	*76460101*	*74840089*	*75360004*	*77360026*
Grid ref.	*938843*	*938843*	*928861*	*931855*	*932844*
%					
SiO_2	69.91	69.83	70.19	69.90	66.83
TiO_2	0.47	0.48	0.47	0.48	0.89
Al_2O_3	13.63	13.29	14.20	13.94	11.93
Fe_2O_3	2.53	1.34	1.86	2.14	2.60
FeO	0.81	1.81	1.30	1.35	4.25
MnO	0.07	0.13	0.06	0.05	0.10
MgO	1.12	1.60	0.50	0.80	2.82
CaO	1.83	2.27	2.06	2.44	4.01
Na_O	1.54	2.15	2.16	2.21	1.42
K_2O	5.63	4.40	5.21	4.35	1.28
P_2O_5	0.16	0.14	0.07	0.14	0.17
H_2O+	1.52	1.85	1.10	1.12	2.61
H_2O-	0.22	0.17	0.10	0.18	0.17
CO_2	0.95	0.95	0.45	0.55	0.50
Rest	0.20	0.20	0.21	0.21	0.18
Total	100.29	100.25	99.94	99.76	99.76
ppm					
Ba	620	580	680	620	450
Rb	290	190	320	240	55
Sr	80	110	110	135	230
Pb	34	28	28	34	11
Th	18	16	20	18	8
U	6	4	4	4	<4
Zr	195	195	190	170	240
Nb	10	10	<4	<4	<4
Y	38	38	25	40	16
La	40	40	50	50	16
Ce	80	100	80	110	50
V	80	80	85	120	155
Cr	35	30	50	45	20
Co	15	15	6	4	15
Ni	10	10	20	8	18
Cu	10	60	14	12	38
Zn	80	110	75	116	80

tuff into grey nodular limestone at the base of the Silverdale Formation. Link (1971b) gave a thickness of 200 m for the volcanics in this section but about 600 m is more likely.

Lithology and petrography. The Laidlaw Volcanics are remarkably uniform in appearance and composition and consist of a thick sequence of rhyodacitic ignimbrite with minor interbeds of volcaniclastic and marine epiclastic sediments. In the field, the commonest exposures are of rhyodacite which forms low hills and ridges with bouldery outcrops weathering to a thin light-grey skin. Fresh exposures are dark-grey, generally massive and commonly contain autoliths of coarsely porphyritic dacite up to a size of 30 cm; lithic clasts are noticeably absent (c.f. Mount Painter Volcanics). On CANBERRA, the Laidlaw Volcanics crop out continuously along a stretch of the Murrumbidgee River from Lanyon to a few kilometres below Kambah Pool. A fine exposure of columnar-jointed rhyodacite occurs at Red Rocks Gorge (MR 860/788).

The Laidlaw Volcanics are closely related petrogenetically to the underlying Deakin Volcanics. As both formations belong to the Laidlaw Volcanic Suite, they are petrologically similar, containing the same phenocrystic assemblages. The clearest distinctions are in terms of their field character (Table 8).

The Laidlaw Volcanics show abundant phenocrysts of quartz, plagioclase (commonly labradorite with zoning An_{40-65}), lesser amounts of pink potash feldspar (sanidine), relatively fresh biotite, and hypersthene. A felsic cryptocrystalline groundmass with eutaxitic layering contains accessory zircon, allanite and magnetite. Further petrographic detail and aspects of the geochemistry are given in Owen & Wyborn (1979), Wyborn & others (1981) and Wyborn & others (1982).

Table 8. Field and petrographic comparisons of the Laidlaw and Deakin Volcanics

Laidlaw Volcanics	*Deakin Volcanics*
Homogeneous, thick ignimbritic unit with little lithological differentiation	Heterogeneous sequence of thin volcanic, volcaniclastic and sedimentary units
Resistant to weathering; hard, and form relatively high ground.	Prone to weathering; softer, and form relatively low ground.
Uniformly dark-grey and usually fresh in outcrop	Multi-coloured, caused by alteration and oxidation (purple, red and green); fresh outcrop uncommon
Massive	Layered
Mafics: biotite fresh and suitable for radiometric dating; orthopyroxene more common and euhedral	Mafics: biotite very altered to chlorite and iron oxide; orthopyroxene occasionally altered
Pink potash feldspar phenocrysts present	Pink potash feldspar (sanidine) phenocrysts common
Allanite common	Allanite unknown
Non-spherulitic matrix	Matrix may be spherulitic

Chemical analyses for the Laidlaw Volcanics are listed in Table 9.

Volcaniclastic and marine epiclastic sediments crop out sporadically along the Murrumbidgee valley between Lanyon and Pine Island. Originally these rocks were mapped by Best & others (1964) as the Yarralumla Formation on the Second Edition of the Canberra 1:250 000 Geological Sheet and later

Table 9. Laidlaw Volcanics: major and trace element analyses (rhyodacitic ignimbrites)

Sample no.	*74950009*	*74950027*	*75840001*	*75840002*	*75840004*	*75840005*	*75840006*	*75840007*	*75840012*	*75840020*	*75360005*
Grid ref.	*(a)865838*	*(a)864843*	*867805*	*867805*	*865827*	*865832*	*865837*	*864851*	*(a)864851*	*822027*	*851847*
%											
SiO_2	72.44	73.96	68.60	69.62	70.10	70.70	71.17	71.30	72.78	72.01	70.55
TiO_2	0.27	0.27	0.51	0.48	0.46	0.46	0.42	0.40	0.24	0.31	0.45
Al_2O_3	13.32	12.88	14.42	13.44	14.01	12.80	14.20	13.47	13.76	13.34	14.16
Fe_2O_3	1.09	0.73	0.77	0.56	0.64	0.19	0.49	0.73	0.33	0.85	2.00
FeO	1.10	1.10	2.70	2.75	2.50	2.70	2.30	2.15	1.50	1.48	1.55
MnO	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.05
MgO	1.22	1.16	1.53	1.52	1.28	1.37	1.08	1.03	0.74	0.95	1.16
CaO	1.75	1.55	3.11	3.43	3.88	2.06	3.44	3.20	1.67	2.17	3.68
Na_2O	2.92	2.23	2.79	2.40	2.24	3.50	2.56	2.52	2.98	2.79	2.50
K_2O	3.32	4.01	2.86	2.78	2.81	2.44	3.07	2.96	4.54	3.93	2.81
P_2O_5	0.05	0.05	0.14	0.10	0.10	0.09	0.09	0.12	0.06	0.12	0.10
H_2O+	1.33	1.32	1.68	1.11	0.57	1.70	1.02	0.83	0.94	1.04	0.92
H_2O-	0.11	0.10	0.12	0.09	0.05	0.32	0.02	0.05	0.04	0.04	0.06
CO_2	0.05	0.25	0.35	0.30	0.30	0.90	0.05	0.05	0.25	0.05	<0.05
Rest	0.20	0.17	0.21	0.25	0.21	0.17	0.21	0.20	0.18	0.18	0.20
Total	99.19	99.80	99.84	98.88	99.20	99.45	100.17	99.06	100.06	99.29	100.19
ppm											
Ba	520	640	700	680	680	540	740	660	620	680	720
Rb	125	150	130	125	115	110	140	130	185	155	135
Sr	175	130	190	200	210	110	200	190	170	170	200
Pb	24	14	40	500	50	26	32	42	40	46	22
Th	22	20	12	12	16	14	16	16	26	22	10
U	6	6	<4	4	6	<4	4	4	6	<4	4
Zr	125	120	200	200	195	195	170	170	125	140	180
Nb	<4	<4	<4	<4	<4	<4	10	<4	<4	<4	10
Y	36	28	25	20	30	20	25	25	30	25	20
La	190	70	50	50	70	50	60	90	60	70	60
Ce	280	100	100	90	120	110	120	130	110	130	100
V	65	70	140	120	140	100	100	85	35	35	80
Cr	10	15	30	25	30	25	25	25	15	20	30
Co	78	<5	2	<2	6	2	<2	<2	<2	<2	8
Ni	4	12	10	16	10	6	6	6	10	12	12
Cu	4	3	24	24	18	20	18	20	14	24	10
Zn	40	33	50	59	57	64	58	61	45	35	59

(a) Tuggeranong tunnel

interpreted as northerly outliers of the 'Bransby beds' (Strusz, 1975).

These sediments are now regarded as interbedded within the Laidlaw Volcanics. A sequence of pale-brown bedded tuff and tuffaceous sandstone (Sul_1) exposed north of Mount Stromlo is taken to represent a brief airfall eruptive phase at the base of the Laidlaw Volcanics. Northeast of 'Freshford' homestead (MR 844/765) a predominantly volcaniclastic sequence consists of rhyodacitic airfall tuff with occasional accretionary lapilli, ashstone and thin beds of brown and grey fossiliferous shale (Sul_2). Calcareous nodules up to 6 cm across occur in shale at MR 861/773. On the right bank of the Murrumbidgee, 1 km downstream from the picnic area at Pine Island (MR 862/776), a rhyodacitic mudflow deposit is well exposed (Pl. 6), consisting of a poorly sorted assemblage of angular to rounded clasts of mainly chert (muddy ashstone) and dacitic porphyry up to 10 cm across in a medium-grained tuffaceous matrix. Local stratification results from grainsize variation in the matrix and from the concentration of coarse-grained clasts into 'agglomerate' layers. Penecontemporaneous faults and irregular cross-cutting contacts between flow units are common. On the left bank of the Murrumbidgee River 0.5 km below Point Hut Crossing (MR 881/747) and near 'Lambrigg' homestead (MR 862/739) thin interbeds of tuffaceous sandstone and laminated shale are overlain by well-bedded rhyodacitic tuff that also contains thin lenses of mudflow 'agglomerate'.

Boundary relationships. The Laidlaw Volcanics overlie the Deakin Volcanics with apparent conformity west of Canberra. A contact between the two units was temporarily exposed in excavations for the Tuggeranong–Weston Creek sewer tunnel (Purcell, 1977) where soft, banded and multi-coloured rhyodacitic tuffs of the Deakin Volcanics were seen to be overlain by blue–grey massive rhyodacitic tuff of the Laidlaw Volcanics. In the Gooroomon Ponds area the Laidlaw Volcanics are conformable on the Yass Formation.

The top of the Laidlaw Volcanics is not exposed on CANBERRA but on YASS the volcanics are overlain conformably by the Silverdale Formation. Elsewhere they are in contact with the eastern margin of the Murrumbidgee Batholith and Ordovician metasediments (Adaminaby beds) along the Murrumbidgee Fault.

Thickness. Thickness cannot be estimated accurately as the top of the Laidlaw Volcanics is not exposed and there is a lack of structural data. However, from shallow westerly dips of underlying volcanic rocks the Laidlaw Volcanics are judged to have a minimum thickness of 400 m. According to Owen & Wyborn (1979) the Laidlaw Volcanics thicken towards BRINDABELLA where they are estimated to reach 500–1000 m, whilst on YASS the same authors quote a thickness varying from 200–1000 m. The unit thins southwards onto MICHELAGO (Henderson, 1990.)

Environment of deposition. The uniform lithology, massive appearance and presence of coarse porphyry autoliths suggest the Laidlaw Volcanics were erupted essentially as a single thick ignimbrite unit. The lack of sedimentary xenoliths suggests the unit was deposited over pre-existing volcanic terrain containing little sedimentary material. The presence of interbedded fossiliferous shale indicates that shallow-marine conditions still persisted locally on CANBERRA.

Age and correlation. In the Yass area the stratigraphic age of the Laidlaw Volcanics is tightly constrained by the early Ludlow age of the underlying Yass Formation and overlying Silverdale Formation. Wyborn & others (1982) have summarised the faunal and stratigraphic age constraints on the Laidlaw Volcanics and state the age as earliest Ludlow. On CANBERRA, fossiliferous units within the Laidlaw Volcanics are sparse but pale-brown shale beds in volcaniclastic sediments

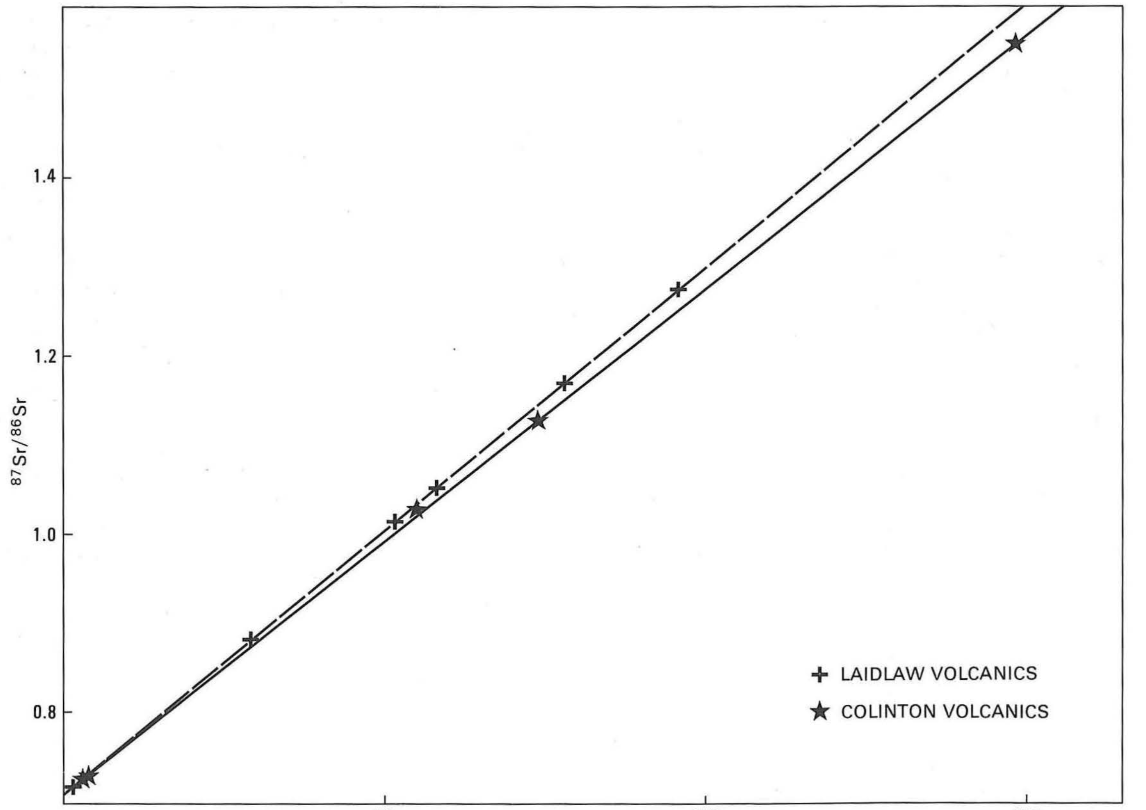


Fig. 11. Rubidium/strontium isotopic plots for the Laidlaw and Colinton Volcanics (data from Wyborn & others, 1982).

outcropping near 'Freshford' homestead have yielded a brachiopod fauna consisting of *Howellella* sp., *Brachyprion*? sp., *Molongia* sp. and the odd sponge spicule and bryzoan fragment. However, these forms are not sufficiently diagnostic to date the formation. Fresh biotite in many volcanic outcrops has been dated using K-Ar and Rb-Sr dating techniques (Wyborn & others, 1982) (Fig. 11). An absolute age of 420.7 ± 2.2 Ma is based partly on samples collected near Mount Arawang (MR 860/842) and confirms the previously established early Ludlow age for the Laidlaw Volcanics.

The Laidlaw Volcanics form a large volcanic field extending from the Yass–Taemas region southward through and beyond CANBERRA on to MICHELAGO. On CANBERRA it is the youngest unit of the Laidlaw Volcanic Suite exposed in the Canberra Block. Stratigraphic studies on MICHELAGO (Henderson, 1990) suggest that the Laidlaw Volcanics may be equivalent to upper portions of the Colinton Volcanics. On BRINDABELLA, Owen & Wyborn (1979) correlate the Laidlaw Volcanics with the Uriarra Volcanics on the basis of similar chemistry and mineralogy.

Cappanana Formation (Scp)

The Cappanana Formation (shale, siltstone, limestone; minor quartzite, tuff and hornfels) is best exposed on MICHELAGO where it forms a discontinuous strip adjacent to the western margin of the Cullarin Block. The derivation, nomenclature and type section are given in Richardson (1979).

Outcrops of this formation south of Queanbeyan were originally mapped by Phillips (1956) as part of the 'Morley Formation' and correlated with lithologies in what is now termed the Canberra Formation. Stauffer & Rickard (1966) interpreted the same outcrops as beds of intercalated sediments within the Colinton Volcanics. Although the lower boundary is cut out locally by faulting, the sediments are now assigned to the Cappanana Formation since they are clearly overlain by, rather than intercalated in, the Colinton Volcanics.

On CANBERRA the formation is exposed as a disrupted, meridional belt of sediments rarely exceeding 1 km in width. Much of the former belt of outcrop has been flooded by Googong Reservoir. The formation crops out near 'London Bridge' homestead (MR 047/693) and northwards makes a minor appearance in the vicinity of Googong Reservoir. After being cut out locally by the Queanbeyan Fault, the formation reappears and can be traced for a short distance along Jumping Valley Creek towards Queanbeyan.

Description. Outcrops are generally poor. Numerous acid intrusions and complex tectonics disrupt outcrop continuity. The rocks have a strong meridional cleavage with a steep dip similar to bedding. Small-scale folding is apparent, particularly kink-folding, which is assumed to relate to transcurrent fault movements.

Before Googong Dam was built, the Cappanana Formation was well exposed in the Queanbeyan River valley. Clearing of vegetation in the area to be dammed provided additional outcrop which enabled the lithological distribution to be mapped in detail (Goldsmith & Evans, 1980). Most of the outcrop area of the Cappanana Formation on CANBERRA below a datum of 663 m a.s.l. is now submerged by Googong Reservoir.

The formation comprises shale, siltstone and limestone with minor beds of quartzite, tuff and hornfels. Well-bedded, white to grey limestone (Scp_1) occurs as elongate, lenticular bodies with a strike length rarely exceeding 1.5 km. Outcrops are extensive enough to support terra rossa soils. In places the limestone has recrystallised to marble and associated massive and banded calc-silicate hornfels (Scp_2; MR 053/722). A thickness estimate of up to 180 m is given by Goldsmith & Evans (1980). Similar limestone beds on MICHELAGO were informally named the 'London Bridge Limestone' by Veevers (1953).

Boundary relationships. Ordovician and Early Silurian rocks are known to underlie the Cappanana Formation on MICHELAGO (Richardson, 1979). Immediately south of CANBERRA (MR 053/689 on MICHELAGO) shale and siltstone of the Cappanana Formation unconformably overlie an erosion surface of Late Ordovician quartz turbidite (before Googong Reservoir filled, the unconformity was exposed in Burra Creek near its junction with the Queanbeyan River). The 30° angle of the unconformity suggests a major break. On CANBERRA, the lower boundary is not exposed but it is assumed by extrapolation from MICHELAGO that it is more likely to be an unconformity disrupted by faults rather than an E–W trending slide fault as interpreted north of the Barrack Creek Adamellite by Stauffer & Rickard (1966).

The Cappanana Formation is conformably overlain by the Colinton Volcanics. The boundary is transitional and may be diachronous (Strusz, 1975). The upper boundary approximates to the base of the first persistent flow of dacitic ignimbrite in the Colinton Volcanics.

Thickness. Estimates of thickness are affected by poor outcrop and complex tectonics. On CANBERRA, Goldsmith & Evans (1980) estimated a thickness of up to 800 m in the Googong Reservoir area. This is probably a maximum as the strata may be repeated by folding and are faulted. A major thickness variation was reported by Veevers (1953) who noted a thickness of 450 m in the vicinity of London Bridge with a marked reduction to 30 m in the same area, attributed to stratigraphic or tectonic thinning. On MICHELAGO, Richardson (1979) gives an approximate thickness of 700 m.

Environment of deposition. The presence of limestone and the dominance of shelly fossils (corals, brachiopods and crinoids) indicate a shallow-marine environment. Proximal volcanism is indicated by the influx of volcanic detritus in the sediments as conditions gradually changed from marine to subaerial.

Age and correlation. Fossil listings on MICHELAGO given by Strusz (1975) and Richardson (1979) indicate a prolific fauna. However, few fossils have been identified to species level and those that have appear to be long-ranging forms. On CANBERRA, the calcareous and interbedded shaly rocks are only sparsely fossiliferous. A few indeterminate conodonts undiagnostic of age (R. Nicoll, pers. comm., 1982) were recovered from limestone outcrops near 'London Bridge' homestead and Jumping Valley Creek (Table 10). Without providing definite fossil evidence, Strusz & Henderson (1971) gave an early Ludlovian age for the Cappanana Formation and correlated the unit with sequences at Canberra and Yass. A more definite early Ludlovian age is suggested by the brachiopod *Atrypoidea australis* which was recorded from the formation near Bredbo (Sherwin, 1974). This species is also known from other early and mid-Ludlovian stratigraphic units such as the Yarralumla Formation and Silverdale Formation on YASS (Strusz, 1984). A similar age is suggested by two species of conodonts, *Spathognathodus snajdri* and *S. inclinatus hamatus*, from the Cooma region (Strusz, 1975).

From the fossil evidence it is probable that the shallow-marine Cappanana Formation correlates with the Yarralumla Formation. The Ludlow age of the older sedimentary and volcanic sequences east of the Cullarin Block suggests the Cappanana Formation may be coeval with the Cooper Creek Formation in the Captains Flat Block and perhaps the De Drack Formation in the Rocky Pic Block.

Colinton Volcanics (Svc)

The Colinton Volcanics are best developed on MICHELAGO where they have been mapped over the full north–south extent of the western portion of the Sheet (Richardson, 1979). The unit was introduced without definition by Best & others (1964) on the Second Edition of the Canberra 1:250 000

Table 10. Occurrence of conodonts in limestone from the Cappanana Formation

'London Bridge' homestead (MR 047/693)									
Sample no.	294A	294B	294C	294D	294E	294F	294G	294H	Total
Processed weight (kg)	5.73	5.0	4.25	3.25	4.67	4.6	4.7	5.4	37.6
Conodonts	7	9	—	4	2	—	2	—	24
Jumping Valley Creek. Abandoned quarry (MR 051/828)									
Sample no.	293A	293B	293C	293D					18.61
Processed weight (kg)	4.26	4.85	5.0	4.5					
Conodonts	—	—	—	1					1
Jumping Valley Creek. Abandoned quarry (MR 047/831)									
Sample no.	292A	292B	292D	292E					
Processed weight (kg)	4.25	5.0	5.18	4.82					19.52
Conodonts	—	—	—	—					—

Geological Sheet. Derivation, nomenclature and type area for the Colinton Volcanics are given in Richardson (1979) but a more detailed description of the Formation, incorporating revised stratigraphic relationships, petrography and geochemistry, is provided by Henderson (1990). On CANBERRA, the Colinton Volcanics form a wedged-shaped belt of rocks tapering north towards Queanbeyan. The unit is tightly folded along north-northeast-trending fold axes.

Description. Several lithological divisions within the Colinton Volcanics were mapped by Richardson (1979) on MICHELAGO. A rhyodacitic crystal tuff was distinguished as a member and named the 'Tuggeranong Tuff'. A massive rhyodacite named the 'Williamsdale Volcanics' was mapped as a separate formation, in part equivalent to the Colinton Volcanics. The outcrop boundaries drawn up for the Colinton Volcanics on CANBERRA now place the 'Tuggeranong Tuff' within the Deakin Volcanics. The 'Williamsdale Volcanics' are recognised only as a lithofacies within the Colinton Volcanics. However, this unit has now been redefined as the Williamsdale Dacite Member (Henderson, 1990).

On CANBERRA, the bulk of the Colinton Volcanics consists of massive and foliated dacitic ignimbrite. Sedimentary interbeds become more prominent as the volcanics thin northwards. Massive volcanic rocks become common as the outcrop belt widens southwards.

Massive ignimbrite (Svc_3) crops out over a triangular area of about 12 km^2. It forms bouldery outcrops in hilly country immediately south of 'Fernleigh Park' homestead (MR 002/743) and west of the Burra road. The ignimbrite represents the northern limit of the 'Williamsdale Volcanics' as mapped on MICHELAGO. The rocks are bluish–grey and are composed of a framework of quartz, feldspar and biotite phenocrysts in a fine-grained equigranular groundmass of recrystallised quartz and feldspar. Quartz forms a prominent phenocryst phase as large subangular crystals up to 6 mm. Most crystals show relict embayments, fracturing and undulose extinction. Feldspar phenocrysts are mainly albitic plagioclase showing multiple twinning; a few crystals show relict zoning. Potash feldspar, subordinate to plagioclase, occurs as grey untwinned or sometimes microperthitic crystals. Most of the feldspar is strongly altered to sericite. Biotite normally occurs as prismatic laths up to 5 mm long; where it is fresh, it shows a strong red-brown pleochroism. In many cases biotite is partially or completely altered along prismatic cleavage planes to pale-green chlorite, epidote and opaques. Some biotite flakes exhibit kink bands. Altered rock fragments occur as subangular and rounded clasts composed of quartz, chlorite, epidote and opaque iron ore. Also, distinct angular fragments of quartz and feldspar up to 1 mm in size, patches of epidote and accessory zircon occur in the groundmass mosaic, which is essentially fresh. Eutaxitic layering is locally developed.

Foliated dacitic ignimbrite mostly characterises the Colinton Volcanics on CANBERRA. It forms elongate knife-edged outcrops reflecting the strong foliation. The freshest exposures occur along drainage lines, particularly Jerrabomberra Creek and minor creeks draining towards Googong Reservoir. In outcrops close to faults the foliation is affected by small-scale kink folds. The rocks are bluish–green from chloritisation, and dark-grey patches and streaks of altered mafics up to 5 mm long are drawn out and flattened in the plane of foliation. Differences in the thin-section mineralogy and texture of these rocks compared with the massive variety are attributable to shearing. Phenocrysts of quartz and feldspar are aligned along the foliation. Quartz is strongly strained and granulated along fracture planes. Feldspar is strongly sericitised but a few fresh crystals of albitic plagioclase survive in the less foliated specimens. The mafics (originally biotite) have been totally altered to chlorite, epidote and opaques and drawn out in streaky patches parallel to the foliation. The strongly sheared cryptocrystalline groundmass is composed largely of sericite, quartz, feldspar and opaques. Locally the foliation in the groundmass shows some deflection around rotated phenocrysts. Pressure shadows of fibrous quartz and muscovite locally occur around opaque grains of pyrite.

Chemical analyses are given in Table 11. The rocks plot close to the dacite/rhyolite boundary on the total alkali/silica diagram (Fig. 12; after Le Maitre, 1984). Although the mineralogy and the chemical analyses show evidence of metamorphism (albitisation and sericitisation), most specimens analysed fall just within the dacite field.

A strip of tuffaceous shale (Svc_1) and limestone (Svc_2) interbedded in the Colinton Volcanics extends north-northeast for about 7 km near the old Queanbeyan–Cooma road. The strip swings around the southeastern side of the Barrack Creek Adamellite and appears to lens out southeast of Queanbeyan. Phillips (1956) originally named these sediments the 'Morley Formation' and gave them a minimum thickness of 150 m near Queanbeyan. Stauffer & Rickard (1966) implied member status when mapping them as a limestone–shale marker unit. The sediments are mapped here as a continuous unit, but detailed mapping indicates several closely spaced and interfingering beds separated by dacitic tuff. Smaller outcrops of shale and limestone abut against the southern side of the Barrack Creek Adamellite. Shaly beds also occur near the base of the Colinton Volcanics near Googong Dam.

Limestone and minor dolomitic rocks form pods rarely exceeding 1.5 km in length. The limestone is normally well-bedded and enclosed by shale. Limited outcrop has precluded widespread solution-cavity development, but a small cave has formed along a bedding plane at White Rocks (MR 042/826) (Brush & Nicoll, 1975). Strike length and thickness variation in the limestone is attributed partly to tectonism. This is illustrated on a small scale in the Queanbeyan River opposite White Rocks quarries where discrete dolomitic limestone masses have been tectonised (Pl. 7). Well bedded micritic limestone encloses and is deflected around elliptical masses of brown massive dolomite. The dolomitic masses are unfossiliferous but their mound-like shape and evidence of internal

Table 11. Colinton Volcanics: major and trace element analyses (dacitic ignimbrites)

Sample no. *Grid ref.*	*76460079* *038756*	*76460082* *997711*	*76460083* *002707*	*76460084* *999700*	*76460085* *005719*	*76460086* *015731*	*76460269* *018805*	*76460344* *031784*	*76460345* *023693*
%									
SiO_2	68.04	69.57	68.92	68.91	69.02	69.80	62.90	66.60	69.80
TiO_2	0.62	0.55	0.57	0.57	0.58	0.42	0.77	0.61	0.53
Al_2O_3	14.19	13.83	13.74	13.85	14.00	14.25	15.50	14.40	13.80
Fe_2O_3	1.52	1.56	1.65	1.46	1.55	1.52	6.33	1.45	3.72
FeO	3.00	2.55	2.60	2.95	2.55	1.77	<0.02	2.98	1.10
MnO	0.05	0.07	0.07	0.05	0.07	0.06	0.06	0.04	0.06
MgO	2.10	2.00	1.66	1.76	1.57	1.24	4.48	1.88	1.66
CaO	1.90	1.53	2.77	2.03	3.01	2.44	1.07	3.56	1.72
Na_2O	4.65	2.90	2.45	3.10	2.40	2.55	5.00	3.16	3.06
K_2O	0.95	3.34	3.12	2.69	3.36	3.73	0.61	3.36	2.78
P_2O_5	0.14	0.13	0.13	0.13	0.13	0.09	0.14	0.11	0.10
H_2O+	1.84	1.92	1.74	1.92	1.08	1.12	2.90	1.58	1.53
H_2O-	0.12	0.02	0.02	0.12	0.08	0.04	0.13	0.08	0.11
CO_2	0.05	0.05	0.10	0.05	0.05	0.10	—	—	—
Rest	0.12	0.22	0.19	0.18	0.19	0.19	—	—	—
Total	99.29	100.24	99.73	99.77	99.64	99.32	99.90	99.81	99.97
ppm									
Ba	100	940	560	560	540	600	60	280	400
Rb	42	120	130	95	160	140	28	130	140
Sr	180	160	200	160	180	160	120	200	150
Pb	8	14	17	11	22	28	24	10	17
Th	14	16	16	12	14	14	14	22	18
U	4	8	6	4	4	6	<4	—	—
Zr	205	190	200	205	200	170	270	180	190
Nb	8	12	10	14	10	8	10	8	10
Y	30	30	30	28	30	38	44	28	26
La	30	50	30	50	50	40	<20	30	60
Ce	80	100	100	100	100	120	90	70	70
V	100	90	100	100	100	80	60	90	75
Cr	40	30	30	30	25	25	20	—	—
Co	20	15	15	15	15	15	15	10	10
Ni	15	10	10	10	10	5	15	5	5
Cu	30	25	15	20	20	30	6	20	10
Zn	40	60	60	40	60	60	36	40	40

structure suggest they were originally biohermal or algal. There is no evidence of an allochthonous origin. Further south along strike Wynn (1962) has mapped dolomite in association with limestone in a southwest plunging syncline near 'Sunset' homestead at approx. MR 029/786.

The sediments show evidence of low-grade regional metamorphism. The shale has been altered to phyllite and some limestone has been recrystallised to fine-grained saccharoidal marble.

Boundary relationships. A conformable lower boundary with the Cappanana Formation is indicated by a progression

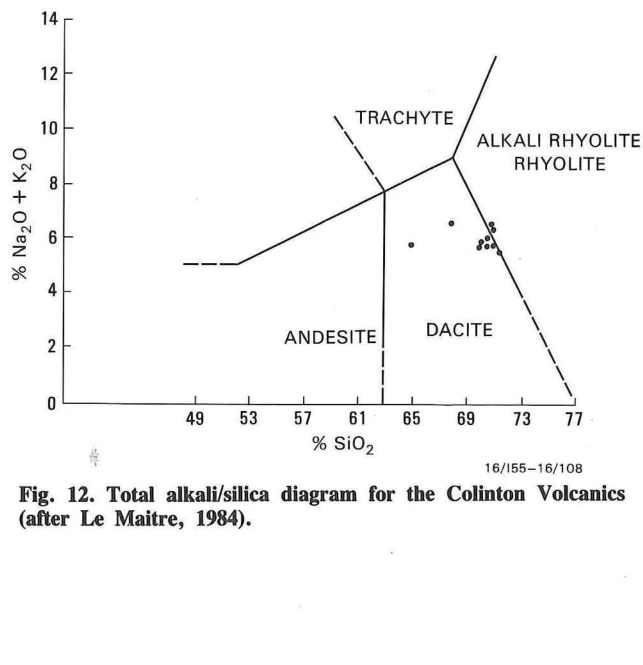


Fig. 12. Total alkali/silica diagram for the Colinton Volcanics (after Le Maitre, 1984).

from sedimentary to volcanic rocks. It may be an onlapping boundary since the Colinton Volcanics appear to lie unconformably on Ordovician rocks south of Queanbeyan.

The top of the Colinton Volcanics is not exposed on CANBERRA. However, the western boundary is taken as the Jerrabomberra Fault where strongly foliated dacitic tuff of the Colinton Volcanics is juxtaposed with thickly bedded rhyodacitic ignimbrite of the Deakin Volcanics.

Thickness. On MICHELAGO, where the succession is most complete, Richardson (1979) has estimated a thickness of 4000 m. On CANBERRA, the uppermost beds have been eroded and the outcrop pattern suggests the unit thins depositionally northwards. Henderson (1981) gives a thickness of 2000 m south of Queanbeyan.

Environment of deposition. The Colinton Volcanics were probably erupted on land. Interbedded limestone, dolomite and tuffaceous shale suggest the existence of local shallow-marine conditions and marginal volcaniclastic deposition during periods of volcanic quiescence. The limestone bodies appear to have formed as isolated carbonate complexes.

Age and correlation. An early Ludlow age for the Colinton Volcanics is indicated by their conformable relationship with the underlying Cappanana Formation and the presence of the brachiopod *Atrypoidea australis* from two localities on MICHELAGO (Sherwin 1974(b) *in* Richardson, 1979). Some indeterminate conodonts undiagnostic of age (R. Nicoll, pers. comm., 1982) were recovered from limestone outcrops south of Queanbeyan (Table 12).

A mean calculated age of 400 ± 6 Ma (Early Devonian) based on total-rock–biotite joins was obtained by AMDEL (Amdel report GS 6227/82) from massive dacitic ignimbrite 2 km southeast of the radio mast on the old Queanbeyan–Cooma

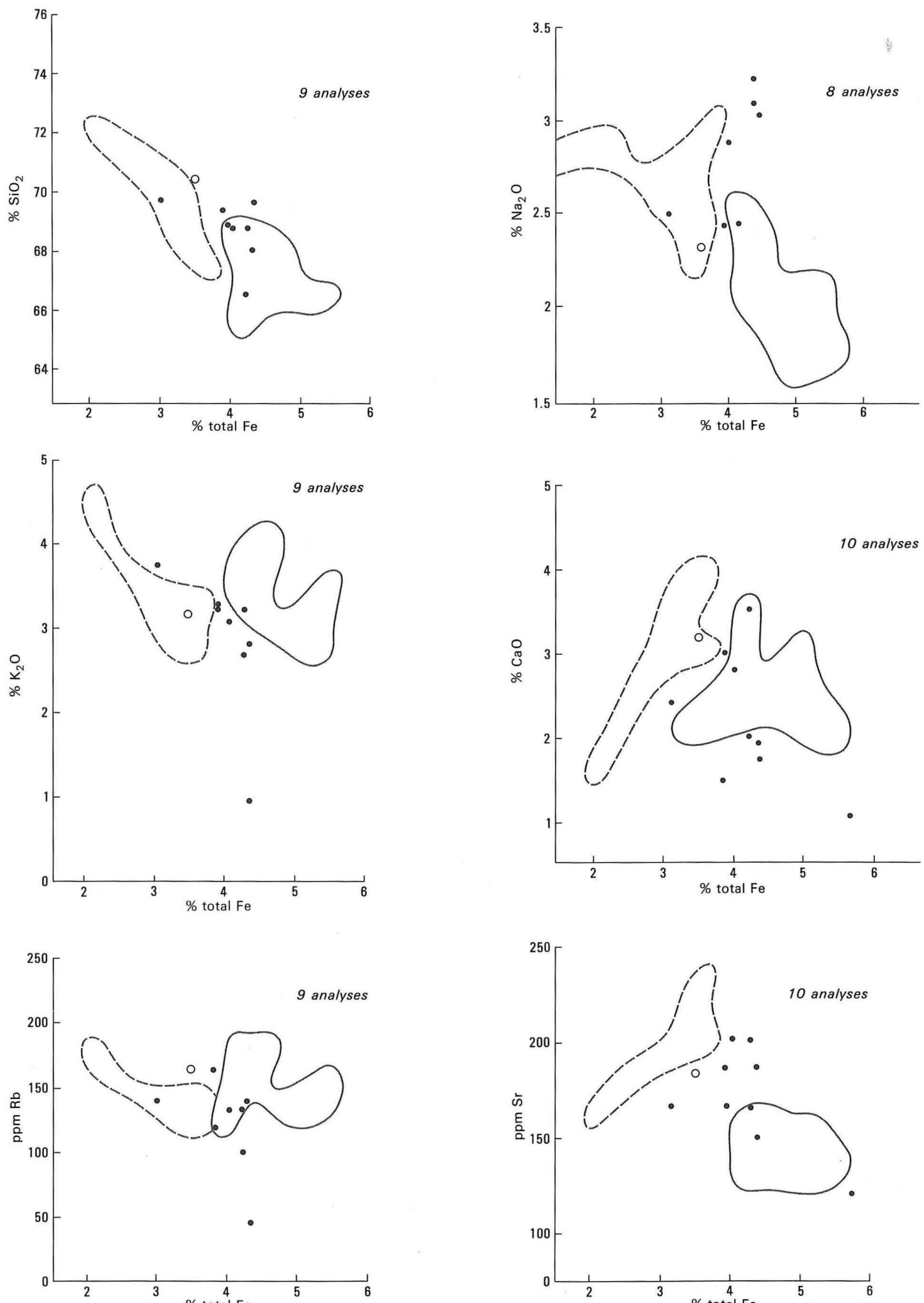
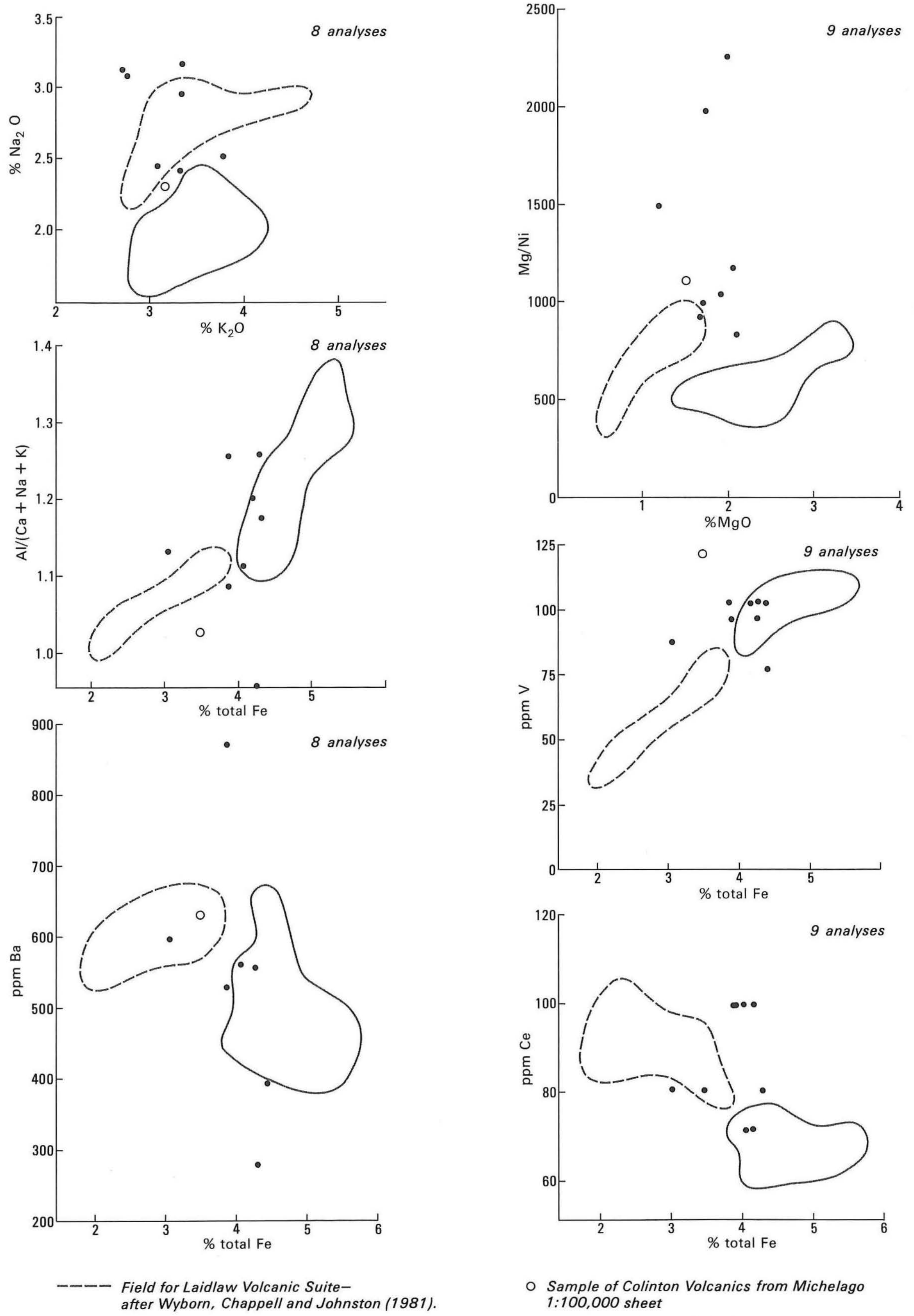


Fig. 13. Element variations in the Colinton Volcanics.



---- *Field for Laidlaw Volcanic Suite– after Wyborn, Chappell and Johnston (1981).*

—— *Field for Hawkins Volcanic Suite– after Wyborn, Chappell and Johnston (1981).*

o *Sample of Colinton Volcanics from Michelago 1:100,000 sheet*

• *Sample of Colinton Volcanics from Canberra 1:100,000 sheet*

16/I55–16/109–1

Fig. 13 (continued).

Table 12. Occurrence of conodonts in limestone from the Colinton Volcanics

'Sunset' homestead (MR 029/787)																	
Sample no.	287A	287B	287C	287D	287E	287F	287G	287H	287I	287J	287K	287L	287M	287N	287O	287P	Total
Processed weight (kg)	4.73	3.73	4.30	5.24	5.22	5.0	4.75	5.68	5.65	5.16	4.86	5.33	5.79	4.67	5.00	4.85	79.96
Conodonts	—	2	1	3	3	5	—	1	—	—	—	—	—	—	—	—	15
White Rocks, southern quarry (MR040/820)																	
Sample no.	288A	288B	288C														
Processed weight (kg)	5.32	5.25	4.93														15.5
Conodonts	—	—	1														1
White Rocks, middle quarry (MR 040/823)																	
Sample no.	289A	289B	289C	289D													
Processed weight (kg)	4.55	3.47	5.0	4.77													17.79
Conodonts	—	—	—	—													—
White Rocks, northern quarry (MR 041/826)																	
Sample no.	290A	290B	290C														
Processed weight (kg)	4.85	3.37	5.38														13.6
Conodonts	—	2	—														2
Quarry (Ready Mix), Old Cooma Rd (MR 022/803)																	
Sample no.	291A	291B	291C	291D													
Processed weight (kg)	4.88	4.50	4.78	5.28													19.44
Conodonts	—	—	—	—													—

road at MR 005/719. Henderson (1990) gives two K–Ar ages of 418 ± 3 Ma and 413 ± 3 Ma and Rb–Sr ages of 411 ± 5 Ma and 403 ± 4 Ma respectively for two samples of the Colinton Volcanics (Williamsdale Dacite Member) outcropping on MICHELAGO (AMDEL report G6406/86). Total-rock and biotite Rb–Sr data for the Colinton Volcanics also plot close but just below the isochron for the Laidlaw Volcanics (Fig. 11). The extent to which the younger ages may reflect subsequent intrusive or deformational events is unkown.

The Colinton Volcanics do not appear to correlate with other Late Silurian volcanic formations on the Canberra–Yass Shelf. The early Ludlow age deduced from their stratigraphic position precludes correlation with formations in the Hawkins Volcanic Suite. Although the chemical and petrographic character of the Colinton Volcanics suggests an association with the Laidlaw Volcanic Suite, element-variation plots (Fig. 13) show a spread of data falling with some overlap between the fields of the Hawkins and Laidlaw Volcanic Suites. Thus the Colinton Volcanics may represent another suite of volcanic rocks originating from a separate volcanic centre. The equivocal nature of this formation may relate to its close proximity to the line separating I and S-type granites.

Captains Flat Block

On CANBERRA the Late Silurian sediments east of the Cullarin Block were originally part of an extensive marine basin, recently termed the 'Ngunawal basin' by Bain & others (1987). This basin was bounded on the east by the Capertee High but its western extent is less well known because erosion has removed parts of the Late Silurian and younger sequences from the Canberra Block. Sedimentation ended when the 'Ngunawal basin' was finally deformed during the mid-Devonian (Tabberabberan) earth movements. The Captains Flat Graben (Strusz, 1971), later termed the 'Captains Flat Trough' (Scheibner, 1973), was left as a fault bounded erosional remnant of this larger marine basin.

According to Scheibner (1973) and Gilligan & others (1979) the 'Captains Flat Trough' is a separate fault-bounded volcanic rift basin which is a southern continuation and 'en echelon' equivalent of the Hill End Trough. Deep-water greywacke sediments at Captains Flat, Tarago and Taralga were also taken by Talent & others (1975) to indicate a southward extension of the Hill End Trough to at least 36°S. A stratigraphic link between the Captains Flat Graben and Hill End Trough is provided by a Siluro–Devonian proximal quartz turbidite sequence (Covan Creek Formation), northeast of Lake George, that may be coeval with portions of the Towrang beds around Goulburn and possibly also elements of the Burraga beds around Taralga (Henry, 1978; Pickett, 1982).

An alternative regional setting places the Captains Flat Graben as a southern extension of a rift zone termed the 'Wollondilly tract' (Powell 1983, 1984). This rift zone when extended northwards appears to link up with the Murruin Basin — an interarc basin east of the Capertee High (Scheibner, 1973). In this speculative model the 'Wollondilly tract' cuts across the Capertee High in a north-northeasterly direction. However, south of the Hill End area, the Capertee High is expressed as the Bindook Volcanic Complex (Fergusson, 1980; Carr & others, 1980) and subaerial volcanics on BRAIDWOOD (Felton & Huleatt, 1977) and ARALUEN (Wyborn & Owen, 1986).

According to Scheibner (1973), the 'Captains Flat Trough' originated as a marginal sea (interarc basin) by the rifting of the Ordovician Molong Volcanic Rise, which would imply that the Captains Flat Graben was floored by oceanic crust. The proposed larger Ngunawal Basin of Bain & others (1987) is thought to have formed as a shallow basin with minor volcanism between and/or above rising granite batholiths that fed extensive subaeral volcanics to the west (Canberra High) and east (Capertee High). Further, the emplacement of silicic volcanics and granitoids during the Siluro–Devonian implies that continental basement exists beneath the Captains Flat Block.

About 5000 m of epiclastic sediment with minor acid and basic volcanics of Late Silurian age is preserved in the Captains Flat Block. Bounding marginal highs are composed of Late Ordovician quartz turbidite sediments intruded by Late Silurian and Early Devonian acid and basic rocks. A Silurian stratigraphic succession originally established around Captains Flat mine by Glasson & Paine (1965) was later modified by Oldershaw (1965). The modified stratigraphy was extrapolated northwards to Hoskinstown and the southern margin of the Lake George Basin by Wilson (1964) and into the western 'limb' of the Captains Flat Block by Richardson (1979). The stratigraphic sequence of Oldershaw (1965) has been adopted here, with some revision, on CANBERRA. This rather subjective approach has been influenced (1) by the nature of the sedimentary and volcanic environment, with its rapid thickness and facies variations; (2) a strong tectonic and metamorphic overprint; (3) lack of palaeontological control; (4) deep weathering and a cover of superficial Cainozoic sediments. Nevertheless the short-lived stratigraphic record spanning Ludlow to Pridoli preserved in the Captains Flat Block is characterised by a shallow-marine environment with proximal quartz turbidite units, and the limited occurrence of primary volcanism. Most volcanic rocks are secondary acid volcaniclastic sediments (derived from primary volcanic sources on bounding highs) and thin basalt flows in association with felsic tuffs, suggesting a short period of shallow-marine bimodal volcanism.

Hoskinstown Group

Derivation. Village of Hoskinstown (MR 225/775).

Nomenclature. In the vicinity of Captains Flat, Glasson & Paine (1965) informally grouped the 'Copper Creek Beds', Kohinoor Volcanics and 'Captains Flat Beds' as the 'Captains Flat Group'. The extension of mapping northwards to Hoskinstown enabled Oldershaw (1965) to use the name Hoskinstown Group for Silurian rocks within the 'Captains Flat Syncline'. The group comprised the following stratigraphic units, oldest to youngest: Rutledge Quartzite, Copper Creek Shale, Kohinoor Volcanics, 'Carwoola Beds' and Captains Flat Formation. On CANBERRA, Hoskinstown Group has been retained and follows the original usage of Oldershaw (1965).

Distribution. The Hoskinstown Group underlies a broad topographic depression expressed as low rounded hills and ridges and alluvial flats, coinciding broadly with the Captains Flat Block. Southwest of Hoskinstown it separates into two 'limbs' that continue onto MICHELAGO. In the western limb, the sediments persist along Primrose Valley Creek towards the Queanbeyan River, while in the eastern limb they reach Captains Flat and contract as fault-bounded remnants as far south as the Bredbo River.

Description. Units of the Hoskinstown Group on MICHELAGO have been described by Richardson (1979), but their formal definition needs to take account of their northward extent on CANBERRA. The stratigraphic relationships between the formations of the Hoskinstown Group are summarised in Figures 14 and 15. The oldest formation is the Copper Creek Shale, a turbiditic sequence with discontinuous basal beds of quartzite and conglomerate (the Rutledge Quartzite Member). The Kohinoor Volcanics are a primary acid volcanic unit of dacitic composition with interbedded shale and breccia. They are conformable with the Copper Creek Shale and in turn are overlain conformably by the Carwoola Formation. The Kohinoor Volcanics constitute the first evidence of sustained volcanicity in the Captains Flat Graben. The Carwoola Formation is a proximal quartz turbidite sequence of local derivation that occupies much of the centre of the Graben. Where the Kohinoor Volcanics are missing in the western limb and axial portions of the Captains Flat Graben, the Carwoola Formation may lie disconformably on the Copper Creek Shale. The Carwoola Formation is overlain by and may in part be a lateral

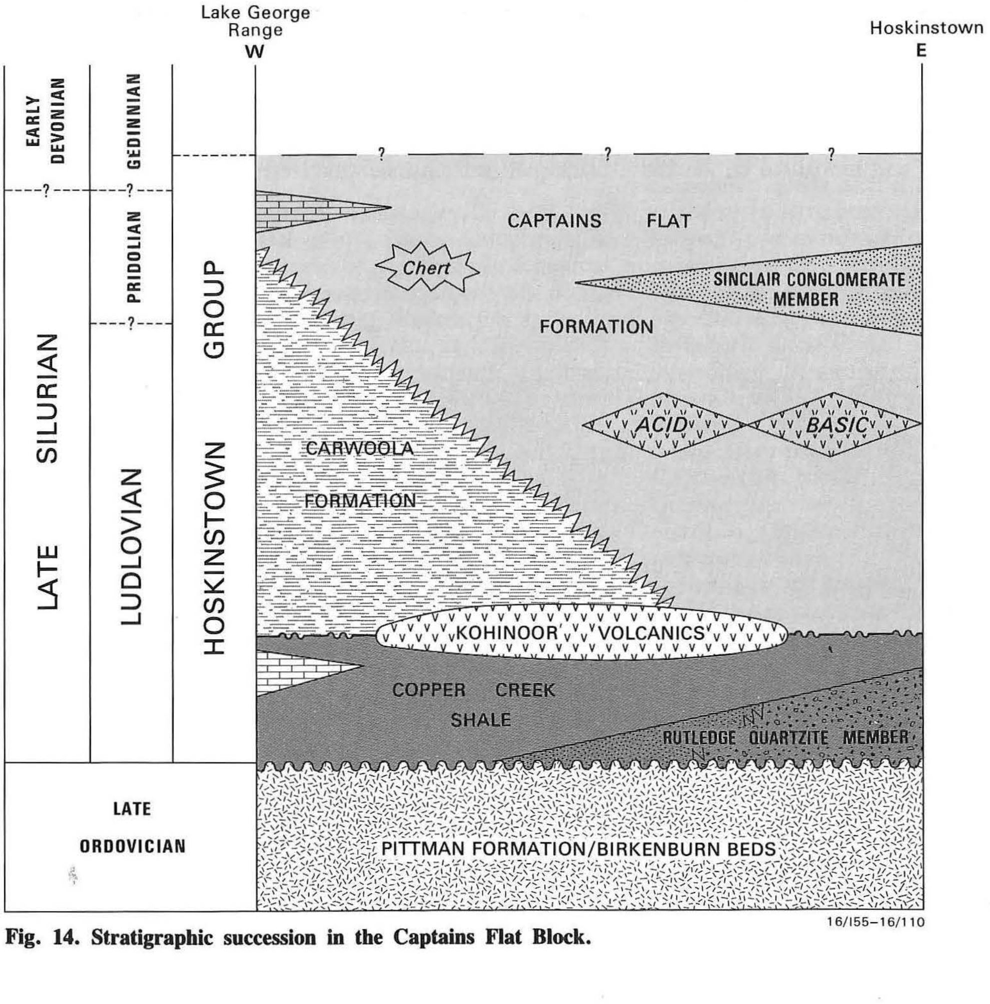


Fig. 14. Stratigraphic succession in the Captains Flat Block.

facies equivalent of volcano-sedimentary units of the Captains Flat Formation. Distinctive lithologies in the Captains Flat Formation include felsic and basaltic volcanics and a volcaniclastic unit, the Sinclair Conglomerate Member. Where the Carwoola Formation is missing in the eastern limb of the Captains Flat Graben, older formations in the group are overlain disconformably by the Captains Flat Formation.

Boundary relationships. The lower boundary is obscured by a strong deformation which has folded the Hoskinstown Group into tight meridional synclines separated by a central north-plunging anticlinorium of Ordovician rocks. Conglomeratic beds of the Rutledge Quartzite Member are taken as evidence of a stratigraphic break at the base of the Hoskinstown Group. Elsewhere the Group is faulted against Ordovician rocks along the Whiskers and Ballallaba Faults.

The topmost units of the Hoskinstown Group are bounded by the present erosion surface and by Cainozoic alluvium.

Thickness. A minimum thickness of 4000 m is given by Oldershaw (1965). On CANBERRA, the Hoskinstown Group thickens to about 5000 m in the axial portions of the Graben.

Environment of deposition. Although the rock assemblage is marked by a general lack of limestone, the sediments and volcanic rocks of the Hoskinstown Group were probably deposited in quiet, relatively shallow-water marine conditions.

Age and correlation. Fossils are scarce throughout the sequence and the volcanic units are too weathered and tectonised for radiometric dating. The Hoskinstown Group is regarded as Late Silurian (Ludlow to Pridoli). The Group is probably a facies equivalent of the Mount Fairy Group on BRAIDWOOD, a shallow-marine volcano-sedimentary sequence at the western edge of the Capertee Shelf (Felton & Huleatt, 1977). It may in part be coeval with the Late Silurian Laidlaw Volcanic Suite on the Canberra–Yass Shelf.

Copper Creek Shale (Suo)

Derivation. From Copper Creek, a small tributary of the Molonglo River at Captains Flat.

Nomenclature. The shale, which is the oldest Silurian sedimentary unit in the Captains Flat district, was originally named the 'Copper Creek beds' by Glasson & Paine (1965). The name, Copper Creek Shale, was formalised on the 2nd Edition of the Canberra 1:250 000 Geological Sheet (Best & others, 1964) and was used by Stauffer & others (1964) and later Oldershaw (1965). The nomenclature on CANBERRA follows Richardson's (1979) usage whereby the Copper Creek Shale contains the basal Rutledge Quartzite Member.

Distribution. The Copper Creek Shale crops out poorly along the eastern edge of the Captains Flat Block, where it can be traced with difficulty as far north as 'Belloun' homestead (MR 214/928). A few outcrops are found in Primrose Valley and a section is exposed in a road cutting at MR 160/710; nearer the Molonglo River the formation is obscured by alluvium except for a few outcrops south of Foxlow Stud (MR 215/698).

Type locality. Following Oldershaw (1965) and Richardson (1979) the type locality is designated as Copper Creek and an adjacent road cutting near Captains Flat Railway Station (disused). Here the Copper Creek Shale crops out as tightly folded beds of dark-grey shale and siltstone with subordinate sandstone.

On CANBERRA, a representative section of the formation is exposed in a road cutting in the Koolambahlah Subdivision (MR 160/710). Steeply dipping beds of bleached, dark-grey and black shale, siltstone and pale-brown sandstone are exposed over a distance of about 175 m. The shaly units are strongly laminated, carbonaceous, and pyritic and are up to 5 cm thick. Sandstone beds reach a thickness of 2 m. They are often massive at the base and show low-angle current laminations as they grade up into siltstone and shale; graded and current-bedded units face east. Beds of dark-grey cherty shale develop at the eastern end of the cutting. Bedding, which parallels cleavage, is vertical, with local dips of 80°E; minor folds plunge steeply north. Sedimentological features are affected by a tectonic overprint that has caused thickening and thinning of beds and local boudinage. The thickness of the Copper Creek Shale in this section is unclear as the unit may be isoclinally folded.

Description. Lithological descriptions of the Copper Creek Shale on MICHELAGO are given in Glasson & Paine (1965), Oldershaw (1965) and Richardson (1979). On CANBERRA, the formation consists dominantly of thinly bedded greyish-black shale and siltstone which resembles similar lithotypes in

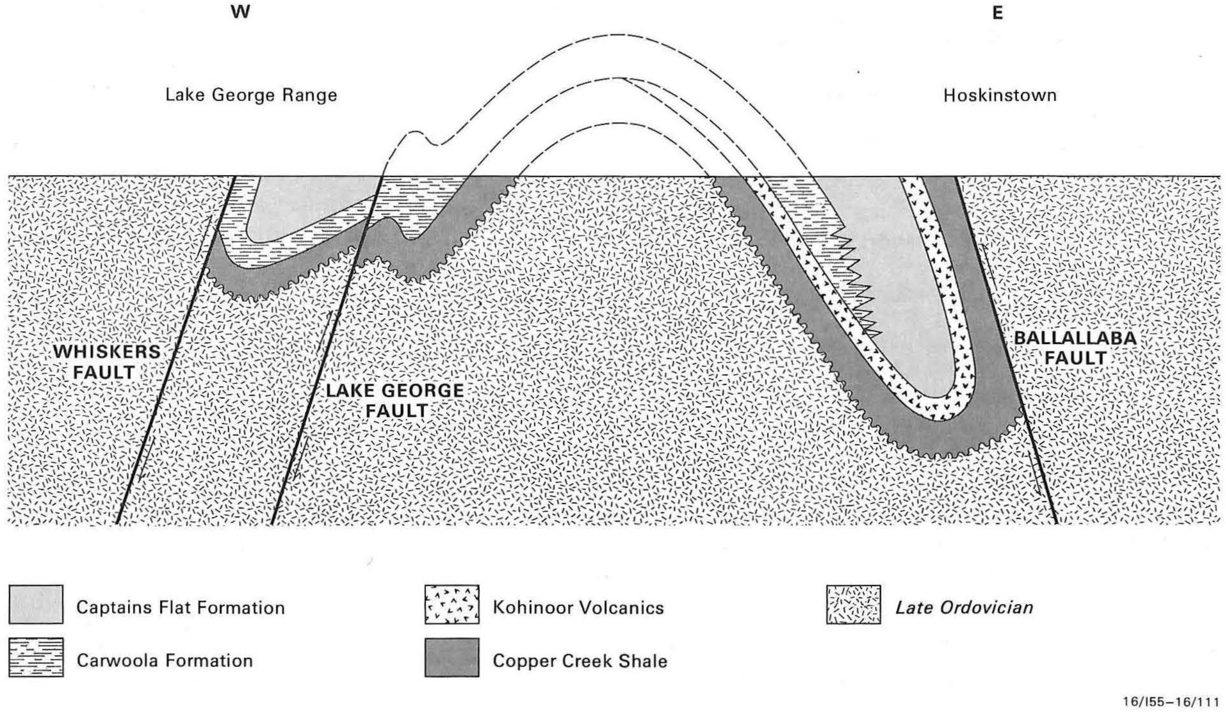


Fig. 15. Schematic stratigraphic section across the Captains Flat Block.

the Ordovician. Sandy beds are common near the base but tuffaceous sediments are not clearly evident in upper parts of the formation. A thin bed of grey, unfossiliferous, brecciated limestone (Suo_2) occurs at the base of a low ridge west of Koolambahlah Subdivision (MR 145/713). The sporadic development of limestone in the Copper Creek Shale suggests an allochthonous origin (Talent & others, 1975). Wilson (1964) has mapped overturned beds of the Copper Creek Shale in creeks near 'Woodbine' homestead (MR 221/849). The Rutledge Quartzite Member represents a local development of conglomerate and quartzite at the base of the formation.

Boundary relationships. The basal unit of the Copper Creek Shale — the Rutledge Quartzite Member — rests unconformably on Late Ordovician rocks. However, where this basal unit is absent, the nature of the lower boundary is conjectural since the Copper Creek Shale is lithologically similar to the Ordovician rocks. Along the eastern margin of the Captains Flat Graben, the Copper Creek Shale is in contact with the Ordovician along the Ballallaba Fault and directly overlying the Birkenburn beds south of Forbes Creek.

The upper boundary is complex. Near Captains Flat mine, on MICHELAGO, tuffaceous beds of the Copper Creek Shale pass gradationally up into acid porphyry of the Kohinoor Volcanics (Richardson, 1979). This conformable relationship is assumed here to extend northwards onto CANBERRA. However, along Primrose Valley, the Kohinoor Volcanics are absent and the Copper Creek Shale appears to dip conformably beneath quartzitic beds of the Carwoola Formation (the contact is obscured by alluvium). Similarly, where the Kohinoor Volcanics wedge out northwards along the eastern margin of the Captains Flat Block, it is conjectured that the Copper Creek Shale is in contact with the Captains Flat Formation.

Thickness. On MICHELAGO, Richardson (1979) has estimated a thickness of 60–150 m. On CANBERRA, estimates of thickness must be speculative since the distribution of the formation is uncertain. The narrow outcrop width of the Copper Creek Formation in the eastern limb and along the eastern margin of the Captains Flat Graben suggests that much of the formation could have been displaced by faults. On the other hand, the greater outcrop width in Primrose Valley may indicate that the formation has been repeated by isoclinal folding.

Environment of deposition. Lithologies in the Copper Creek Shale are representative of a marine turbidite facies. Disseminated pyrite in the shales suggests euxinic conditions. The possibly allochthonous limestone was probably derived from a shallower environment along bordering highs.

Age. The formation is unfossiliferous on CANBERRA. Small lenses of limestone a few kilometres north of Captains Flat have yielded the rugose corals *Entelophyllum yassense* and *Phaulactis shearsbyi* (Oldershaw, 1965; Talent & others, 1975), which indicate a probable Late Silurian (Ludlow?) age for the Copper Creek Shale.

Correlation. The Late Silurian volcano-sedimentary sequence on CANBERRA and BRAIDWOOD was probably part of a much larger basin of deposition. Thus, and following Huleatt (1971), the Copper Creek Shale is correlated with the De Drack Formation on BRAIDWOOD based on lithological similarity and stratigraphic position beneath acid volcanics (Kohinoor and Woodlawn Volcanics). On similar grounds Richardson (1979) correlates the Copper Creek Shale with the Cappanana Formation. The feasibility of the correlations is complicated by the structural separation of these formations by tracts of Ordovician rock, lack of palaeontological control, and facies variation.

Rutledge Quartzite Member (Suo_1)

Derivation. Derived from Rutledge Sugarloaf (MR 167/702) where the unit is exposed as a pure greyish-white quartzite interbedded with shale.

Nomenclature. Near the abandoned Captains Flat mine, rocks corresponding with this member at the base of the 'Copper Creek beds' were described, although not named, by Glasson & Paine (1965). The name 'Rutledge Quartzite' was formalised on the 2nd Edition of the Canberra 1:250 000 Geological Sheet by Best & others (1964) and was subsequently given formation status by Stauffer & others (1964) in anticipation of Oldershaw (1965). However, as the marker lithologies of the Rutledge Quartzite are only locally developed, it has since been considered to have member status at the base of the Copper Creek Shale (Richardson, 1979).

Distribution. The outcrop distribution of the Rutledge Quartzite Member generally follows the mapping of Oldershaw (1965). The unit crops out sporadically around the southern end of the Captains Flat Graben. On CANBERRA, extensive outcrops of conglomerate and quartzite are found near Grose Meadow Hill (MR 204/722), Foxlow Creek valley and along Rutledge Ridge.

Type area. A type section has not been specified. Instead, a type area is here designated at Grose Meadow Hill and along Foxlow Creek Valley where discontinuous outcrops of shale-clast conglomerate appear to grade laterally into grey quartzite in the faulted nose of a north-plunging anticline.

Description. Short descriptions of the Rutledge Quartzite Member are given in Glasson & Paine (1964) and Oldershaw (1965). On CANBERRA it crops out as narrow ridges and knolls of pale-grey quartzite interbedded with conglomeratic quartzite, siltstone and shale (Suo_1).

Quartzitic rocks along Rutledge Ridge are pale-grey to white and show little evidence of bedding or other sedimentary structures. They consist in thin-section of well-sorted, rounded recrystallised grains of quartz set in a sparse fine-grained silicified matrix. Many of the recrystallised quartz grains have granulated and sutured margins.

The conglomerate is best exposed around Grose Meadow Hill, where it contains rounded clasts of pale-grey silicified slate and siltstone up to 30 mm with rarer cobbles of quartzite and angular vein quartz in a matrix of sand. The conglomeratic texture is accentuated by weathering. A lithic quartzite interbedded with the conglomerate shows framework clasts of subrounded quartz grains about 1 mm across and angular shale and siltstone up to 3 mm. A poorly developed matrix consists of granular quartz with a few grains of accessory zircon.

The rocks have been extensively cleaved, boudinaged and invaded by veins of white quartz. Shale and quartzite clasts in conglomerate have been flattened and elongated parallel to the cleavage. Boudinaged lenses of quartzitic rocks ranging from 50 to 500 m long and up to 100 m wide in cleaved siltstone and shale occur along a ridge northeast of Rutledge Sugarloaf. In thin-section, the sheared texture is expressed by wispy laths of muscovite and alignment of quartz clasts sometimes showing incipient augen.

Boundary relationships. A lower contact is not exposed on CANBERRA, but in the Grose Meadow Hill area the Rutledge Quartzite Member shows some discordance in strike with the underlying Ordovician strata. The conglomerate lenses suggest an unconformity.

Southwest of Rutledge Sugarloaf, Richardson (1979) included quartz sandstone beds of the Rutledge Quartzite Member as part of the Late Ordovician sequence. Structural conformity, lack of conglomerate and field similarity of the sandstone beds illustrate the difficulty of mapping the Ordovician/Silurian boundary in this area. The position of the boundary may depend on recognising geochemical and petrological differences in the sandstone beds as outlined by Wyborn & Chappell (1983).

The upper boundary with the Copper Creek Shale is not exposed on CANBERRA. It is assumed to be gradational and is mapped at the topographic break between low-lying terrain underlain by the Copper Creek Shale and the more elevated topography of the Rutledge Quartzite Member.

Thickness. A maximum thickness of 100 m is given by Oldershaw (1965) and Richardson (1979). Variable outcrop width and the strongly sheared nature of the Rutledge Quartzite Member indicate thickness variation across an anticlinorial structure northwest of Grose Meadow Hill.

Environment of deposition. The Rutledge Quartzite Member is presumed to have been a shallow-marine deposit with clastic material in the conglomerate derived locally from underlying Ordovician rocks (Oldershaw, 1965). The very high percentage of quartz and the lack of feldspar in the quartzite suggest that it was at least partly derived from the Ordovician strata.

Age. The unit is unfossiliferous. A Late Silurian age is suggested, based on the sparse fossil evidence available in the overlying Copper Creek Shale.

Correlation. On the basis of lithology, Strusz (1971) suggested an Early Silurian (Llandovery) age for the Rutledge Quartzite Member, making it synchronous with the Black Mountain Sandstone in the Canberra district and the Tidbinbilla Quartzite on BRINDABELLA. Such a regional correlation implies that sediments deposited in the Captains Flat Graben have a parallel time range to the volcano–sedimentary rocks laid down on the Canberra–Yass Shelf. However, there is apparant conformity between the Rutledge Quartzite Member and the Copper Creek Shale, which is regarded as Ludlow in age. Early Silurian rocks were possibly deposited and then eroded, since a substantial time break is indicated by the unconformity at the base of the Rutledge Quartzite Member.

It is concluded that Early Silurian rocks are absent from this area. The Rutledge Quartzite Member is a unit of local derivation. A possible correlative on BRAIDWOOD is a basal conglomerate at the base of the De Drack Formation exposed in Fairy Meadow Creek (Felton & Huleatt, 1977).

Kohinoor Volcanics (Suk)

The derivation and nomenclature of the Kohinoor Volcanics are outlined in Richardson (1979). The formation has been described in detail around Captains Flat Mine by Glasson & Paine (1965) and Davis (1972). In this type area much of the information is now obscured by dangerous underground workings and an extensive spoil tip. A type section has not yet been designated since contact relationships with other stratigraphic units are poorly exposed. Outcrops of undifferentiated acid volcanic rocks are taken to be representative of the Kohinoor Volcanics south of Captains Flat.

Distribution. The Kohinoor Volcanics extend onto CANBERRA as two narrow limbs of a north-plunging syncline which is more fully developed in the vicinity of Captains Flat. The formation is poorly exposed and appears to lens out northwards in the medial portions of the Captains Flat Block. The eastern belt of the Kohinoor Volcanics may extend northwards to 'Woodbine' homestead (MR 221/850). To the west the formation crops out sporadically east of 'Foxlow' homestead and when traced northwards disappears around the nose of an anticlinorium. The Kohinoor Volcanics or their equivalent have not been recognised along the western margin of the Captains Flat Block.

Description. The Kohinoor Volcanics have been studied in detail around Captains Flat mine, since they are the host formation for base metal mineralisation in the Captains Flat Block. A lithological and petrological summary given in Richardson (1979) draws heavily on a report by Davis (1972).

On CANBERRA the formation consists of foliated rhyodacitic ignimbrite, volcaniclastic rocks, and minor shale interbeds. Apart from a gossanous outcrop of iron at MR 218/729, there is no extensive mineralisation in these rocks. Individual lithological units are not easily traced in the field. It appears that the primary volcanic rocks, which are thickest around Captains Flat, gradually thin northwards as they grade into breccia and finer volcaniclastic units in deeper axial portions of the Captains Flat Block.

The Kohinoor Volcanics commonly crop out as poorly foliated grey quartz-feldspar porphyry with occasional relict banding. Good exposures are found at MR 220/694 where the Captains Flat – Hoskinstown road crosses the Molonglo River and further north at MR 206/736. Thin sections of primary volcanic rocks show a phenocryst assemblage dominated by quartz and feldspar; mafics are rare. Quartz consists of rounded forms with resorbed margins, euhedral 8-sided crystals and angular fragments up to 3 mm in size. Albitised plagioclase and potash feldspar crystals are usually euhedral and range up to 2 mm, the proportions depending on whether the rock is dacitic or rhyodacitic in composition. Fresh plagioclase is unzoned and shows multiple twinning; partial replacement by calcite, epidote and sphene suggests some of it was originally calcic. Brownish-grey turbid crystals of potash feldspar may be anhedral or show good crystal outline. Granitic xenocrysts are indicated by myrmekitic growths around relict plagioclase or graphic intergrowths of potash feldspar and quartz. Fragments of sedimentary chert occur as irregular patches of cryptocrystalline quartz. The microcrystalline groundmass comprises quartz, feldspar and muscovite; accessories are few — mainly opaque iron and zircon.

A strong tectonic and metamorphic overprint has obliterated original rock textures. A strong foliation is defined by muscovite and the alignment of phenocrysts and clasts. Many phenocrysts are fractured and show a matrix infilling — in some cases plagioclase crystals have been reduced to diffuse outlines and almost totally replaced by the matrix. Cross-hatched twinning in potash feldspar suggests low-grade metamorphism has unmixed sanidine to form microcline. The matrix is segregated into quartz and mica-rich zones: some quartz phenocrysts are rimmed by fine grained recrystallised quartz. Wispy laths of biotite in the matrix indicate upper-greenschist-facies regional metamorphism.

Pyroclastic/volcaniclastic rocks occur as thin lensoid bodies. Volcanic conglomerates are exposed in Yandyguinula Creek at MR 247/737 and the Molonglo River at MR 220/690. They consist of volcanic rock fragments enclosed in a tuffaceous matrix; in the absence of well-defined clasts, the texture is outlined by shades of grey and white colour-mottling. Fragments vary in size, but rarely exceed a metre; they are usually rounded to subangular and aligned in the plane of foliation.

A volcanic chert a few metres thick can be traced for about 50 m near the top of the Kohinoor Volcanics (MR 203/752). The rock is dark-grey, massive, siliceous and strongly veined by quartz. In thin-section, the chert consists of a fine-grained mosaic of recrystallised quartz with numerous inclusions, and contains disseminated cubes of yellow pyrite up to 3 mm, altered to hematite. The chert is probably a discrete volcanic exhalite horizon formed by the precipitation of silica-rich fluids in a restricted, reducing marine environment.

Boundary relationships. There are no exposed contacts. The Kohinoor Volcanics appear to overlie the Copper Creek Shale conformably in the vicinity of 'Foxlow' Station.

The upper boundary is complex. The Kohinoor Volcanics are conformable with the Carwoola Formation. On the northern side of the Molonglo River, the upper boundary is expressed, along the eastern limb of an anticlinorial crest, by a gradation from volcaniclastic tuff and chert into shale and siltstone of the Carwoola Formation. On MICHELAGO, the Carwoola Formation is missing and the Kohinoor Volcanics are overlain by the Captains Flat Formation (Richardson, 1979). This contact appears conformable, but is no doubt a disconformity.

Thickness. Glasson & Paine (1965) estimate a maximum thickness of about 1300 m in the Captains Flat area. Oldershaw (1965) gives 800 m in the same area. On CANBERRA, the Kohinoor Volcanics thin gradually north and west into the axis of the Captains Flat Graben. East of Hoskinstown, Wilson (1964) gives a thickness of 300 m. Generally, thickness estimates are constrained by poor outcrop and tectonic thinning on the limbs of folds.

Environment of deposition. The depositional environment was possibly subaerial south of Captain Flat, becoming shallow-marine northwards to Hoskinstown where the volcanics are brecciated and interbeded with shale and chert. The fragmented rocks may represent subaqueous quenching of thin volcanic flows.

Age and correlation. No fossils have been found in the Kohinoor Volcanics. Based on its position relative to other stratigraphic units, the formation is probably Ludlow in age (Talent & others, 1975). A similar age is suggested by correlation with the Woodlawn volcanics on BRAIDWOOD (Huleatt, 1971) and the Colinton Volcanics on MICHELAGO (Richardson, 1979). However, Bain & others (1987) have suggested that the volcanics do not correlate, at least in chemical composition, and can be thought of as separate volcanic centres extruding magmas from different volcanic suites.

Carwoola Formation (Sur)

Derivation. Richardson (1979) cites the origin of the name as Carwoola trig station at MR 193/766 (Hoskinstown 1:25 000 Topographic Sheet 8727–11–5).

Nomenclature. The unit was first mapped as the 'Carwoola Beds' on the 2nd Edition of the Canberra 1:250 000 Geological Sheet by Best & others (1964). Later authors (Oldershaw, 1965; Strusz, 1971; Talent & others, 1975) retained this informal nomenclature. Since the stratigraphic characteristics of the unit are now better known it has been redefined as the Carwoola Formation (Richardson, 1979; Pickett, 1982).

In the Molonglo River valley around MR 160/808, Wilson (1964) described an Ordovician sequence of quartzite, metagreywacke and slate which he named the 'Balcombe Outlier'. This outlier represented the core of an overturned anticline separated from an envelope of Silurian strata by a low-angle thrust fault known as the Balcombe Slide, a hypothetical fault along which strata had moved westward. The same sequence was interpreted as an 'Ordovician? inlier' by Stauffer (1964). Subsequently Stauffer & Rickard (1966) reverted to the original interpretation of an Ordovician klippe resting on top of Silurian rocks. Further north and west of the Balcombe–Burke ridge, a belt of quartzose metasediments overlying the Captains Flat Formation in the overturned limb of a recumbent fold were assigned in part to the 'Carwoola Beds' (Wilson, 1964; Stauffer & Rickard, 1966). The quartz turbidite sequences in these two areas have been combined and the revised nomenclature places them in the Carwoola Formation.

Distribution. On CANBERRA, the Carwoola Formation occurs over much of the central portion of the Captains Flat Block. Outcrops are in two main areas separated by a tract of alluvium around Molonglo Lagoon (MR 199/818). The southern area west of Hoskinstown forms hilly country sloping gently northwards and also a broad low ridge extending from Molonglo Church (MR 162/755) south towards MICHELAGO. The northern area forms a low rise in the vicinity of Halfway Hill (MR 199/855) and then tapers northwards as scattered outcrops towards Bungendore and the southern shore of Lake George. The Carwoola Formation underlies alluvium in the Molonglo Flats and the southern portion of the Lake George basin. Quartz-turbidite sediments up to 45 m thick have been logged in BMR stratigraphic drillholes C295, C297 and C298.

The Carwoola Formation is also exposed east of the Whiskers Fault between Widgeewah Estate and the Kings Highway.

Type area. A type area is designated west of Hoskinstown and in the vicinity of Carwoola Trig, where interbeds of sandstone, siltstone and shale are folded into open north-plunging folds. The formation appears to rest conformably on the Kohinoor Volcanics; the top is not exposed.

A representative section crops out continuously for 1 km along the Molonglo River where it cuts through the Lake George escarpment (Molonglo defile) around MR 160/808. Detailed sketch sections are given in Wilson (1964) and Bird (1984). The section consists of well-bedded pure and argillaceous sandstone, siltstone and shale. The sediments are cut by a small acid porphyry and extensively veined with quartz. Sandstone beds outline a series of shallow plunging disharmonic folds; complex cleavage/bedding relationships are evident in the finer-grained silty and shaly units. Graded and low-angled cross-bedding in the turbidite units indicates the sequence is the right way up. The top and bottom of the section are obscured by alluvium. Estimates of thickness are complicated by folds and small faults. (Note: access on foot from the concrete road bridge at the eastern end of the section (MR 165/808) is only safe when the river is low.)

Description. The Carwoola Formation is a quartz turbidite sequence of lithic and quartz sandstone, siltstone and shale which has been regionally metamorphosed to quartzite and phyllite. Volcanics are absent. Brief lithological descriptions are given by Wilson (1964) and Oldershaw (1965).

In the southern area, sandstone is the most obvious lithology. Lithic sandstones are pale-brown and form frequent pavement outcrops on ridges a few kilometres west of Hoskinstown; they become softer and more lithic towards the boundary with the Captains Flat Formation. Purer quartz sandstone beds (Sur_1) become more common east of Carwoola Trig, and along Primrose valley. These sandstones are greyish-white, hard, generally massive and invaded by numerous stringers of vein quartz. Cleaved, brownish-yellow shale and siltstone with thin beds of lithic sandstone are commonly exposed along drainage lines. Bedding and an axial plane cleavage outline minor folds that plunge gently northwards. These folds reflect an upward-facing anticlinorium which can be traced in the field and from aerial photographs by the thicker sandstone beds.

A quartz turbidite sequence in the northern part of the Captains Flat Block was originally given an Ordovician age by Wilson (1964). However, similar lithologies to the south are mapped here with the Carwoola Formation (although tuffaceous and agglomerate beds suggest elements of the Captains Flat Formation may be present).

Mapping is hampered by the deep weathering and the alluvium. Uniformly kaolinised beds of cleaved pale-grey and white shale and sandstone are exposed in drainage ditches along the Bungendore–Hoskinstown road and in brick-shale pits at MR 210/870. The sediments have been deformed into a series of tight variably plunging folds. Graded beds, low-angled current laminations and sole markings confirm the folds are upward-facing; a spaced secondary crenulation cleavage forms kink folds. Reddish-brown and purple ferruginous colour-banded weathering structures cut across or follow bedding planes. Between 'Carlton' homestead (MR 189/904) and 'Stoneville' homestead (MR 192/886) there are scattered outcrops of micaceous sandstone near the base of the Lake George escarpment. A few of the thicker beds form parallel ridges which trend obliquely to the escarpment and dip steeply westwards towards the escarpment.

The sandstone petrology shows that lithic varieties consist of an assemblage of poorly sorted quartz grains and clasts of shale, siltstone and igneous rocks. A clay matrix has recrystallised to wispy laths of sericite and rare biotite. The purer quartz sandstones contain bimodal quartz but otherwise are matrix-poor and contain fewer lithic clasts. Accessory minerals are opaque iron and rounded grains of tourmaline and zircon; feldspar is rare. Post-depositional tectonics are indicated by the alignment of quartz, deflection of micas around quartz, and a matrix drawn into streaky patches along the foliation. Comminution in the purer sandstones is indicated by elongate aggregates of fine quartz; many of the larger quartz grains are recrystallised around the edges.

Along the Lake George Range, south of the Kings Highway, the Carwoola Formation consists of an overturned turbidite sequence of quartz and argillaceous sandstone, siltstone and shale. Volcanic rocks are absent. The base of the unit can be mapped in part by a persistent massive greyish-brown quartzite which is up to 20 m thick and strikes northwards from the Molonglo River valley to beyond Burke Hill. Towards the west, quartzitic sediments give way to finer-bedded argillaceous sediments of more distal aspect. The overall dip of the unit is to the west but open asymmetrical folds may be traced out by sandstone marker beds or deduced by the strike and dip pattern of bedding and cleavage.

In this area the quartzites are composed of poorly sorted detrital bimodal quartz. The larger subrounded grains (up to 1 mm) show crude tectonic crystallographic alignment. Recrystallisation is evident where the matrix quartz has been incorporated into the larger quartz crystals. Rock fragments are minor. Some quartzite beds are remarkably pure, but where there is an argillaceous matrix it consists of elongate felted masses of chlorite and sericite, fine angular quartz and the occasional grain of plagioclase. Accessories include rounded grains of zircon and tourmaline; opaque minerals are anhedral grains of ilmenite with white encrustations of leucoxene and euhedral grains of pyrite. Modal analyses of the quartzitic rocks are given in Bird (1984).

Boundary relationships. The Carwoola Formation conformably overlies the Kohinoor Volcanics. A basal contact is not exposed; a lower boundary is placed above the uppermost volcanic beds in the Kohinoor Volcanics. Along Primrose Valley, the Carwoola Formation appears to rest with structural conformity on the Copper Creek Shale, but the actual contact is obscured by alluvium.

East of Hoskinstown and along Primrose Valley the Carwoola Formation dips beneath and appears to be overlain conformably by the Captains Flat Formation. The boundary is probably gradational and is mapped at the first indication of volcaniclastic detritus in the Captains Flat Formation. The Carwoola Formation is probably in part a lateral facies equivalent of the Captains Flat Formation (Figs. 14 and 15). The absence of the Carwoola Formation in the Captains Flat area led Oldershaw (1965) to postulate a mid–late Silurian fold episode prior to the deposition of the Captains Flat Formation. This would have required the removal of a considerable thickness of the Carwoola Formation west of Hoskinstown. The formation appears to lens out southwards onto MICHELAGO, leaving the Captains Flat Formation to overlap onto the Kohinoor Volcanics. At the mine and 30 m east of the Molonglo River bridge there is no evidence of an erosional break at this boundary.

Along the base of the Lake George escarpment, the Carwoola Formation dips steeply westwards and is faulted against the Captains Flat Formation. The relationship can be seen in a railway cutting at MR 186/889. East of the brick shale pits (MR 210/869) the Carwoola Formation dips steeply beneath the Captains Flat Formation in the same relationship as that established near Hoskinstown, i.e. a facies change.

East of the Whiskers Fault, the Carwoola Formation appears to overlie the Captains Flat Formation. A contact is not exposed but Teck Explorations Ltd (1982) and Bird (1984) have postulated an intertonguing relationship between the two formations in the vicinity of the old Briars base-metal mine (MR 169/829). However, the reversed stratigraphic position suggests the Carwoola Formation overlies the Captains Flat Formation on the overturned limb of a syncline (Fig. 15). To the west, the Carwoola Formation is faulted against the Late Ordovician quartz turbidite sediments along the Whiskers Fault, although it is hard to distinguish the two units in the field.

The uppermost beds of the Carwoola Formation form an erosion surface which has been deeply incised by the Molonglo River and covered by colluvial and alluvial deposits adjacent to the Lake George escarpment.

Thickness. An accurate estimate of thickness is hindered by a poorly defined base, an eroded top, repetition of beds by folding, and faulted contacts. A minimum thickness of 230 m is based on the difference in topographic elevation of Balcombe Hill and the Molonglo River. Oldershaw (1965) gives a thickness of at least 1200 m west of Hoskinstown. The unit thins southwards onto MICHELAGO.

Environment of deposition. The quartz-turbidite units of the Carwoola Formation indicate a continuing development of marine conditions and probably rapid subsidence in the axis of the Captains Flat Graben. The intermix of clean and argillaceous sandstone, poor sorting and bimodality of the quartz population indicates proximal quartz turbidite deposition. The source material is uncertain, but the lack of feldspar and volcanic detritus in matrix-poor sandstone beds on the western side of the trough suggests some recycling of Late Ordovician rocks from the Cullarin High.

Age and correlation. The age of the Carwoola Formation is uncertain since it is unfossiliferous. A Late Silurian age is deduced from its stratigraphic relationships with the underlying Kohinoor Volcanics and overlying Captains Flat Formation.

The Carwoola Formation is tentatively correlated with quartz turbidite sediments of the Covan Creek Formation and the Palerang beds which also overlie Late Silurian shallow-marine and felsic volcanic sequences on BRAIDWOOD and ARALUEN.

Captains Flat Formation (Suf)

Derivation. The formation is named after the township of Captains Flat, on MICHELAGO (Richardson, 1979).

Nomenclature. Glasson (1957) originally named the unit the 'Captains Flat Beds'. Later this was modified by Best & others (1964) to Captains Flat Formation. Oldershaw (1965) described the formation and recognised two member units: the 'Yandyguinula Shale' and the Sinclair Conglomerate. On CANBERRA the 'Yandyguinula Shale' is not distinctive enough to warrant member status.

Distribution. The bulk of the formation is found on CANBERRA where it forms two meridional belts in two synclinoria on the 'limbs' of the Captains Flat Graben. The eastern belt is up to 2 km wide and stretches from 'Woodbine' homestead south for 20 km onto MICHELAGO. The western belt, of similar width, follows the Lake George Range from the Bungendore–Gundaroo road south for 30 km to the edge of the Sheet area. The continuity of this belt is broken by quartz turbidite units of the Carwoola Formation cropping out in the Molonglo River valley where it cuts across the Lake George Range.

Type locality. According to Oldershaw (1965), the Captains Flat Formation is well exposed on 'Town hill' at Captains Flat, where there is up to 1200 m of shale, lithic and crystal tuff, dacite and basalt in a tight north-plunging syncline. Richardson (1979) gives this locality as the type section for the Captains Flat Formation but does not cite boundary relationships.

Description. The Captains Flat Formation is a heterogeneous sequence of shale, siltstone, thin acid and basic volcanic flows, tuff and minor limestone and chert. Wilson (1964) attempted a detailed lithological correlation between eastern and western belts of the Captains Flat Formation to support his structural model of the 'Captains Flat Trough'. Correlations can be made in a gross sense but are hampered by few marker lithologies, arbitrary lithologic boundaries, poor continuity of outcrop and complex structure. The formation has been mapped in some detail along the Lake George Range north of the Molonglo River by Teck Explorations Ltd (1981 and 1982), and two drillholes (>300 m) give subsurface data on lithologies around Briars mine. Chemical analyses of rock types in the western belt are given in Table 13.

Table 13. Captains Flat Formation: major and trace element analyses

Sample no.	*76460069*	*76460070*	*76460074*	*76460075*	*76460302*
Rock type	*rhyodacite*	*rhyodacite*	*lithic tuff*	*crystal tuff*	*limestone*
Grid ref.	*180963*	*1759622*	*161951*	*178939*	*170908*
%					
SiO_2	66.55	62.91	62.81	64.35	0.93
TiO_2	0.62	0.57	0.58	0.52	0.01
Al_2O_3	15.13	13.56	14.66	14.39	0.31
Fe_2O_3	0.85	0.89	1.92	1.79	0.04
FeO	3.35	4.60	3.60	3.70	0.08
MnO	0.09	0.11	0.18	0.10	0.02
MgO	1.43	3.45	2.75	3.00	0.89
CaO	2.20	3.97	3.82	4.87	53.80
Na_2O	6.10	2.25	2.90	2.70	0.02
K_2O	0.33	1.64	2.97	1.46	0.03
P_2O_5	0.13	0.14	0.14	0.12	1.01
H_2O+	1.64	3.17	2.27	2.38	0.23
H_2O-	0.04	0.15	0.13	<0.02	0.13
CO_2	0.50	1.80	0.60	0.10	43.10
Rest	0.15	0.25	0.26	0.23	0.20
Total	99.11	99.46	99.59	99.71	99.60
ppm					
B	—	—	—	—	20
Ba	210	960	1050	520	—
Rb	10	70	75	50	—
Sr	320	260	260	500	—
Pb	4	16	2	11	—
Th	8	10	14	6	—
U	6	<4	<4	<4	—
Zr	200	165	170	215	—
Nb	14	12	4	10	—
Y	32	28	34	26	—
La	30	50	50	30	—
Ce	90	70	80	80	—
V	150	180	150	170	—
Cr	20	55	60	60	—
Co	15	20	20	20	—
Ni	10	20	15	70	—
Zn	50	70	100	70	—

Shale and siltstone are ubiquitous and form subdued knife-edged outcrops which emphasise a strong meridional cleavage. The rocks are greyish-green but weather to pale-brown. Bedding, where found, dips at a shallow angle, and may be recognised by subtle changes in grainsize and texture. Phyllite, with minute porphyroblasts of biotite on cleavage planes, occurs in the eastern belt, and indicates an upper-greenschist level of regional metamorphism. Oldershaw (1965) regarded the bottom 60 m of the Captains Flat Formation as distinctive enough to have member status and named it the 'Yandyguinula Shale'. A brief definition of it is given by Richardson (1979). However, on CANBERRA, a separate status is not justified as shale and siltstone form a background lithology that has complex and sometimes interfingering relationships with other rock types.

A few acid volcanic flows (Suf_3) occur in the sequence. In the eastern belt, porphyritic and autobrecciated dacite forms boulders and bare rock surfaces. Banding is rare and the rocks are patchily foliated. Outcrops of dacite are closely associated with basaltic rocks south of the Forbes Creek road. Near Hoskinstown, Wilson (1964) and Oldershaw (1965) mapped a dacite flow as a marker unit defining the northern keel of the 'Captains Flat Synclinorium'. Detailed mapping did not verify this fold closure and it is possible that the dacite peters out into discontinuous lenses. The dacite becomes a more coherent unit where it forms higher ground crossed by the Hoskinstown–Captains Flat road near Yandyguinula Creek before lensing out to the south. In thin-section the phenocrysts in the dacite are mainly albitic plagioclase; the crystals reach a size of 3 mm and have resorbed and slightly embayed margins. Quartz phenocrysts are much less abundant. Aggregates of epidote, sphene and opaques pseudomorph mafics. Patches of calcite have formed from a more calcic plagioclase during albitisation. A devitrified glassy groundmass is quartzo-feldspathic. Abundant metamorphic biotite defines a weak foliation.

In the western belt, acid volcanics have not been mapped south of the Molonglo River. A porphyritic rhyodacite flow interbedded with shale and tuff between Millpost Creek and the Bungendore–Gundaroo road has prominent quartz phenocrysts and is weakly foliated. The quartz phenocrysts are both rounded and angular, and up to 12 mm in size; extensive fracturing is indicated by granular quartz and infillings of calcite. Glomerocrysts of albitic plagioclase are altered to sericite. Rare potash feldspar phenocrysts show cross-hatched twinning. Mafics (possibly amphibole) have been altered to epidote, chlorite and opaques. An occasional basaltic rock fragment is indicated by clusters of plagioclase microlites. A cryptocrystalline groundmass of quartz and feldspar is veined with calcite and locally preserves a eutaxitic texture. A weak foliation is expressed by sericite, chlorite and trains of opaques; pressure shadows of calcite are associated with quartz phenocrysts. A low metamorphic grade is suggested by the absence of biotite.

Thin flows of basalt and associated beds of basaltic breccia (Suf_2) form a significant but minor component of the Captains Flat Formation. Basalt forms subdued outcrops of limited strike length south of Hoskinstown and in the vicinity of Balcombe Hill. The rocks usually occur as float of lichen-covered subangular blocks, locally supporting a reddish-brown soil. Fresh basalt is bluish-green and may be distinguished from the dolerites in the area by fine grainsize and vesicular texture. Contacts with surrounding lithologies are not exposed, but

Pl. 1. Dipping quartz turbidite units, Birkenburn beds (Ob). Eastern foreshore area of Lake George, NSW (MR 252/149).

Pl. 2. Detail of graded quartz turbidite units in Plate 1. Note Bouma divisions B, C, (D), E, and ball-&-pillow structure.

Pl. 3. Autolith of dacitic porphyry in dacitic ignimbrite, Mount Painter Volcanics (Smp). Near intersection of Bedulluck road with Barton Highway, NSW (MR 864/117).

Pl. 4. Current-bedded quartz sandstone, Yarralumla Formation (Suy), Yarralumla Creek, Curtin, ACT (MR 896/896).

Pl. 5. Spheroids in massive rhyodacitic ignimbrite, Deakin Volcanics (Sud), Tuggeranong Parkway, ACT (MR 875/873).

Pl. 6. Rhyodacite mudflow deposit, Laidlaw Volcanics (Sul). Murrumbidgee River, 1 km downstream from the picnic area at Pine Island, ACT (MR 862/774).

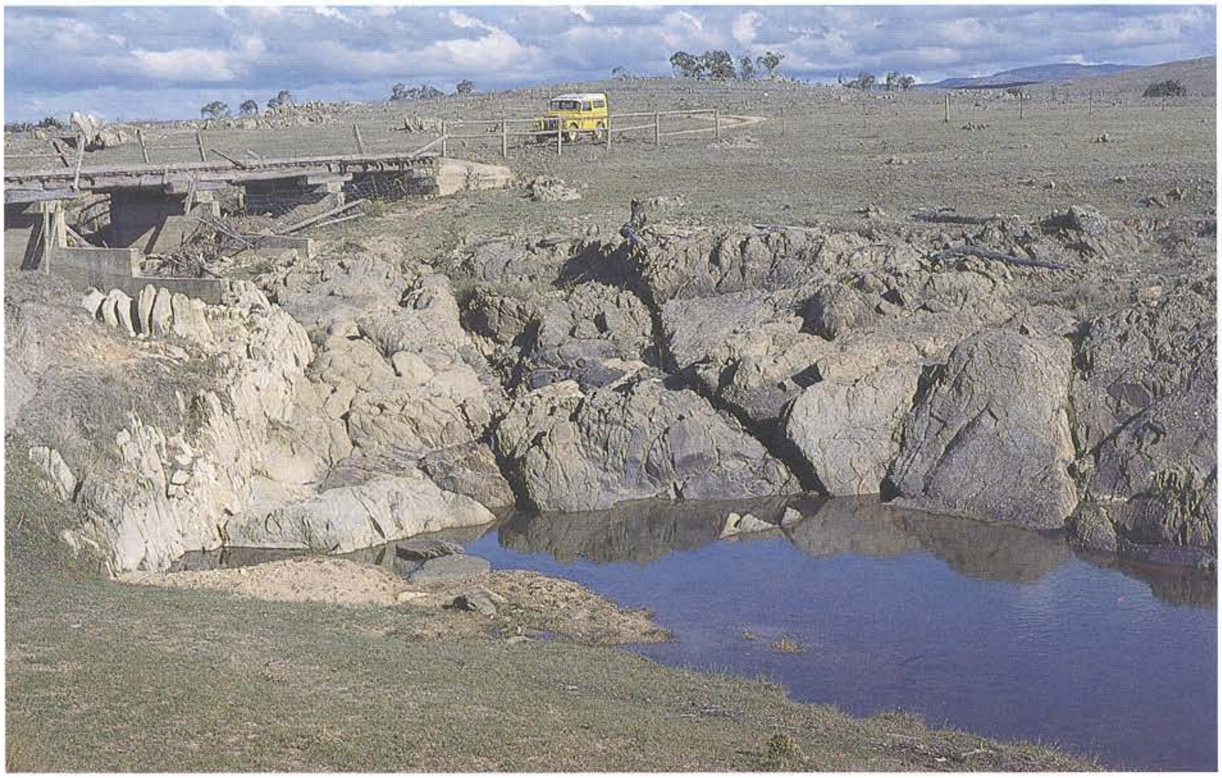
Pl. 7. Tectonised biohermal limestone, Colinton Volcanics (Svc). Thinly bedded bluish-grey limestone encloses a core of massive, brown, dolomitic limestone. Queanbeyan River, opposite White Rocks quarries (disused), NSW (MR 042/825).

Pl. 8. Tertiary ferruginous quartz-pebble conglomerate (Tg_1). Carwoola Flats, 500 m north of Captains Flat road, NSW (MR 197/740).

Pl. 9. Tertiary siliceous quartz-pebble conglomerate (silcrete, Tg_2). Western foreshore area of Lake George, 2 km south of Gearys Gap, NSW (MR 170/113).

Pl. 10. Quaternary iron-cemented colluvium (Qc). Note dominance of subangular lithic clasts derived from underlying bedrock. Murrumbateman Creek, NSW (MR 937/215).

Pl. 11. Unconformity between Late Ordovician kaolinised phyllite (Pittman Formation, Op) and Quaternary indurated colluvium (Qc), in turn overlain by alluvium (Qa). Murrumbateman Creek, NSW (MR 904/244).



Pl. 12. Dolerite dyke (d_2 Early Devonian?, centre) intruding Ellenden Granite (Dge), which has in turn intruded bleached and cleaved Woodlawn Volcanics (Suw, left). Creek 1 km east of 'Lakelands' homestead, NSW (MR 270/012).

Pl. 13. Foliated felsic porphyry intrusion, 1 m thick, of probable Early Devonian age, intruding Late Ordovician metasediments (Birkenburn beds, Ob). Creek 1 km south of the Hoskinstown–Rossi road, NSW (MR 260/724).

Pl. 14. Angular blocks of amphibolite (Lockhart Basic Intrusive Complex, Sa) enclosed by foliated Rossi Granodiorite (Dgr). Hillslope 2 km northeast of Turallo Creek, NSW (MR 265/854).

Pl. 15. Coarse-grained Ellenden Granite (Dge) veining amphibolite of the Lockhart Basic Intrusive Complex (Sa). Eastern foreshore area of Lake George, NSW (MR 243/079).

Pl. 16. Calc-silicate bed in Late Ordovician quartz turbidite (Pittman Formation, Op). Note metamorphic rim and paler calcareous core. Gundaroo Creek, 1 km north of 'Treehaven', NSW (MR 092/240).

flows are unlikely to exceed 10 m in thickness. The original texture of the basalt is partly preserved as unoriented laths of microlitic plagioclase. Remnants of a mafic mineral (possibly clinopyroxene) are indicated by dark-brown hypidiomorphic patches of epidote. The groundmass has been largely reconstituted into a fine-grained aggregate of epidote, sphene, calcite, chlorite and opaques. Vesicles reach a size of 3 mm and are flattened and elongated in the plane of foliation. They are variously filled with polycrystalline aggregates of quartz, calcite and chlorite (sometimes altered to metamorphic biotite). Chemical analyses of basalt in the Balcombe Hill area are given by Bird (1984). Basaltic tuffaceous conglomerate forms discontinuous knife-edge outcrops north of 'Woodbine' homestead and southeast of Hoskinstown (MR 242/760). Similar rocks have been intersected in drilling at Briars mine (Teck Explorations Ltd, 1982). The conglomerate is dark-green and contains a mixture of subrounded clasts of basalt with amygdales of calcite and angular clasts of fine-grained basalt. The clasts are flattened in the plane of foliation and set in a coarse tuffaceous matrix. Thin shales are interbedded in the conglomerate. Greenish-yellow epidote occurs at the margins of some vesicular basalt clasts. Petrographically the rocks comprise subangular fragments of basalt up to 15 mm containing corroded phenocrysts of labradorite in a groundmass of microlitic plagioclase. The tuffaceous matrix consists of coarse angular quartz and plagioclase fragments up to 3 mm, set in a finer aggregate of quartz, feldspar, calcite, opaques, metamorphic biotite and accessory allanite.

The formation also contains beds of crystal and lithic tuff up to 30 m thick. Crystal tuffs form impersistent blocky outcrops. The outcrop pattern of the tuff beds in the western belt is more complex than that given by Wilson (1964) and will require detailed field mapping to elucidate relationships. The crystal tuff consists of poorly sorted angular fragments of quartz with relict embayments, altered albitic plagioclase and rare pale-green amphibole. Clasts of basalt with microlitic plagioclase suggest in part a provenance of basaltic rocks. The groundmass, consists of granular quartz, epidote, chlorite, sericite, calcite and abundant opaques. Accessory grains of rounded tourmaline, brown allanite and flakes of metamorphic biotite are more common in crystal tuffs of the eastern belt. On higher ground, lithic tuff forms elongate strongly cleaved outcrops. The rocks have a similar texture and mineralogy to the crystal varieties, but have a higher proportion of angular clasts of shale, siltstone and quartzite aligned and flattened in the plane of the cleavage. In the eastern belt a series of lithic tuff beds are thick and persistent enough to warrant stratigraphic definition within the Sinclair Conglomerate Member.

A small lens of limestone (Suf_1) enclosed in shale crops out 1 km southeast of 'Millpost' homestead (MR 171/909). The outcrop trends north for about 300 m and locally supports a reddish-brown soil. The limestone is pale-grey and dips to the east. Petrographically it consists of fine-grained micritic calcite containing boudinaged and crumpled layers of coarse recrystallised calcite. Carbonaceous stylolites are concentrated close to the layering. Pyrite is an accessory. A chemical analysis is given in Table 13. The limestone is unfossiliferous and has been sampled without success for conodonts. Its stratigraphic affinities are unclear but it is assigned to the Captains Flat Formation on the basis of surrounding lithologies.

Chert (Suf_5), about 30 m thick, is exposed in a valley just below the Gundaroo–Bungendore road where it crosses the Lake George escarpment (MR 183/988). The fine-grained rock is greenish-grey, siliceous and shows widely spaced bedding. The exposure has limited strike length and conformably underlies beds of shale which dip gently westwards. The rock consists of fine angular clasts of quartz with subordinate plagioclase in a siliceous cryptocrystalline groundmass which is cut by folded veinlets of quartz containing calcite and feldspar. Fine wispy laths of biotite altered to chlorite and opaques are strongly aligned in the plane of the foliation. The chert may have originated as an ashfall tuff.

Boundary relationships. On CANBERRA, the Captains Flat Formation in part conformably overlies the Carwoola Formation. However, south of Hoskinstown the Carwoola Formation thins out to leave the Captains Flat Formation apparently conformable on the underlying Kohinoor Volcanics. This suggests that the two formations in this area are in part laterally equivalent (Fig. 14). North of Hoskinstown the base of the Captains Flat Formation appears to progressively overlap onto the Copper Creek Shale as the Kohinoor Volcanics thin out towards 'Woodbine' homestead. Along the base of the Lake George escarpment there is a faulted contact with the Carwoola Formation.

Along the western margin of the Captains Flat Block the Captains Flat formation is faulted against the Ordovician along the Whiskers Fault. Further south, on MICHELAGO, the formation is faulted against the Ordovician along the Queanbeyan Fault (Olley, 1984). The Canberra 1:250 000 scale Geological Sheet (Best & others, 1964) and Metallogenic Sheet (Gilligan, 1974) show undifferentiated Silurian rocks (now assigned to the Captains Flat Formation) lensing out to the north along the Lake George Range, north of the Bungendore–Gundaroo road. In this area the boundary appears to be a cross-fault bringing the formation against Late Ordovician black siliceous shale beds and a Late Silurian intrusive acid porphyry. However, detailed mapping and drilling in this area by Jododex (Australia) Pty Ltd (1974) and Teck Explorations Ltd (1982) seems to indicate that the Late Silurian volcano-sedimentary sequence in this area lenses out northwards and has an infolded boundary with the Ordovician.

Thickness. Estimates of a minimum thickness for the Captains Flat Formation are affected by uncertain boundaries and complex tectonics. In the vicinity of Captains Flat, Oldershaw (1965) estimated 800–1220 m, while west of Hoskinstown, Wilson (1964) gave 1100 m.

Environment of deposition. The predominance of shale and siltstone with minor limestone and an influx of volcaniclastic sediments suggests development of shallow-marine conditions during deposition of the Captains Flat Formation. Vesicle sizes in the intercalated subaqueous basalt are comparable with data supplied by Moore (1969) and Jones (1969) and suggest the lavas were erupted in shallow water at depths of <500 m. Similar depths for extrusion are given by Henry (1978) for the Currawang Basalt on BRAIDWOOD. The presence of limestone implies that a shallow-water facies may have developed locally near the western margin of the Captains Flat Graben. The volcaniclastic rocks were in part derived from sediments and subaerial volcanics marginal to the depositional basin, the presence of allanite suggesting a terrain containing I-type granitoids. Basaltic conglomerates were derived more locally by reworking and mixing detritus from basic and acid volcanic rocks.

Age and correlation. The fossil listing of corals and brachiopods in Richardson (1979) suggests an age no older than Silurian for the Captains Flat Formation. By stratigraphic superposition with the underlying Kohinoor Volcanics and Carwoola Formation, a Late Silurian age (Ludlow or younger) has been proposed by Strusz (1971), Talent & others (1975) and Richardson (1979). Basaltic units in the formation tentatively point to a correlation in part with the Currawang Basalt on BRAIDWOOD. The upper portion of the Captains Flat Formation may be the same age as quartz turbidite sediments of the Covan Creek Formation and Palerang beds.

Sinclair Conglomerate Member (Suf_4)

Derivation. Named after Sinclair Trig (859 m) at MR 225/604 on MICHELAGO (Richardson, 1979).

Nomenclature. The Sinclair Conglomerate Member was originally named by Oldershaw (1965) for a sequence of lithic tuff and shale near the top of the Captains Flat Formation. The nomenclature is here restricted to lithic tuff and conglomerate beds in the eastern belt of the Captains Flat Formation.

Distribution. The member forms two narrow outcrop belts (probably the limbs of an overturned syncline — see cross-section H–J) separated by argillaceous sediments in the south-east corner of the Sheet area. The western belt extends south for about 11 km onto MICHELAGO. The member is absent in the western belt of the Captains Flat Formation.

Type locality. Beds of lithic tuff locally with rounded boulders of slate, quartzite and dacitic porphyry up to 45 cm crop out in a drainage line adjacent to sheepyards at MR 229/298 on MICHELAGO. The unit is interbedded with shale and dips steeply eastwards. The 'conglomerate facies' is a local development in the unit with limited strike extent.

Description. The Sinclair Conglomerate Member forms a sequence of lithic tuff and interbedded shale and conglomerate in the upper part of the Captains Flat Formation. The member is mapped as a single unit, but it is probably several closely spaced tuff beds that interfinger with shale. Most commonly the lithic tuff is brownish-yellow with numerous rounded and flattened clasts of grey shale and subordinate pale-brown quartzite up to 4 cm in a tuffaceous matrix. Originally the Sinclair Conglomerate Member was used as a marker lithology to define the northern keel of the 'Captains Flat Synclinorium' (Wilson, 1964; Oldershaw, 1965). Detailed mapping near Yandyguinula Creek (approx. MR 233/735) now indicates that the Sinclair Conglomerate Member lenses out northwards into shale and siltstone.

Boundary relationships. The unit is interbedded conformably within the Captains Flat Formation. It lenses out in the vicinity of Yandyguinula Creek and a few kilometres north of Captains Flat.

Thickness. The top and bottom boundaries have not been accurately mapped, but an estimate of 100 m is in accord with a thickness of 130 m given by Oldershaw (1965).

Environment of deposition. The high proportion of lithic clasts and locally conglomerate boulders suggests a marine debris flow deposit. The unit is devoid of current bedding and other sedimentary structures that might indicate source direction. However, its distribution and limited lateral extent suggest local derivation from a provenance of volcanics in the eastern part of the graben.

Age and correlation. A few fossil fragments (mainly crinoid) are undiagnostic and indicate broadly a Silurian age. The Sinclair Conglomerate Member is of local derivation without a known correlative outside the Captains Flat Block.

Rocky Pic Block

The Siluro-Devonian sedimentary and volcanic rocks on BRAIDWOOD represent the development of a marginal shallow-water facies along the western margin of the Rocky Pic Block where it extends south as a belt of volcanic rocks onto BRAIDWOOD and ARALUEN (Scheibner, 1973; Talent & others, 1975; Wyborn & Owen, 1986). On CANBERRA the Late Silurian formations of the Rocky Pic Block are separated from the Captains Flat Block by a belt of quartz turbidite sediments of Ordovician age.

A stratigraphic sequence for the Woodlawn area (Fig. 16) is adopted here from Felton & Huleatt (1977) and Henry (1978). Elements of the Mount Fairy Group extend westwards onto CANBERRA, where the middle and upper portions of the Group are brought to the surface (Gilligan & others, 1979) in the Currawang Anticline (whose axis is on BRAIDWOOD).

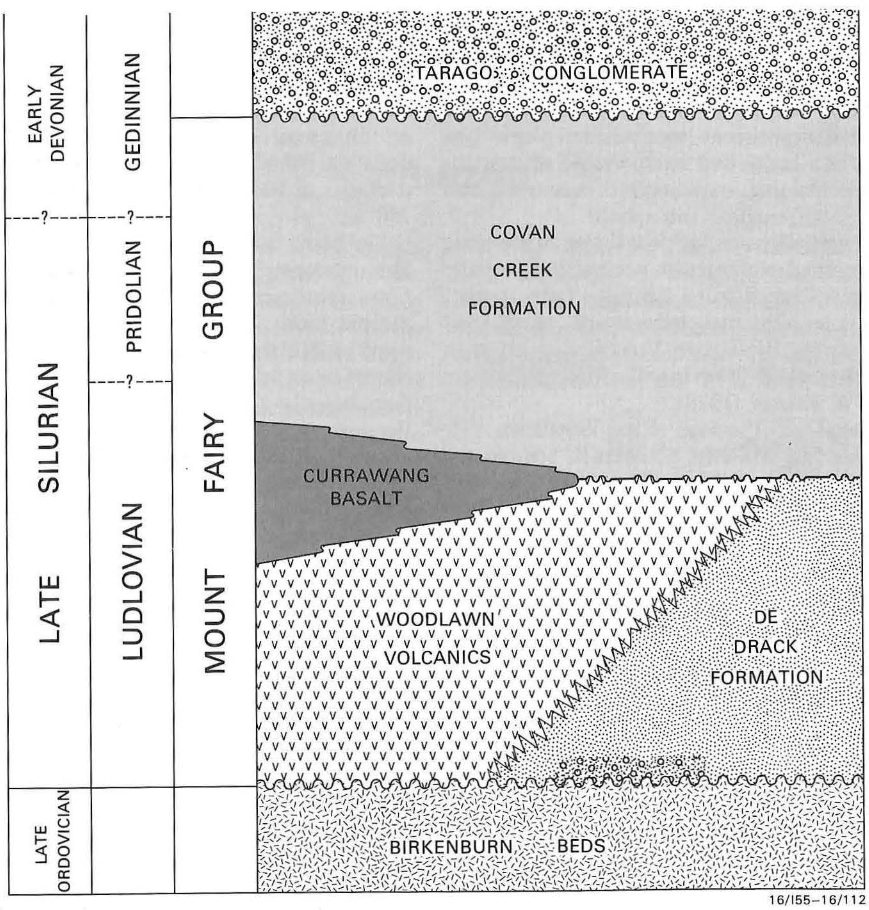


Fig. 16. Stratigraphic succession in the Woodlawn area (after Felton & Huleatt, 1977; Henry, 1978).

The De Drack Formation is not exposed but the Woodlawn Volcanics and Currawang Basalt crop out along the northeastern edge of Lake George. The youngest unit is the Covan Creek Formation, part of a Siluro–Devonian succession more fully developed in the Goulburn 1:250 000 Sheet area (Brunker & Offenberg, 1968; Offenberg, 1974). The Covan Creek Formation forms almost all of the outcrop area of the group on CANBERRA.

Woodlawn Volcanics (Suw)

On BRAIDWOOD, the Woodlawn Volcanics have been formally named and defined by Felton & Huleatt (1977). The volcanics thin westwards onto CANBERRA where they were originally mapped as 'granite and granite gneiss' (Garretty, 1936). In the Dinton–Kennys Point area, the Woodlawn Volcanics are about 100 m thick and consist of folded beds of rhyodacitic ignimbrite and minor ashstone. A detailed geological map of this area (Henry, 1978) shows that the felsic volcanics are intimately associated with the Currawang Basalt, although stratigraphic continuity is broken by dolerite intrusions and alluvium. Drilling has proved felsic volcanics beneath alluvium in Allianoyonyiga Creek (Jododex Australia Pty Ltd, 1971). Local exposures of the Woodlawn Volcanics occur as meridional rafts in the Ellenden Granite. In erosion gullies north of 'Currandooley' homestead (MR 275/050), westerly-dipping acid volcanics and tuffaceous sediments are cut by northwest-trending dolerite dykes. Similar rocks occur in a cutting on the Bungendore–Tarago road and creeks east of 'Lakelands' homestead (MR 263/012). The close association of felsic tuff with basalt containing pillows suggests that on CANBERRA the Woodlawn Volcanics may have been deposited as subaqueous flows.

Lithology. The felsic volcanics are hard, pale-grey siliceous rocks in which banding is locally developed near contacts with mafic volcanics. In thin-section, the broadly rhyodacitic composition of the volcanics is indicated by a primary mineralogy of euhedral crystals of albitic plagioclase and lesser amounts of quartz. Potash feldspar and mafic phenocrysts appear absent. A strongly foliated quartzo-feldspathic groundmass wraps around the phenocrysts. In other specimens large euhedral plagioclase phenocrysts are set in a hornfelsed microcrystalline quartzo-feldspathic matrix containing metamorphic muscovite and biotite, secondary calcite, epidote and sphene.

The ashstone is a grey siliceous rock consisting of a mosaic of quartz, plagioclase and biotite, with accessory muscovite and rare large euhedral crystals of hematite (after pyrite) rimmed with a quartz–chlorite intergrowth. Additional petrological detail on the Woodlawn Volcanics is given in Henry (1978). Geochemical data are listed in Malone & others (1975) and Gulson & Rankin (1978).

Boundary relationships. The base of the Woodlawn Volcanics is not exposed but drillholes to bedrock beneath the Allianoyonyiga Creek flats suggest the Woodlawn Volcanics lie unconformably on Late Ordovician rocks (Jododex Australia Pty Ltd, 1971). At 'Montrose' homestead (MR 278/206), the Woodlawn Volcanics appear to be overlain conformably by the Currawang Basalt. In a contact exposed near Kennys Point (MR 259/189), banded felsic volcanics containing large unoriented clasts of basalt rest on an irregular surface of basic volcanics. Such a contact indicates that a complex interbedded relationship probably exists between the Woodlawn Volcanics and Currawang Basalt.

Age. The identification of a poorly preserved specimen of *Monograptus bohemicus* ? in the underlying De Drack Formation (Strusz & Nicoll, 1973) suggests a lower age limit of Late Silurian (Ludlow) for the Woodlawn Volcanics. An upper limit is indicated by the intrusive relationship of the Early Devonian Ellenden Granite. A Late Silurian age is also indicated by a U/Pb whole-rock age of 413 ± 6 Ma from the Volcanics near Woodlawn mine (Gulson, 1977).

Regional relationships. The Woodlawn Volcanics may correlate broadly with the Kohinoor Volcanics of the Captains Flat Graben. Both formations are in part underlain by shallow-marine sequences (the De Drack Formation and Copper Creek Shale) and overlain by distinctive quartz turbidite sequences (Covan Creek and Carwoola Formations). Each formation also contains stratabound volcanogenic base-metal deposits (Woodlawn and Captains Flat) which have originated from volcanic exhalations introduced into a submarine felsic volcano–sedimentary environment. However, the Woodlawn Volcanics differ geochemically to some extent from the Kohinoor Volcanics in having higher silica and lower Ti, Fe, Mn, Ca and P (D. Wyborn, pers. comm., 1985).

Currawang Basalt (Suc)

Nomenclature. Garretty (1936) originally described the Currawang Basalt as hornblende schist. The rocks formed the northern part of an 'amphibolite series' which he mapped as far south as Bungendore. Best & others (1964) portray these rocks as intermediate and basic intrusions ('ib') on the 2nd Edition of the Canberra 1:250 000 Geological Sheet. In the Explanatory Notes that later accompanied the map, Strusz (1971) partly corrected the error by noting that the rocks consist of dolerite intrusions and basic metavolcanics. Brunker & Offenburg (1968) present the same rocks on the Goulburn 1:250 000 Geological Sheet as an unnamed unit (S–Da) consisting of spilite, amphibolite, quartzite and claystone. On BRAIDWOOD the unit was formally named and defined as the Currawang Basalt (Felton & Huleatt, 1977).

Description. On CANBERRA, the Currawang Basalt forms a discontinuous belt of basic volcanics and sediments cropping out on the western limb of the Currawang Anticline. The unit wedges out westwards across a complementary syncline and disappears under Quaternary colluvium and strandline deposits along the northern edge of Lake George.

On CANBERRA the Currawang Basalt consists mainly of a marine sequence of basalt flows with minor interbedded shale and quartz arenite, chert and felsic tuff. A reddish-brown terra rossa soil helps to outline the unit, particularly on a ridge north of 'Montrose' homestead where basalt is interbedded with shale. On BRAIDWOOD, Felton & Huleatt (1977) estimated a thickness of 1000 m and in the same area Henry (1978) gives 750 m.

The basalt is fine-grained, bluish-grey and forms pavement-like outcrops. There is a gradation from easily recognisable flows containing pillows with chert infillings to featureless sheared rocks. The best exposures are at Kennys Point and north of 'Montrose' homestead. The mafic minerals have been altered to an intergrowth of epidote and pale-green uralite and the plagioclase phenocrysts to epidote, sericite and calcite. Remains of an original extrusive texture are represented by microlitic laths of plagioclase and by amygdales of quartz and epidote rosettes. Additional petrological detail is given by Henry (1978).

Boundary relationships. The Currawang Basalt probably has a transitional relationship with the underlying Woodlawn Volcanics. The top is also conformable with quartz-turbidite sediments of the Covan Creek Formation. The upper contact is not well exposed on CANBERRA but appears to be gradational: basalt becomes progressively interbedded with pale-brown, fine-grained quartz arenite beds. Small bodies of Early Devonian gabbro and dolerite intrude the mafic sequence.

Age and correlation. There is no internal evidence of age for the Currawang Basalt. Fossils have not been found in the interbedded sediments and the basalt is too altered for radiometric dating. A Late Silurian age is indicated by stratigraphic superposition above the Woodlawn Volcanics. Definitive fossils are unknown from the overlying Covan Creek Formation. The Currawang Basalt is correlated lithologically with mafic volcanics in the Captains Flat Formation, and is probably the extrusive equivalent of tholeiitic dolerite sills near the Woodlawn mine on BRAIDWOOD.

Covan Creek Formation (Sua)

Nomenclature. Garretty (1936) originally mapped the Covan Creek Formation as unnamed quartzite, slate and felsite. He regarded the sediments as Late Devonian in age by lithological analogy with white quartzite at Memorial Hill, Goulburn, and by overlapping of the Silurian 'Mt Fairy Series'. In the Explanatory Notes accompanying the Canberra 1:250 000 Geological Sheet (Strusz, 1971, table 5) the formation is presented as unnamed Late Devonian sandstone and conglomerate. The unit is incorrectly shown as the Late Silurian De Drack Formation ('B_7L_3') on the Canberra 1:250 000 Metallogenic Sheet (Gilligan, 1974). On BRAIDWOOD, the unit was formally named and defined as the Covan Creek Formation by Felton & Huleatt (1977).

Description. On CANBERRA, the Covan Creek Formation covers an area of about 25 km^2 centred on hilly country north of Lake George. The formation extends eastwards onto BRAIDWOOD and northwards towards Collector and Gundary Plain on the Goulburn 1:250 000 Geological Sheet.

The Covan Creek Formation is an interbedded sequence of quartz sandstone, siltstone and shale. Most of the high ground is formed by pale-grey, medium-grained, massive quartz sandstone in meridional strike ridges rising to over 880 m. Siltstone and shale crop out mainly in gullies. Graded shale–sandstone units indicate the sequence is the right way up. Small-scale cross-bedding occurs in finer clastic units, while sole markings may be found on the bases of sandstone beds. Near 'Dewrang' homestead (MR 260/220) an open north-plunging synclinorium is evident from the curved trend of a sandstone ridge and a persistent bedding/cleavage lineation in minor parasitic folds. Isoclinal folding is suggested further west as bedding and cleavage become subparallel.

The sandstones have a framework of rounded grains of recrystallised quartz (~1 mm) and larger angular clasts of micaceous shale and siltstone. The groundmass (about 20%) is fine-grained angular quartz; wispy muscovite defines the folia tion. Accessories are rounded grains of tourmaline, zircon and opaques. Potash feldspar and felsic rock fragments are absent. Additional petrological detail is given by Henry (1978).

Felton & Huleatt (1977) estimated a maximum thickness of 1200 m on BRAIDWOOD. A minimum thickness of 1000 m is probable on CANBERRA; the base is poorly exposed, the top has been removed by erosion, and lithological units are repeated by folding. Lithology and sedimentary structures indicate the Covan Creek Formation was deposited by turbidity currents in a marine environment. The bimodality of the quartz population and the presence of angular sedimentary rock fragments suggest recycling of Late Ordovician sediments.

Boundary relationships. On CANBERRA, the Covan Creek Formation overlies the Currawang Basalt gradationally. An approximate boundary can be mapped at a topographic break near the base of a prominent quartz sandstone ridge east of Mount Baby (MR 270/230). Further south and along the northern edge of Lake George, the contact is obscured by superficial deposits. A gradational contact is suggested by a progressive increase in arenite intercalations near the top of the Currawang Basalt. The Covan Creek Formation overlaps progressively eastwards onto the Woodlawn Volcanics and De Drack Formation.

The top of the formation is not exposed on CANBERRA. Further east on BRAIDWOOD, the Covan Creek Formation is overlain unconformably by the Early Devonian Tarago Conglomerate (Felton & Huleatt, 1977).

Age and correlation. On stratigraphic grounds the Covan Creek Formation appears to be of Late Silurian (Pridoli) age. Definitive fossils have not been found. An upper age limit is constrained by the Tarago Conglomerate.

Since the Covan Creek Formation is underlain by a Late Silurian volcano-sedimentary sequence it is probably the same age as the Carwoola Formation and the Palerang beds (Rocky Pic Block).

Cainozoic

There is no record of Late Palaeozoic and Mesozoic sediments on CANBERRA. The regional landscape prior to the Cainozoic was a broad deeply weathered plain with residual hills dating back possibly to the Permian. The tectonic modification of the landscape is exemplified by the Murrumbidgee, Queanbeyan and Lake George Faults which form a series of meridional escarpments. The distribution of Cainozoic sediments reflects the history of long-term landscape lowering on the Southern Tablelands of New South Wales. The superimposed pattern and long established nature of the drainage on CANBERRA is emphasised by the unconformable distribution of Cainozoic sediments in the Murrumbidgee, Molonglo and Yass River systems. Further, extensive deposits of Neogene and Quaternary continental sediments are preserved in shallow tectonic basins in depressions close to the Great Divide, e.g. the Lake George basin and Carwoola Flats.

Tertiary volcanic rocks are unknown. The nearest outcrops of Tertiary basalt are on BRAIDWOOD (Felton & Huleatt, 1977; Ruxton & Taylor, 1982) and in the vicinity of Crookwell (Young, 1981), to the east and northeast. Small outcrops of high-level indurated ferruginous and silicified quartz gravels are the only early Tertiary sediments that crop out. The extent and nature of Tertiary sedimentation is largely obscured by Quaternary sediments. Of the latter, alluvium is most common and is currently forming along existing drainage lines. Colluvium has accumulated on flanking slopes. Lacustrine, strandline and aeolian deposits surround Lake George.

A long weathering history is indicated by the preservation of thick sequences of kaolinitic and ferruginous bedrock in downfaulted areas around Canberra, Bungendore and Hoskinstown. The deep weathering profile has been stripped from higher topographic areas on the Cullarin Block. Weathering profiles are incomplete in the Quaternary sequences.

Lake George basin

Sedimentation in the Lake George depositional basin has been controlled by a combination of tectonics and climate. Here, fluvial and lacustrine sediments have accumulated in a faulted depression. A detailed map of the Cainozoic geology is given by Abell (1985a) and the geological history is summarised in Figure 17.

Most recently, at the end of a drought, Lake George dried out completely from July 1982 until May 1983. Drilling on the dry lake bed penetrated up to 100 m of fluvio-lacustrine sediments overlying Palaeozoic bedrock; details of the drillhole logs, clay mineralogy and history of the Lake George basin are given in Abell (1985a and b).

Subsurface stratigraphy

The subsurface Cainozoic sediments at Lake George have been divided into three units. Recognition of their lateral extent is obscured by abrupt facies changes resulting from expansions

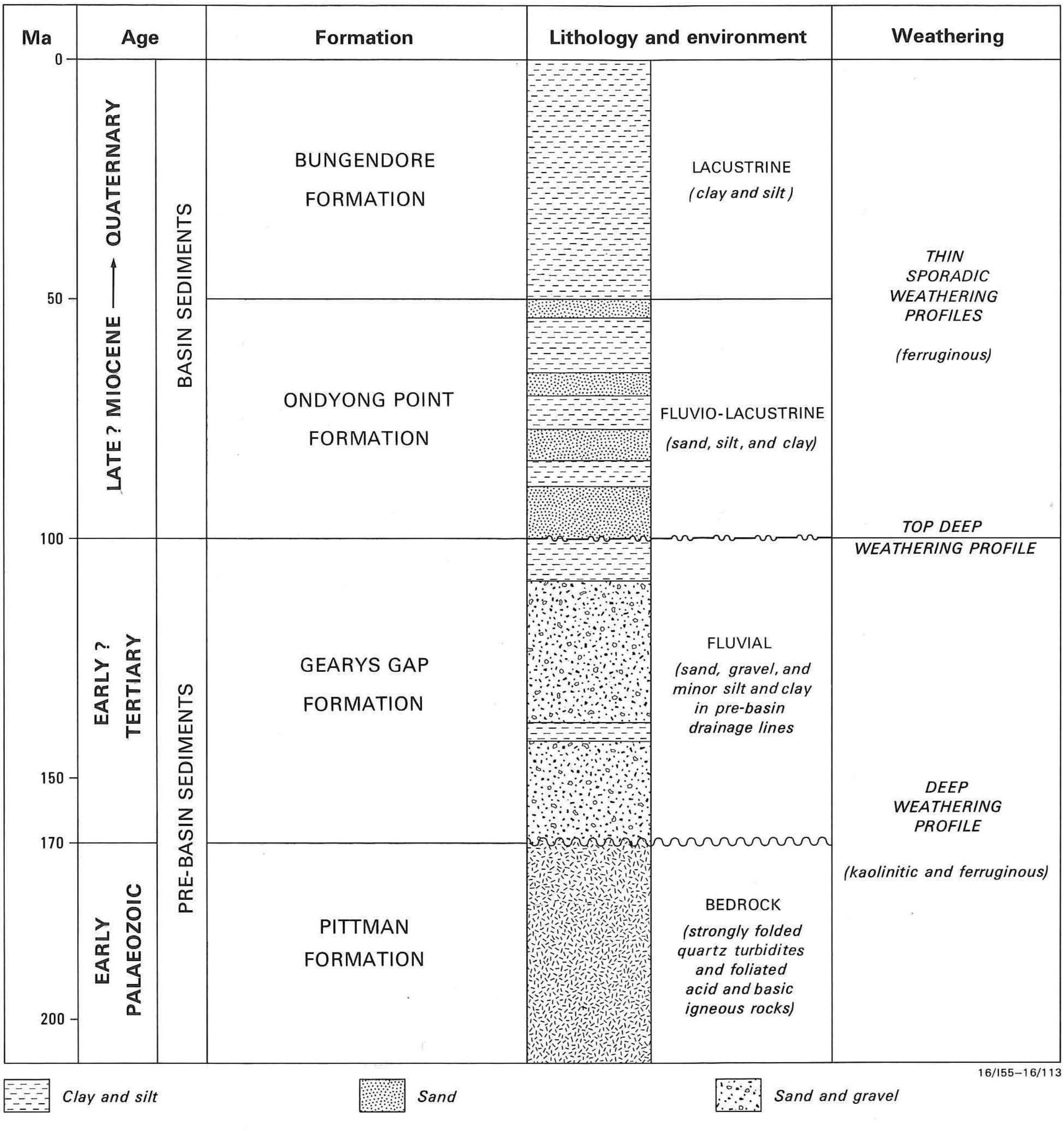


Fig. 17. Summarised geological and environmental history of the Lake George basin and underlying strata.

and contractions of the lake. The descriptions that follow are largely interpreted from the lithological and geophysical drill logs.

The Cainozoic stratigraphy, based on the deepest drillhole (C354), is summarised in Figure 18. The relationship of the units is shown in a diagram on the geological map.

The Gearys Gap Formation (early Tertiary?) is older than the Lake George basin. It consists of deeply weathered fluvial sand and gravel with minor silt and clay burying a terrain of Palaeozoic bedrock and is the remains of a prior drainage system which flowed northwest. The older of the two units forming the basin sequence is the Ondyong Point Formation (probably Late Miocene) which consists of fluvio-lacustrine sand, silt and clay deposited on the Gearys Gap Formation. The overlying Bungendore Formation (Late Miocene(?) to Recent) comprises lacustrine silt and clay. The dates are based on preliminary palynological determinations by Truswell (1984).

Gearys Gap Formation (new name) (Tg)

Derivation. Named after Gearys Gap (MR 165/133), a low saddle on the Lake George escarpment about halfway along the western watershed of the basin.

Distribution. The subsurface distribution relates to the arrangement of palaeodrainage lines beneath Lake George, as inferred from structure contours of the bedrock surface (Abell, 1985a, fig. 12). The unit is also identified with patches of ferruginous quartz gravel on the escarpment near Gearys Gap

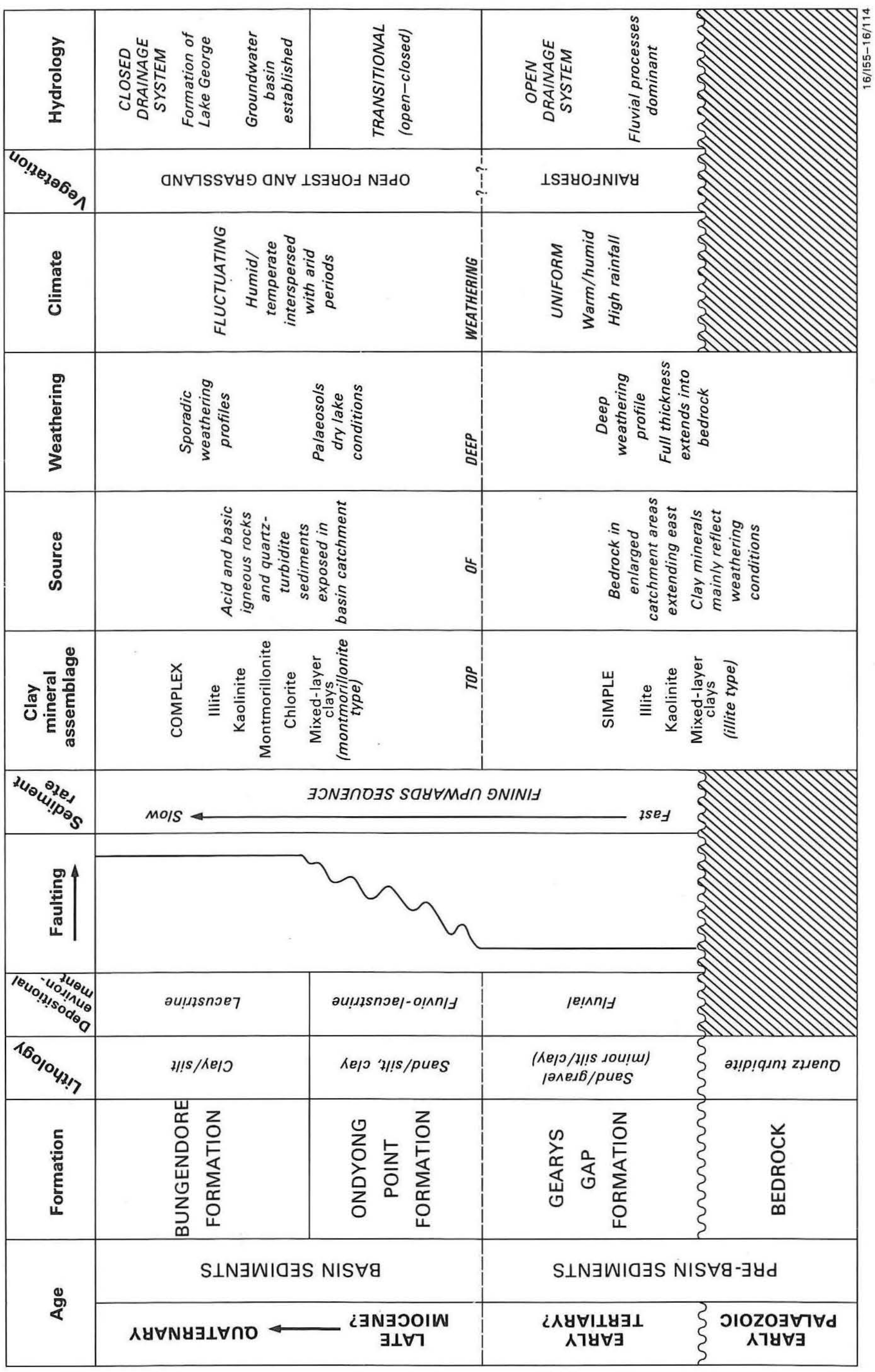


Fig. 18. Lithostratigraphic units in and beneath the Lake George basin.

and a silicified gravel (silcrete) outcropping on the western shore of Lake George.

Type section. A fully cored type section is unavailable because drillcore recovery in this formation is generally poor. A representative section is designated from drillhole C354 over the intervals 116.5–132.0 m, 135.5–149.5 m, and 160.0–164.5 m. Over these intervals deeply weathered sand and gravel with minor clay and silt have been cored at recovery levels mostly in excess of 90%.

Description. The formation consists of deeply weathered, horizontally bedded sand and gravel with minor silt and clay interbeds. Lithological contrasts within the unit are apparent on downhole gamma and neutron logs (Abell, 1985a). A few beds are cemented but generally the formation lacks hard-pan layers. Coarse sand and gravel beds up to 15 m thick consist of quartz and subordinate amounts of lithic clasts up to 4 cm. Normal and reverse-graded units occur throughout. A colluvial facies is locally developed in C354 (155–163 m) where ferruginous gravelly clay contains subangular clasts of kaolinised shale, siltstone and sandstone. At 110–153 m greyish-white kaolinitic sandy clay, sandy silt and sand is similar to drill log descriptions of fluvial sediments from palaeodrainage lines in the Montrose–Willeroo plain (Australian Groundwater Consultants, 1976; 1977). The clay minerals in the Gearys Gap Formation reflect deep weathering. The unit is characterised by illite and illite-mixed-layer clays; the high levels of residual kaolinite reflect the degradation of feldspar in the original sediments (Abell, 1985b).

Boundary relationships. The Gearys Gap Formation was deposited unconformably on an irregular surface of Ordovician quartz-turbidite sediments and Late Silurian volcano-sedimentary strata.

The unit appears to pass upwards into finer sand and clay of the Ondyong Point Formation. In cored holes, the top of the Gearys Gap Formation is arbitrarily taken at the top of the deep weathering profile, which suggests a disconformable boundary with the Ondyong Point Formation (Figs. 17 and 18).

Along the western margin of the basin, the formation is displaced by the Lake George Fault. Its full extent to the northern, southern and eastern extremities of the basin is unknown.

Thickness. Thickness variations are common. Locally the formation is thicker where drillholes have penetrated topographic lows (palaeodrainage lines); a maximum known thickness of 58 m has been recorded in hole C354. The formation thins abruptly towards topographic highs.

Environment of deposition. Before Lake George formed, sand and gravel of the Gearys Gap Formation was deposited by upper tributaries of the Yass River. The subrounded and poorly sorted quartz clasts and the orientation of low-angle current bedding around Gearys Gap suggest a flood plain with braided and point-bar sands and gravels.

Age. Fossils have not been found in outcrop or drill core. An Early Miocene or older age is likely because of the probable Late Miocene age of the overlying Ondyong Point Formation and the mid to late Tertiary age placed on the deep weathering profile in the Shoalhaven area by Ruxton & Taylor (1982).

Correlation. Beyond the limits of the Lake George Basin, the Gearys Gap Formation correlates with unnamed indurated quartz gravels east of the Molonglo River, south of Hoskinstown, and in the Yass River basin. In the Goulburn–Crookwell area, the formation may be coeval with quartzose sediments in the Hollymount Formation (Bishop, 1984).

Ondyong Point Formation (new name)

Derivation. Ondyong Point, a small spur at the northern end of Lake George (MR 206/205).

Distribution. The formation is known only from drillholes in the bed of Lake George. It may extend laterally beneath alluvial plains marginal to the Lake.

Type section. A fully cored type section is unavailable, as recovery from the unit was poor. Representative sections are designated from the best recovered intervals of core, as given in Table 14.

Table 14. Representative sections of the Ondyong Point Formation

Hole	*Cored intervals (m)*
C251	36.0–48.2
C352	42.5–48.0*
C353	58.0–71.0
C358	40.0–59.0*

* Includes the upper boundary with the Bungendore Formation.

Over these intervals patchily weathered sand, silt and clay have been cored at recovery levels mostly in excess of 90%.

Description. The formation consists of horizontally bedded sand, silt and clay. Sandy units near the base of the formation may be coarse-grained and normally graded; some fine-grained well-rounded sand may be aeolian. Towards the top, the unit becomes dominated by mottled and laminated clay, gravelly clay, and silt. Reddish-brown ferruginous weathering profiles occur intermittently throughout. Gamma and neutron logs (Abell, 1985a) record lithological contrasts. The relative distribution of clay and non-clay minerals for the Ondyong Point Formation is given in Abell (1985b, table 9).

Boundary relations. The base of the formation is arbitrarily placed at the top of the deep weathering profile in the Gearys Gap Formation, although the existence and/or position of this boundary is obscured by poor core recovery and weathering.

The Ondyong Point Formation is conformably overlain by the Bungendore Formation; the upper boundary is taken at the highest and most persistent sand bed in the formation, which is readily picked out by gamma and neutron logs.

Along the western margin of the basin the formation is truncated by the Lake George Fault. It presumably grades laterally into alluvial sediments at the northern, eastern and southern margins of the Lake George basin.

Thickness. Drillhole evidence suggests a fairly uniform thickness of 20–40 m beneath the lake. The maximum known thickness of 53 m is in C354 and the minimum 10 m in C360.

Environment of deposition. A transitional fluvio-lacustrine sequence in which clay units become thicker and gradually dominate over sand. The upward-fining pattern of sedimentation and development of lacustrine conditions towards the top reflect faulting which temporarily raised the spillway threshold for drainage at Gearys Gap. Intermittent thin weathering profiles in the formation suggest a change to a fluctuating wet and dry climate.

Age. A pollen assemblage in carbonaceous clays above the deep weathering profile has given a preliminary age of Late Miocene (Truswell, 1984).

Correlation. Based on pollens, the Ondyong Point Formation may be at least partly the same age as the *Triporopollenites bellus* zone of the Gippsland Basin and perhaps rainforest-dominated intervals in the Lachlan River valley (Truswell, 1984).

Bungendore Formation (new name)

Derivation. Bungendore, south of Lake George.

Distribution. The unit immediately underlies the present bed of Lake George.

Type section. It is proposed here that core from BMR stratigraphic hole C354 be designated as the type section. From the surface, 54 m of clay and silt was recovered (mostly in excess of 90%) from the greatest thickness of the formation so far drilled in the Lake George basin. The base is defined by thin beds of dark-greenish-grey, fine to medium-grained sand and silt at the top of the Ondyong Point Formation.

Description. The formation consists of three lithotypes: (1) mottled clay, (2) gravelly clay with quartz and lithic clasts, and (3) clay with coloured, carbonaceous or silty laminations. Colour varies in shades of grey, green, olive and black. Reddish-brown ferruginous weathering profiles occur intermittently throughout. High gamma counts in C358, C361 and C362 denote above-average levels of radioactivity in clay at depths of 6–8 m. The clay and non-clay mineralogy for the Bungendore Formation is described in Abell (1985b).

Boundary relations. The base of the Bungendore Formation is not exposed but is taken to be at the top of the highest and most persistent sand bed of the Ondyong Point Formation. The top of the formation is the lake bed, which is exposed when Lake George dries out.

Drillhole data marginal to the lake (C1, C294 and C295) suggest the upper part of the Bungendore Formation grades laterally into coarse alluvium in embayments at the southern and eastern margin of the basin. Westwards the unit grades laterally into colluvium and alluvial fans at the base of the Lake George escarpment.

Thickness. The maximum known thickness is 54 m (BMR stratigraphic hole C354). The formation thins towards the margins of Lake George.

Environment of deposition. Lacustrine. Four subfacies are recognised:

- — horizontally laminated clays deposited from suspension in a low-energy environment below wave base;
- — mottled hydromorphic clays (gleys) in shades of green, grey and blue which are typical of waterlogged, reducing conditions;
- — gravelly clay originating as colluvium on the escarpment and redeposited on the lake bed by stream runoff; and
- — ferruginous mottled and banded clays related to oxidation and pedogenesis during periods of prolonged dry lake bed.

The ostracod ecology (De Dekker, 1982) and the existence of the gastropod *Coxiella striata* (W.F. Ponder, pers, comm., 1983) in the upper 3 m of the Bungendore Formation indicate a lacustrine environment of changing size and salinity that broadly confirms the history of late Quaternary lake level fluctuations proposed by Coventry (1976). The pollen assemblages retrieved from the upper 18 m of sediment in ANU drillhole LG4 give a vegetational history that indicates at least six glacial/interglacial cycles in the Quaternary up to the Brunhes–Matuyama reversal at 730 000 B.P. (Singh & Geissler, 1985). Below 18 m, sedimentological and geochemical data also give evidence of past lake level changes and the long-term palaeoclimatic record (Singh & others, 1981b).

Age. A study of palaeomagnetic reversals through the upper 36 m of lacustrine and slopewash sediments in LG4 has given a Pliocene age of 3.5 Ma (Singh & others, 1981b, fig. 8) for the lowermost part of the formation. A similar, although perhaps greater, age range can be extrapolated to the thicker lacustrine sequence in C354.

Correlation. The upper part of the Bungendore Formation presumably correlates with Late Quaternary colluvial, alluvial, strandline and lagoonal sediments in marginal areas of the Lake George drainage basin and also with fluvio-lacustrine sediments on the Carwoola Flats and sediments in perched drainage basins associated with the Murrumbidgee River in the Tuggeranong and Lanyon areas south of Canberra. In the Lake Bathurst drainage basin on BRAIDWOOD cored sediments have yielded a palaeomagnetic date at the Brunhes–Matuyama reversal and possibly an older Plio–Pleistocene reversal (D. Gillieson, pers. comm., 1984).

Quaternary morphostratigraphy

Late Quaternary sediments are presently distributed over about 40% of the Lake George drainage basin. Most of the exposure is in broad alluvial valleys and around Lake George. The sediments and associated landforms are grouped into five morphostratigraphic units: (a) colluvium, (b) strandline deposits, (c) lagoonal deposits, (d) aeolian deposits, and (e) alluvium. These units are defined on landform and composition following a standard proposed by Grimes (1983). Differentiation of alluvial fans from colluvium is not attempted because of the limitations of map scale. A schematic section (Fig. 19) across the southeastern margin of Lake George shows relationships between the various units. The modern sedimentary environment in the Lake George basin is discussed by Abell (1985a).

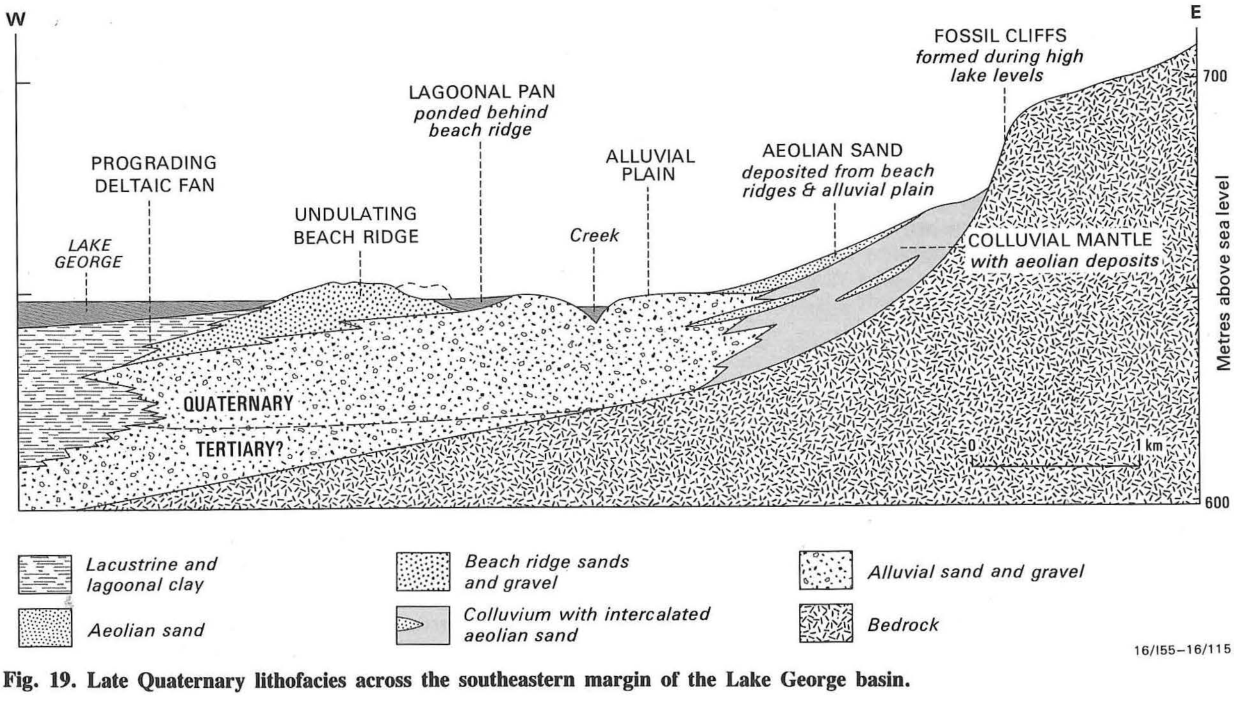


Fig. 19. Late Quaternary lithofacies across the southeastern margin of the Lake George basin.

Colluvium (Qc)

Colluvium is most widespread along the east-facing slopes of the Lake George escarpment and to a lesser extent on hillslopes at the northern end of Lake George. The colluvium is commonly polygenetic, reflecting several cycles of erosion and soil differentiation. It comprises scree of mainly sandstone, acid porphyry, slate and vein quartz up to cobble size; stratification is imperfect. Colluvial mantles are dissected by small creeks which deposit alluvial fans at the foot of the slopes.

The age range of the colluvium preserved in the Lake George basin has not yet been fully determined. In Fernhill Gully just north of the Sheet area (MR 214/282) charcoal from a quartz gravel reworked by wave action gives a radiocarbon age of 26 870 ± 900 years BP (Coventry & Walker, 1977). This age compares favourably with a similar date obtained for colluvium at Black Mountain, ACT (Costin & Polach, 1973). The colluvium probably formed through slope instability during cycles of arid, cold climate in the Pleistocene.

Strandline deposits (Qbs)

Beach ridges, arranged concentrically around the lake margin, provide some of the more obvious evidence for Quaternary sedimentation in the basin.

Some of the lower sand ridges adjacent to the lake are currently being mined or are subject to mining plans. The pits provide access and temporary sections through the uppermost portions of these deposits. An account of the shoreline features is given by Jennings & others (1964) and Coventry (1976). Detailed descriptions of the embankment geomorphology, sediments and soils at the northern end of Lake George are given by Coventry (1973).

South of the lake, Turalla embankment is a curving ridge subparallel to the axis of the basin. The ridge is asymmetrical in cross-section, with a gentle slope facing the lake and a steeper outer slope. Strandline deposits with limited topographic expression occur along the eastern margin of the lake. Minor vegetational changes on the undulating surfaces of these deposits give subparallel air-photo lineations which assist in the mapping. Lowered ridge height results from exposure to persistent westerly winds which have promoted beach drift and flattened the ridges by removal of fine sand and clay to other parts of the basin. From the elevation and distribution of the deposits, Coventry (1976) was able to map the former extent of Lake George during the Late Quaternary when it stood at its highest level of 37 m a.l.b. (above lake bed).

The beach ridges consist of poorly to well sorted gravel interbedded with medium to coarse sand and occasional loess. A section of bedded gravel, sand and loess is exposed in an old gravel pit on the crest of Turalla bank (MR 198/983). The clastic material consists of locally derived quartzite, black slate, acid porphyry, basic rock and vein quartz. Cross-bedding and the presence of well-rounded, flat pebbles (cleaved lithic clasts) up to 30 mm is evidence of further abrasion and deposition in a shoreline environment. Strandlines have formed by erosion and reworking of beach deposits during lengthy stillstands. Upon lake level decline these strandlines are preserved as a sequence of beach terraces, e.g. east of Ondyong Point (MR 208/207). Terracing and cliffing can be seen in an alluvial fan complex at Silver Wattle Point (MR 178/080). The remains of an old, elevated shoreline is represented by a series of small 'bays' and 'headlands' along the eastern shore north and south of Taylors Creek. Resistant outcrops of Ordovician metasediments have been cliffed up to the 700 m contour. Persistent northwesterly winds have caused a southerly beach drift along this stretch of the lakeshore; sediment has accumulated on the northern sides of headlands and has been eroded away on their southern sides (Abell, 1985a, fig. 4).

Radiocarbon dates for shoreline deposits at the northern end of Lake George range from about 27 000 to 3000 years B.P. (Coventry, 1976). The shape and height of Turalla embankment suggest a correlation with the Winderadeen embankment (on GUNNING; 37 m a.l.b.); this coincides with the height at which Lake George would have overflowed through Gearys Gap into the Yass River drainage system (Coventry, 1976). Beach ridges along the eastern shore have not been dated, but are doubtless younger because they are lower and closer to the lake.

Lagoonal deposits (Ql)

Lacustrine clays are thickest and most widespread at Lake George. Thin layers of grey-black clay are also preserved in small lagoonal depressions at higher levels and at varying distances from Lake George. Lagoonal clay pans occupy depressions behind the steeper outer flanks of strandline ridges. They fill with water after heavy rain or when the water level in Lake George is high. A clay-filled depression behind a low gravel bar south of 'Wave Hill' homestead (MR 196/927) provides apparent evidence for the most southerly extent of Lake George during the Late Quaternary.

Aeolian deposits (Qs)

Windblown sand deposits near Lake George were first noted by Garretty (1936). The sands occur as a thin patchy cover in alluvial embayments and on bedrock slopes in the eastern portion of the basin; their distribution follows the mapping of Coventry (1976) and Coventry & Walker (1977). The deposits consist of fine to medium-grained well-sorted quartz sand derived from adjacent strandline and fluvial deposits. Wind-induced currents have also shaped the eastern outline of Lake George. Coventry (1976) compared the modern wind patterns at Lake George with current-bedding directions in beach ridges and deduced that the prevailing westerly wind direction has been consistent over the last 4000 years.

Four phases of aeolian sand have been dated in Fernhill Gully (on GUNNING) spanning the period 23 000–2000 years B.P. (Coventry & Walker, 1977). The presence of aeolian sand suggests the existence of arid conditions and poorly vegetated country during late-glacial and post-glacial time.

Alluvium (Qa)

Alluvial fans up to 10 m thick occur along the Lake George escarpment and consist of subangular, poorly sorted sand and gravel (becoming finer towards the toe of each fan), interbedded with well-sorted beach deposits of pebbly gravel. Beach terraces are etched into the fans up to 36 m a.l.b. Enough time has elapsed between lake level stands for weathering profiles to have developed on these surfaces. Alluvial fans build out gradually from colluvium. Locally the coarse clastic material is imbricated in the current direction. A model for contemporary fan growth along the Lake George escarpment is given by Wasson (1974). Along the base of the Lake George Range west of Bungendore, older fans have coalesced to form a bajada. Radiocarbon dates from bajada deposits at the northern end of the basin range from 26 840 (+ 860, − 2100) years B.P. to 2380 ± 360 years B.P. (Coventry & Walker, 1977). Smaller alluvial fans that occur along part of the escarpment adjacent to the lake barely coalesce. Deposits in two of these fans south of Gearys Gap have been dated at 2350 ± 75 years B.P. and 1630 ± 110 years B.P. (Coventry & Walker, 1977). These younger fans were deposited during low lake levels.

Floodplain deposits occur in alluvial embayments surrounding Lake George. Around Bungendore and on Allianoyonyiga flats, drillhole logs reveal a complex sequence of sediments probably ranging back into the Tertiary. A lower succession contains weathered, pale-grey, coarse sand and gravel interbedded with thin clay layers which are confined to erosion channels in bedrock. A more extensive upper succession comprises a complex of brown, yellow and white clay and silt with beds of poorly sorted subangular sand and gravel which show considerable vertical and lateral variation. Although the present creeks appear to be underfit they have incised their courses into their floodplains. The more active streams are currently developing small deposits of point-bar sands in meander loops, e.g. Butmaroo Creek. A few old meander scars partly define the narrow width of their channel floodplains. Southwestward beach drift along the southeastern shore of Lake George has deflected the northwest-flowing course of Butmaroo Creek. The creek has extended its course and now forms a small delta into Lake George about 1 km southwest of its original entry point. Generally, the larger creeks have been strong enough to cut across old beach ridges and build out small deltas. In any one place, this is an ephemeral process, as the lakeshore migrates back and forth in response to changing water levels.

Other Tertiary sediments (Tg_1, Tg_2)

Patches of quartz-pebble conglomerate are distributed in close association with major drainage lines. In the Yass River basin, Taylor (1907) described elevated river gravels on the crest of the Lake George escarpment. A detailed description of these and similar deposits along Shingle House Creek valley is provided by Coventry (1967). Above tributaries of the Yass River near Gundaroo, deposits of 'pebble to cobble conglomerate with subsidiary sandstone and minor shale' were named the 'Barnsdale Conglomerate' (Smith, 1964). These deposits and others east of 'Bywong' homestead (MR 055/121) are discussed briefly by Henderson (1978b). Coarse river gravels above Yandyguinula Creek and the Molonglo River floodplain near 'Foxlow' homestead were mapped by Oldershaw (1965). Quartzose conglomerate and coarse sandstone bordering Dairy Flats on the Molonglo River was named the 'Fyshwick Gravel' (Öpik, 1958) and at Queanbeyan the 'Wall Conglomerate' (Phillips, 1956). The distribution of indurated quartz gravel around Canberra is shown on the Second Edition of the Canberra, Queanbeyan & Environs 1:50 000 geological map (Henderson, 1980); these exposures are now obscured by urban development except for remnants of gravel float near Lake Burley Griffin and north of Pine Island.

Ferruginous quartz gravel (Tg_1) up to 5 m thick locally caps low hills and terraces at elevations up to 60 m above, and often 2 km from, the entrenched water courses of major drainage lines. Poorly sorted, subangular and rounded pebbles and boulders (up to 70 mm) of vein quartz (up to 80%) typically occur in a sandy matrix hardened by a brownish-yellow cement of hydrated iron oxide (goethite–limonite). The small proportion of subangular quartzite, chert and acid volcanic rock retained locally in the gravel reflects resistant bedrock lithologies (Pl. 8). A poorly developed stratification is indicated by lenses of coarse sandstone. The gravel is unconformable on irregular surfaces of Silurian and Ordovician bedrock; a rare contact is visible in a pit west of the Federal Highway at MR 133/110, where a strongly leached deep-weathering profile is evident in the gravel and underlying bedrock.

Patches of siliceous quartz conglomerate ('grey billy') or silcrete (Tg_2) occur in lower-lying areas at the base of the Lake George escarpment (MR 170/112), at the eastern margin of Carwoola Flats (MR 221/800 and 216/723) and in the headwaters of Ginninderra Creek, too small to map (MR 958/037). Brief references to the silcrete deposit at Lake George (Pl. 9) are given in Taylor (1907), Garretty (1937) and Browne (1972). The silcrete forms low-lying, sometimes elongate, outcrops of hard, pale-grey, massive quartz conglomerate with rare lithic clasts, resting directly on bedrock.

Geopetal cappings up to 15 mm thick on the upper side of some quartz clasts characterise the silcrete at Lake George (Abell, 1985a).

In thin-section the silcrete is seen to consist of poorly sorted clasts of vein quartz in a matrix of microcrystalline quartz with disseminated ilmenite and accessory zircon. The clasts vary in size from large pebbles to silt; the larger clasts are usually well-rounded, the sand and silt-sized grains generally angular. Many of the larger clasts are fractured and have etched and embayed margins. Accumulations of ilmenite occur primarily as geopetal caps on the larger clasts or disseminated in the matrix. The 'graded' nature of the caps is evident from the decrease in the concentration of ilmenite from the clast surface into the matrix. Optical emission spectrometry shows that the geopetal caps are rich in titanium (possibly brookite) and iron (Table 15). A whitish-brown colour under reflected light confirms the presence of leucoxene. The major element chemistry of the silcrete (Table 16) compares well with analyses of silcrete given in Langford-Smith (1978) and Taylor & Ruxton (1987). Significant features are the high silica values (> 98%) and low titanium values (< 1.0%). Abundances of other major elements are typically < 0.5%. Trace-element concentrations are also low, except for Zr, Ba and Sr.

The quartz gravels on CANBERRA are similar to those described elsewhere on the tablelands of New South Wales (Packham, 1969; Taylor & Ruxton, 1987). The high proportion of quartz, low-angled current-bedding and channel deposition in the sandy beds are evidence of more extensively developed fluvial deposits along the ancestral courses of the Yass, Molonglo and Murrumbidgee Rivers. This interpretation is supported by a progressive decrease westwards in the altitude of the bases of the quartz gravels mapped along the valley of Brooks Creek (Coventry, 1967) and for similar gravels along Yandyguinula Creek and the Molonglo River near 'Foxlow' homestead. The gravels near Fyshwick were considered as fluvio-glacial deposits of Permian age (Öpik, 1958). This interpretation was later refuted by Jennings (1972) and Ollier & Brown (1975). Ferruginisation and silicification of the quartz gravels is presumed to have developed during long periods of humid chemical weathering, involving the breakdown of silicate minerals and the release of silica to leave ferruginous and kaolin-rich residues (ferruginous gravels). The silicification was doubtless accomplished through the precipitation of silica from impeded surface drainage or shallow groundwater in low-lying areas.

The age of the gravels is uncertain; definitive fossils have not been found. Attempts to date the gravels by palaeomagnetic methods have been unsuccessful. M. Idnurm (pers. comm., 1983) reports the goethite-limonite cement is magnetically unstable iron probably resulting from successive weathering

Table 15. Optical emission spectroscopy data for a geopetal cap from silcrete at Lake George. The values are relative abundances of elements at 1:1 (1 unit weight of sample to 1 unit of weight of pure graphite) and 1:100 dilution (1 unit weight of sample to 100 unit weights of graphite). The largest concentration of an element is shown as 1 and the lowest as 7.

	Light mineral fraction (S.G. <2.96)		*Heavy mineral fraction (S.G. >2.96)*			
			Nonmagnetic		*Magnetic*	
	1:1	1:100	1:1	1:100	1:1	1:100
Ti	1	3	1	2	2	4
Si	1	2	1	2	2	3
Al	2	6	2	6	4	7
Fe	3	6	2	6	1	1
Mg	3	5	2	5	2	4
Mn	6	tr	4	6	2	4
Cu	4	tr	5	—	2	5
Ca	3	—	3	—	6	—
Zr	4	tr	3	5	5	—

cycles. However, they are clearly post-early Palaeozoic but appear stratigraphically older than the late Tertiary fluvio-lacustrine sediments in the Lake George basin. They are also older than the mid to late Tertiary age placed on deep weathering by Schmidt & others (1982) and Ruxton & Taylor (1982). Thus the best available age is Miocene or older. The gravels are possible correlatives of sub-basalt sand and gravel in the Crookwell area described by Bishop & Bamber (1985).

Other Quaternary sediments

Grant (1976) has mapped the distribution of unconsolidated Quaternary sediments around Canberra, showing that the thickest sequences underlie the Canberra Plain. In the elevated terrain of the Cullarin Block, the sediments are thinner and confined mainly to drainage lines. Colluvium and alluvium are closely associated and aeolian sand occurs locally at the margins of the wider floodplains. Cyclic soil patterns superimposed on these sediments reflect climatic change in the Quaternary (Van Dijk, 1959). However, the development of a broadly based surficial stratigraphy will depend on a clearer understanding of lithofacies and soil relationships and on better dating techniques.

Table 16. Cainozoic silcrete: major and trace element analyses

Sample no. / *Grid ref.*	*76460325B* / *170112*	*76460325C* / *170112*	*76460356* / *948037*	*76460357* / *218728*	*76460358* / *221803*
%					
SiO_2	98.50	98.70	97.20	99.00	99.00
TiO_2	0.17	0.20	1.47	0.19	0.38
Al_2O_3	0.17	0.14	0.09	0.07	0.05
Fe_2O_3	0.22	0.10	0.01	<0.01	<0.01
FeO	0.04	0.04	0.20	0.09	0.18
MnO	<0.01	<0.01	<0.01	<0.01	0.02
MgO	0.02	0.02	0.03	0.02	0.03
CaO	0.13	0.10	0.03	0.05	0.04
Na_2O	0.02	0.02	0.04	0.01	0.02
K_2O	0.02	0.02	0.07	0.02	0.04
P_2O_5	0.03	0.04	<0.01	0.05	0.06
H_2O+	0.14	<0.01	0.34	0.28	0.15
H_2O-	0.12	0.13	0.05	0.02	0.03
Total	99.59	99.55	99.05	99.82	100.01
ppm					
Ba	340	190	<10	<10	125
Rb	3	<2	<4	4	6
Sr	44	28	4	<4	15
Pb	<2	<2	6	6	
Th	<4	<4	<4	<4	<4
U	4	<4	6	<4	<4
Zr	270	250	1220	245	375
Nb	4	4	40	<4	12
Y	4	<4	24	<4	4
La	<20	<20	20	25	25
Ce	20	30	20	<20	<20
Nd	—	—	—	—	—
Sc	—	—	—	—	—
V	<20	<20	<20	—	—
Cr	15	15	50	<10	10
Mn	—	—	—	65	180
Co	<5	<5	<5	<5	<5
Ni	10	5	10	12	20
Cn	15	15	6	10	55
Zn	<5	<5	6	2	2
Sn	—	—	—	<4	<4
Mo	—	—	—	<4	<4
Ga	—	—	—	<4	<4
As	—	—	—	2	2

Colluvium (Qc)

Colluvium is widely distributed but only the major areas are mapped. The colluvium rests directly on bedrock and consists of crudely stratified and poorly sorted rock fragments. Clast size commonly reaches up to pebble or cobble. Induration of the sediments is effected by clay and silt fines distributed through the open framework texture of the colluvium by groundwater circulation. The interclast fines are subsequently hardened by subaerial weathering to form cement. The thickness of the colluvium is variable; more than 40 m is reported in drillholes on the eastern slopes of Black Mountain by Henderson (1986).

Indurated colluvial slope deposits on the eastern side of Black Mountain ('fanglomerates' of Öpik, 1958) have been described in detail by Costin & Polach (1973). A 10 m section is exposed in a gully on the Nature Trail in the National Botanic Gardens. The outcrops consist of angular clasts of Black Mountain Sandstone in a cemented matrix of ferruginous clay and silt. Hollows (cave-like features in the creek bank) have formed where flood runoff has undercut and scoured out loose material from the deposit.

Local patches of indurated polymictic colluvium a few metres thick are described by Smith (1964) from near Nanima in the valley of Murrumbateman Creek. They are derived locally from Ordovician bedrock and consist of poorly sorted angular clasts of arenite, banded siliceous black slate, vein quartz, chert and phyllite up to 10 cm in a cemented matrix of reddish-brown goethite–limonite (Pl. 10). The best exposure is at MR 904/244 where lateritised colluvium forms an unconformable capping on strongly leached kaolinised phyllite; the colluvium is overlain by dark-grey alluvial soil (Pl. 11).

In the Canberra district several occurrences of colluvium have been dated by radiocarbon methods using samples of organic material from within 3 m of the surface. Costin & Polach (1973) give an average age of 27 800 (+2500, −1900) years B.P. for carbonised wood in soil horizons in colluvium on Black Mountain. Similarly, Walker & Gillespie (1978) give an age of 31 770 ± 1160 years B.P. for the lowest of two buried palaeosols in colluvium near the Campbell Park Defence offices on the eastern flank of Mount Ainslie. These ages are similar to that of colluvial fan deposits in the Lake George Basin (Coventry & Walker, 1977), and possibly a gravel deposit in a limestone cave at Wombeyan (Gillieson & others, 1985). The dates so far recorded have levelled out at a Late Quaternary age of about 30 000 years B.P., which is close to the limits of the carbon-14 dating method (~35 000 years B.P.). In perched alluvial basins at Lanyon, one of the younger fanglomerate units (the 'Big Monk pedoderm') is correlated lithologically with colluvium at Black Mountain (Kellett, 1981). However, efforts to date three older fanglomerate units in the Lanyon sequence have been unsuccessful.

The colluvium is believed to have originated as scree in a cold, arid climate associated with the last glaciation in south-eastern Australia. It is thought to have arisen as a result of solifluction originating from widespread hillslope instability during seasonal freezing and thawing on a landscape bare of vegetation (Costin & Polach, 1973; Coventry & Walker, 1977; Gillieson & others, 1985). At present the colluvium has stabilised under a much thicker vegetation cover; creek dissection reflects increased runoff under more humid temperate climatic conditions.

Aeolian sand (Qs)

Deposits of fine-grained aeolian sand are restricted to the more extensive areas of alluvial flats on CANBERRA. On the southern flank of Dairy Flat (approx. MR 960/900) the sands form east-southeast-trending dunes up to 2 m high overlying a river terrace of sand and gravel (Goldsmith & Pettifer, 1977). Accumulations of windblown sand were probably derived from strong westerly winds deflating open, dry, sandy alluvial flats during arid periods in the Late Quaternary.

Alluvium (Qa)

There are extensive tracts of alluvium along many of the major drainage lines. In the Cullarin Block north of the Federal Highway continuous alluvial tracts are present along the Yass River and its tributaries. In the higher terrain south of the highway the only alluviated tract is on a downthrown segment of the Block at Queanbeyan. In the Canberra Plain the alluvium is present essentially as remnants perched at elevations up to 150 m above the entrenched drainage of the Molonglo and Murrumbidgee Rivers. The alluvium consists of well stratified dark-grey clay and silt and fine to coarse sand with pebble beds. Grading and low-angled cross-bedding is common in the sandy units. Layers of black organic, hydromorphic clay (gley) represent swampy periods. Alluvial deposits grade laterally into colluvium in places.

The alluvium on the Carwoola Flats is associated with a local base level of the Molonglo River. In 1979 it was briefly investigated by drilling and a short seismic refraction survey as part of this mapping (Fig. 20 and Appendix). The results can be summarised as follows:

— The Carwoola Flats overlie a shallow bedrock depression containing a wedge of alluvium and fan-gravels which thickens westwards. The greatest thickness recorded was just over 30 m in drillhole C 298.
— Palyniferous material sampled appears to be no older than Quaternary (Truswell, 1980). Many of the same palynomorphs have been recorded from the top 8.6 m of core from drillhole LG4 in the Lake George Basin (Singh & others, 1981a).
— Alluviation was controlled by small fault movements and changing climate in the Quaternary. Fault movements were never severe enough to actually truncate the Molonglo River. However, climatic changes probably slowed the rate of downcutting of the Molonglo River periodically so that it became an underfit stream and a lake filled east of the escarpment. The apparent absence of a Tertiary sequence suggests that prior to the Quaternary, the Molonglo River was always able to maintain a base level that kept pace with the uplift of the Cullarin Block.
— Lack of weathered bedrock in hole C298 is supportive evidence for the antiquity of the present route of the Molonglo River.

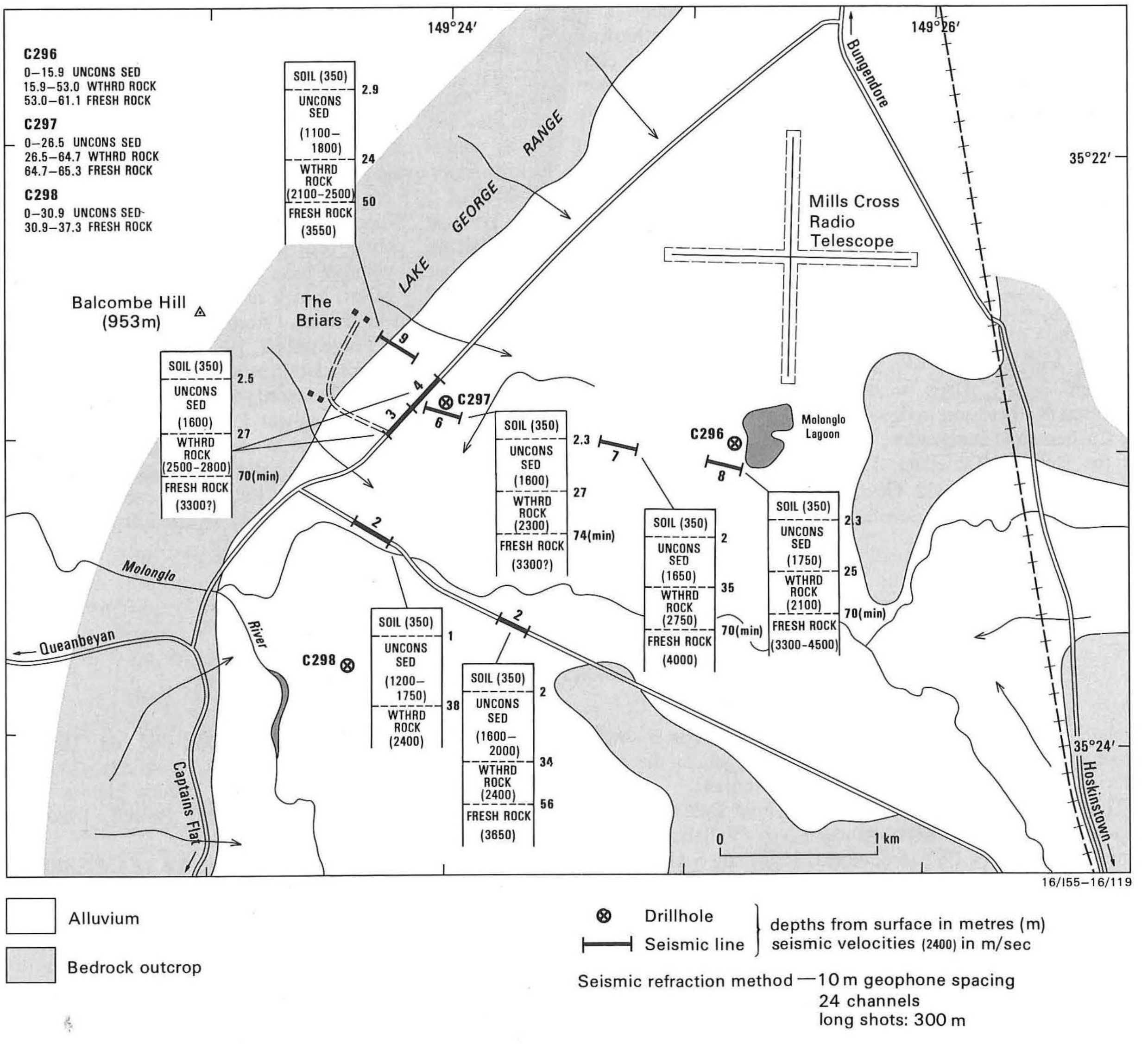


Fig. 20. Subsurface geology of the Carwoola Flats.

— The seismic reflection data indicate a greater thickness of low-velocity cover in the Carwoola Flats than is apparent from the thickness of alluvium encountered in drillholes. This suggests weathered bedrock is poorly distinguishable in velocity from the overlying alluvium.

West of the Cullarin Block remnants of an alluvial plain, the downstream half of which has been covered by Lake Burley Griffin since 1963, coincides with a low-gradient section of the Molonglo River. Soft argillaceous sediments of the Canberra Formation have been eroded to form a shallow basin. Surficial sediments along the Molonglo River and its tributaries were regarded by Legge (1937) as lake deposits. The idea was developed further by Öpik (1958) who postulated a lake on Sullivans Creek as a result of temporary damming by colluvium from Black Mountain, an interpretation refuted by Ollier & Brown (1975). The surficial geology of the Canberra Plain has been reported on by Van Dijk (1959) and considerable subsurface detail is also available in Henderson (1986).

Alluvial sediments in perched basins occur on minor tributaries of the Murrumbidgee River. Jacobson & others (1976) refer briefly to alluvium at Isabella Plains, while Kellett (1981) gives a detailed Quaternary stratigraphy with soil associations for small basins east of Lanyon and Point Hut Crossing. Between Tuggeranong and Tharwa these alluvial basins are perched 30–50 m above the entrenched course of the Murrumbidgee River. They are probably the remains of a former flood plain that developed on the eastern, downthrown, side of the Murrumbidgee Fault. Layers of black organic clay in the alluvial profiles suggest swampy conditions. Similar tracts of alluvium along Gooromon Ponds Creek and tributaries of Jeir Creek are perched up to 150 m above the Murrumbidgee River.

Contemporary alluvium consisting of moderately well-sorted sand, gravel and boulder deposits is confined to the channels of major streams.

Weathering

A long and complex weathering history has affected the Canberra region. Deep weathering profiles (saprolite) are protected from erosion in downfaulted low-relief areas such as the Canberra and Bungendore Plains. Thinner remnants remain on the Cullarin Tableland. Field work and drilling in the Carwoola Flats and Lake George basin (Abell, 1981; 1985a and b) have provided details of weathering profiles. The profiles consist of related iron and kaolinitic-rich zones. The upper, ferruginous, part of the profile contains sesquioxides of iron (haematite and limonite) and occasional manganese and passes down into a pallid, leached kaolinitic zone sometimes with pale-brown iron mottling and colour banding. The base of deep weathering appears to have a relatively abrupt boundary with fresh rock. Multiple weathering cycles are suggested by a thickness of > 90 m of weathered material in drillhole C354 at Lake George. The presence of kaolinite indicates that a warm, humid climate persisted well into the late Tertiary. A model proposed by Mann & Ollier (1985) suggests that deep weathering can evolve by progressive upward migration of iron-rich solutions from a bedrock weathering front (the original source of iron) to the water table, where iron is precipitated.

In other parts of Australia deep weathering can be equated with a late Mesozoic or even early Tertiary landscape surface (Idnurm & Senior, 1978), but because it is a continuous process spanning a long time interval, the profiles cannot be precisely dated. It seems probable that the palaeomagnetic results will tend to reflect the youngest weathering cycle and therefore only provide a minimum age. M.Idnurm (pers. comm., 1983) reports that magnetisation directions in core samples containing hematite from the Lake George basin are stable enough to provide a mid to late Tertiary age for the profile. Similar ages have been obtained from the Shoalhaven plain to the east (Ruxton & Taylor, 1982) and near Cooma to the south (Schmidt & others, 1982). In the Lake George basin the deep weathering profile is covered by up to 100 m of late Tertiary–Quaternary fluvio-lacustrine sediments. Pollen retrievals from the base of this sequence give a preliminary age of Late Miocene (Truswell, 1984), suggesting that deep weathering is unlikely to have extended far into the late Tertiary. Confirmatory evidence of this is provided by a palaeomagnetic result of 15 ± 5 Ma for deeply weathered bedrock in a brick shale pit near 'Woodlands' homestead (Alexander, 1984).

Intermittent, poorly differentiated ferruginous weathering profiles occur in younger parts of the Cainozoic sequence. A series of these profiles, which range from 0.5 to 7 m thick, have been logged in drill core from late Miocene–Quaternary sediments at Lake George (Abell, 1985a). Across the lake they show broad zones of correlation as individual profiles or groups of weathering units. The mottled zones of pedogenic iron enrichment and lack of in-situ kaolinisation characterise a weathering pattern that reflects oxidation and soil formation brought on by fluctuating climatic conditions. Kellett (1981) describes several intermittent weathering events associated with a Quaternary soil stratigraphy in the Lanyon Basin.

Felsic intrusions

Granite* bodies on CANBERRA were emplaced in a single major episode of magmatic activity that began in the Late Silurian and continued into the Early Devonian.

The granite intrusions in the Lachlan Fold Belt have been variously classified as Murrumbidgee-type (Vallance, 1969), contact-aureole type (White & others, 1974) and S and I types (Chappell & White, 1976; White & Chappell, 1983). From the distribution of felsic plutons in southeastern Australia an 'I/S' line has been plotted that separates fundamentally different types of lower crust; S-type granites are restricted to west of a line joining Bathurst and Cooma. The position of the I/S line on CANBERRA is shown in Figure 21. Rb–Sr dates show that the granites have an age range of about 415–395 Ma. The time/space plot for intrusions on CANBERRA (Fig. 22) is in accord with a general eastward younging of granitic plutons across southeastern Australia (Vistelius, 1980; Powell, 1984, fig. 197d).

Felsic intrusives crop out over about 5% of CANBERRA. One group are the *felsic plutonic rocks* which comprise small portions of the Murrumbidgee and Bega Batholiths, and other smaller plutons that are probably apophyses of larger and deeper granites. A more varied group are the high-level *subvolcanic intrusions*, consisting of stocks and dykes of adamellite and felsic porphyry related to felsic volcanic rocks.

The exposed felsic plutonic rocks are mainly distributed along structural highs such as the Cullarin Block, where erosion has exposed extensive tracts of Ordovician basement.

* 'Granite' is used here to denote a large group of acid plutonic rocks including alkali–feldspar granite, granite, adamellite, granodiorite and tonalite (Streckeisen, 1976).

Exposed plutons are less common in the down-faulted Canberra and Captains Flat Blocks where a thick cover of Silurian strata has been preserved.

The oldest plutons are Late Silurian and may be either S or I type; they include units of the Murrumbidgee Batholith (Shannons Flat Adamellite and Booroomba Leucogranite), Sutton Granodiorite, Barracks Creek Adamellite, Googong Adamellite, Federal Golf Course Tonalite, a small portion of the Urialla Granite, and other minor granite intrusions.

The youngest plutons, of Early Devonian age, are exclusively I-type and crop out along the eastern margin of the Sheet area; they include units of the Bega Batholith (Ellenden Granite, Rossi Granodiorite and Gibraltar Adamellite) and small unnamed granites.

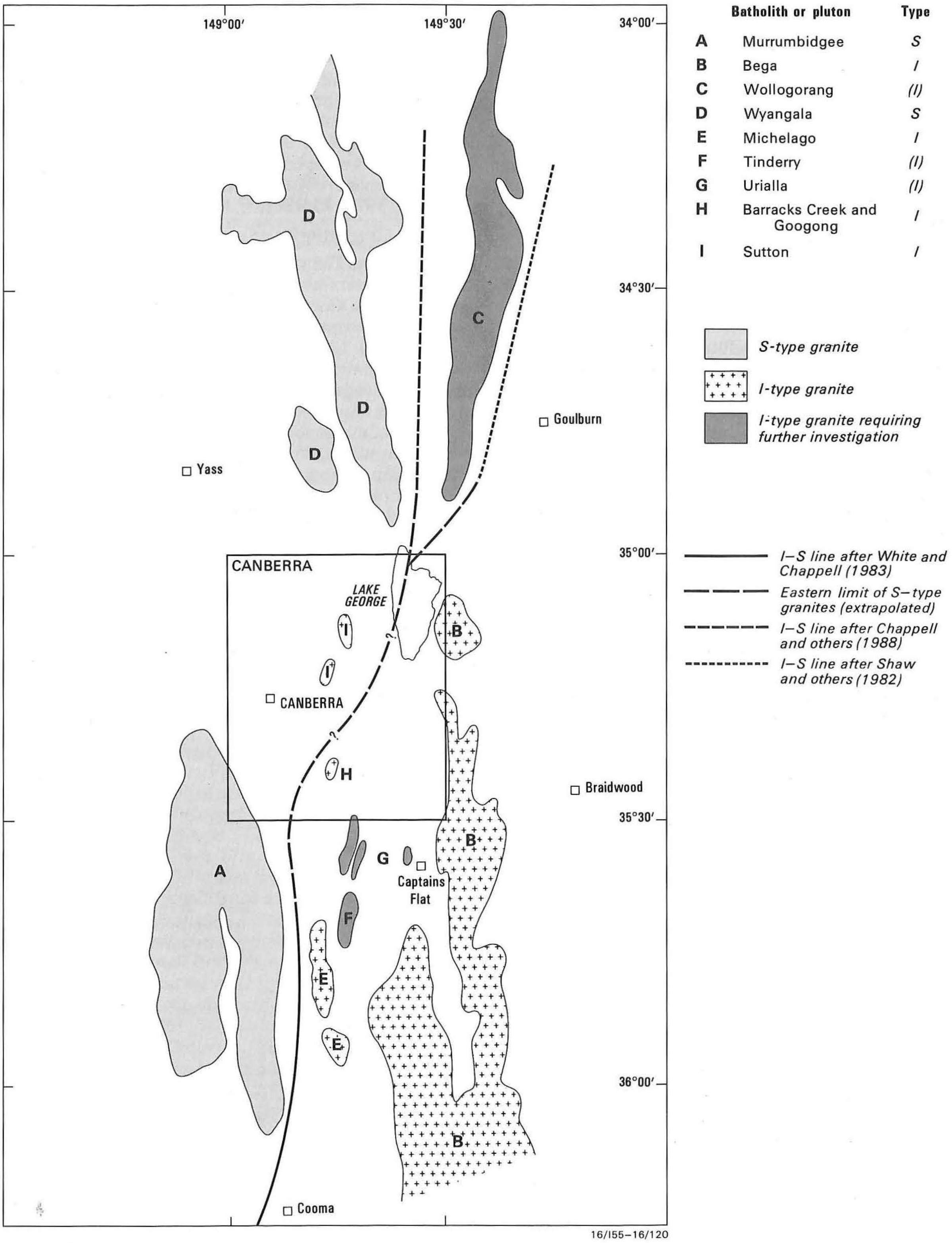


Fig. 21. I and S type granites in the Canberra region.

Late Silurian plutons

Murrumbidgee Batholith

A small part of this large batholith crops out over about 28 km^2 in the southwest corner of CANBERRA. Details of the petrogenesis and geochemistry of the component intrusions are presented by Snelling (1960) and Joyce (1973). Along the Bullen Range southwest of Canberra the Murrumbidgee Batholith intrudes and is faulted against the Late Ordovician Adaminaby beds. A narrow zone of contact metamorphism is indicated by the development of biotite in hornfelsed strata. Elsewhere the batholith has been upfaulted against the Late Silurian Laidlaw Volcanics along the Murrumbidgee Fault.

Outcrops of the batholith correspond generally with cleared hilly terrain. Scattered knolls are formed by clusters of large tors. At lower elevations outcrops form whalebacks with exfoliation surfaces. The spectrum of rock types, which include granodiorite, adamellite and leucogranite, is predominantly S-type (Owen & Wyborn, 1979; Richardson, 1979). The Rb–Sr geochronology of Roddick & Compston (1976) indicates emplacement at about 415 ± 2 Ma. The named intrusions of the batholith outcropping on CANBERRA are the Shannons Flat Adamellite and the younger Booroomba Leucogranite.

The **Shannons Flat Adamellite**(Sgh) is the larger intrusion. Detailed descriptions are given for BRINDABELLA by Owen & Wyborn (1979) and MICHELAGO by Richardson (1979). A third intrusive phase, the Tharwa Adamellite, has been recognised along the northeast margin of the Shannons Flat Adamellite (Snelling, 1960; Joyce, 1973; Richardson, 1979; Henderson, 1981). The two adamellites are here regarded as synonymous since field, mineralogical and chemical data can not conclusively separate them. Probably it is a single phase that becomes increasingly variable towards the eastern margin of the batholith. This is in accord with the observations of Joyce (1973) who noted an increase in xenoliths, a greater abundance of microcline, and a higher degree of foliation towards the Murrumbidgee Fault. Other supportive evidence for a single phase are the unclear boundary relationships, similar chemical analyses (Joyce, 1973), and the same isotopic dates of 414 ± 2 Ma for the Shannons Flat Adamellite and 414 ± 6 Ma for the Tharwa Adamellite (Roddick & Compston, 1976).

The **Booroomba Leucogranite** (Sga) on CANBERRA is a northerly extension of outcrops more widely developed on BRINDABELLA and MICHELAGO. The intrusion as defined by Owen & Wyborn (1979) is a weathered fine to medium-grained unfoliated leucogranite free of xenoliths. The Rb–Sr isochron for the Booroomba Leucogranite gives an age of 415 ± 2 Ma (Roddick & Compston, 1976). The similar (statistically identical) age to that of the Shannons Flat Adamellite suggests that the Booroomba Leucogranite may be a late acid phase of the Shannons Flat Adamellite (Joyce, 1973). That the Booroomba Leucogranite is the younger is deduced from marginal aplitic dykes intruding the Adamellite (Owen & Wyborn, 1979; Richardson, 1979).

Sutton Granodiorite (Sgs)

Derivation. The village of Sutton, NSW, at MR 051/063.

Nomenclature. Acid intrusions near Sutton were originally named 'Sutton Granite' and 'Greenwood Granite' on the First Edition of the Canberra 1:250 000 Geological Sheet (Joplin & others, 1953). Later, Moore (1957) used 'Bywong Granite' as a synonym for 'Sutton Granite' and described the 'Greenwood Granite' as 'a fine grained biotite granite cut by several quartz reefs'. The 'Sutton Granite', which is the largest and most northerly of the intrusions, was briefly referred to as 'a boss of adamellite with aplitic phases' (Stauffer & others, 1964). A relationship between the two granitic intrusions was implied by Strusz (1971) when he used the term 'Sutton Group'. It is now evident that these scattered intrusions with their unifying contact metamorphic aureole represent outcropping apophyses of a large pluton or small batholith. The name Sutton Granodiorite is introduced here for this group of intrusions, which range in composition from granodiorite in the north to adamellite and felsic porphyry in the south.

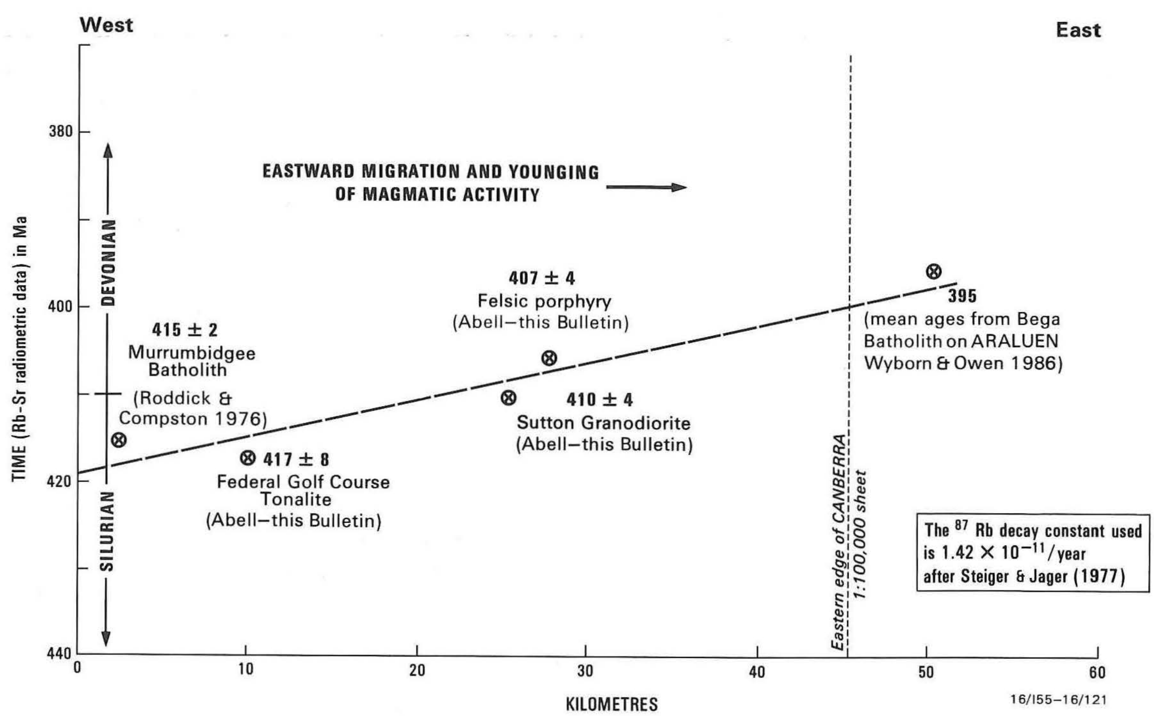


Fig. 22. Time/space plot for acid plutonic rocks in the Canberra region.

Distribution. The Sutton Granodiorite crops out as stocks with a total area of about 16 km^2. The elongate outcrops are roughly parallel to the meridional trend of the enclosing Ordovician metasediments. The most northerly intrusion (10 km^2) forms the western half of a small range culminating in Bywong Hill (MR 079/083). To the southwest, a smaller intrusion with an area of 4 km^2 is poorly exposed in elevated wooded terrain west of Greenwood Hill (MR 040/989). The subsurface extent of the Sutton Granodiorite may be inferred from hornfelsed and spotted sediments in an extensive contact metamorphic aureole.

Type locality. Hill slopes west of Bywong Hill, where the unit is represented by tors and pavements of mildly deformed coarse-grained biotite-rich granodiorite. There is a particularly fresh exposure about 100 m north of the old alignment of the Federal Highway at MR 074/053.

Description. The fresh Sutton Granodiorite is pale-grey, consisting of white feldspar, milky-grey quartz, and black biotite flakes. Hornblende-rich xenoliths are small and sparsely distributed through the intrusion. In a sand pit near the Federal Highway (MR 079/049) fresh corestones are preserved in a profile of decomposed granodiorite. A rare exposure of aplite occurs in Donnellys Creek at MR 080/048. The intrusion is generally undeformed but there is a weak foliation in a marginal body south of 'Oakdale' homestead (MR 092/115). There is a belt of meridional quartz reefs between the two main intrusive masses ('Bywong' and 'Greenwood'), while a major E–W-trending quartz reef cuts the northern intrusion east of 'Ashburton' homestead (MR 075/068). Two magnetic highs on the 1:250 000 scale magnetic intensity contour map of Canberra (Bureau of Mineral Resources, Geology & Geophysics, 1978) indicate these intrusions are relatively rich in magnetite.

Thin-sections of granodiorite show a coarse intergrowth (0.5–3 mm) of subhedral quartz and euhedral prismatic crystals of zoned plagioclase. Perthitic potash feldspar in large anhedral poikilitic crystals was the last felsic phase to crystallise. Ragged prismatic laths and basal sections of biotite generally measure 0.5–1.5 mm. They contain inclusions of zircon and apatite, and show an intense red–brown pleochroism. Pale-yellow euhedrally zoned crystals of accessory allanite up to 0.5 mm are closely associated with the biotite.

Alteration of plagioclase to fine granular epidote and flakes of sericite is concentrated in the calcic cores of zoned crystals, while biotite is marginally chloritised. The rock has been mildly deformed, producing sutured and granular boundaries around quartz. Localised fracturing can also be seen in biotite flakes and feldspar crystals. Fine-grained xenolithic material consists of stubby crystals of biotite, hornblende and zoned plagioclase scattered through large poikilitic crystals of quartz and pale-grey potash feldspar. Chemical analyses of the intrusions are given in Table 17.

The less well-exposed intrusions south of the Federal Highway are composed of adamellite and quartz-feldspar porphyry. Rafts of bedded hornfels suggest less of the Ordovician cover has been removed than from the granodiorite. Boundaries between rock types are not clearly defined but it appears from the chemical analyses that the more leucocratic intrusions may be a fractionated sequence cogenetic with the granodiorite.

Age and relationships. The Sutton Granodiorite intrudes and hornfelses the Late Ordovician Pittman Formation. Sharp contacts are evident where country rock is veined by granite and felsic porphyry. Contacts are exposed on Macs Reefs Road (MR 081/043), along the Yass River north of Wattle Flat (MR 060/066) and near 'Lumley' homestead (MR 072/046). The overall patterns of granite outcrops, quartz reefs and metamorphic aureole are believed to be related to left-lateral movement along the Queanbeyan Fault.

Radiometric dating indicates a latest Silurian age for the Sutton Granodiorite. Bofinger (1964) obtained a total-rock Rb–Sr age of 422 Ma. The same isotopic data have been replotted to give an isochron of 411 Ma. This recalculated age agrees with a biotite/total-rock Rb–Sr age of 410 ± 4 Ma obtained by AMDEL (AC 3536/79). The upper age limit of the Sutton Granodiorite is constrained by an E–W trending dolerite dyke of presumed Early Devonian age which cuts a marginal intrusion south of 'Oakdale' homestead (MR 093/109).

Table 17. Sutton Granodiorite: major and trace element analyses

Sample no.	*76460058*	*76460258*	*ANU Sample*	*76460359*
Rock type	*quartz-feldspar porphyry*	*granodiorite*	*granodiorite*	*adamellite*
Grid ref.	*022984*	*032951*	*074053*	*074053*
%				
SiO_2	75.29	73.90	72.22	77.80
TiO_2	0.10	0.35	0.34	0.07
Al_2O_3	13.00	13.38	13.48	12.65
Fe_2O_3	0.85	0.28	0.51	0.42
FeO	0.63	2.16	2.14	0.35
MnO	0.05	0.08	0.06	0.02
MgO	0.31	0.76	0.88	0.23
CaO	0.20	2.82	2.79	0.14
Na_2O	2.85	2.90	2.85	7.48
K_2O	5.82	2.69	3.16	0.05
P_2O_5	0.04	0.06	0.08	0.07
H_2O+	0.94	0.55	0.78	0.48
H_2O-	0.02	0.04	0.14	0.04
CO_2	0.05	—	0.24	—
SO_3	—	—	<0.02	—
Total	100.30	99.86	99.98	99.80
ppm				
Ba	400	260	470	<10
Rb	200	140	141	8
Sr	160	180	177	70
Pb	90	19	17.5	5
Th	18	16	17.6	14
U	6	4	1.6	6
Zr	85	150	142	75
Nb	10	8	10	4
Y	44	30	30	40
La	40	30	32	25
Ce	100	100	69	25
Nd	—	—	26	—
Sc	—	—	12	—
V	15	30	35	—
Cr	15	15	6	<10
Mn	—	—	460	90
Co	8	50	6	<5
Ni	5	120	3	14
Cu	25	5	0.5	4
Zn	100	35	4.1	5
Ga	—	—	15	12

Using the geochemical and mineralogical criteria of White & Chappell (1983) and the presence of allanite and hornblende-rich xenoliths, the Sutton Granodiorite is probably an I-type intrusion. The initial Sr^{87}/Sr^{86} ratio of 0.7092 is high for an I-type granite and is similar to ratios reported for the Bega Batholith and other felsic intrusions whose initial Sr ratios gradually increase westwards towards the I/S line (Wyborn & Owen, 1986; Compston & Chappell, 1979). The Sutton Granodiorite is probably the same age as the Barracks Creek Adamellite and other acid intrusions south of Queanbeyan.

Barracks Creek Adamellite (Sgb)

Derivation. From Barracks Creek, a tributary of the Queanbeyan River, south of Queanbeyan.

Nomenclature. Phillips (1956) first used the name 'Barrack Creek Adamellite' for a stock intruding Ordovician and Silurian strata 5 km south of Queanbeyan. Stauffer (1964) and Stauffer & Rickard (1966) referred to it as the 'Queanbeyan Granite'. Stauffer (1967) later corrected this to Phillips's usage. The name 'Barracks Creek Adamellite' (corrected spelling) is recommended.

Distribution. The Barracks Creek Adamellite is poorly exposed over an area of 4 km^2. The arcuate outcrop pattern is bounded to the southeast by a prominent strike swing in steeply dipping Colinton Volcanics (Stauffer, 1967). The deeply weathered, soft adamellite is topographically negative.

Type locality. None previously: the freshest exposures are in a large quarry on the old Cooma–Queanbeyan road (MR 019/807) and this is nominated as the type locality. The rock is a pale-grey, medium-grained adamellite composed of equigranular white–pink feldspar, grey quartz and altered interstitial biotite. The rock is strongly jointed, permeated by networks of quartz veinlets and locally intruded by thin dark-grey dolerite dykes. Exposure of the contact zone with the Colinton Volcanics depends on the state of quarrying operations. Within the zone, grey foliated dacitic ignimbrite becomes progressively silicified and veined with quartz over a width of about 30 m. At the contact, the adamellite becomes finer-grained and appears to dip steeply beneath the volcanics.

Description. The intrusion ranges in composition from adamellite to leucogranite. Outcrops of rubbly, coarse, porphyritic adamellite occur on the left bank of the Queanbeyan River at MR 042/817, while weathered pale-brown kaolinitic leucogranite is commonly exposed in disused pits and cuttings along the old Queanbeyan–Cooma road. Xenoliths are sparse, but a few Ordovician and Silurian sedimentary rafts occur in marginal areas. Syn-emplacement deformation is indicated by zones of crushing and fracturing, allowing access for kaolinite- and epidote-rich deuteric alteration. A narrow poorly exposed contact metamorphic zone is indicated by local spotting in Ordovician phyllite (Stauffer, 1964).

In thin-section the Adamellite shows fractured quartz, plagioclase and perthitic potash feldspar phenocrysts with greenish-brown laths of biotite in a granophyric groundmass of quartz and feldspar. Further petrological detail is available in Phillips (1956) and Stauffer (1964, 1967). Determination of the S or I-type affinities of the intrusion is precluded by the weathered state of the rocks and consequent absence of geochemical data.

Age and relationships. Contacts with surrounding rocks are rarely exposed. Along its northwestern boundary the Barracks Creek Adamellite intrudes and is faulted against the Late Ordovician Pittman Formation; a contact was temporarily exposed in the Googong Pipeline excavation (Henderson, 1978c). Along the southern boundary a Late Silurian (possibly post-Ludlovian) age for the Barracks Creek Adamellite is indicated by a discordant contact with the Colinton Volcanics. A minimum age is indicated by intrusion of east–west trending, probably Early Devonian, dolerite dykes.

The Barracks Creek Adamellite is probably comagmatic with the Googong Adamellite and other minor granite bodies that intrude the Late Silurian volcano–sedimentary sequence of the Canberra Block.

Googong Adamellite (Sgo)

Derivation. From old 'Googong' homestead, now covered by the Googong Reservoir. The intrusion crops out along the access road to the Googong Foreshore Area and also downstream of Googong Dam.

Nomenclature. Stauffer (1964), Stauffer & Rickard (1966) and Stauffer (1967) introduced the name 'Googong Granite' for a small stock lying about 1.5 km south of the Barracks Creek Adamellite. Subsequently Strusz (1971) revised the name to Googong Adamellite, which he included with other felsic intrusions in his 'Tuggeranong Group'. It is recommended that the name Googong Adamellite be retained since it reflects the petrographic character of the intrusion.

Distribution. The Adamellite covers an area of about 3 km^2 west of Googong Dam. The inverted U-shaped outcrop pattern of the intrusion does not make a topographic feature since it is fully enclosed by more resistant dacitic ignimbrite. There are good outcrops in the Queanbeyan River below Googong Dam; the intrusion is poorly exposed except in streams.

Type locality. Moderately weathered buff-coloured adamellite is well exposed in cuttings on the road between the Googong Foreshore Area office and the dam. There is a sharp, steeply dipping contact at MR 048/781, where fine-grained adamellite has veined and silicified dark-grey foliated dacitic ignimbrite.

Description. The Googong Adamellite is fairly uniform in the field. It is a medium to coarse porphyritic adamellite containing phenocrysts of quartz, and pinkish-white potash feldspar up to 2 cm, and small aggregates of altered black biotite. Partial alteration of plagioclase to epidote imparts a greenish-grey tinge to the rock. The main part of the intrusion is massive; jointing and a weak foliation develop marginally. Dacitic xenoliths are found within 100 m of the contact. Pegmatite and quartz–epidote veins are associated with a narrow contact metamorphic zone around the intrusion (Stauffer, 1964).

In thin-section the rock contains a phenocrystic assemblage of embayed and fractured quartz, perthitic potash feldspar, and plagioclase strongly altered to epidote and sericite. Prismatic and basal sections of biotite are totally altered to chlorite and accessory apatite, with alignment of epidote and opaques along cleavage planes. A patchy groundmass shows granophyric growth of quartz and feldspar, interstitial patches of secondary epidote rosettes, and accessory allanite and zircon. Further petrological detail is available in Stauffer (1964, 1967).

Age and relationships. A Late Silurian (possibly post-Ludlow) age for the Googong Adamellite is evident from an intrusive and faulted relationship with the Colinton Volcanics. A dacite/adamellite contact was temporarily exposed during construction of Googong Dam (Goldsmith, 1979). Geochemical data are not available but the presence of hornblende (Stauffer, 1964) and allanite suggests the Googong Adamellite has I-type affinities. The intrusion is probably comagmatic with the Barracks Creek Adamellite and other minor I-type granite bodies south of Queanbeyan.

Federal Golf Course Tonalite (Sgf)

Derivation. From Federal Golf Course, between Garran and Hughes (approx. MR 917/880).

Distribution. The intrusion forms subdued topography and is poorly exposed over an area of about 1 km^2 southwest of Red Hill.

Type locality. Federal Golf Course. A boulder of the tonalite can be seen near the course curator's depot about 100 m northwest of the clubhouse.

Description. There is a fresh exposure on the northeast side of the access road to the golf course (MR 920/884). The rock consists of a holocrystalline assemblage of plagioclase, hornblende, biotite and interstitial quartz. Following the usage of Johanssen as outlined in Hatch & others (1961), the absence of potash feldspar and presence of essential hornblende classifies the intrusion as a tonalite (quartz diorite).

In thin-section the tonalite is dominated by subhedral to euhedral crystals of plagioclase up to 1 mm showing strong zoning and complex calcic cores altered to sericite. The mafics (biotite and hornblende) are commonly intergrown. Biotite forms brown pleochroic flakes containing inclusions of zircon, apatite and sphene; there is partial alteration to chlorite, epidote and opaques. Basal and prismatic sections of hornblende are pleochroic in shades of pale-green and brown; they contain inclusions of plagioclase, epidote and opaques. Late interstitial quartz contains inclusions of plagioclase, biotite and hornblende.

Geochemical analyses (Table 18) show about 60% SiO_2, 18% Al_2O_3 and 6.5% CaO. A value of 500 ppm Cu was recorded from the southwestern margin of the intrusion. The tonalite is I-type, based on the presence of hornblende, a very low initial $^{87}Sr/^{86}Sr$ ratio of 0.7041 (cf. White & Chappell, 1983), and coincidence with a small aeromagnetic high on the 1:250 000 scale total-magnetic-intensity contour map of Canberra (Bureau of Mineral Resources, Geology & Geophysics, 1978).

Age and relationships. There are no exposed contacts. Detailed mapping shows the tonalite is discordant across the strike of the Yarralumla Formation and lower units of the Deakin Volcanics. Hornfelsing of the Yarralumla Formation along Red Hill Ridge is probably due to this intrusion.

A biotite K–Ar age of 422 ± 6 Ma and a biotite–total-rock Rb–Sr age of 417 ± 8 Ma have been obtained by AMDEL (AC 2641/80). The 5 Ma difference supports the systematic error in K–Ar chronology outlined in Owen & Wyborn (1979). The Rb–Sr age is slightly younger than the Ludlow age of 420.7 ± 2.2 Ma given for the Laidlaw Volcanics (Wyborn & others, 1982) but significantly older than the Late Silurian age of 410 ± 4 Ma placed on the Sutton Granodiorite. The large error of ± 8 Ma for the Rb–Sr chronology means that only a minimum age of Late Silurian (Ludlovian) can be reliably assigned to the Federal Golf Course Tonalite. The recalculated age of 414 ± 9 Ma for the Mugga Mugga Porphyry (W. Compston, pers. comm., 1982) suggests that this may be an age reset by the tonalitic intrusion because the porphyry is stratigraphically older than the Laidlaw Volcanics.

The Federal Golf Course Tonalite shows similarities to tonalites in the Late Silurian I-type Jindabyne Suite (Hine & others, 1978). The geochemical data (major oxides and trace elements vs. SiO_2) correlate positively with tonalites in this suite, although they plot at the mafic end of the fractionated sequence (Hine & others, 1978; Owen & Wyborn, 1979).

Table 18. Federal Golf Course Tonalite: major and trace element analyses (tonalites)

Sample no.	*76460099*	*76460262*	*ANU Sample*
Grid ref.	*912878*	*920884*	*920884*
%			
SiO_2	59.68	61.00	60.84
TiO_2	0.56	0.57	0.56
Al_2O_3	18.03	18.00	17.72
Fe_2O_3	1.53	5.10	1.73
FeO	3.70	<0.02	3.24
MnO	0.08	0.10	0.08
MgO	3.10	2.68	2.92
CaO	6.28	6.55	6.48
Na_2O	3.15	3.26	3.39
K_2O	1.36	1.28	1.29
P_2O_5	0.16	0.14	0.13
H_2O+	2.13	0.87	1.23
H_2O-	0.11	0.10	0.20
CO_2	0.05	—	0.12
Total	99.92	99.67	99.93
ppm			
Ba	—	220	235
Rb	70	48	43.5
Sr	200	290	285
Pb	3	90	3.5
Th	4	4	5.8
U	<4	4	1.2
Zr	105	130	102
Nb	10	8	7.5
Y	20	28	19.0
La	30	<20	18.0
Ce	60	50	40.0
Nd	—	—	17.0
Sc	—	—	21.0
V	100	90	132.0
Cr	20	<10	5.0
Co	20	15	16.0
Ni	5	5	6.0
Cu	500	44	47.0
Zn	30	44	41.0
Mn	—	—	595
Ga	—	—	16.8

Table 19. Minor granite intrusions (Sg): major and trace element analyses

Sample no.	*76460278*	*76460068*	*76460295*	*76460296*
Rock type	*adamellite*	*granodiorite*	*adamellite*	*adamellite*
Grid ref.	*055199*	*122241*	*046723*	*046698*
%				
SiO_2	75.70	64.57	71.20	72.90
TiO_2	0.09	0.82	0.40	0.35
Al_2O_3	13.30	14.70	14.10	13.90
Fe_2O_3	1.40	1.07	0.96	0.58
FeO	<0.02	3.90	1.49	1.49
MnO	0.04	0.11	0.03	0.03
MgO	0.13	2.45	0.87	0.71
CaO	1.65	3.16	3.56	3.25
NaO	2.83	5.00	3.00	3.00
K_2O	4.25	0.54	2.60	2.80
P_2O_5	0.02	0.15	0.09	0.09
H_2O+	0.49	2.28	1.13	0.84
H_2O-	0.08	0.04	0.09	0.12
CO_2	—	1.05	—	—
Total	100.00	99.99	99.52	100.66
ppm				
Ba	580	150		
Rb	200	19		
Sr	160	330		
Pb	46	5		
Th	14	6		
U	6	<4		
Zr	110	230		
Nb	10	16		
Y	85	32		
La	20	30		
Ce	70	70		
V	<20	150		
Cr	<10	30		
Co	<5	20		
Ni	<5	10		
Cu	5	10		
Zn	36	50		

Urialla Granite (Sgu)

A meridionally elongate mass of fine to medium-grained adamellite, concordant with surrounding Ordovician sediments, crops out over about 0.8 km² at the southern edge of the Sheet area, near Googong Reservoir (MR 068/698). This is the northern tip of the Urialla Granite on MICHELAGO, which is probably Late Silurian in age (Richardson, 1979).

Minor granite intrusions (Sg)

Small Late Silurian granite bodies (< 1.0 km² in area), no doubt the apophyses of larger plutons, intrude Ordovician sediments in the Cullarin Block.

Smith (1964) informally named an adamellite outcropping at 'Bowylie' homestead (MR 063/197) and at the old Gundaroo graveyard (MR 057/199) the 'Graveyard intrusion'. A sharply crosscutting contact with Ordovician sediments is exposed in a roadcut about 1 km southwest of Gundaroo (Henderson, 1978). In thin-section relict highly-strained quartz grains up to 5 mm are elongated parallel to the foliation. Plagioclase crystals up to 3 mm are compositionally zoned, with the more calcic cores altered to sericite. Subordinate potash feldspar is perthitic. Dark-brown pleochroic biotite partly replaced by chlorite occurs as wispy distorted flakes drawn out parallel to the foliation. A recrystallised quartzo-feldspathic groundmass contains secondary muscovite. A chemical analysis is given in Table 19. Further west, a small stock of granodiorite, referred to as the 'Balbriggan intrusion' by Smith (1964), outcrops in Spring Flat Creek (MR 032/190).

An altered microgranodiorite in the headwaters of Gundaroo Creek (MR 122/241) consists of pale-green chlorite, euhedral sphene, calcite and epidote in a framework of quartz and stubby sericitised crystals of plagioclase and subordinate potash feldspar (see also Table 19).

A small adamellite body cut by northwest-trending basic dykes intrudes Late Ordovician psammo-pelitic schist about 2 km southeast of Yarrow Peak (MR 127/752). The rock, which shows some degree of deformation, consists of fractured crystals of zoned plagioclase and perthitic potash feldspar, granulated quartz, kinked biotite and accessory epidote.

Minor granitic intrusions of Late Silurian age are also common in the volcano–sedimentary sequence in the Canberra Block. In the central Belconnen area of Canberra, Strusz & Henderson (1971) gave the name 'Glebe Farm Adamellite' to porphyritic adamellite intruding the Pittman Formation and Hawkins Volcanic Suite. The outcrop distribution on the present map follows that in the 2nd Edition of the 1:50 000 Geological Map of Canberra & Environs (Henderson, 1980). Northwest-trending exposures parallel the upthrown side of the Deakin Fault and are apparently displaced by the northeast-trending Winslade–Gungahlin Fault. Urban development has now restricted outcrops of the intrusion to a few boulders in a recreation area and creek below the dam wall of Lake Ginninderrra (MR 877/007). The massive pale-grey holocrystalline rock contains large phenocrysts of clear quartz up to 10 mm and whitish-pink feldspar. In thin-section the distinctive hexagonal shape of the quartz indicates it is the high-temperature beta form. Plagioclase shows multiple twinning and zoning; it is extensively altered to sericite. Potash feldspar is represented by grey sanidine with inclusions of quartz; a brown turbid appearance may be kaolinitic alteration. Prismatic sections of biotite with inclusions of zircon, quartz and plagioclase are totally altered to pale-green chlorite, epidote and opaques. The phenocrysts are embedded in a fine-grained crystalline groundmass of equigranular quartz, potash feldspar and plagioclase; a few pale-yellow zoned crystals of accessory allanite are in close association with biotite. The mineralogy suggests an I-type intrusion which has affinities with the Barracks Creek and Googong Adamellites.

Adamellite porphyry intrudes the Cappanana Formation and Colinton Volcanics in a triangular area bounded by the Jerrabomberra and Queanbeyan Faults. A narrow belt of these porphyry intrusions is aligned parallel to the regional trend of the country rock north of 'London Bridge' homestead. Two other bodies of similar composition appear to have been emplaced discordantly across the regional trend of the Colinton Volcanics west of 'Glenola' homestead (MR 017/705). The rocks consist mainly of rounded, embayed quartz and zoned, multiply twinned plagioclase phenocrysts strongly altered to sericite and epidote; potash feldspar occurs infrequently as turbid brown phenocrysts of perthite altered to kaolinite. Biotite is totally replaced by chlorite, epidote and opaques. A patchy groundmass consists of a fine intergrowth of quartz, potash feldspar and plagioclase with accessory calcite and rosettes of epidote. Partial chemical analyses of these rocks, sampled at MR 046/723 and 046/698, are given in Table 19. Accessory allanite in the adamellite porphyry near 'Glenola' suggests affinities with other I-type granites outcropping south of Queanbeyan. Another small granite body is exposed at MR 124/157.

Late Silurian subvolcanic porphyry intrusions

Unnamed dacite and rhyodacite porphyries normally < 2 km^2 in area intrude and are intimately associated with the Hawkins and Laidlaw Volcanic Suites. Contacts rarely occur, so that field identification and differentiation from ignimbritic tuffs is based on restricted outcrop pattern and detailed petrographic study. The intrusive nature of these rocks is usually suggested in thin-section by unbroken, euhedral phenocrysts set in a uniform, fine-grained, crystalline groundmass. The stock or sill-like character of the bodies suggests they may correspond to volcanic centres.

Hawkins Volcanic Suite (Sp$_1$)

A large dacite porphyry intrusion exposed over an area of about 8 km^2 extending northeast from Lake Ginninderra to 'Gold Creek' homestead (MR 914/053) has been described by Henderson (1975, 1980). Much of the exposure is now obscured by urban development in the north Belconnen area. Northeast of the Barton Highway the intrusion crops out as a massive greenish-grey porphyry with prominent white feldspar and dark-grey cordierite phenocrysts up to 5 mm. In thin-section the phenocryst framework consists of euhedral albitic plagioclase strongly altered to epidote and sericite, and unstrained embayed beta quartz. Prismatic laths of biotite are strongly altered to chlorite, epidote, sphene and opaques; the chlorite may show anomalous purple colours under crossed polarisers. Cordierite with inclusions of quartz and epidote forms irregular embayed crystals altered to pale-green, fine-grained isotropic chlorite. Orthopyroxene occurs as basal sections and prismatic laths altered to greenish-yellow chlorite, sphene and opaques. Garnet is an accessory. A uniform, fine-grained groundmass contains a high proportion of potash feldspar. Chemical analyses are given in Table 20. A northeast extension of this intrusive activity is evident from arcuate outcrops of dacite porphyry near Oak Hill on the ACT–NSW border. Calc-silicate hornfels is closely allied with a small acid porphyry intrusion at Oak Hill (MR 957/089) (too small to map); hornfelsed calcareous rocks also occur near Nobby Hill (MR 986/150).

A small (< 1 km^2), massive plagioclase–orthopyroxene porphyry forms bouldery knolls east of Fairbairn Airport (MR 007/913). The phenocryst assemblage consists of zoned, heavily albitised plagioclase, pale-green orthopyroxene altered to bastite, and minor embayed quartz. Potash feldspar is absent in the phenocrystic phase. The groundmass consists of a fine mosaic of quartz, plagioclase, chlorite, epidote and calcite. The porphyry is a stock-like intrusion into the Mount Ainslie Volcanics. A chemical analysis is given in Table 20.

Ollier & Brown (1975) and Henderson (1980) have mapped dacitic porphyry at the base of the Ainslie–Majura ridge between the Federal Highway and Hackett. These rocks are not clearly distinguishable from beds of dacitic ignimbrite near the top of the Canberra Formation in this area. However, there are beds of calcareous hornfels at MR 975/995.

The geochemistry and mineralogy (plagioclase, cordierite and accessory garnet) identify these felsic porphyries as comagmatic with the Hawkins Volcanic Suite. A pre-Ludlovian age is assumed since these intrusions postdate the Mount Ainslie Volcanics but have not been found cutting rock units of the Laidlaw Volcanic Suite. These rocks may be coeval with dacitic porphyry intrusions associated with the Walker Volcanics on BRINDABELLA (Owen & Wyborn, 1979; Henderson, 1980).

Laidlaw Volcanic Suite (Sp$_2$)

Small bodies (< 2 km^2) of massive rhyodacite porphyry intrude the Laidlaw Volcanic Suite. In the Kambah area of Canberra, two porphyry plugs form Forster Hill (MR 833/823) and Neighbour Hill (MR 847/832). A field and petrographic description is given by Rossiter (1971). Similar rocks mapped by Henderson (1980), which may be sills, occur on the east side of Mount Taylor and in the Weston Creek area. At a contact in the Murrumbidgee River 0.5 km east of 'Lambrigg' homestead (MR 867/739), a sill of rhyodacite porphyry concordantly overlies and locally hardens and bleaches shale and siltstone interbeds in the Laidlaw Volcanics. Peperite along the contact suggests shallow intrusion of magma into soft sediment.

Outcrops of rhyodacite porphyry are pinkish and greyish-brown with phenocrysts of white and pale-pink plagioclase, pink potash feldspar and grey translucent quartz up to 2 cm. A few clasts of vein quartz occur in outcrops along the Murrumbidgee River near the Outward Bound School (MR 869/725). In thin-section euhedral crystals of albitic plagioclase show some zoning but otherwise are extensively altered to sericite. Potash feldspar forms perthite or grey crystals of sanidine with occasional carlsbad twinning. Some phenocrysts are poikilitic, with inclusions of plagioclase; a brown turbid colour in ordinary light is caused by a fine dusting of haematite. Clear beta-quartz occurs as hexagonal crystals. Prismatic sections of biotite are altered to pale-green chlorite, sphene, epidote and opaques. Lesser amounts of orthopyroxene can be identified by crystal shape and alteration to greenish-yellow chlorite, quartz and opaques. In some cases the mafics are completely altered to aggregates of epidote and chlorite. Zircon and allanite are accessories. The groundmass is a uniform mosaic of finely crystalline quartz, plagioclase and potash feldspar. Chemical analyses are given in Table 21.

A weathered pink rhyodacite porphyry east of Mugga Lane garbage tip has a crosscutting contact with basal units of the Deakin Volcanics (Evans, 1983). Secondary black manganese dioxide locally coats outcrops and joints.

Near a radio beacon on the old Queanbeyan–Cooma road (MR 990/730), a small slightly foliated porphyry intrusion is roughly concordant with the Colinton Volcanics. In thin-section, quartz and feldspar phenocrysts are fractured and streaks of sericite occur in the groundmass. The intrusion is cut by an E-W trending dolerite dyke (Early Devonian?).

The geochemistry and mineralogy (pink potash feldspar megacrysts, sanidine and accessory allanite) identify these porphyries as comagmatic with the Laidlaw Volcanic Suite. The rhyodacite porphyry intrusions on CANBERRA are similar in appearance to, and probably comagmatic with, the sill-like Ginninderra Porphyry on BRINDABELLA (Owen & Wyborn, 1979) and Livingstone Porphyry on MICHELAGO (Richardson, 1979).

Table 20. Subvolcanic felsic porphyry intrusions (Sp_1): major and trace element analyses

Sample no.	*75360015*	*LFV 45*	*76460106*
Rock type	*dacite porphyry*	*dacite porphyry*	*plagioclase ortho-pyroxene porphyry*
Grid ref.	*883027*	*912056*	*007913*
%			
SiO_2	67.09	66.57	63.12
TiO_2	0.57	0.60	0.55
Al_2O_3	14.17	14.23	14.45
Fe_2O_3	1.17	1.28	1.78
FeO	3.25	3.26	4.65
MnO	0.04	0.04	0.10
MgO	2.32	2.37	2.15
CaO	2.51	2.65	4.97
Na_2O	2.45	2.39	1.76
K_2O	3.41	3.57	2.00
P_2O_5	0.14	0.14	0.12
H_2O+	2.21	2.07	2.71
H_2O-	0.05	0.25	0.15
CO_2	0.40	0.27	0.05
Total	99.97	99.87	98.73
ppm			
Ba	560	530	320
Rb	165	157	—
Sr	140	159	90
Pb	18	12	140
Th	14	17.8	15
V	6	3.6	8
Zr	190	168	<4
Nb	—	10.5	125
Y	30	31	6
La	40	25	24
Ce	90	62	30
Nd	—	—	70
Sc	—	14	180
V	100	94	140
Cr	65	57	25
Co	6	17	25
Ni	20	22	40
Cu	4	2	80
Zn	69	76	—
Mn	—	275	—
Ga	—	17.4	—

Table 21. Subvolcanic felsic porphyry intrusions (Sp_2): major and trace element analyses (rhyodacite porphyries)

Sample no.	*76460091*	*76460211*	*76460276*	*77840158*
Grid ref.	*988754*	*869726*	*988731*	*849833*
%				
SiO_2	76.41	70.20	73.90	68.62
TiO_2	0.07	0.43	0.20	0.47
Al_2O_3	12.67	13.90	13.80	14.79
Fe_2O_3	0.55	1.40	1.58	1.10
FeO	0.33	1.93	<0.02	2.03
MnO	0.04	0.04	0.04	0.06
MgO	0.26	1.53	0.33	1.43
CaO	0.31	1.20	1.82	2.19
Na_2O	3.20	3.70	2.83	3.25
K_2O	4.58	3.86	4.00	3.77
P_2O_5	0.02	0.10	0.04	0.10
H_2O+	0.74	1.20	0.89	1.88
H_2O-	0.08	0.12	0.12	0.02
CO_2	0.25	—	—	0.10
Total	99.61	99.61	99.67	100.01
ppm				
Ba	210	470	700	680
Rb	210	170	170	150
Sr	70	130	160	180
Pb	19	60	26	260
Th	16	16	16	16
V	8	8	4	4
Zr	65	190	140	220
Nb	12	20	8	4
Y	65	36	110	28
La	30	40	60	30
Ce	50	100	130	90
Nd	—	—	—	—
Sc	—	—	—	—
V	<10	75	20	—
Cr	5	<25	10	—
Co	6	<5	10	8
Ni	<5	10	<5	8
Cu	4	<5	6	8
Zn	15	30	22	35

Early Devonian plutons

Ellenden Granite (Dge)

Derivation. After Ellenden trig. point, the highest point on Governors Hill (MR 265/084), east of Lake George.

Nomenclature. Outcrops of the intrusion were first described as 'gneissic granite' by Garretty (1936). The name Ellenden Granite was first used on the 2nd Edition of the Canberra 1:250 000 geological sheet (Best & others, 1964) and subsequently defined on BRAIDWOOD by Felton & Huleatt, (1977). The nomenclature is retained here, although much of the intrusion is adamellite.

Distribution. The Ellenden Granite is the most northerly extension of the Bega Batholith, only a portion of the western margin of the intrusion being exposed on CANBERRA. Outcrops cover a cleared area of about 20 km^2 extending north from the Bungendore–Tarago road to Rocky Point on the eastern side of Lake George; outcrop continuity is broken by alluvium in Taylors Creek.

Description. The north-northwest-trending outcrop pattern and prominent ridge of Governors Hill are a response to the foliation of the Ellenden Granite. Meridional rafts of cleaved felsic volcanics and interbedded tuffaceous sediments of the Woodlawn Volcanics occur within the intrusion. Late-stage magma segregation is represented by northwest-trending foliated felsic porphyry intrusions that cut the Ellenden Granite and adjacent Ordovician metasediments.

On CANBERRA the intrusion consists of pink to pale-grey medium to coarse adamellite. Fine-grained biotite-rich xenoliths up to 10 cm are commonly aligned with the foliation. Thin-sections show highly strained ovoid crystals of quartz with recrystallised granular boundaries, some of which have been recrystallised to a fine-grained mosaic. Subhedral crystals of plagioclase show multiple twinning and complex oscillatory zoning; there is strong alteration to sericite.

Perthitic potash feldspar dominates over plagioclase. Crystals are fresh and may show graphic intergrowths with quartz. Ragged crystals of primary brown biotite with inclusions of zircon and apatite are marginally altered to chlorite and opaques — an unusual variety is an Fe-rich chlorite exhibiting deep-emerald-green to straw-coloured pleochroism. Strings and aggregates of epidote and stubby laths of fresh brown recrystallised metamorphic biotite define the foliation. Laths of muscovite probably derived from the breakdown of plagioclase are closely associated with metamorphic biotite. The presence of hornblende (Felton & Huleatt, 1977, appendix 1, p. 83) and a few accessory crystals of brown allanite in the more mafic varieties of the intrusion indicates the Ellenden Granite is I-type. Chemical analyses are given in Table 22.

Age and relationships. Originally the Ellenden Granite was included with unnamed foliated granites of Late Silurian age on the 1st Edition of the Canberra 1:250 000 geological sheet (Joplin & others, 1953). However, on field and petrographic relationships Felton & Huleatt (1977) regarded the intrusion as the same age as the Early Devonian Boro and Braidwood Granites. On CANBERRA, the Ellenden Granite intrudes and hornfelses Late Ordovician metasediments, and near Red Hill (MR 249/081) strongly veins the Late Silurian Lockhart Basic Complex. An Early Devonian age is suggested by an exposure east of 'Lakelands' homestead (MR 270/012) where Late Silurian Woodlawn Volcanics are intruded by the Ellenden Granite, which is in turn cut by a northwest-trending Early Devonian(?) dolerite dyke (Pl. 12); all rocks are well foliated.

Chemical analyses suggest that the Ellenden Granite may be comagmatic with a group of foliated granites west of the Mulwaree Fault on ARALUEN. A biotite/whole-rock Rb–Sr age of 380 ± 6 Ma on one of these intrusions (Gourock Granodiorite) suggests the isotopic system was reset by the Middle Devonian Tabberabberan deformation.

Gibraltar Adamellite (Dgi)

Derivation. From Gibraltar Hill (897 m), 3 km east of Bungendore.

Distribution. The Gibraltar Adamellite crops out over an area of about 2 km^2. The outcrop area is elongated meridionally and forms a prominent wooded ridge extending about 3 km south from the Kings Highway.

Type locality. Bouldery and pavement outcrops at and near Gibraltar Hill.

Description. The Gibraltar Adamellite is well exposed as a bouldery hump-backed ridge/hill. The main rock type is a medium to coarse biotite adamellite with discoidal mafic-rich xenoliths. A strong foliation is concordant with the regional cleavage in surrounding country rocks.

The rock is composed of multiple-twinned plagioclase which retains strongly sericitised and saussuritised oscillatorily-zoned cores. Anhedral perthitic K-feldspar, in large crystals up to 5 mm, is relatively fresh. Aggregates of polygonal fine-grained quartz and laths of fresh brown metamorphic biotite intergrown with epidote are drawn out into the foliation. A few brown euhedral grains of allanite confirm the intrusion is I-type.

Age and relationships. The Gibraltar Adamellite intrudes Late Ordovician metasediments. The boundary can be accurately mapped at the change in slope with the softer

Table 22. Ellenden Granite: major and trace element analyses (adamellites)

Sample no.	*76460164*	*76460174*	*LFB 281 (ANU)*
Grid ref.	*250140*	*264087*	*273007*
%			
SiO_2	71.66	77.33	73.79
TiO_2	0.49	0.17	0.24
Al_2O_3	13.42	11.57	12.86
Fe_2O_3	1.00	0.71	0.91
FeO	2.36	1.00	1.43
MnO	0.06	0.04	0.02
MgO	1.03	0.14	0.48
CaO	1.24	0.52	2.41
Na_2O	2.62	3.21	2.78
K_2O	4.28	4.39	3.46
P_2O_5	0.18	0.05	0.05
H_2O+	1.08	0.48	0.81
H_2O-	0.08	0.10	0.15
CO_2	0.13	0.12	—
Total	99.80	100.00	99.39
ppm			
Ba	530	520	550
Rb	190	200	140
Sr	100	36	177
Pb	20	16	36
Th	20	28	21.4
U	4	6	4.6
Zr	220	220	161
Nb	8	10	9.5
Y	40	80	36
La	40	60	32
Ce	100	150	81
Nd	—	—	30
Sc	—	—	10
V	50	10	21
Cv	20	10	4
Mn	—	—	175
Co	5	5	4
Ni	10	5	1.5
Cu	12	6	2.5
Zn	43	37	16
Ga	—	—	14.6

metamorphics. In a creek east of the intrusion (MR 257/934) a contact is indicated by fine-grained adamellite-gneiss with abundant Ordovician metasedimentary xenoliths. A contact aureole in the surrounding metamorphics is masked by the higher regional metamorphic grade. The intrusion is the same age as the strongly foliated Early Devonian Ellenden Granite and Rossi Granodiorite.

Rossi Granodiorite (Dgr)

The Rossi Granodiorite (Wyborn & Owen, 1986, p. 14) forms part of a group of foliated granitoids in the extreme east of the Sheet area, west of the Mulwaree Fault (on BRAIDWOOD).

On CANBERRA the intrusion crops out over a total area of about 5 km^2, extending north intermittently for 30 km from the southeast corner of the Sheet area in a series of strongly aligned linear outcrops. The granodiorite has a strong meridional foliation. Along its western edge the granodiorite intrudes Late Ordovician metasediments and gabbro and amphibolite of the Late Silurian Lockhart Basic Intrusive Complex (Pl. 14). Wyborn & Owen (1986, p. 15) consider the Rossi Granodiorite to be probably Early Devonian.

Several small poorly exposed foliated stocks of granite, adamellite and granodiorite of probable Early Devonian age are marginally associated with the Ellenden Granite and Rossi Granodiorite. Their I-type affinities are indicated by the presence of allanite and cognate hornblende-rich xenoliths.

Other porphyry intrusions (p)

Minor unnamed bodies of dacitic and rhyodacitic porphyry are spatially associated with Siluro-Devonian and Early Devonian granitic intrusions on CANBERRA. Similar rocks have been noted on BRAIDWOOD (Felton & Huleatt, 1977) and MICHELAGO (Richardson, 1979; Hayden, 1980).

The porphyries normally occur as north-trending dykes which are rarely more than a few metres wide and can be traced only over short distances. In areas of good outcrop, they can be seen to have sharp irregular contacts and occasionally a thin zone of contact metamorphism. Lack of continuity along strike and lack of discordance with bedding, together with the presence of foliation, suggests the dykes may have been drawn out into lenticular bodies, i.e. boudinaged, such that they now appear concordant with the tectonic trend of the country rock. However, in a triangular area between the Molonglo River and the Kings Highway, especially between the highway and the railway, a complex outcrop pattern of irregular intrusions trending northeast and northwest may be a result of deformation (Wilson, 1964; Stauffer, 1964).

In the field the porphyries are white, cream or grey. They contain quartz and feldspar phenocrysts (1–5 mm) and a few small, dark-grey, discoid metasedimentary xenoliths dispersed through a fine-grained groundmass. A visible foliation, expressed in severe flattening of the quartz phenocrysts and shredding of altered mafics, parallels the slaty cleavage in the surrounding metasediments. The more intensely deformed porphyries east of the Ballallaba Fault are now quartzo-feldspathic gneisses, in places showing a mineral-streaked lineation that parallels minor fold axes in the adjacent sediments. At the western margin of the Captains Flat Block a strongly deformed, meridional-trending felsic porphyry intrusion crops out extensively east of 'Clare' homestead (MR 160/987) and 'Summerhill' homestead (MR 155/033). Some portions of this intrusion may contain a component of volcanic rock (undifferentiated on the map).

The original porphyritic igneous texture of the rocks is preserved as phenocrysts of slightly embayed, bipyramidal beta-quartz. Feldspar phenocrysts are predominantly subhedral, polysynthetically twinned, albitic plagioclase, commonly altered to sericite, epidote and calcite; some crystals preserve a concentrically zoned internal structure. Anhedral microperthitic potash feldspar is much reduced in the phenocrystic phase and generally subordinate to plagioclase. Mafic minerals normally constitute < 10% of the rock. Primary mafics are indicated by fresh brown biotite, simply twinned prismatic and basal sections of greenish-brown pleochroic hornblende and minor pale-green orthopyroxene. The groundmass is a fine granular mosaic of quartz and feldspar with rosettes of epidote and minor chlorite and opaques. Myrmekitic and spherulitic growths around plagioclase and quartz phenocrysts occur in some of the less deformed specimens.

The porphyries have undergone varying degrees of regional deformation and metamorphism. Quartz shows undulose extinction and is commonly fractured and marginally granulated. Plagioclase phenocrysts may have bent or broken twin lamellae but otherwise show little preferred direction of elongation or shape change. Kinked prismatic sections of biotite are altered to chlorite. Amphibole is replaced by actinolite and epidote while orthopyroxene is rimmed by uralite. Completely altered mafics are outlined by patches of intergrown greenish-brown actinolite, epidote and opaques. In the intensely deformed rocks, segregated felsic bands are emphasised by elongate and lenticular patches of recrystallised polycrystalline quartz, flattened and drawn out into the plane of foliation. Mafic bands

Table 23. Other felsic porphyry intrusions: major and trace element analyses (quartz-feldspar porphyries)

Sample no.	*76460036*	*76460063*	*76460279*
Grid ref.	*163015*	*105872*	*021207*
%			
SiO_2	73.62	70.87	75.60
TiO_2	0.26	0.46	0.12
Al_2O_3	13.03	13.56	13.10
Fe_2O_3	0.70	1.19	1.24
FeO	1.33	2.70	<0.02
MnO	0.07	0.10	0.02
MgO	0.74	1.16	0.20
CaO	0.39	2.23	0.75
Na_2O	4.65	3.70	4.04
K_2O	2.89	1.93	3.70
P_2O_5	0.05	0.10	0.02
H_2O+	1.16	1.39	0.70
H_2O-	0.04	0.07	0.05
CO_2	0.05	0.25	—
Total	99.14	99.90	99.56
ppm			
Ba	680	620	960
Rb	50	50	120
Sr	110	330	220
Pb	8	28	42
Th	12	10	14
U	<4	6	6
Zr	260	200	130
Nb	<10	8	10
Y	34	34	80
La	30	30	40
Ce	80	80	130
V	15	50	<20
Cr	15	15	<10
Co	8	15	5
Ni	<5	5	<5
Cu	30	10	13
Zn	50	80	12

Table 24. Summary of mafic intrusions

Age	*Rock type*	*Mineralogy*	*Magma type*	*Geographic trend*	*Deformation*	*Metamorphic facies*	*Relationships*
TERTIARY (d_3)	Olivine dolerite	Olivine, titanaugite; plagioclase-undersaturated	Subalkaline basalt	?	Undeformed		Intrude Hawkins Volcanic Suite (Wenlockian)
	Olivine teschenite	Olivine; analcime; titanaugite and kaersutite; quartz and plagioclase absent; 15% magnetite; undersaturated	Alkali basalt	NW	Undeformed	Unmetamorphosed	Intrude Laidlaw Volcanic Suite (Ludlovian)
EARLY DEVONIAN (d_2)	Dolerite; minor quartz dolerite and gabbro	*HS* — dark-grey; fine-grained; may be magnetic. *TS* — clinopyroxene interstitial to plagioclase (albitised); aggregates of serpentine, chlorite & magnetite may be altered mafics (olivine, orthopyroxene). Titanaugite partly altered to actinolite; up to 8% magnetite; up to 6% quartz. Some geochemical analyses give 5% SiO_2	Tholeiitic basalt with alkaline associations	E–W to NW—SE	Weakly deformed in volcanics and granitoid rocks in the Canberra and Cullarin Blocks; foliated east of Whiskers Fault by mid Devonian Tabberabberan deformation	Greenschist	Intrude Early Devonian granitoids (Ellenden Granite) Coeval with latitudinal dykes on MICHELAGO and ARALUEN
LATE SILURIAN (d_1)	Gabbro and minor dolerite; includes hybrid diorite and contaminated gabbro of the Lockhart Basic Intrusive Complex (Sa)	*HS* — greyish-green; coarse-grained mottled texture, non-magnetic. *TS* — ophitic/subophitic plagioclase/clinopyroxene (altered to actinolite-hornblende). Quartz accessory or absent. Ilmenite associated with sphene; clinozoisite; albitisation of plagioclase; some geochemical analyses give 16% Al_2O_3	High-Al tholeiitic basalt	N–S	Foliated by mid Devonian Tabberabberan deformation	Upper greenschist to lower amphibolite	Postdate Late Ordovician metasediments and Late Silurian Hoskinstown Group. Predates Siluro-Devonian and Early Devonian granites. Coeval with Lockhart Basic Intrusive Complex

are denoted by streaks of metamorphic biotite, muscovite, epidote and blue-green amphibole that are also deflected around plagioclase and quartz augen. In some cases the sheared groundmass has been recrystallised into a granulitic mosaic of sutured quartz and feldspar containing biotite and muscovite flakes and grains of epidote.

Chemical analyses for these rocks are given in Table 23.

Felsic porphyry dykes intrude Late Ordovician metasediments in the Cullarin and Rocky Pic Blocks. Contacts can be seen in a creek section south of the Collector–Gundaroo road (MR 140/210), in a steep track leading down to 'Silver Wattle' homestead (MR 173/083), in a cutting on the Federal Highway at Gearys Gap (MR 165/133), in creeks east of 'Grove Creek' homestead (MR 155/119), and in an excellent exposure (Pl. 13) in a creek about 1 km south of the Hoskinstown–Rossi road (MR 260/724). A biotite/total-rock Rb–Sr age of 407 ± 4 Ma (initial $^{87}Sr/^{86}Sr$ ratio 0.7110) obtained by AMDEL (AC3536/79) from a relatively undeformed dacitic porphyry at MR 111/134, is slightly younger than that obtained from the Sutton Granodiorite (latest Silurian). A few felsic porphyry bodies intrude the Late Silurian sequence in the Captains Flat Graben. At Burke Hill (MR 182/871) and along the eastern margin of the trough discontinuous dyke-like bodies of dacitic porphyry intrude the Copper Creek Shale and Captains Flat Formation (Wilson, 1964; Stauffer, 1964; Bird, 1984). Early Devonian(?) northwest-trending dolerite dykes vein and cut across these acid porphyries in the Cullarin Block.

The concentration of felsic porphyry intrusions along the western margin of the Captains Flat Block suggests they might have been a source for acid volcanism on the Cullarin Block during the Late Silurian, of which the products have been eroded. The presence of allanite and hornblende in these rocks indicates affinities with the Laidlaw Volcanic Suite and probably the I-type granites. The dacitic and rhyodacitic porphyry intrusions near the eastern margin of the Captains Flat Graben and in the Rocky Pic Block appear related spatially to the Early Devonian granitoids (Ellenden Granite and Rossi Granodiorite) cropping out at the eastern margin of the Sheet area.

Mafic intrusions

Three groups of basic intrusive rocks are distinguished on CANBERRA (Table 24). The emplacement of two Palaeozoic suites, each of tholeiitic gabbro and dolerite, represents magmatic activity that began in the Late Silurian and extended through into the Early Devonian. A few alkaline mafic intrusions provide evidence for renewed activity in the Tertiary.

Parallel Palaeozoic basic dykes with meridional and latitudinal trends, minor basic sills and small basic stocks mainly crop out along structural highs flanking the Captains Flat Block. Over a small area of the Cullarin Block, Stauffer & Rickard (1966) attributed the outcrop pattern of differently oriented groups of basic intrusions to synformal folding. However, it is likely that these trend differences are related to periods of crustal extension in the Late Silurian–Early Devonian (Wyborn, 1977; Cas, 1983; Wyborn & Owen, 1986). Whatever structural controls may have determined their emplacement, they are distinguished as two suites of basic intrusions on mineralogy and age relationships (Table 24).

Late Silurian

Dykes, sills, and plugs (d_1)

North-trending basic dyke swarms are common in the eastern half of the Sheet area. Primary rock types are gabbro and dolerite, subsequently deformed and regionally metamorphosed to amphibolite.

With careful mapping, some intrusions can be traced for several kilometres on the western side of the Captains Flat Block. A discontinuous sill of gabbro up to 100 m thick crops out for about 3 km along the Balcombe–Burke ridge (Stauffer, 1964). A sill of gabbro and dolerite offset by small faults can be traced for 7 km along the Lake George Range, north of the Kings Highway. However, most of the intrusions are intermittently exposed as meridional dykes < 5 m thick subparallel to the regional strike. Small stocks and plugs of gabbro occur in Primrose Valley Creek (MR 150/730), along the shore of Lake George northwest of 'Dinton' homestead, and a few kilometres northeast of One Tree Hill (MR 936/114).

The main rock type is a mottled greyish-green gabbro (altered to amphibolite) which crops out as elongate bouldery knolls. Dark-green amphibole megacrysts up to 5 mm and greyish-white groundmass plagioclase are responsible for the mottling. The mineralogy is dominated by relict igneous plagioclase and metamorphic amphibole. Plagioclase is largely a groundmass mineral which forms a plexus of elongate subhedral crystals up to 2 mm. Complex twinning and low extinction angles indicate that albite (An_{10}) has totally replaced calcic plagioclase. Zoned crystals have calcic cores altered to sericite and epidote. Sporadic phenocrysts of plagioclase occur in the doleritic rocks. Phenocrysts of clinopyroxene (titanaugite?) are pseudomorphed by pale-green actinolite that has regressed to patchy chlorite. Subophitic and ophitic textures are preserved where plagioclase laths project into or are totally enclosed by large pseudomorphs of clinopyroxene. Actinolite also occurs as clusters of needles intergrown with plagioclase. Irregular patches of chlorite and small laths of highly birefringent clinozoisite may represent an altered mafic mineral (orthopyroxene?). Quartz occurs in an accessory capacity as interstitial polygonal granules. Other accessories are sphene in close association with ilmenite, microcrystalline aggregates of calcite, and brown hornblende. The primary igneous texture of these rocks has been modified by deformation and regional metamorphism. This is evident from bent and fractured plagioclase, lenticular strings of sphene and ilmenite elongated parallel to the foliation and the growth of secondary minerals such as albite, actinolite, clinozoisite, chlorite, sericite and calcite. Chemical analyses of these rocks are given in Table 25. Malone & others (1975) also provide analyses for dolerite intrusions of this age at Woodlawn Mine (on BRAIDWOOD).

A Late Silurian age is probable for this group of basic intrusions. They postdate Late Ordovician metasediments and the Late Silurian Hoskinstown Group. According to Hayden (1980) similar rocks (termed amphibolites) on MICHELAGO are truncated by Siluro–Devonian granite intrusions. These basic rocks were probably derived from a common tholeiitic or high-Al basaltic magma similar to the Lockhart Basic Intrusive

Complex (see below). Bird (1984) notes a geochemical similarity between basic volcanics and intrusions along the western margin of the Captains Flat Block, a relationship consistent with gabbro and dolerite being source rocks for the periodic extrusion of thin basaltic units in the Captains Flat Formation. The meridional trend of the dykes suggests their emplacement was associated with active fracture systems of deep crustal or mantle depth (Whiskers and Ballallaba fault zones). Their orientation also indicates that a latitudinal tensional regime (rifting) existed during the Late Silurian.

Lockhart Basic Intrusive Complex (Sa)

Derivation. After 'Lockhart' Station (homestead on BRAIDWOOD, MR276/872).

Nomenclature. Garretty (1936) mapped a belt of metamorphosed mafic rocks (amphibolite and hornblende schist) on the eastern foreshore area of Lake George which he termed 'Amphibolite Series'. Read (1961) mapped this belt of rocks south into the Bungendore–Hoskinstown area where he reinterpreted it as basic intrusives and named it the 'Lockhart Igneous Complex'; a summary description was given by Vallance (1969). On the Second Edition of the Canberra 1:250 000 Geological Sheet the complex is delineated as intermediate and basic intrusions (ib) or shown as Silurian acid volcanics (Sv). Enough detail is now available on the extent, nature and association of rock types to justify formalising the name to Lockhart Basic Intrusive Complex.

Distribution. Mafic rocks of the Complex form a belt up to 2 km wide cropping out along the border between CANBERRA and BRAIDWOOD. The western boundary extends from southeast of Hoskinstown 25 km north to the Bungendore–Tarago road, where it is overlain by alluvium. The intrusion reappears trending north-northwest on the eastern side of Lake George. The eastern limits of the complex require further definition on BRAIDWOOD (Felton & Huleatt, 1977).

Table 25. Late Silurian basic intrusives: major and trace element analyses

Sample no.	76460072	76460073	76460076	76460142	76460158
Rock type	*dolerite*	*dolerite*	*gabbro*	*gabbro*	*gabbro*
Grid ref.	167962	178945	175935	934112	251193
%					
SiO_2	46.59	48.83	49.67	47.28	47.61
TiO_2	1.08	1.13	2.02	0.88	2.03
Al_2O_3	17.15	16.33	15.59	17.22	14.78
Fe_2O_3	1.81	2.00	2.70	1.18	1.56
FeO	7.25	6.95	8.55	6.88	9.97
MnO	0.18	0.17	0.20	0.14	0.14
MgO	9.40	7.55	5.20	9.74	7.60
CaO	9.76	10.87	7.72	10.25	9.82
Na_2O	2.35	2.20	4.25	2.52	2.74
K_2O	0.55	0.24	0.12	0.24	0.18
P_2O_5	0.12	0.16	0.25	0.14	0.20
H_2O+	3.83	3.17	3.04	3.18	3.18
H_2O-	0.09	0.07	0.04	0.04	0.04
CO_2	0.05	0.10	0.10	0.23	—
Rest	0.20	0.19	0.19	0.16	—
Total	100.41	99.96	99.64	100.08	99.86
ppm					
Ba	290	85	70	30	46
Rb	22	8	2	11	8
Sr	220	220	300	320	150
Pb	<2	5	<2	<2	500
Th	<4	<4	<4	8	—
U	<4	<4	<4	<4	4
Zr	75	85	135	90	135
Nb	<5	6	10	<4	<4
Y	24	24	34	20	<4
La	<10	<10	20	<20	<20
Ce	<10	40	50	30	50
V	250	270	430	160	240
Cr	300	340	20	280	80
Co	50	40	40	45	45
Ni	70	70	20	75	70
Cu	70	60	90	76	35
Zn	70	80	90	53	80

Type area. Fresh outcrops of amphibolite and gabbro along a watershed in the vicinity of 'Lockhart' homestead.

Description. The Lockhart Basic Intrusive Complex is a narrow meridional belt of metabasic intrusions separating Late Ordovician metasediments (Birkenburn beds) from the Rossi Granodiorite. The bulk of the complex consists of amphibolite, lesser amounts of gabbro with local cumulate layering, and minor quartz diorite. Petrological descriptions for these rock types are available in Read (1961), Rigden (1976), and Felton & Huleatt (1977); full geochemical analyses are given in Rigden (1976).

Specimens examined from the complex show textures consistent with primary dolerite and gabbro that have been deformed and regionally metamorphosed to the lower amphibolite facies. Some of the amphibole in rocks of the complex may be primary hornblende but generally regional metamorphism has progressively altered the original pyroxene to actinolite. The excess calcium produced during metamorphism has given rise to widespread development of epidote and sphene. Rigden (1976) considered the presence of amphibole in place of biotite to be a function of the low-K content of these rocks (av. 0.32%). A foliation which is most pronounced in the amphibolite is a product of aligned amphibole, lenticular quartz, occasional augen, and deformed twin lamellae in plagioclase.

Coarse, massive, mottled, greenish-grey gabbroic rocks crop out as tors and knolls and contain megacrysts of dark-green amphibole up to 5 mm. The varieties of amphibole identified are brownish-green hornblende with diagnostic basal sections and blue-green actinolite sometimes with four-sided cross-sections. The amphiboles show remnant areas of pyroxene and inclusions of accessory apatite, sphene and opaques. Groundmass minerals include orthopyroxene granules, uralite and aggregates of clinozoisite enclosed by quartz, microcline and albitic plagioclase.

Dark-green, fine-grained, equigranular amphibolite weathers to low lying rubbly outcrops. The essential mineralogy comprises ragged subhedral crystals of uralitic hornblende or actinolite pleochroic in shades of brown, green and blue. Calcic plagioclase occurs either as subhedral microphenocrysts up to 3 mm or as smaller elongate laths which are zoned, complexly twinned and invariably saussuritised. Patches of polygonal recrystallised quartz may form up to 10% of the rock. Epidote and ilmenite rimmed by sphene are acccessories. A remnant intergrowth of subophitic plagioclase and uralite is preserved in coarse-grained specimens.

Hybrid dioritic rocks which may be a marginal facies of the complex are denoted by increased plagioclase (often as phenocrysts) and quartz. Brown metamorphic biotite may exist as an intergrowth with blue-green pleochroic amphibole.

Age and associations. The complex is probably Late Silurian. It intrudes the Late Ordovician Birkenburn beds and is itself intruded by the probably Early Devonian Ellenden Granite and Rossi Granodiorite. A well exposed contact at MR 265/854 shows angular blocks of amphibolite entrained and intermixed on a fine scale with the Rossi Granodiorite (Pl. 14). At another contact, on the Lake George foreshore west of Red Hill (MR 243/079), amphibolite of the complex is veined by the Ellenden Granite (Pl. 15).

Rigden (1976) states that the complex is chemically similar to the Late Silurian Micalong Basic Igneous Complex on BRINDABELLA. Wyborn & Owen (1980) confirmed this and also showed that there is a significant chemical difference from the Late Devonian Donovan Basic Complex in the Comerong Rift Zone on ARALUEN. Although geochemical data are lacking it is tempting to speculate on a petrogenetic relationship with the Late Silurian Currawang Basalt to the northeast.

The petrological and geochemical data suggest the Lockhart Basic Intrusive Complex evolved by differentiation of a high-alumina tholeiitic basalt magma (Rigden, 1976). There is no chemical or mineralogical evidence for a genetic relationship with granitic rocks as suggested by Read (1961). However, it is possible that mobilisation of mafic rocks in the mantle or base of the crust provided a heat source for the production of granites higher in the crust, e.g. Rossi Granodiorite.

Early Devonian

Local dolerite dyke swarms and isolated dykes up to 5 m in width (d_2) with trends varying from west to northwest become more abundant and progressively altered and foliated eastwards as far as the Mulwaree Fault on BRAIDWOOD. Minor gabbro occurs in the centres of some dykes.

The dolerite dykes are best preserved and most easily mapped in fractured granites and felsic volcanics. In hand specimen they are dense, fine-grained, dark-green rocks, some of which attract a hand magnet and this enables them to be distinguished in the field from the older metamorphosed meridional basic intrusions. The thin-section mineralogy is dominated by an interlocking mosaic of plagioclase, clinopyroxene and magnetite. Subhedral plagioclase laths up to 1 mm are complexly twinned and sometimes zoned, and have a composition varying from An_{10-55}; late alteration is to albite, chlorite and saussurite. Colourless to pale-pink subhedral titanaugite up to 0.5 mm is usually interstitial to plagioclase, although subophitic growths are found in the gabbroic phases. Titanaugite may alter to blue-green uralite and brown amphibole (barkevikite?). An altered mafic mineral (olivine or orthopyroxene) is represented by aggregates of epidote, bright-green chlorite, brown serpentine and magnetite. Clear, interstitial quartz sometimes in myrmekitic growth with plagioclase is a late primary phase. Dispersed phenocrysts of strained beta-quartz rimmed by uralite occur in a dolerite dyke cutting a marginal intrusion of the Sutton Granodiorite (MR 088/107). Rocks in this group containing up to 6% quartz are saturated enough to be termed quartz dolerite. Secondary magnetite (up to 8%) is abundant as equant subhedral crystals formed by the release of iron during the alteration of mafic minerals. Sphene and calcite occur as accessories. Chemical analyses for these rocks are given in Table 26.

The best estimate for the age of these basic dykes is Early Devonian. West of the Queanbeyan Fault the dykes are undeformed and postdate the Laidlaw Volcanics (e.g. MR 883/753) and Late Silurian (Pridoli?) Barrack Creek Adamellite. East of Lake George this group of dolerite dykes intrudes the Early Devonian Ellenden Granite. Since both dykes and granite are foliated, they are taken to predate the mid Devonian Tabberabberan deformation. The west to northwest-trending dolerites on CANBERRA have a mineralogy and age relationship which compares with similarly oriented dykes on MICHELAGO (Richardson, 1979; Hayden, 1980) and on ARALUEN (Wyborn & Owen, 1986). A whole-rock K–Ar age of 338 ± 5 Ma is reported by Wyborn & Owen (1986. p. 21) from an undeformed east-west dyke swarm cutting the Early Devonian Jinden Adamellite on ARALUEN. This Early Carboniferous date could be a minimum age for these intrusions, representing progressive long-term argon leakage initiated during the Tabberabberan and Kanimblan deformations. The mineralogy and chemistry of the dolerite intrusions indicate that they are tholeiitic and therefore unrelated to the alkaline Tertiary Monaro basalts (Kesson, 1973).

Table 26. Early Devonian basic intrusives: major and trace element analyses

Sample no.	*76460037*	*76460053*	*76460061*	*76460090*
Rock type	*dolerite*	*dolerite*	*dolerite*	*gabbro*
Grid ref.	*129007*	*122967*	*091887*	*990733*
%				
SiO_2	48.75	50.17	51.80	47.25
TiO_2	1.18	1.11	2.12	3.39
Al_2O_3	15.71	15.38	14.65	13.20
Fe_2O_3	2.57	2.60	2.96	4.95
FeO	6.55	6.15	8.80	9.65
MnO	0.17	0.18	0.22	0.25
MgO	7.80	7.50	4.00	5.25
CaO	11.72	10.78	7.59	9.40
Na_2O	2.05	2.10	3.50	2.90
K_2O	0.40	0.34	0.31	0.50
P_2O_5	0.14	0.17	0.52	0.50
H_2O+	2.76	2.93	3.17	1.90
H_2O-	0.06	0.03	0.03	0.28
CO_2	0.05	0.10	0.15	0.05
Rest	0.16	0.18	0.16	0.23
Total	100.07	99.72	99.98	99.70
ppm				
Ba	70	70	120	150
Rb	28	16	7	16
Sr	200	220	180	290
Pb	<2	4	4	<2
Th	<4	<4	<4	<4
U	<4	<4	<4	<4
Zr	60	100	215	230
Nb	<10	6	8	12
Y	22	24	50	46
La	<10	<10	<10	<10
Ce	40	20	60	40
V	300	280	280	550
Cr	190	250	25	60
Co	40	40	30	50
Ni	60	70	15	25
Cu	70	70	30	40
Zn	80	80	140	130

Tertiary

Basic intrusions of probable Tertiary age (d_3) are known from two locations on CANBERRA. An undeformed tabular body of olivine teschenite, intrudes the Laidlaw Volcanics near Red Rocks Gorge (MR 841/798). Its northwest trend parallels the regional strike of the host volcanic rocks; a weathered exposure of the same rock in a creek at MR 860/776 suggests it may extend a further 2 km southeast. In outcrop the intrusion comprises two parallel bodies each about 0.5 m thick; a strong layering accentuated by weathering parallels the margins. In thin section the rock consists of dispersed subhedral microphenocrysts of olivine in varying degrees of alteration to serpentine. The groundmass consists of intergrown zoned pinkish-brown titanaugite (concentrated into layers) and brown amphibole (kaersutite?) laths with octahedral granules of magnetite (15% of the rock) embedded in an interstitial goundmass of colourless, isotropic analcime. The age and affinities of this intrusion are unclear but the undersaturated nature of the rock suggests it may be related petrologically to an olivine teschenite plug of Tertiary age on MICHELAGO (Richardson, 1979).

In geological investigations for the Molonglo Valley interceptor Sewer (Purcell & Simpson, 1973), an olivine dolerite was intersected in drillholes (MV3 and MV5) on the line of Ryans Tunnel (MR 867/915). The dolerite intrudes the Mount Painter Volcanics and from the subsurface data was interpreted as a sill. It consists of randomly oriented laths of plagioclase enclosing olivine and clinopyroxene. Simply twinned plagioclase laths (An_{35-60}) average about 1 mm; calcic cores of zoned crystals may be altered to sericite. Subhedral brownish-green olivine is totally serpentinised. Fresh anhedral brownish-pink titanaugite is in subophitic intergrowth with plagioclase. Accessories are magnetite (closely associated with altered olivine), quartz and calcite.

Metamorphism

Early Palaeozoic rocks in the Canberra region have been affected by regional and contact metamorphism. Veevers (1951) established that chlorite, biotite and andalusite characterised Ordovician pelites on MICHELAGO. Hayden (1980) used these index minerals to map regional metamorphic zones in similar rocks near Jerangle (MICHELAGO). On TANTANGARA, metamorphic zones reaching upper-greenschist facies were demonstrated for basic rocks in the Late Ordovician Kiandra Group and Gooandra Volcanics (Owen & Wyborn, 1979). In the Canberra Block Late Silurian volcano-sedimentary rocks have metamorphic assemblages 'for the most part of lower grade than greenschist' (Crook & others, 1973). Wilson (1964) has described metamorphic assemblages reaching upper-greenschist facies in Late Silurian sequences in the Captains Flat Block and lower-amphibolite facies in the Late Silurian Lockhart Basic Intrusive Complex. Contact-metamorphic rocks have received only passing reference on CANBERRA. Stauffer & others (1964) refer to the contact aureole of the Sutton Granodiorite and Öpik (1958), Smith (1964) and Goldsmith & Evans (1980) briefly describe hornfelsed calcareous rocks in the Canberra Block. A metamorphic facies map and tabulated summary of metamorphism on CANBERRA is given in Figure 23 and Table 27.

Regional metamorphism

As a result of the present work, two separate episodes of regional metamorphism — M_1 and M_2 — can be identified on CANBERRA. M_1 is represented by prehnite–pumpellyite to lower amphibolite facies, associated with anatexis and magma emplacement into shallow crustal levels prior to volcanism in the Late Silurian. M_2 is represented by upper greenschist to lower amphibolite facies expressing renewed magmatic activity in the Early Devonian, followed by the Tabberabberan deformation in the mid-Devonian.

Ordovician rocks

Late Ordovician quartz-rich turbidites have been affected by low-to-medium-grade regional metamorphism (M_1). Widespread biotite-bearing and locally calc-silicate rocks indicate the upper greenschist facies, and cordierite porphyroblasts in knotted schist represent the lower amphibolite facies.

The western limit of the biotite isograd on CANBERRA coincides with the western fault-bounded margin of the Cullarin Block where there is a fault contact between the biotite-grade Ordovician metasediments of the Cullarin Block and the chlorite-grade volcano-sedimentary rocks of the Canberra Block (Fig. 23). In the Ordovician rocks, the biotite isograd coincides almost everywhere with faults and is rarely observed as such in the field.

Incipient weakly pleochroic biotite is microscopically visible in psammitic rocks (< 1%) as small flakes roughly aligned in the cleavage. In lepidoblastic pelites, biotite is more fully developed as thin streaky flakes unimpeded by quartz.

Lower-amphibolite-grade psammitic and pelitic schist and knotted schist are exposed in a central north-trending area measuring 11 x 4 km (Op_1) in the southern part of the Cullarin Block. They are described in varying detail on MICHELAGO by Veevers (1951), Hill (1975) and Hayden (1980). The schists grade northwards into lower-grade phyllite and quartzite. The psammites are pale-grey with crenulated pelitic laminae up to 10 mm apart. The pelites are lustrous brownish-black biotite schist with psammitic laminations up to 2 mm thick; sporadic diffuse cordierite porphyroblasts occur on foliation planes. The mica- and quartz-rich laminae probably represent bedding or an early segregation layering. The pelitic laminae are rich in biotite, muscovite and opaques. The quartz-rich layers consist of a framework of quartz grains up to 1 mm set in an intergranular mosaic of quartz, subordinate biotite, muscovite and accessory tourmaline and zircon. The crenulation cleavage, spaced at intervals of about 0.05 mm, is expressed in the re-aligned growth of biotite and quartz augen.

Higher-grade, knotted schist (Op_2) occurs in two parallel belts separated by psammitic and pelitic schist. The best exposures are in Bradleys Creek at MR 100/750 and along the fire trail leading into the Googong Reservoir catchment from the abandoned homestead 'Rogers' at MR 075/694. The knotted schist is easily mapped. The knots are pseudomorphs (retrogressed porphyroblasts) of cordierite occurring on silvery-grey, lustrous foliation planes. The pseudomorphs are zoned, with a soft inner core of chlorite with accessory quartz, biotite, muscovite and opaques and an outer rim of sericite and quartz. The porphyroblasts were pre-tectonic (or possibly syntectonic): their long axes (max. 4 mm) are parallel to and wrapped around by the foliation; they are bordered by quartz-rich pressure shadows and in some cases they contain inclusions oblique to the foliation, implying rotation after growth (Vernon, 1978).

Calc-silicate beds (Pl. 16) occur in overturned quartz-turbidite beds in a 100 m section of Gundaroo Creek at MR 092/240. The beds average 10 cm in thickness. They consist of a thin, hard, bluish-grey siliceous envelope and a softer pale-grey cross-laminated core emphasised by small elongate solution holes. The envelope is a reaction rim of granular quartz and pale-green fibrous clusters of tremolite–actinolite; the core consists of granular clinozoisite, quartz and patches of relict calcite. The sandy framework of the beds is typified by subrounded quartz, feldspar and rock fragments. The assemblage is taken to have resulted from prograde regional metamorphism of calcareous arenites.

Biotite-grade Ordovician rocks also crop out in the Rocky Pic Block (M_2). Foliated beige psammo-pelitic schist (Ob_1) forms a belt up to 3 km wide marginal to the Lockhart Basic Intrusive Complex and Rossi Granodiorite. The pelitic laminae are defined by segregated muscovite and biotite with accessory

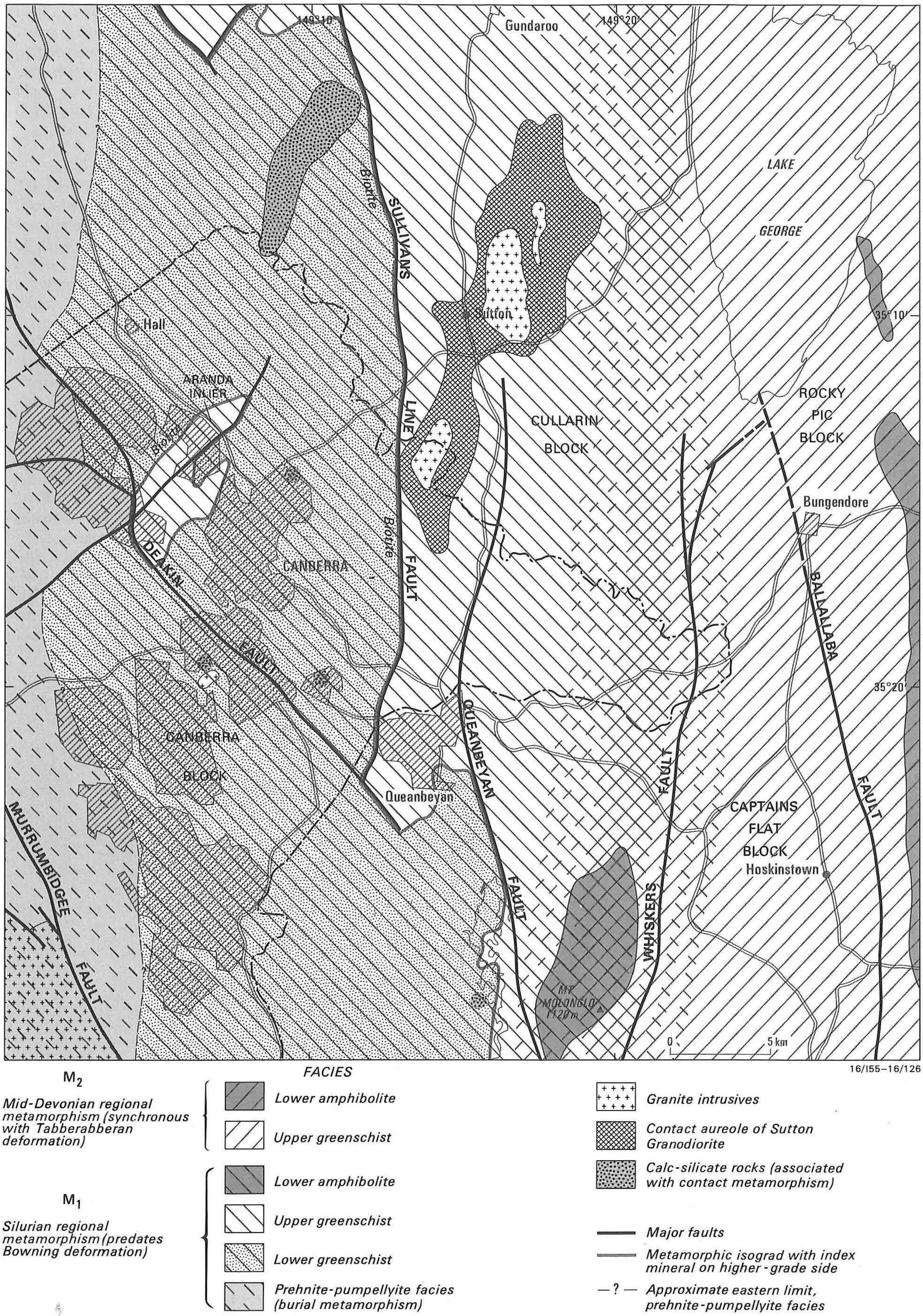


Fig. 23. Distribution and age of metamorphism.

Table 27. Summary of metamorphism

Type	*Distribution*	*Lithology*	*Index minerals*	*Facies*	*Age*	*Remarks*
Regional (M_2)	Rocky Pic Block; Captains Flat Block westwards to Whiskers Fault and beyond to the eastern margin of the Cullarin Block	Amphibolite (Lockhart Basic Intrusive Complex) Psammo-pelitic schist	Hornblende, biotite	Lower amphibolite – upper greenschist	Mid Devonian	1) Increased geothermal gradient associated with Early Devonian magmatic activity 2) Regional metamorphic peak coincident with Tabberabberan deformation (mid-Devonian) 3) Age control by metamorphic sericite (370–380 Ma) and biotite (374 ± 3 Ma) from Kohinoor Volcanics in Captains Flat Block
Declining regional phase (M_1)	Cullarin Block; Canberra Block	Mineral alteration; no specific rock types	Chlorite, albite	Lower greenschist – prehnite-pumpellyite	Early Devonian	Retrograde effects in Ordovician rocks. Burial metamorphism in Silurian rocks
			D_2 DEFORMATION			
Contact	Canberra Block; Cullarin Block	Pelitic and psammitic hornfels; calc-silicate hornfels	Cordierite, biotite, tremolite, diopside, grossularite	Hornblende hornfels; albite-epidote-hornfels	Latest Silurian	1) Movement of felsic magma to higher crustal levels 2) Distinct contact aureole rocks. Superimposed on regional metamorphic isograds. 3) Age control by Sutton Granodiorite (~410 Ma); Koolambah Granodiorite (~419 Ma) (MICHELAGO)
Regional (M_1)	Cullarin Block	Knotted schist; peltic and psammitic schist	Cordierite, biotite	Lower amphibolite – upper greenschist	Early Silurian	1) Prolonged high regional geothermal gradient (> 500°C) associated with anatexis and magma emplacement from deep crustal levels. 2) Age control uncertain; post-dates Late Ordovician/Early Silurian sediments but pre-dates Late Silurian felsic volcanism

quartz and opaques. Close to intrusions, the thicker arenaceous layers have been annealed to form a granoblastic mosaic of polygonal quartz with subordinate phyllosilicates and accessory plagioclase and tourmaline. A spaced-out cleavage in the hinge zones of folded laminae is indicated by plicated muscovite and biotite.

Silurian rocks

The Late Silurian sediments and acid volcanics in the Canberra Block have also been regionally metamorphosed but only to a low grade (declining M_1). In the pelitic rocks there is alignment of chlorite and sericite parallel to the cleavage. Wyborn & others (1981) have demonstrated that little textural change has occurred in the volcanics despite alteration of the phenocryst mineralogy. The main changes are sericitisation, saussuritisation and albitisation of plagioclase and retrogression of primary mafic minerals such as biotite to chlorite, sphene, epidote and opaques. Similar alteration is apparent in the subvolcanic acid porphyries. The mineral assemblages typify chlorite-grade, lower-greenschist-facies metamorphism. Evidence of shallow burial metamorphism is indicated by the presence of the prehnite-pumpellyite facies along the western margin of the Sheet area. The approximate boundary between this facies and the lower-greenshist facies is based largely on the presence of unalbitised plagioclase in the Laidlaw Volcanics and to a lesser extent the Walker Volcanics (Owen & Wyborn, 1979).

The volcano-sedimentary sequence in the Captains Flat Block has been regionally metamorphosed to a higher grade (M_2). The increasing abundance of fresh, brown biotite towards the eastern margin of the trough suggests the sequence was raised from lower to upper greenschist facies during the Tabberabberan deformation (mid Devonian). The mineral assemblage in basalt and basic intrusions is calcite-epidote-actinolite; the presence of blue-green actinolite and green-brown hornblende in the Lockhart Basic Intrusive Complex indicates the lower amphibolite facies.

Contact metamorphism

Pelitic and psammitic hornfelses are associated with acid intrusions such as the Sutton Granodiorite and Murrumbidgee Batholith. Calc-silicate hornfels occurs sporadically in the shallow-marine sequence in the Canberra–Yass Block.

Pelitic and psammitic hornfels

Low-grade, regionally metamorphosed Late Ordovician sediments have been raised to the hornblende-hornfels facies of contact metamorphism in the aureole around the Sutton Granodiorite (Fig. 24). The unusual outcrop width of this aureole at the northeastern margin of the intrusion suggests a shallow subsurface granite contact.

In the outer, albite-epidote hornfels, zone, the country rocks are indurated, dip gently, and have a less pervasive cleavage. Towards the granite, dark-grey spots up to 2.0 mm across first appear in phyllites; they consist of diffuse concentrations of muscovite in a fine matrix of biotite, chlorite, quartz and muscovite. The inner, hornblende-hornfels, zone contains more indurated rocks; spotting gives way to the porphyroblastic growth of grey cordierite, seen in thin-section as euhedral prismatic laths up to 15 mm and sometimes as basal orthorhombic (pseudohexagonal) sections. A weak alignment of the porphyroblasts into the cleavage defines a mineral lineation on bedding planes. The porphyroblasts increase in size and abundance into the pelitic portions of graded beds. Where the

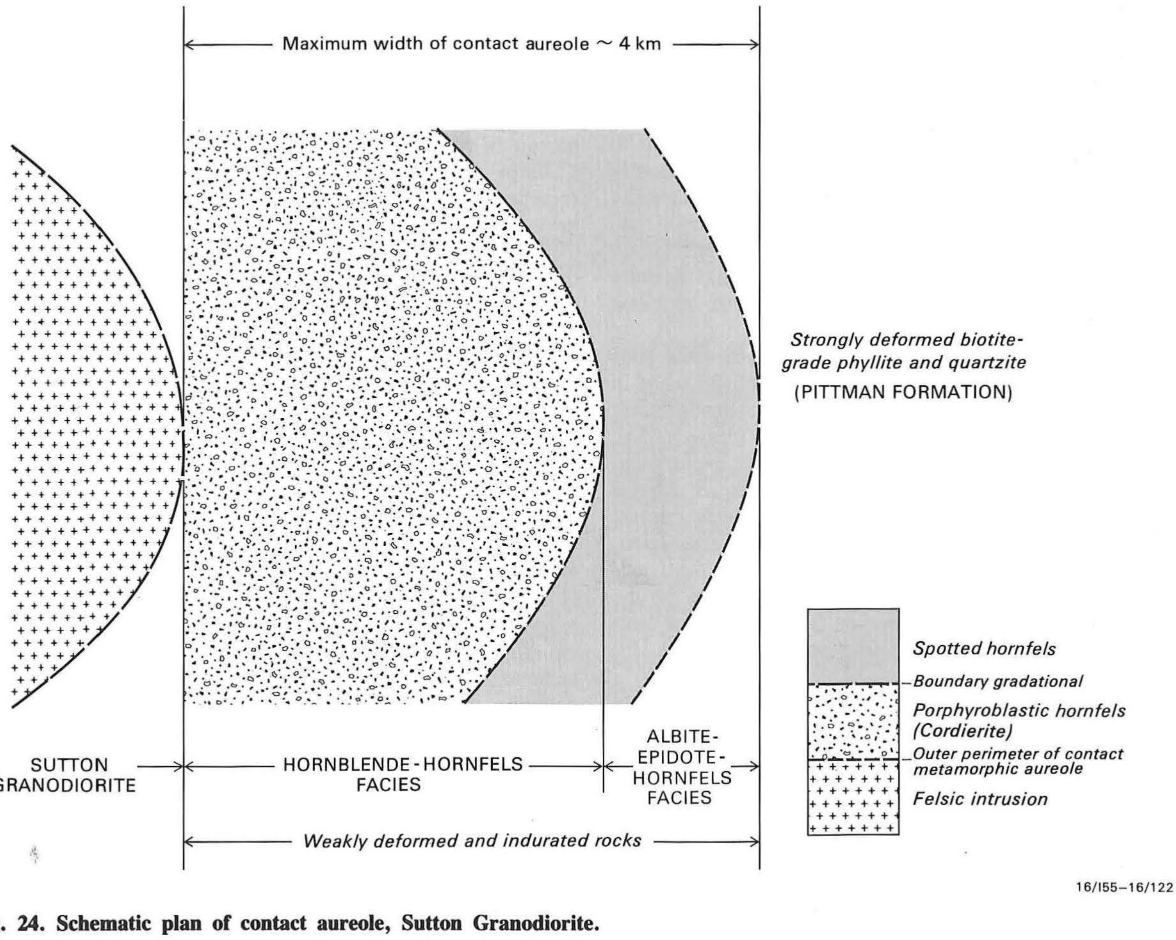


Fig. 24. Schematic plan of contact aureole, Sutton Granodiorite.

quartz-turbidite sequence has been inverted this appears as 'reverse grading' as seen in cuttings on the Bungendore–Gundaroo road 2 km north of the Federal Highway (MR 118/103). Here the cordierite porphyroblasts have been retrogressed to finely crystalline sericite and quartz in a weakly lepidoblastic matrix of biotite, muscovite and quartz. The original porphyroblasts are pre-tectonic. Post-metamorphic rotation is evident from a penetrative cleavage which wraps around and is refracted across the porphyroblasts. Quartz-rich pressure shadows occur in low-stress zones. The arenaceous beds are less altered by contact metamorphism; within the aureole they form hard, massive psammitic hornfels. The original sandy framework has been retained; a faintly spotted texture is from aggregates of reddish-brown metamorphic biotite, muscovite and opaques up to 1 mm in the clay matrix.

Contact metamorphism is not apparent in psammo-pelitic rocks marginal to Early Devonian acid plutons along the eastern edge of the Sheet area south of Hoskinstown, and it is likely that any contact effects have been overprinted by the Tabberabberan deformation. However, in the less deformed areas on ARALUEN, spotted hornfels with cordierite has been noted adjacent to the Gourock Granodiorite (Wyborn & Owen, 1986).

Calc-silicate hornfels and marble

Calc-silicate hornfels occurs at several stratigraphic levels in the Canberra Formation (Smc_3) mainly in an area extending from Oak Hill northeast to the Gundaroo–Murrumbateman road. The hornfels generally forms residual outcrops among reddish-brown soil. The hornfels is usually well bedded, aphanitic and hard. The hornfelsing accentuates bedding as a compositional colour banding in shades of green and grey according to the distribution of newly formed contact metamorphic minerals. Crinoidal and coral remains are preserved in outcrops on Nobby Hill and on the northwestern slopes of Mount Majura.

The presence of tuffaceous detritus in the hornfelses is indicated by sandy layers consisting of quartz, albitised plagioclase and pyritised volcanic and carbonate detritus up to 2 mm. These layers grade into finer but thicker layers of silt and shale. Calcium- and iron-rich varieties of epidote with randomly oriented or sub–radiating aggregates of tremolite-actinolite have grown in a carbonate-rich matrix. Sphene, zircon and opaques are accessories. Late-stage alteration is suggested by aggregates of coarse prismatic epidote, quartz and acicular tremolite–actinolite, epidote rimming grains of albitised plagioclase, and late quartz–epidote veins.

Marble and calc-silicate hornfels also form lenses and pods in the Yarralumla Formation (MR 915/889 and 923/883) and in the Cappanana Formation (Scp_2). Dolomitic limestone containing saddle dolomite occurs in the Colinton Volcanics. The saddle dolomite was identified by its brown turbid appearance, curved cleavage and sweeping extinction. Radke & Mathis (1980) have described saddle dolomite in an epigenetic context and associated with base-metal sulphide mineralisation. Vallance (1974) described vesuvianite (idocrase) from calcareous rocks of the Colinton Volcanics marginal to the Barracks Creek Adamellite. Grossular garnet occurs in calc-silicate rocks in the Yarralumla Formation along Red Hill ridge.

Calcareous sediments are sensitive to small changes in thermal gradients and the resulting calc-silicate hornfels must have formed at relatively low temperatures since the surrounding sediments are only slightly metamorphosed. Smith (1964) interprets calc-silicate rocks in the Nobby Hill area as due to the subsurface presence of acid intrusions. Similar rocks crop out near dacitic porphyry at Oak Hill (MR 956/090) and near the Federal Golf Course Tonalite at Red Hill in central Canberra. Calcareous hornfels in the Fyshwick area was attributed to 'hybrid porphyry' dykes by Öpik, (1958). An alternative explanation is that the calc-silicate rocks in the Canberra Block may represent skarn deposits. Stanton (1986, 1987) refers to stratiform skarn deposits in eastern Australia that contain abundant calc-silicate minerals such as grossular–andradite garnet, epidote, pyroxene and amphibole similar to those in contact-metamorphosed rocks; he has interpreted these deposits as primary marine exhalative accumulations in moderately restricted environments of carbonate sedimentation.

Conditions and timing of metamorphism

The regional and contact metamorphic rocks preserved on CANBERRA represent part of a widespread high-temperature, low-pressure metamorphic system with accompanying granitic rocks which characterises the Lachlan Fold Belt in southeast Australia (Miyashiro, 1982). The temperature/pressure regime for regionally metamorphosed Late Ordovician sediments in the Cullarin Block is considered to have been similar to the conditions detailed on MICHELAGO by Hayden (1980). He estimated a temperature for the biotite isograd of ~350° ± 50°C and the cordierite isograd in the zone of knotted schist at ~525°C in a low-pressure system of ~200 MPa. Similar temperature/pressure conditions are considered to have applied to Late Ordovician biotite-grade metamorphic rocks in the Rocky Pic Block. The presence of metamorphic amphibole in the Lockhart Basic Intrusive Complex is taken to correspond with a minimum temperature/pressure limit of ~500°C at 200 MPa for the amphibolite facies as stated in Winkler (1979, p. 65). Similarly, the growth of cordierite typifying the hornblende-hornfels facies in the contact zone around the Sutton Granodiorite represents a local increase in temperature to > 400°C (Turner, 1981, p. 296).

The metamorphic history of the rocks in the Sheet area and its relationship to magmatism and deformation is summarised in Table 27 and Figure 25. An early phase of regional metamorphism (M_1) is evident from the biotite isograd and narrow belts of knotted schist in Late Ordovician rocks of the Cullarin Block. A high geothermal gradient of ~70°/km (Hayden, 1980), indicated by cordierite porphyroblasts in knotted schist, represents an intense thermal event at depth. The thermal peak of this metamorphism must have preceded the Late Silurian felsic volcanism on the Canberra–Yass Shelf to allow enough time for deep-seated anatectic magmas to reach the surface. In the declining phase of this regional metamorphism granitic magmas that had already participated in regional-scale heating rose to form the subvolcanic felsic intrusions and those with contact metamorphic aureoles superimposed on the existing regional metamorphic isograds. Hence the M_1 metamorphic event predates the Sutton Granodiorite (~410 Ma) and on MICHELAGO the slightly older Koolambah Granodiorite (~419 Ma, Hayden, 1980).

During the Early Devonian, retrograde metamorphism affected rocks in the Cullarin Block and in the Canberra Block. However, the pulse of regional metamorphism and granitic magmatism continued to migrate eastwards with time across the Sheet area. In the Cullarin Block a second-generation metamorphic biotite concentrate extracted from Late Ordovician psammo-peltic rocks exposed in Bradleys Creek (~MR097/753) gives a K–Ar age of 382 ± 3 Ma (AMDEL rept. G7287/88) and Rb–Sr ages of 387 ± 3 Ma (initial ratio 0.715) and 392 ± 3 Ma (initial ratio 0.710). East of the Whiskers Fault this later phase of regional metamorphism (M_2) is taken as expressing the Tabberabberan deformation. Metamorphic biotite is strongly developed in tightly folded and cleaved Ordovician and Late Silurian rocks and foliated Early Devonian acid intrusions (Ellenden Granite and Rossi Granodiorite).

Age control on this metamorphism is provided by dates obtained on metamorphic sericite and biotite in the Kohinoor Volcanics in the Captains Flat Block. The sericite separations give a K-Ar geochronology of 370–380 Ma (AMDEL reports G 6433/86 and G 6695/86) while the biotite separation yields a Rb-Sr age of 374 ± 3 Ma and an initial ratio of 0.7099 (L. Black, pers. comm., 1986).

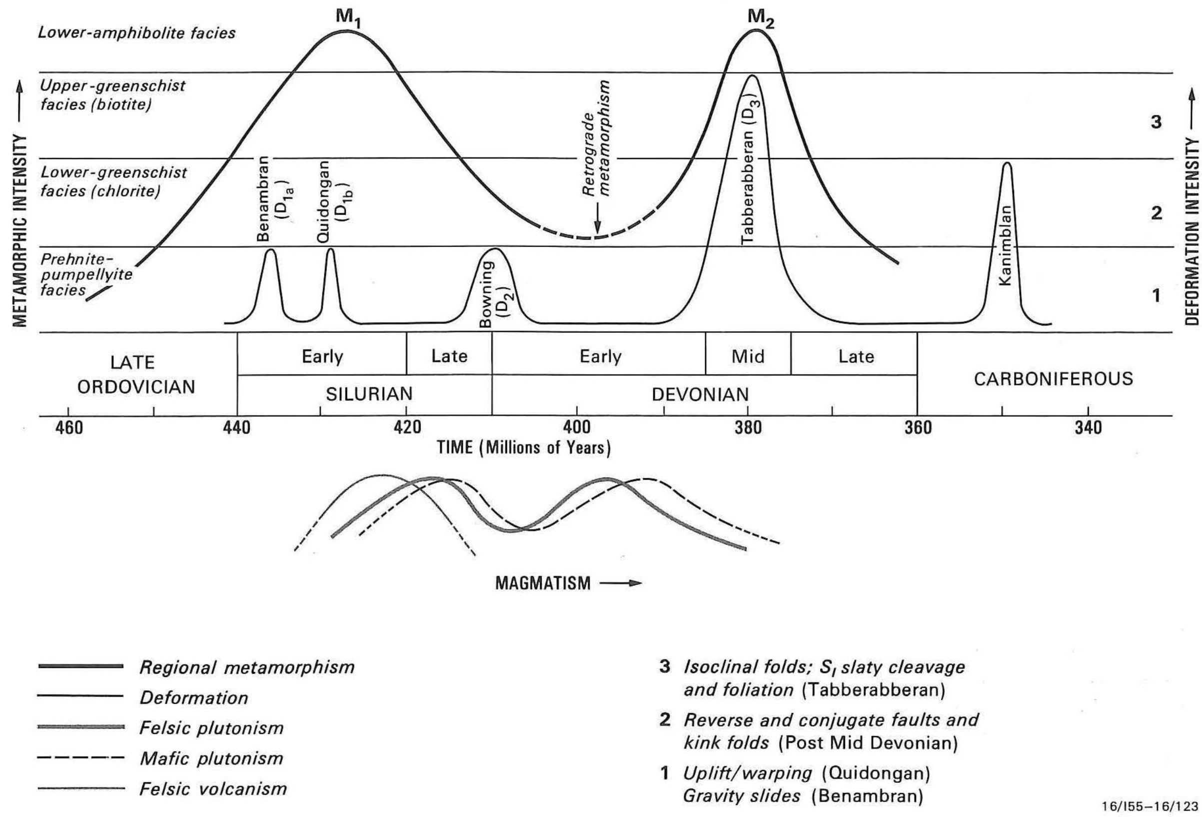


Fig. 25. Schematic representation of regional metamorphism and its relationship to folding and plutonism.

Structure

The regional submeridional tectonic grain and structural configuration of the southeastern part of the Lachlan Fold Belt was completed during the Devonian. The Sheet area is divided into structural elements (Fig. 26), with differing degrees and styles of deformation, along deep-seated marginal reverse faults of possible Proterozoic origin. Conjugate faulting and kink tectonics followed during the Carboniferous. In addition to the main tectonism in the Palaeozoic, epeirogenic uplift occurred in the Tertiary, principally by renewed movement along major meridional faults. The generalised geology and structure are shown as an inset map on the accompanying 1:100 000 geological map. The structural history is summarised in Table 28.

D_1 deformation

Clear evidence of D_1 (e.g. fold closures, axial plane structures and refolded lineations) has not been seen on CANBERRA. However, an early deformation may be inferred from segregation layering and the existence of early latitudinal folds and downward-facing folds in Ordovician rocks. More obvious episodes of tectonic movement (D_{1a}, D_{1b}) can be demonstrated by unconformities.

Segregation layering

Segregation layering expressed by the development of mica-rich laminae is locally developed in Late Ordovician metasediments (Op_1 and Ob_1) in the Cullarin and Rocky Pic Blocks. This layering (termed 'metamorphosed segregation cleavage' by Hayden, 1980), occurs in higher-grade psammopelitic rocks as sub-parallel, anastomosing micaceous laminae up to 10 mm apart, commonly at a shallow angle to the bedding. The layering is often crenulated and crossed by a steeply inclined axial plane cleavage probably associated with a later D_3 deformation. The affinities of this layering are not fully known but it may reflect an epi-Ordovician deformation later enhanced by metamorphic differentiation.

Early folds

Early folds may exist in the contact aureoles of Siluro–Devonian granites. Shallow-dipping beds (locally overturned) with variable strike and much reduced penetrative fabric occur locally in hornfelsed Ordovician strata surrounding the eastern margin of the Sutton Granodiorite. Furthermore, Crook (1978) describes latitudinal folds adjacent to the Sutton Granodiorite

Table 28. Summary of deformation

	Age	*Extent*	*Character*	*Evidence of age*	*Effects*	*Remarks*
UPLIFT	Cainozoic	Localised along meridional faults	Continuous epeirogenic uplift (E–W tension with minor N–S compression); normal faulting and latitudinal warping (E–W axes); tilted fault blocks	Mid Tertiary basalts (19–25 Ma) associated with Lake George and Shoalhaven Faults; mid Tertiary–Quaternary sedimentary record preserved in fault-angled depressions	Intracratonic sediments in drainage basins, e.g. Lake George, Carwoola Flats; morphotectonic effects, e.g. incised drainage, stream capture, linear escarpments	Cainozoic tectonics superimposed on deeply weathered landscape dating back to the Mesozoic and possibly earlier
FAULTING	Post mid-Devonian to Carboniferous	Localised in and near discrete zones	Intense deformation along reverse faults (overturned folds, locally downward-facing with crenulation cleavage S_2; chevron-like folds and foliated rocks); conjugate NW and NE faults coeval with kink folds which have steep axial plane crenulation cleavage; development of lineament pattern	Reverse faults post-date Early Devonian granitoids; conjugate faults post-date meridional reverse faults; kink folds post-date D_3 slaty cleavage	Change to continental environment completed prior to sedimentation in the Sydney Basin	End of major tectonic activity in Lachlan Fold Belt
D_3 (Tabberabberan)	Mid Devonian	Widespread across Sheet area	Main fold phase (E–W compression); isoclinal folds with asymmetric limbs; axial plane slaty cleavage (S_1) in sediments parallels foliation in volcanics and minor acid and basic intrusions	Post-dates Ordovician and Silurian rocks and Early Devonian Tarago Conglomerate on BRAIDWOOD; post-dates Sutton Granodiorite and acid intrusions in Cullarin Block; post-dates Early Devonian granitoids in Rocky Pic Block; post-dates Early Devonian latitudinal basic dykes; age of metamorphic sericite and biotite (M_2) ~380 Ma	Terrestrial conditions except for shallow-marine embayments on BRINDABELLA and BRAIDWOOD; rise of 'Tabberabberan highlands'	Major deformation on CANBERRA; strong penetrative fabric east of the Whiskers Fault; anomalous NE and NW fold trends in Canberra Block; associated with M_2 regional metamorphism
D_2 (Bowning)	Late Silurian to Early Devonian	Probably affected Ordovician and Silurian rocks across Sheet area	Mild phase of warping and faulting: lack of definable fold geometry	Unconformities (a) Ordovician and Late Silurian Mount Fairy Gp/Early Devonian Tarago Conglomerate (BRAIDWOOD) (b) Late Silurian Laidlaw Volcs. and Ginninderra Porphyry/Early Devonian Mountain Creek Volcanics (BRINDABELLA)	Subaerial conditions on BRINDABELLA and western half of CANBERRA; marine conditions persist in Captains Flat Graben, becoming subaerial on Capertee Shelf (BRAIDWOOD–ARALUEN)	Uplift partly due to emplacement of Late Silurian granites into shallow crustal positions; post M_1 regional metamorphism
D_1 (Benambran–Quidongan)	Episodic movements spanning Late Ordovician (D_{1a}) and Early Silurian (D_{1b})	Late Ordovician and Early Silurian rocks in Canberra, Cullarin and Rocky Pic Blocks	Segregation layering; latitudinal folds penecontemporaneous slump folds locally associated with regional growth faults; possible evidence of recumbent (gravity-collapse) geometry	Unconformities with variable angular discordance between (a) Late Ordovician and Early Silurian rocks (D_{1a}) (b) late Ordovician/Early Silurian and Late Silurian rocks (D_{1b})	Change from distal to proximal turbidite deposition in Monaro Trough due to rising landmass along Wagga Metamorphic Belt (D_{1a}); shallow-marine conditions develop in the Silurian (Wenlock) (D_{1b})	Penetrative fabric absent; subaqueous unconformities associated with growth faults, e.g. Sullivans, Whiskers Faults, etc.; associated with M_1 regional metamorphism

STRUCTURAL ELEMENTS	OTHER BROADLY EQUIVALENT STRUCTURAL UNITS
CANBERRA BLOCK (Owen & Wyborn, 1980)	Canberra Graben (Strusz, 1971); Cowra–Yass Synclinorial Zone (Scheibner, 1973); Canberra Synclinorium (Richardson, 1979).
CULLARIN BLOCK	Cullarin Horst (Strusz, 1971); Molong–South Coast Anticlinorial Zone (Scheibner, 1973); Cullarin Anticlinorium (Richardson, 1979).
CAPTAINS FLAT BLOCK	Captains Flat Graben (Strusz 1971); Captains Flat–Goulburn Synclinorial Zone (Scheibner, 1973); Captains Flat Synclinorium (Richardson, 1979).
ROCKY PIC BLOCK	Rocky Pic Horst (Strusz, 1971); Molong–South Coast Anticlinorial Zone (Scheibner, 1973); Rocky Pic Anticlinorium (Richardson, 1979).

Fig. 26. Distribution of major structural elements.

in Donnellys Creek (MR 085/053). These structures have been interpreted as evidence of early fold trends since they are oblique to and appear to predate the younger meridional trends in the Lachlan Fold Belt (Cas & others, 1980, appendix 2; Powell, 1984, fig. 195c). On MICHELAGO, Hill (1975) and Hayden (1980) have mapped shallow-dipping beds with a virtual absence of cleavage in a narrow contact zone on the western margin of the Tinderry Granite. In the Nanima area, an unusual north-northeast-trending fold pattern ('Glenlee overturned syncline') outlined by Late Ordovician black siliceous shale beds in the Nanima area (Smith, 1964) may also relate to this group of early fold structures. Downward-facing folds displayed locally in the Molonglo gorge suggest an early phase of recumbent folding may have affected Ordovician rocks on CANBERRA.

Early tectonism (D_{1a})

Late Ordovician ('Benambran') tectonism has been recognised in the Canberra region. On BRINDABELLA the event is represented by an angular unconformity between the Late Ordovician Adaminaby beds and Late Llandovery–Early Wenlock Tidbinbilla Quartzite (Owen & Wyborn, 1979). These movements may have been milder on CANBERRA since the Late Ordovician Pittman Formation is overlain with only apparent unconformity by the Late Llandovery State Circle Shale (Crook & others 1973) and Early Silurian (probably Llandovery) Murrumbateman Creek Formation.

On MICHELAGO meridionally trending Ordovician sediments are overlain with little apparent discordance by the Gungoandra Siltstone, a basal member of the Late Llandovery Ryrie Formation (Richardson, 1979). East of the Cullarin Block the extent of this tectonic event and its associated time break is poorly known.

The main effect of this tectonism in the Canberra region was a change in sediment type and distribution. Distal turbidite derived principally from the south in the Late Ordovician (Cas & others, 1980), was replaced in the Early Silurian (Llandovery) by proximal quartz-rich turbidite derived from the west (Crook & others, 1973).

Late tectonism (D_{1b})

The D_{1a} tectonism was followed, still in the Early Silurian (Wenlock), by another phase of movement (D_{1b}) that can be equated with the 'Quidongan Orogeny' of Crook & others (1973). In the Canberra Block this tectonism is evidenced by unconformities with variable angular discordance although not by a cleavage-creating fold episode.

On Capital Hill, Late Llandovery State Circle Shale showing soft-sediment deformation features is unconformably overlain by mildly folded shallow-marine sediments of the Late Wenlock Canberra Formation (Henderson, 1973). Locally, considerable uplift and erosion must have been associated with this tectonism since an angular discordance of about 60° was exposed temporarily in excavations for the new Parliament House (Henderson, 1982). Crook & others (1973) reported that slightly overturned proximal turbidites of the Black Mountain Sandstone near the junction of Ginninderra Creek and the Barton Highway, are overlain with high angular discordance by shallow dipping Canberra Formation. Further north, Henderson (1978b) mapped an unconformable boundary between intensely folded Early Silurian Murrumbateman Creek Formation and less intensely folded basal sandstone units of the Canberra Formation.

At other places a larger time gap represents this tectonism. During construction of the Molonglo Parkway at Acton, Henderson (1979a) reported an unconformity between the Late Ordovician Pittman Formation and the Canberra Formation (Wenlock). On MICHELAGO, the Cappanana Formation (Ludlow) rests with angular discordance on Late Ordovician sediments and, further south, on the Ryrie Formation (Llandovery) (Richardson, 1979).

Eastwards there is evidence of mid Early Silurian tectonism in the Captains Flat Block where the Rutledge Quartzite Member (Ludlow) is in apparent unconformity with Ordovician rocks (Oldershaw, 1965). However, where the Rutledge Quartzite Member is absent, this time break is obscured by the lithological similarity between the Ordovician rocks and Late Silurian Copper Creek Shale and by intense structures associated with the mid-Devonian D_3 deformation. On BRAIDWOOD and ARALUEN a major time break is indicated by an unconformity between Late Ordovician quartz-rich turbidite and the Late Silurian De Drack Formation and Woodlawn Volcanics (Felton & Huleatt, 1977; Wyborn & Owen, 1986).

In the Canberra region unconformable relationships and changes in sedimentary patterns at the end of the Ordovician and in the mid Early Silurian are traditionally associated with movements along the 'Benambran landmass' as it was elevated to form the Wagga Metamorphic Belt (Crook & others, 1973). Low angular discordances and changes in sedimentation that characterise Late Ordovician/Early Silurian relationships, may reflect these early movements. The increased intensity of the later (Wenlock) D_{1b} tectonism (Quidongan) is evidenced by higher angular discordance at unconformities, and a marked change in environment of deposition, from turbidite to shallow-marine-shelf. The proliferation of subaqueous unconformities, changes in sedimentary facies and local penecontemporaneous slumping during D_1 tectonic events could have been triggered locally by movements on regional faults within the Monaro Basin.

D_2 deformation

Past studies of structure in the Canberra region have assigned the most intense period of deformation to the Siluro–Devonian 'Bowning Orogeny' (Oldershaw, 1965; Stauffer & Rickard, 1966; Felton & Huleatt, 1977; Gilligan & others, 1979; Richardson, 1979). At the eastern margin of BRINDABELLA this deformation is represented by an unconformity between the Late Silurian Laidlaw Volcanic Suite and Early Devonian Mountain Creek Volcanics that probably involved only a few hundred metres of uplift and erosion (Owen & Wyborn, 1979). Early Devonian strata are not found on CANBERRA, but on BRAIDWOOD Felton & Huleatt (1977) show Late Ordovician sediments and the Late Silurian Mount Fairy Group as being transgressed by the Early Devonian Tarago Conglomerate; removal of a substantial thickness of the Late Silurian sequence indicates that tectonism may have been more intense in that area.

Stauffer & Rickard (1966) deduced from the geometric variations of upward and downward facing second-generation folds east of Queanbeyan that an early phase of gravity-type recumbent folding affected Ordovician and Silurian rocks in that area. A Late Silurian age was assigned to these fold phases and they were correlated with the 'Bowning Orogeny'. Published literature and student theses use this model as the starting point for many descriptions of geological structure in the Canberra region. Gravity-type recumbent folding associated with the 'Bowning Orogeny' implies that allochthonous blocks of Ordovician overlie Silurian rocks along low-angle thrusts or slides (Wilson, 1964; Stauffer, 1964).

Folds and a penetrative cleavage associated with the D_2 deformation have not been recognised on CANBERRA. Since recumbent folds have yet to be actually observed in the Ordovician strata, the regional structural pattern is perhaps better explained by invoking a mild phase of warping and faulting at the end of the Silurian followed by intense 'in situ' folding in the mid Devonian. Movement of Late Silurian–Early Devonian granitic intrusions into higher levels of the crust may have assisted or been associated with the warping and faulting.

D_3 deformation

On CANBERRA the D_3 deformational event involved prolonged east–west compression which formed north-trending folds followed by complex structures in zones of reverse faults. The intensity of deformation increases eastwards where it was synchronous with the M_2 phase of regional metamorphism in the Captains Flat Block and Rocky Pic Block. This deformation may be equated with the mid-Devonian 'Tabberabberan Orogeny'.

This fold phase affects all early Palaeozoic rocks on CANBERRA. According to Creaser (1973) and Henry (1978) the same deformation (which they assign to the 'Tabberabberan Orogeny') occurs in a belt of Palaeozoic rocks extending north from Tarago to Goulburn. Further, Hill (1975) ascribed second-generation folds in Ordovician rocks in the Michelago area to this mid-Devonian deformation.

Canberra Block

Most of the stress in the Canberra Block was taken up by sedimentary rocks that were deformed into upward-facing, upright, moderately plunging folds with an axial planar slaty cleavage (S_1). The more rigid acid volcanic rocks were warped and only locally foliated. The anomalous fold trends in the Canberra Block were probably influenced by the competent Murrumbidgee Batholith and the heterogeneity of the volcano-sedimentary sequence.

North of the Deakin Fault the Silurian sedimentary rocks have been compressed into open north-northeast-trending variably plunging folds which gradually tighten eastwards towards the Sullivans Fault. This deformation also affected the underlying Ordovician and Llandovery rocks which are now exposed as the complexly folded and marginally faulted 'Aranda inlier' (Cullarin Block). This inlier also trends north-northeast and shows fold styles and plunge variations similar to the overlying Wenlock to Ludlow sequence.

South of the Deakin Fault, folds in Late Silurian rocks trend north-northwest. The outcrop pattern of the Yarralumla Formation illustrates the fold style. The sediments outline an anticline and complementary syncline plunging south-southeast, the beds thickening into the hinge of the syncline. The trend of the fold is oblique to the Deakin Fault, suggesting it is a primary compressive feature rather than a kink fold associated with transcurrent fault movement. Further south this macro-scale structural pattern is confirmed from the dip of compositional banding in acid volcanic rocks; mesoscopic folds are rare.

East of the Jerrabomberra Fault, the Colinton Volcanics and Cappanana Formation are intensely deformed. This is reflected in the volcanics by a strong north-northeast-striking penetrative foliation and in sedimentary interbeds by boudinaged limestone. The strong, steeply dipping slaty cleavage in the Cappanana Formation has a similar attitude to the foliation in the volcanics. Suspected isoclinal folds in these two formations are hard to prove, possibly because of the 'shredding out' of limbs. The structural trend in these rocks subparallels the Jerrabomberra Fault and is repeated in small inliers of Ordovician rocks (not mapped) along the old Queanbeyan–Cooma road.

Cullarin Block

Folds in Ordovician rocks of the Cullarin Block are arranged in a definite sub-parallel meridional pattern with wavelengths of the order of kilometres. These folds can be readily delineated by regional dip measurements. The most prevalent mesoscopic fold type is tight to isoclinal folds. Asymmetric or overturned limbs are commonly indicated by younging in graded beds. The range of fold styles is illustrated in Stauffer & Rickard (1966, fig. 5). A north-trending slaty cleavage (S_1) with variable dip subparallels the bedding and is axial-planar to the folds; the cleavage is commonly refracted across graded sequences. Cleavage/bedding intersections are visible on S_1 cleavage planes. The cleavage has a similar orientation to a pervasive foliation in acid and basic intrusions. Minor fold axes and intersection lineations plunge north or south at angles of 10–60°. However, the zonal arrangement of upward- and downward-facing second-generation folds reported over a wider area of the Cullarin Block by Stauffer & Rickard (1966, fig. 1) remains equivocal. Downward-facing folds are a rarity in Ordovician rocks near Jerangle (Hayden, 1980) and were judged absent on BRAIDWOOD by Felton & Huleatt (1977).

Captains Flat and Rocky Pic Blocks

Folds in Late Ordovician and Late Silurian rocks are structurally concordant east of the Whiskers Fault. Meridional upward-facing isoclinal folds are disposed in a central north-plunging anticlinorium ('Anthill anticline' of Wilson, 1964) with flanking overturned synclinoria (Primrose Valley synclinorium *nov.* and Captains Flat synclinorium of Oldershaw, 1965). There is a near-vertical axial plane slaty cleavage (S_1) which in areas of more intense deformation may develop into transposed bedding. Granitic intrusions and interbedded volcanics are also foliated with the same orientation as the cleavage.

The intensity of deformation is also indicated by elongation parallel to the fold axes. In Ordovician rocks quartz veins have been boudinaged. Massive quartzite beds with extensive fracturing and quartz infillings in the Rutledge Quartzite Member are deformed to pinch and swell structures. Dacitic clasts in the Kohinoor Volcanics are lengthened in the foliation direction (Oldershaw, 1965, plate 2). In hand specimen and thin section, quartz grains in clastic sediments and quartz phenocrysts in acid volcanics have been flattened in the plane of the S_1 cleavage. Many feldspar phenocrysts have been pulled apart in a direction parallel to the foliation. The variation in plunge geometry of the folds is attributed to axial extension rather than to the presence of earlier fold systems.

Age and relationships

The age of the D_3 deformation is poorly constrained on CANBERRA. There is no evidence of an unconformity in support of this fold episode, since Devonian strata are absent. In the Canberra Block this deformation post-dates the Late Silurian volcano-sedimentary sequence but predates conjugate faults and associated kink folds. In the Cullarin Block this deformation postdates the Siluro–Devonian Sutton Granodiorite (~410 Ma) since the S_1 slaty cleavage wraps around cordierite-andalusite porphyroblasts in the surrounding contact aureole. Elsewhere Late Silurian acid porphyry stocks and dykes and Early Devonian basic intrusions are foliated. In the Captains Flat and Rocky Pic Blocks, a slaty cleavage, widely developed in the Late Silurian Hoskinstown Group, parallels the foliation in Early Devonian granitoids. Detailed structural mapping by Henry (1978) in the Tarago area on BRAIDWOOD shows that the Early Devonian Mulwaree Group has undergone a comparable deformation to the underlying Late Silurian Mount Fairy Group, suggesting the major deformation in this area also relates to the D_3 'Tabberabberan Orogeny'.

A mid Devonian age for this deformation has been obtained from Late Ordovician psammo-pelitic rocks (Op_1) in the Cullarin Block. Second-generation metamorphic biotite, formed during the M_2 regional metamorphism and aligned in the plane of the S_1 cleavage, gives a K-Ar age of 382 ± 3 Ma and Rb–Sr age of 387 ± 3 Ma using an assumed initial ratio of 0.715 (Amdel Rept. G 7287/88). Further confirmation comes from the Captains Flat Block where the M_2 regional metamorphism has been dated at 370–380 Ma (Bain & others, 1987). On ARALUEN, the foliated Gourock Granodiorite has a radiometric age of ~380 Ma (Wyborn & Owen, 1986).

Faulting

The last episodes of Palaeozoic tectonism involved further east–west compression which initiated movement on deep-seated basement fractures to form subparallel reverse faults, followed by a conjugate system of faults with associated kink tectonics.

Reverse faults

The regional distribution of the reverse faults is well shown on the 2nd Edition of the Canberra 1:250 000 Geological Sheet (Best & others, 1964). The faults have a sinuous meridional trace and often have little topographic expression, e.g. Sullivans, Whiskers and Ballallaba Faults. Locally they can be traced from quartz and ironstone veins along major stratigraphic discontinuities or inferred from major lineaments, e.g. Whiskers Fault (Fig. 27). Fault planes are rarely exposed but it appears there is a dominantly vertical sense of movement with dips of up to 80° in the direction of the upthrown side. Imposed structures and a lack of stratigraphic markers make estimates of movement uncertain; Noakes (1957) states that displacements range from 600–1200 m.

Deformation is intense along these fault zones. Near the Murrumbidgee Fault the Shannons Flat Adamellite is strongly foliated, and there is a complex outcrop pattern in sedimentary interbeds in the Laidlaw Volcanics. A strong penetrative foliation in the Mount Ainslie Volcanics subparallels and may be associated with the Sullivans Fault. Alternatively, downward-facing folds in Ordovician rocks on the Kings Highway 0.5 km west of the Ridgeway (Crook & Powell, 1976, figs. 5–12) show a crenulation cleavage which may have developed locally through intense compression along the Queanbeyan Fault. Movement in the Whiskers–Lake George Fault zone formed chevron-like folds with overturned limbs and an associated crenulation cleavage. These structures appear to equate with the F_{2c} folds described by Stauffer (1964). They are visible in railway cuttings about 8 km south-southwest of Bungendore (Wilson, 1964; Crook & Powell, 1976) and in the Molonglo defile about 1 km southeast of 'The Briars' homestead (Wilson, 1964; Bird, 1984). Intense foliation, contorted beds and associated quartz veining also occur along the Narongo and Ballallaba Faults (Oldershaw, 1965). It seems therefore that compression was intense enough in the Queanbeyan and Whiskers Fault zones for the S_1 slaty cleavage to be folded and sometimes obliterated by a later S_2 crenulation cleavage.

Conjugate faults

The fault pattern on CANBERRA may be dominated by meridional reverse faults but the distribution and groupings of airphoto lineaments (Fig. 27) also indicate a northwest and northeast trending fracture system which appears to reflect a conjugate pattern of faults. These faults have little topographic expression but many can be traced locally by quartz and ironstone veins. They are well developed in the Canberra Block; movement is oblique-slip (vertical displacement with a transcurrent component).

The Deakin Fault is a major fracture zone which can be traced northwest from Queanbeyan onto BRINDABELLA and YASS for a distance of about 70 km. The distribution of Ordovician and Silurian stratigraphic units indicates that there has been sinistral movement of about 5 km together with considerable vertical movement on the fault. The northeast trending faults are more numerous and have a smaller vertical component. In the Canberra Block sinistral movement along northeast-trending faults has wedged Silurian strata into re-entrants in Ordovician rocks at the faulted western margin of the Cullarin Block, offsets on the boundary being about 4 km. Although intersections between northwest and northeast striking faults are likely to be fortuitous, mapping has shown that, where the faults intersect, the northeast trend is the younger. For example, the Deakin Fault is slightly displaced by the Winslade–Gungahlin Fault in east Belconnen and truncated south of Queanbeyan by the Jerrabomberra Fault. An analysis of the three fault trends (meridional, northwest and northeast) suggests a conjugate stress-release pattern compatible with continued east–west compression and north–south extension.

Kink tectonics

Conjugate kink-style folds and crenulations are best developed in well cleaved pelitic units. These folds usually show near-vertical hinges and steeply dipping axial planes similar to the 'F_4 type' noted by Stauffer & Rickard (1966) and Stauffer (1967). Small and large scale kink folds are best developed in the Silurian volcano-sedimentary rocks in the Canberra and Captains Flat Blocks where they relate to stress fields set up by reverse and conjugate fault systems. Large-scale kink folds may be inferred from local changes in tectonic grain within an otherwise meridionally trending sequence. Strike swings on the eastern side of the Barracks Creek Adamellite (Stauffer, 1967), and on the southern margin of the Koolambah Granodiorite (Hayden, 1980) on MICHELAGO have been related to the emplacement of these intrusions during late-stage kink folding. Alternatively, the latitudinal strike swing and associated crenulation cleavage southeast of the Sutton Granodiorite could be a megakink fold formed possibly by north–south extension near the Queanbeyan Fault. The localisation of the fold was probably enhanced by the rigidifying effect of the intrusion and its contact metamorphic aureole.

Age and relationships

It appears there have been several periods of movement on reverse faults on CANBERRA. Strusz (1971) considered the faults were active through the Late Silurian. Stauffer & Rickard (1966) considered that the Queanbeyan and Whiskers–Lake George Faults postdate the Silurian rocks and were associated with the Bowning Orogeny. It is probable that reverse faulting is also associated with the D_3 tectonism in the mid Devonian since the Mulwaree Fault on ARALUEN (Wyborn & Owen, 1986) truncates Early Devonian granites.

The conjugate faults postdate the meridional D_3 reverse faults, e.g. the Deakin Fault cuts the Sullivans Fault southeast of Queanbeyan; relationships are similar on BRAIDWOOD (Felton & Huleatt, 1977). The kink folds also plicate the regional D_3 slaty cleavage. According to Powell & others (1985) megakinks in the southeastern Lachlan Fold Belt are of mid-Carboniferous age. The conjugate faults and kink folds appear to be coeval and represent a late-stage deformation in the Lachlan Fold Belt. Both systems were formed during a prolonged phase of east–west compression affecting a crust that had been thickened and strengthened by pluton emplacement, isoclinal folding and metamorphic recrystallisation.

Preliminary palaeomagnetic results

Further evidence for the timing of Palaeozoic deformation on CANBERRA is available from preliminary palaeomagnetic results obtained from Silurian volcanics in the Canberra Block (Table 29). The results, based on a limited set of pilot samples, show the following (C.T. Klootwijk, pers. comm., 1989):

- a minority have a SSW-directed magnetic component that may represent a primary magnetisation or an Early–mid Devonian overprint.
- a majority have a SSE to SE direction of low-inclination magnetic components representing a secondary tectonic overprint in the Early to mid Carboniferous.

Fig. 27. Distribution of faults, lineaments, and seismic centres.

The pole positions of the samples when plotted on the apparent wander path, as proposed by Klootwijk & Giddings (1988), lend general suport to an intense period of folding in the mid Devonian with the waning phases, associated with faults and kinks, persisting into the Carboniferous (Fig. 28).

Cainozoic uplift

The regional landscape prior to the Cainozoic was a broad, deeply weathered plain (Ollier, 1978; 1982). Tectonic instability in the Cainozoic broke up this landscape into parallel tilted fault blocks (Taylor, 1910; 1914). Along the highland crest of southeast Australia the faults formed small tectonic depressions which filled with fluvio-lacustrine sediments.

Modification of the pre-Cainozoic landscape on CANBERRA is exemplified by youthful, steep linear fault scarps associated with normal vertical displacement along the Murrumbidgee, Queanbeyan and Lake George Faults. The fault planes are not exposed because the bases of the escarpments are blanketed by colluvum and alluvial fans. A minimum displacement on the faults can be deduced from the topographic elevation of their escarpments, e.g. the west-facing Queanbeyan and east-facing Murrumbidgee fault scarps exceed 100 m. Other responses to Cainozoic uplift are valley-in-valley landforms along the Murrumbidgee River near Canberra and along the Molonglo River where it crosses the Cullarin Block.

Table 29. Preliminary palaeomagnetic results

Map ref.	*Acronym*	*Formation*	*N*	*Decl.*	*Incl.*	*K*	*95*
Primary (Late Silurian) or secondary (Early-mid Devonian) results (*), corrected for bedding							
890/042	ACHA-C	Mt Ainslie Volcanics	5	45.9	−47.5	16.2	19.6
885/038	ACHA-E	Mt Ainslie Volcanics	2	64.1	−35.6	(125.5)X	(22.7)X
939/793	ACMC	Deakin Volcanics	15	35.8	−22.9	38.9	6.2
930/857	ACMM	Mugga Mugga Porphyry	39	17.2	−19.2	38.8	3.7
937/842	ACMM	Mugga Mugga Porphyry	39	17.2	−19.2	38.8	3.7
926/803	ACBY	Deakin Volcanics	18	45.7	−22.7	122.6	3.1
926/803	ACBY	Deakin Volcanics	16	25.5	−19.8	265.5	3.2
Secondary (Carboniferous overprint) results (*), not corrected for bedding							
956/934	ACAA-E	Mt Ainslie Volcanics	16	351.0	−9.8	35.4	6.3
980/916	ACAF	Narrabundah Ashstone	6	1.3	−9.2	24.6	13.8
890/042	ACHD-C	Mt Ainslie Volcanics	8	327.0	−27.3	28.6	10.5
885/038	ACHD-E	Mt Ainslie Volcanics	7	333.4	−23.7	22.5	13.0
875/058	ACHF-H	Mt Ainslie Volcanics	10	337.2	−11.7	45.8	7.2
870/145	ACBA-D	Mt Painter Volcanics	6	340.2	−25.2	209.2	4.7
867/142	ACCA	Mt Painter Volcanics	9	331.6	+5.7	15.5	13.5
935/863	ACMP	Mt Painter Volcanics	7	334.6	−32.2	149.6	5.0
877/873	ACDV	Deakin Volcanics	6	314.4	−28.7	23.2	14.2
939/793	ACMC	Deakin Volcanics	7	332.3	−35.2	21.1	13.5
946/790	ACMA	Deakin Volcanics	11	356.4	−18.1	17.3	11.3
926/803	ACBY	Deakin Volcanics	10	339.0	+32.9	52.4	6.7
926/803	ACBY	Deakin Volcanics	14	340.8	+16.3	25.3	9.8

*: Results are given as southpole-seeking directions irrespective of actual polarity.
N: Number of pilot specimens in which magnetic component was identified.
K and 95: Statistical parameters following Fisher (1953).
X: Fisher statistics do not apply for N<3.

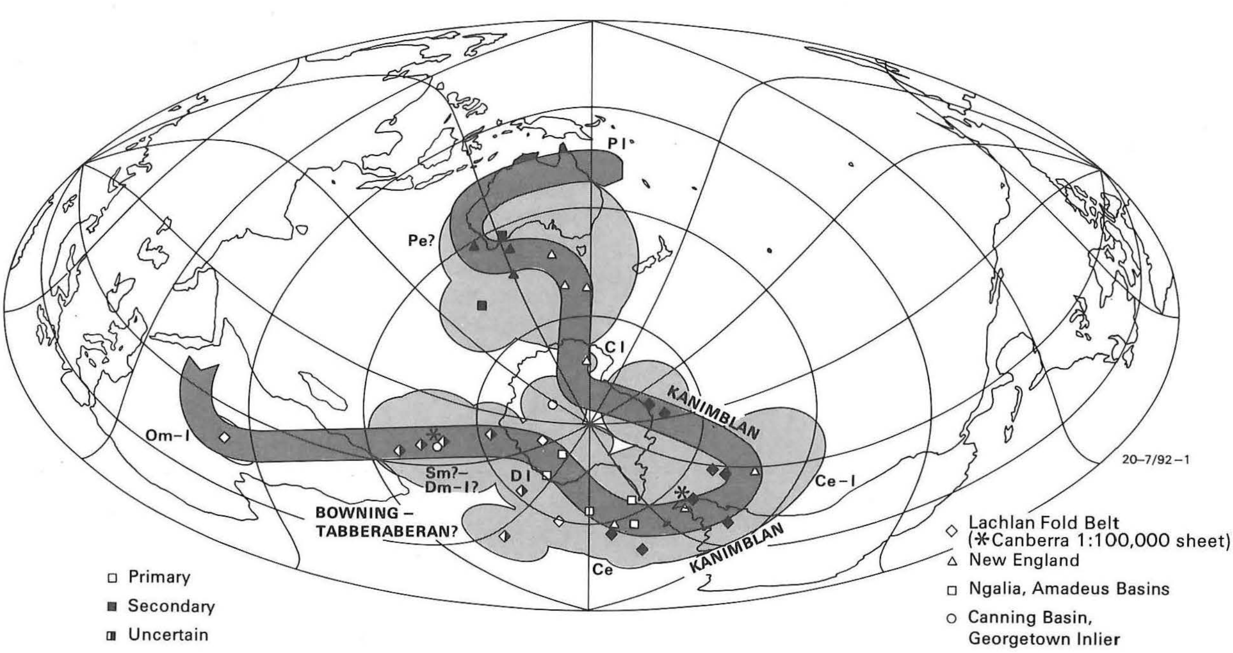


Fig. 28. Samples of Silurian volcanics plotted on an alternative apparent polar wander path (Klootwijk & Giddings, 1988).

These rivers now occupy gorges and entrenched meanders dissected into wide valleys representing the remnants of an early pre-Cainozoic drainage system.

The Lake George basin has apparently resulted from normal faulting (Taylor, 1907; Ollier, 1978). Morphotectonic evidence of such faulting is demonstrated by the broad wind gap at Gearys Gap and the barbed drainage of creeks flowing into the northern end of Lake George. On the supposition that the quartz gravels at the top and bottom of the Lake George escarpment are correlatives, then the minimum displacement (downthrow to the east), is approximately 100 m, which is in close agreement with Taylor (1907). A more realistic total displacement, based on the relative heights of Ordovician bedrock surfaces on either side of the fault (Abell, 1985, figs 14 & 15), would be >200 m. The high-angle-reverse sense of net movement on the Lake George Fault as exposed in the railway cutting close to the Kings Highway 8 km southwest of Bungendore (Wilson, 1964; Crook & Powell, 1976) has been regarded as indicating a reverse fault origin for the Lake George escarpment. Since Tertiary strata do not crop out in the immediate vicinity and there is no topographic break, it is concluded that this part of the Lake George Fault was not reactivated as a reverse fault during the Cainozoic. Furthermore, Jennings (1972) points out that the Lake George escarpment does not show the geomorphic character of a young reverse fault, such as small superficial normal faults through failure of the hanging wall.

The Lake George basin does not appear to have been faulted or tilted since the Pleistocene, because there is a broad similarity in elevation of Pleistocene beach lines in alluvial fans at the base of the Lake George escarpment west of the fault and strandline deposits marginal to the lake east of the fault. However, local movement along the Lake George Fault is suggested by the preservation of a late Quaternary fluvio-lacustrine sequence banked against the escarpment on the western side of the Carwoola Flats (p. 63). Regional uplift may still be in progress in the Canberra region. Minor seismic activity recorded since 1940 shows, up to 1988, more than 140 events, mostly less than 3 on the Richter Scale.

Age of faulting

The earliest Cainozoic fault movement that can be dated in the Canberra region was pre-Miocene. According to Young (1981), a basalt flow south of Crookwell dated at ~23 Ma (at the Oligocene–Miocene boundary) is draped over a low escarpment interpreted as a northward continuation of the Lake George Fault scarp. As there appears to be no visible sign of tectonic deformation of basalts in the Goulburn–Crookwell area it can be concluded that this portion of the escarpment may have existed before the Miocene. Younger fault movements are indicated on ARALUEN by Wyborn & Owen (1986) who describe vertical displacement of an Early Miocene basalt (~19 Ma) along the Shoalhaven Fault. The Lake George basin is probably no older than Late Miocene since preliminary palynological dating of the deeper fluvio-lacustrine sequence gives an age of Late Miocene (Truswell, 1984).

Tectonic processes

There are various models to explain regional uplift and denudation along the southeast Australian continental margin during the Cainozoic (Ollier, 1982; Young, 1982; Jones & Veevers, 1982; Bishop & others, 1985; Lambeck & Stephenson, 1986; Wellman, 1987). Whatever mechanism is proposed, it appears the actual uplift process has been one of epeirogenic doming (cymatogenesis), leading to extension. The meridional faults initiated in the Palaeozoic or earlier would naturally continue to be zones of weakness and become reactivated during any subsequent doming.

Normal faulting is generally associated with tension (in this case east–west extension), with gentle warping formed by compensatory compression. Regional tension along the Eastern Highlands in the Tertiary is evidenced by repeated basaltic volcanism which Wellman & McDougall (1974) attribute to tensional stress in the lithosphere. Although fold structures indicative of crustal shortening are not visible, Craft (1928) has invoked warping, e.g. the Norwood Warp, to explain in part 'differential uplift' in the Southeast Highlands. Based on Craft's ideas, Garretty (1937) suggested that non-fault-related downwarping initiated the formation of Lake George. Support for downwarping focused east of Gearys Gap is indicated by the variation in thickness of Cainozoic sediments in the basin: the sediments are thickest at Gearys Gap (the probable locus of greatest subsidence) and absent in the deeply weathered watershed areas bordering the Molonglo and Lachlan catchments.

According to Denham & others (1981), recent earthquake activity and *in situ* stress measurements indicate that the southeast Australian crust is currently in a general state of compression. Thus it seems unlikely that this modern stress pattern is responsible for the rejuvenation of the meridional faults. However, the inconsistent pattern of pressure axes derived from the focal mechanisms of the earthquakes and the distribution of epicentres close to conjugate faults and lineaments (Fig. 27) suggests that recent tectonism may relate to adjustments along those faults that originated in the late Palaeozoic. Few epicentres lie along the line of the Lake George–Whiskers Fault zone, indicating that this structure and possibly the other meridional faults have not been active in recent times.

Economic geology

Mineral deposits

Mineralisation in the Canberra 1:100 000 Sheet area is typical of much of the Palaeozoic terrain of southeastern Australia. A review of mining activity in and around the ACT was carried out by Smith (1963) and a listing and brief description of the mineral deposits in the Canberra 1:250 000 Sheet area is provided by Gilligan (1974, 1975). Reports on prospecting are held by the Department of Minerals & Energy, Sydney. The historical aspects of mining are referred to in books dealing with the development of Queanbeyan and Bungendore (Lea-Scarlett, 1968) and Gundaroo (Lea-Scarlett, 1972). The known mineral deposits on CANBERRA are small, but the area continues to show some limited economic potential as a source of gold and base metals.

Gold

In the Cullarin Block gold mineralisation seems to be related to an association of Ordovician sediments and granite intrusion (Herzberger, 1974). Gold occurrences are documented largely from the records of output of the Sutton–Gundaroo goldfields. Carne (1896) reported on the workings in the area and produced a map showing the extent of the diggings. In some cases the quartz veins were traced along strike for up to 1.5 km with the gold being won from shafts and open pits. The 'Bywong goldfield' as it became known, which had only a small production (Gilligan, 1975) was worked intermittently for over 100 years (1852–1957). Prospecting interest has now ceased and part of the area has been set aside as a tourist attraction (Bywong mining village). The gold occurs in an arcuate zone of mineralisation in and beyond the metamorphic aureole developed in Ordovician turbidites at the eastern margin of the strongly magnetic I-type Sutton Granodiorite. Hydrous fluids rich in silica and gold were emplaced as quartz-rich veins that appear to parallel the bedding and cleavage.

In the Gearys Gap area placer gold has been worked from shafts sunk into Tertiary ferruginous gravels (Taylor, 1907). Particulate gold has also been won sporadically from Quaternary alluvium in Brooks Creek which drains part of the Sutton–Gundaroo goldfields.

Base metals

Two important base-metal deposits — Captains Flat (MICHELAGO) and Woodlawn (BRAIDWOOD) — occur just beyond the southern and eastern margins of CANBERRA (Gilligan, 1974). These massive-sulphide deposits are confined to Late Silurian marine felsic-volcanic sequences within a once extensive volcano-sedimentary marine basin (the Ngunawal Basin of Bain & others, 1987) which now exists as fault-bounded erosional remnants downfolded into Ordovician rocks, e.g. the Captains Flat Graben.

From 1937–62 a stratiform Zn–Pb–Cu–Ag–Au massive sulphide deposit was mined from the Kohinoor Volcanics at Captains Flat, the mine closing following the depletion of ore. Over 4 000 000 tonnes of ore was mined, averaging 10% Zn, 6% Pb, 0.67% Cu, 56 g/t Ag, and 1.7 g/t Au (Davis, 1975).

In 1969–70 Jododex (Aust.) Pty Ltd discovered a similar base-metal deposit in the Woodlawn Volcanics, a few kilometres west of Tarago (Malone & others, 1975). Pre-mining ore reserves were estimated as 9 000 000 tonnes at 7.5% Zn, 3% Pb, 1.5% Cu, and 42g/t Ag and are now currently exploited at the Woodlawn Mine.

At the Briars prospect (EL 1611) a basic agglomerate in the Captains Flat Formation is locally host to Cu–Pb–Zn mineralisation. An adit and costeaning is evidence of early prospecting but recent soil sampling and drilling have failed to prove economic mineralisation (Teck Explorations Ltd, 1982). Other detail on the geology and geochemistry of the deposit is given by Bird (1984).

Massive-sulphide deposits at Captains Flat originated as stratiform lenses where ore fluids were introduced into felsic volcanics in a volcano-sedimentary marine sequence (Bain & others, 1987). The failure so far to locate significant base-metal mineralisation between Captains Flat and Woodlawn can perhaps be explained by the apparent absence of submarine volcanic centres in this portion of the 'Ngunawal basin', and also by the north-northwest trending Ballallaba Fault along which the Ordovician sequence is upthrown to the northeast. Drilling and fieldwork suggest that most if not all of the bedrock beneath the Lake George basin is Ordovician turbidite (Abell, 1985a). Unfortunately, electrical prospecting techniques here are hindered by the high conductivity of the lake water and surficial sediments.

North of the ACT border, in the Canberra Block, some company interest has been shown in the volcano-sedimentary environment of the Canberra Formation. At the Kingfisher prospect (EL 806; Lowder, 1977) near Nobby Hill (MR 986/150), pyrrhotite occurs in association with metasomatised calc-silicate lenses. This association may be similar to other sulphide-bearing calc-silicate skarns in the Lachlan Fold Belt (Stanton, 1986; 1987). Patchy disseminations of chalcopyrite and pyrite also occur in the Mount Ainslie Volcanics. Pyrite is present in road cuttings (MR 990/010) and a disused quarry (MR 012/015) on the Federal Highway. The Mount Ainslie Volcanics also contain higher than normal element concentrations of Cu and Ba compared to other volcanics in the Canberra district, together with sulphate-rich groundwater with salinities > 1000 mg/L, as reported by Evans (1987).

Gossans and reef quartz occur in places along major fault zones, expecially in the Canberra Block where they are associated with northeast-trending faults, e.g., Winslade–Gungahlin, Glengyle, and Carrington Faults. The gossans are lenticular, with a strike length rarely exceeding 500 m; they normally consist of haematite–goethite and maghemite. A gossan near 'Gungaderra' homestead (MR 956/036) and a skarn deposit at Gossan Hill, Bruce, have been studied in detail and show prominent geophysical and geochemical anomalies (K. McQueen, pers. comm., 1987). The mineralisation is probably hydrothermal, and there are locally high values of Cu, Co, Zn, Pb, and Ag. The gossans formed during prolonged weathering in the Tertiary.

Construction materials

Most of the presently exploited construction materials on CANBERRA are used in the urban development of Canberra and Queanbeyan. Until recently building materials were obtained within the ACT, but demand, competition for land, and environmental pressures have meant an increasing dependence on adjacent areas of New South Wales for these resources.

Rock aggregate

Crushed-rock requirements for Canberra and Queanbeyan are currently met from three quarries. Massive rhyodacitic and dacitic volcanics are quarried at Mugga Lane (Deakin Volcanics) and near the Barton Highway 9 km north of Hall (Deakin Volcanics, Laidlaw Volcanics). Adamellite (Barracks Creek Adamellite) and foliated dacite (Colinton Volcanics) are extracted from a large quarry 5 km south of Queanbeyan. Dacitic rocks of the Mount Ainslie Volcanics have been quarried in the past but the presence of pyrite has an adverse effect on concrete and road aggregate.

Large reserves of volcanic and granitic rock suitable for crushed aggregate are available in areas screened from residential development, but the degree of foliation and the varying thickness of the weathered mantle downgrade many potential quarry sites. However, large quantities of good-quality aggregate in massive volcanics are available in the Pemberton–Enchanted Hill area southeast of Tuggeranong and in hills adjacent to the Barton Highway northwest of Hall.

Plastic 'gravel' (containing a high proportion of clay fines) for surfacing dirt roads is available from a large number of small roadside pits operated by shire councils on private land. Suitable materials have been obtained from highly weathered volcanic, granitic and metasedimentary rocks.

Sand and gravel

Stratified deposits of silt, sand and gravel of Quaternary to Recent age occur along major streams, lake margins and the lower slopes of hills flanking river valleys and surrounding lake basins. Sand and gravel operators extract a large variety of screened products from these deposits for use in the building and construction industry. A description of the various materials, uses and reserves is given by Vanden Broek (1979).

Sand and gravel occur in channels, alluvial flats and terraces along the Queanbeyan, Molonglo and Yass Rivers. Deposits are generally limited and non-uniform; in most cases reserves are regarded as finite since replenishment is restricted by flood control measures. Along the Molonglo River substantial quantities of river-bed sand and fine windblown sand are known at Dairy Flat at the eastern end of Lake Burley Griffin (Goldsmith & Pettifer, 1977) and beneath Carwoola Flats. However, future exploitation of these reserves will depend on environmental considerations and competition for land use. A major part of Canberra's and Queanbeyan's supply of sand and gravel now comes from beach and dune deposits at the southern margin of Lake George.

Brick shale and clay

Silurian shales were the main source of clay for bricks during the early development of Canberra. Calcareous and sandy impurities in the shales led to the closure of quarries at Yarralumla (Yarralumla Formation) and on the eastern slopes of Jerrabomberra Hill at Queanbeyan (State Circle Shale). A brickworks currently operating in the industrial area of Mitchell is based partly on deeply weathered kaolinitic shale and clay (Pittman Formation) extracted from pits near Back Creek at MR 014/133.

White and pale-grey kaolinitic clay occurs in leached Ordovician slates near Bungendore (Birkenburn beds). Several shafts sunk to investigate the economic potential of the clay showed an extension of more than 1 km south of Bungendore and to a depth of more than 20 m (Lloyd, 1960; Loughnan, 1960; Gibbons & Bunny, 1963; Baker & Uren, 1982). Residual kaolinitic clay is also exposed in a deep weathering profile on the watershed between the Lake George and Molonglo drainage basins. The kaolin is present in strongly leached Silurian shale and sandstone (Carwoola Formation) and is currently worked in pits south of 'Woodlands' homestead close to the Bungendore–Hoskinstown road at MR 210/870.

Limestone

Small bodies of limestone crop out within the Late Silurian volcano-sedimentary sequence in the Canberra Block. Mahoney & Taylor (1913) give detailed descriptions of limestone in and around the ACT while Carne & Jones (1919) and Lishmund & others (1986) report on deposits in nearby areas of New South Wales. From early times it has been evident that these deposits are too small and structurally complex to have long-term commercial value; the local demand for cement and lime products is currently supplied from quarries in the Goulburn area.

Natural (including ornamental) stone

Rough stone for facing cuttings and embankments is obtained from a small quarry (Stokmans Quarry) in the Canberra Formation (Camp Hill Sandstone Member) between Pialligo and Queanbeyan and from the Deakin Volcanics (Mugga Mugga Porphyry Member) on Mugga Lane (Henderson, 1981). Stone used to build St Johns Church, Reid and St Ninians Church, Lyneham was probably quarried locally from Black Mountain Sandstone. Ornamental stone used as external cladding and internal feature walls in modern Canberra buildings has always been supplied from other parts of Australia or abroad (Warren, 1966).

BMR holds a card index system which records the use of natural stone in Canberra buildings, monuments and engineering structures. The card index is available not only for public interest, but more specifically as a database for use in restoration, where a source or quarry for matching stone is needed for replacement purposes.

Exposures of rhyodacitic porphyry (Sp_2) worthy of assessment as a source of ornamental stone occur in the Murrumbidgee River between the Outward Bound School and 'Lambrigg' homestead. This unweathered, massive, coarse-grained intrusive porphyry is characterised by large pink potash feldspar phenocrysts up to 2.5 cm long, set in a greyish granular quartz-feldspar groundmass.

Water resources

Water supply development is largely oriented to the growing urban demand in the Canberra–Queanbeyan area. Current water use is dependent on reservoirs established in the Cotter and Queanbeyan river catchments. These sources have the capacity to supply up to 400 000 people and hence will satisfy demand into the early part of the next century (Best, 1981). However, suitable areas for dam sites in the region are diminishing and ultimately there will be a requirement for greater groundwater development.

Surface water

Mean annual precipitation, which exceeds 800 mm west of the Murrumbidgee River, is sufficient to maintain a series of three reservoirs of potable water on the Cotter River (Corin, Bendora and Cotter dams). To augment this supply and provide for future demand, Googong reservoir on the Queanbeyan River was completed in 1978.

Lakes Burley Griffin, Ginninderra and Tuggeranong provide Canberra with recreational facilities as well as flood and water quality control for the Murrumbidgee River. In rural areas surface runoff is collected in earth dams for stock watering.

Lake George is a natural body of water showing seasonal and long-term fluctuations in level and salinity which are mainly attributable to relative changes in rainfall and evaporation. The lake water is too saline for human use but is adequate for livestock (mainly sheep). The hydrograph for Lake George is one of the oldest and most continuous water-level records in Australia (Russell, 1886) and therefore an indicator of relatively long-term climatic variability. A water balance for the lake covering the period 1958–77 has been computed by Jacobson & Schuett (1979).

Groundwater

In the Canberra Sheet area groundwater occurs in fractured-rock aquifers (dacitic, granitic and metasedimentary rocks) and in unconsolidated sand and gravel in thin alluvial and colluvial aquifers (Jacobson, 1982). Yields of bores in fractured-rock aquifers are in the range 0.1–5.0 L/s, and higher yields are obtained in closely jointed rocks along fault zones. Groundwater salinity is generally less than 2000 mg/L TDS and largely determined by complex geology and recharge conditions (Evans, 1987). In the Lake George basin unconsolidated fluvio-lacustrine sediments of Cainozoic age yield good supplies of groundwater capable of sustaining a semi-rural population based on Bungendore and mining operations at Woodlawn mine.

There is considerable scope for further development of groundwater. There has been increased exploitation of groundwater from fractured rocks for rural supplies on subdivided land in the border areas of New South Wales adjacent to the ACT. However, supplementation of urban water supplies with groundwater needs careful surveillance. In the Canberra area shallow aquifers have been polluted by hydrocarbons, leachate, kraft effluent, and sewage (Jacobson & Evans, 1981; Jacobson, 1983; Jacobson, 1984); and water resource development along the Carwoola Flats is constrained by the distribution of heavy metals resulting from mine waste pollution of the Molonglo River downstream from the abandoned Captains Flat mine (Johnson & McQueen, 1984; Norris, 1986; Jacobson & Sparksman 1988).

Geological synthesis

The pre-Ordovician history of the Canberra region is speculative. During the Middle Ordovician (~460 Ma) quartz-rich distal turbidites (Pittman Formation) were deposited in a deep oceanic basin, the Monaro Basin, that developed to the east of the Molong Volcanic Arc. This thick marine sequence of essentially Darriwilian (Llanvirn) age contains sandstone, siltstone and shale deposited by turbidity flows in which indefinite cross-laminations and other sedimentary structures indicate source areas to the south. Quieter conditions prevailed towards the end of the Ordovician (Gisbornian–Bolindian) with deposition of condensed sequences of black pelagic shale and chert containing graptolites, radiolaria and conodonts.

At the close of the Ordovician (~440 Ma), tectonism (D_{1a}) to the west of CANBERRA (Benambran deformation) caused a renewal of sedimentation and a change in the sedimentary environment in the Monaro Basin. On CANBERRA the effects of this tectonism were milder. The region remained a submarine area of deposition marked by a final phase of turbidite sedimentation. A series of submarine fan complexes prograded eastwards to rest with small angular discordance on Late Ordovician sediments. These proximal turbidites (State Circle Shale, Black Mountain Sandstone and Murrumbateman Creek Formation) were probably derived by recycling of Ordovician distal turbidites uplifted in the west (Wagga Wagga region). The occurrence of *Monograptus exiguus* gives a Late Llandovery age to part of this sequence in the Canberra area. How far eastwards deposition continued is unclear, but Llandovery rocks are documented in the Goulburn area by Naylor (1935, 1936) and Creaser (1973), and by Scheibner (1970) on TARALGA (Bummaroo Formation).

In the early Wenlock the Canberra area was uplifted and may have formed land for a period (3–4 Ma). This more intense tectonism (Quidongan deformation, D_{1b}) is represented on CANBERRA by termination of turbidite deposition and a regional unconformity. At this time there was an increase in heat-flow associated with partial melting of the crust, leading to upper greenschist–lower amphibolite facies regional metamorphism (M_1). As the land eroded, marine sediments and acid volcanics of Late Wenlock–Early Ludlow age prograded eastwards towards BRAIDWOOD and ARALUEN.

During the Late Wenlock (~425 Ma), shallow-marine sediments typified by fossiliferous shale, sandstone and limestone (Canberra Formation) were deposited on the Canberra–Yass Shelf. Silicic volcanic activity was initiated on BRINDABELLA, but was only represented at first on CANBERRA by occasional volcaniclastic layers in the upper part of the Canberra Formation. Subsequently, this early phase of volcanic activity, consisting mainly of agglomerate, lava, airfall tuff and ignimbrite flows (Hawkins Volcanic Suite), spread eastwards onto CANBERRA, resulting in a change from shallow-marine to terrestrial conditions.

At the end of this first major phase of acid volcanicity, there was a quiescent interval at the beginning of the Ludlow which was accompanied by further subsidence of the Canberra–Yass Shelf. A shallow-marine transgression deposited fossiliferous shale, limestone and volcaniclastic sediments (Yass, Yarralumla and Cappanana Formations) not only on the Wenlock volcanics but on Ordovician and Llandovery rocks at the now rapidly expanding margins of the Canberra–Yass Shelf. This marine incursion however was short-lived and was followed by a second phase of volcanic activity consisting of lava, tuff with interfingering marine sediments, and ignimbrite flows (Laidlaw Volcanic Suite).

In the Early Ludlow, anatexis extended eastwards to initiate felsic volcanism in the Captains Flat Graben by subsidence and possibly crustal rifting. Elements of the Laidlaw Volcanic Suite (Colinton Volcanics) may have transgressed across the 'Cullarin high' but it is more likely that the acid porphyry stocks and dykes at the eastern edge of the Cullarin Block were feeders or the remains of another volcanic centre associated with a zone of developing crustal weakness (Lake George–Whiskers fault zone).

The volcano-sedimentary sequence in the 'Ngunawal basin' (Hoskinstown Group) represents a relatively shallow-water facies which is probably coeval with the shallow-marine-shelf facies and subaerial felsic volcanics (Mount Fairey Group) deposited along the western margin of the 'Capertee high' on BRAIDWOOD and ARALUEN. Interbedded mafic and felsic volcanics at the base of the Currawang Basalt in the Mount Fairey Group attest to a short period of shallow-marine bimodal volcanism associated with an extensional tectonic regime and thinning of the continental basement. Evidence for extension is also enhanced by the existence of gabbro and dolerite (mainly Lockhart Basic Intrusive Complex) close to the eastern and western margins of the Captains Flat Graben. The basic intrusions (d_1) along the western margin are associated with the Whiskers and Lake George Faults, which probably extended to the upper mantle and permitted basic magmas to rise through the crust.

With the decline of the M_1 regional metamorphism at the end of the Silurian, granitic magmas that had already given rise to regional-scale heating moved upwards through the crust to cool as felsic intrusions. At several places on the Canberra–Yass Shelf, the rising felsic magmas intruded their own comagmatic piles, e.g. S-type Murrumbidgee Batholith, I-type Barracks Creek, Googong Adamellite and Sutton Granodiorite, and other S and I-type porphyry stocks and minor granitic intrusions (Sp_1, Sp_2, and Sg).

Volcanism ceased on the Canberra–Yass Shelf in the mid Ludlow (~420 Ma). After this time it is probable that subaerial conditions continued to exist in this part of the Sheet area for the rest of the Silurian. To the east, marine conditions were maintained in the Ngunawal Basin through the Ludlow and into the Pridoli by transgressive proximal turbidite sedimentation (Carwoola Beds, Captains Flat Formation and Covan Creek Formation). These sequences reflect an environment of tectonic instability (D_2) with sediment recycled into the basin from locally emergent areas of Ordovician and Silurian rocks. Evidence is lacking for an Early Devonian marine transgression on CANBERRA, although rocks of this age are known along the northern edge of BRINDABELLA and on BRAIDWOOD.

The zone of crustal melting which had migrated eastwards across CANBERRA to give rise to I-type felsic volcanics along the western margin of the Capertee High (Kohinoor and Woodlawn Volcanics) now induced emplacement of I-type intrusive units of the Bega Batholith in the Early Devonian. A tensional regime evidently obtained near the end of the Early Devonian to allow the intrusion of mantle-derived tholeiitic magma into the upper crust as latitudinal dykes (d_2) post-dating I-type granitoids.

Widespread tectonism (D_3 deformation) affected all early Palaeozoic rocks on CANBERRA in the mid Devonian (~380 Ma). The D_3 deformation involved strong and prolonged east–west compression which formed open, northeast and northwest trending folds in the Canberra Block and tighter meridional folds with a strong penetrative fabric (axial-plane cleavage and foliation) in the Captains Flat and Rocky Pic Blocks. A second phase of regional metamorphism (M_2) reaching upper-greenschist–lower-amphibolite facies appears to synchronise with this deformation east of the Whiskers Fault. Further stress relief was accomplished by movement on deep-seated basement fractures to form meridional reverse faults. This deformation ended sedimentation on CANBERRA by creating terrestrial conditions. However, shallow-marine deltaic and fluviatile sedimentation continued into the Late Devonian on ARALUEN (Minuma Range and Merrimbula Groups) and on BRINDABELLA and YASS (Hatchery Creek Conglomerate). Tectonic activity on CANBERRA was renewed in the Carboniferous (~350 Ma) with kink-style folds and crenulations associated with pre-existing faults and a younger system of conjugate faults.

The geological history through the late Palaeozoic and Mesozoic is unknown in the Canberra region as rocks of this age are not preserved. It seems unlikely that Permo–Triassic sedimentation extended southwestwards far beyond the present erosional margin of the Sydney Basin, so the CANBERRA terrain may even then have been exposed to subaerial erosion. At all events it seems the region became a stable planated landmass by the end of the Cretaceous.

At the end of the Mesozoic (~80 Ma) the southeast Australian region was uplifted through an epeirogenic process of gentle arching, followed in the Eocene by the extrusion of basalt, although no basalt is now preserved on CANBERRA, the only indicator of this activity being an olivine teschenite dyke (d_3) in the Murrumbidgee River southwest of Canberra. Regional basaltic extrusion continued into the Miocene, followed by further epeirogenic movement along old meridional fault lines in the Late Miocene. On CANBERRA this rejuvenation initiated escarpments associated with fault lines, and created changes in drainage patterns and shallow tectonic basins, e.g. Lake George; deep weathering profiles were stripped from higher ground.

Minor tectonism continued during the Quaternary but sedimentation was largely controlled by climatic changes related to the Pleistocene ice ages. Colluvial deposits accumulated in a cold, arid environment while aeolian, strandline and lagoonal deposits resulted from changes in the level of Lake George. Alluvial deposition continued along major streams. With the advent of European settlement in the 19th century, land clearing, gully erosion and urbanisation have modified the natural land forms.

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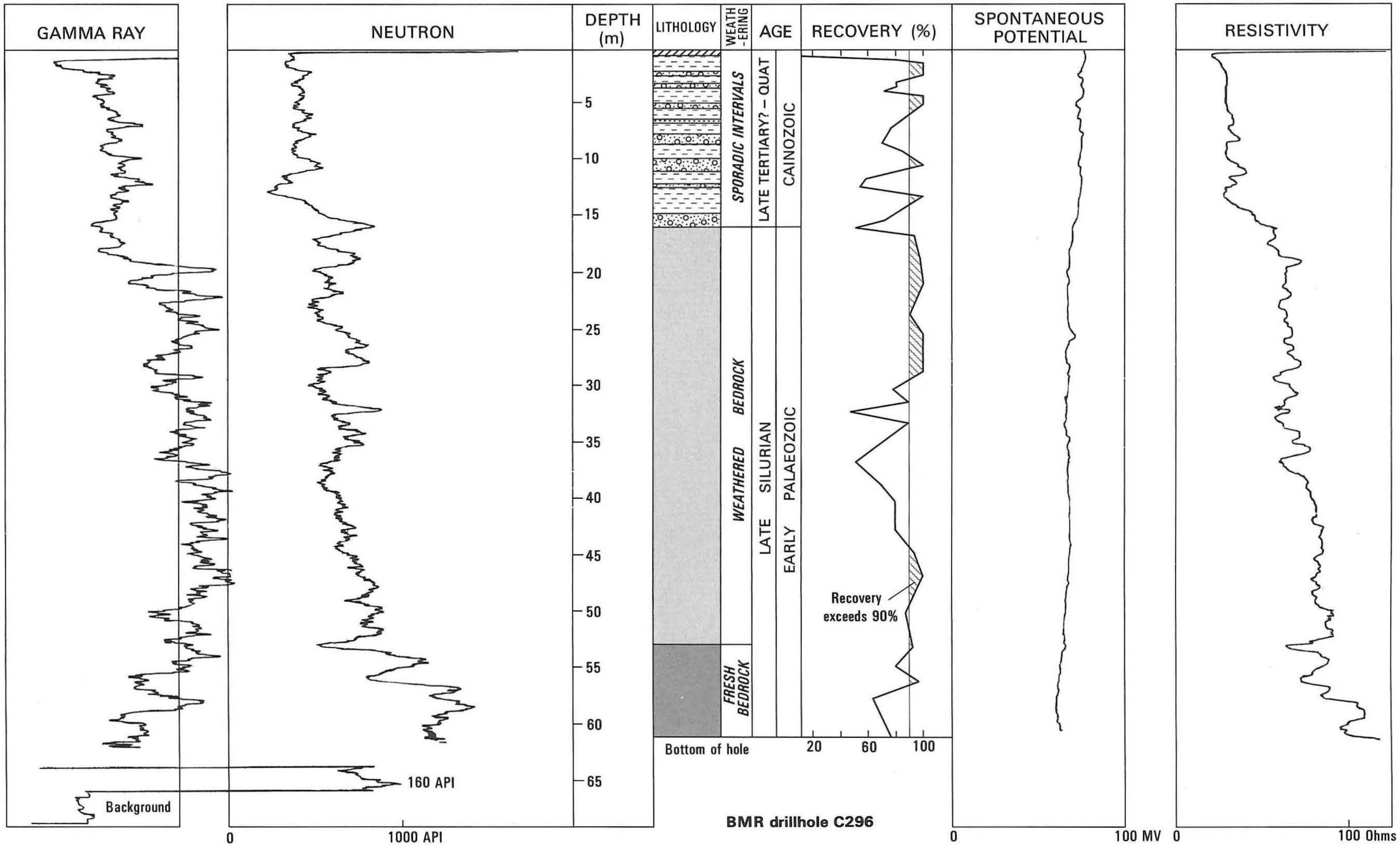
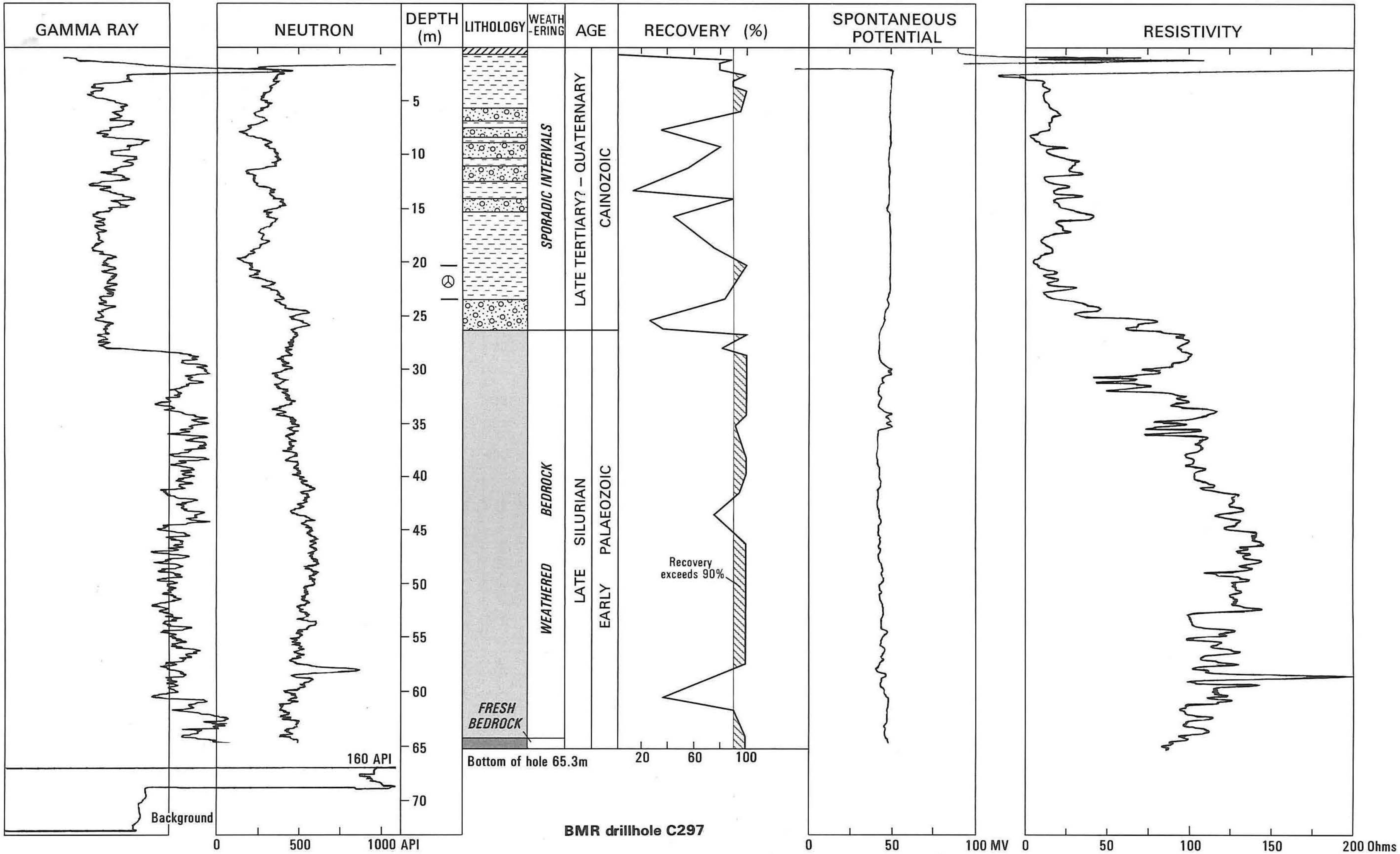
Appendix

Geological and geophysical logs of three BMR drillholes in the Carwoola Flats



16/155-16/116

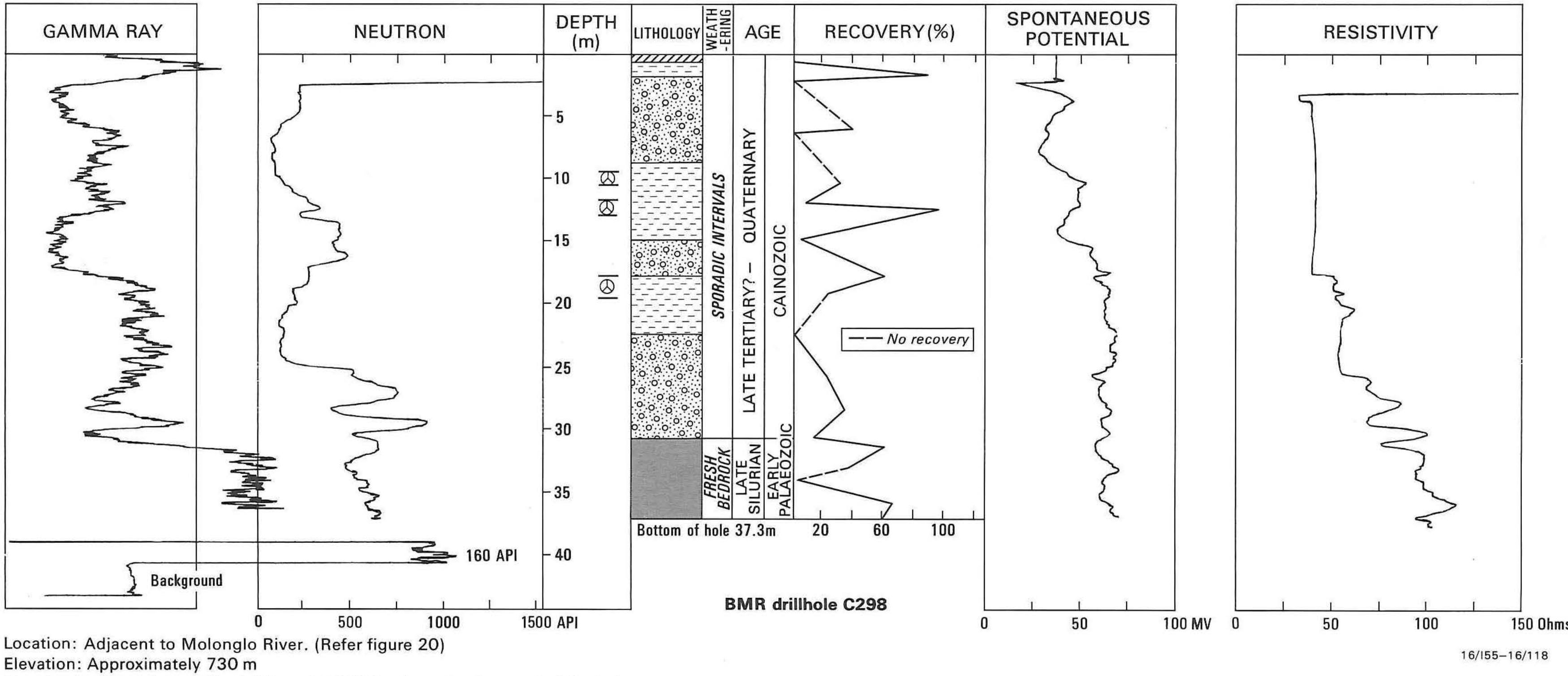
Location: Briars property; west side Molonglo Flats Lagoon. (Refer figure 20)
Elevation: Approximately 730 m
Geophysical logs: Logged by BMR on 8/6/79 using a truck mounted Porta logger. Logging speed 7.5m/min.
Lithological logs: Hole drilled by BMR and compiled on 8/6/79. Interpretation based on core and geophysical logs.



BMR drillhole C297

16/I55–16/117

Location: Briars property; adjacent to Bungendore Road. (Refer figure 20)
Elevation: Approximately 730 m
Geophysical logs: Logged by BMR on 15/6/79 using a truck mounted Porta logger.
Logging speed 9.0m/min
Lithological logs: Hole drilled by BMR and completed on 15/6/79.
Interpretation based on core and geophysical logs.



BMR drillhole C298

Location: Adjacent to Molonglo River. (Refer figure 20)
Elevation: Approximately 730 m
Geophysical logs: Logged by BMR on 22/6/79 using a truck mounted Porta logger.
Logging speed 7.5m/min.
Lithological logs: Hole drilled by BMR and completed on 22/6/79.
Interpretation mainly from gamma–neutron logs.
Poor core recovery.

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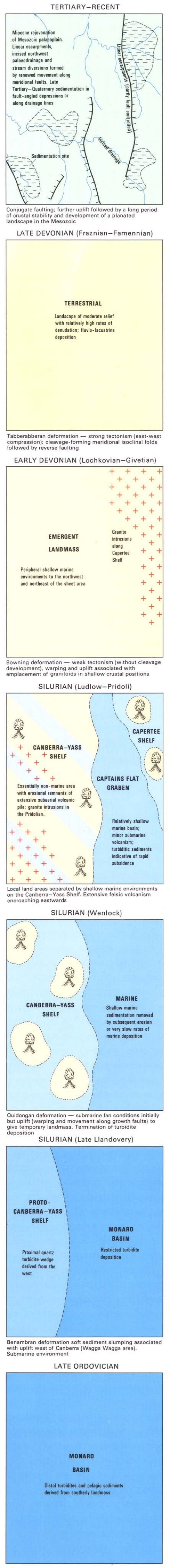

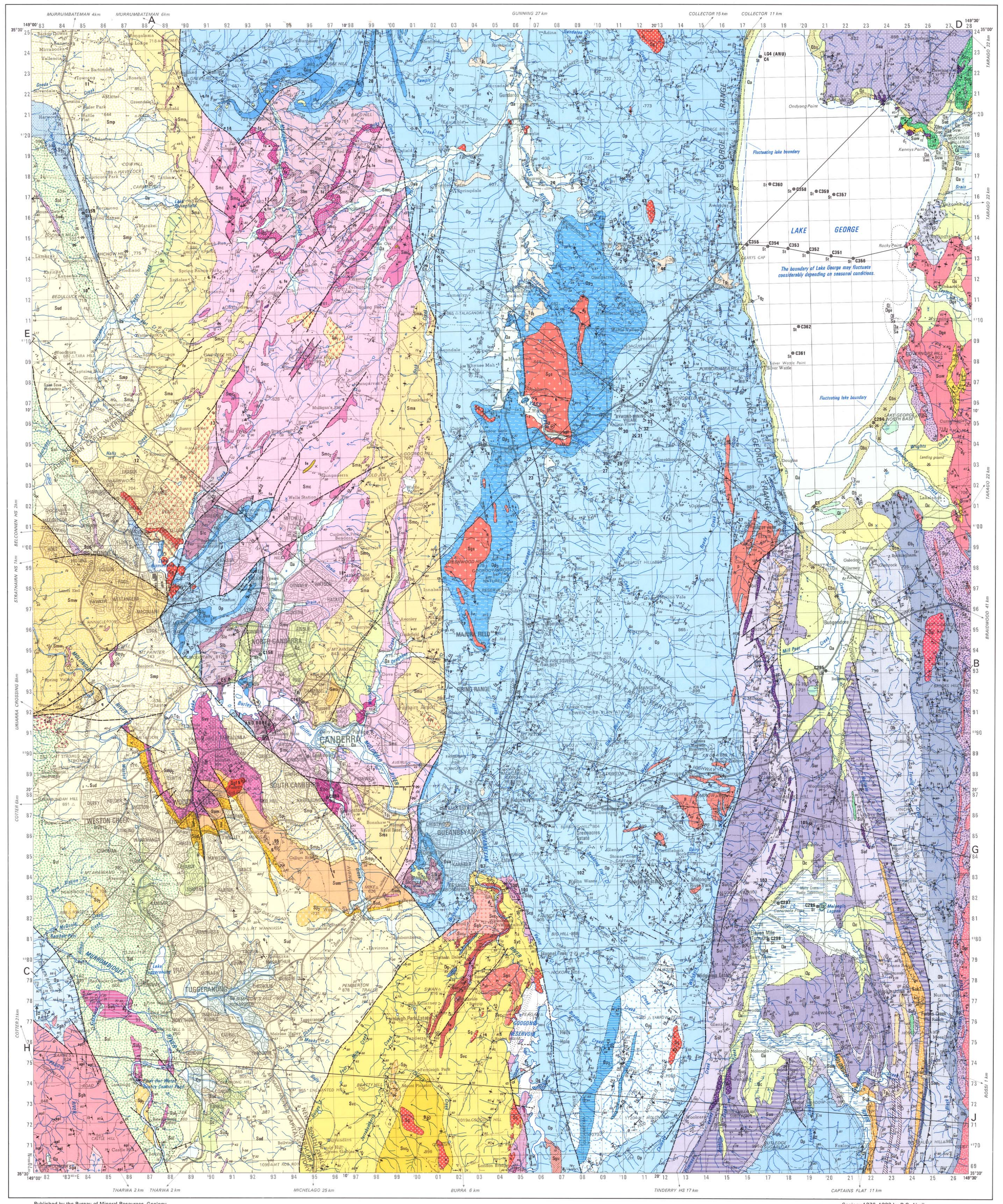

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Revision 1985–1986 by R.S. Abell
Edited 1990 by D. Palfreyman
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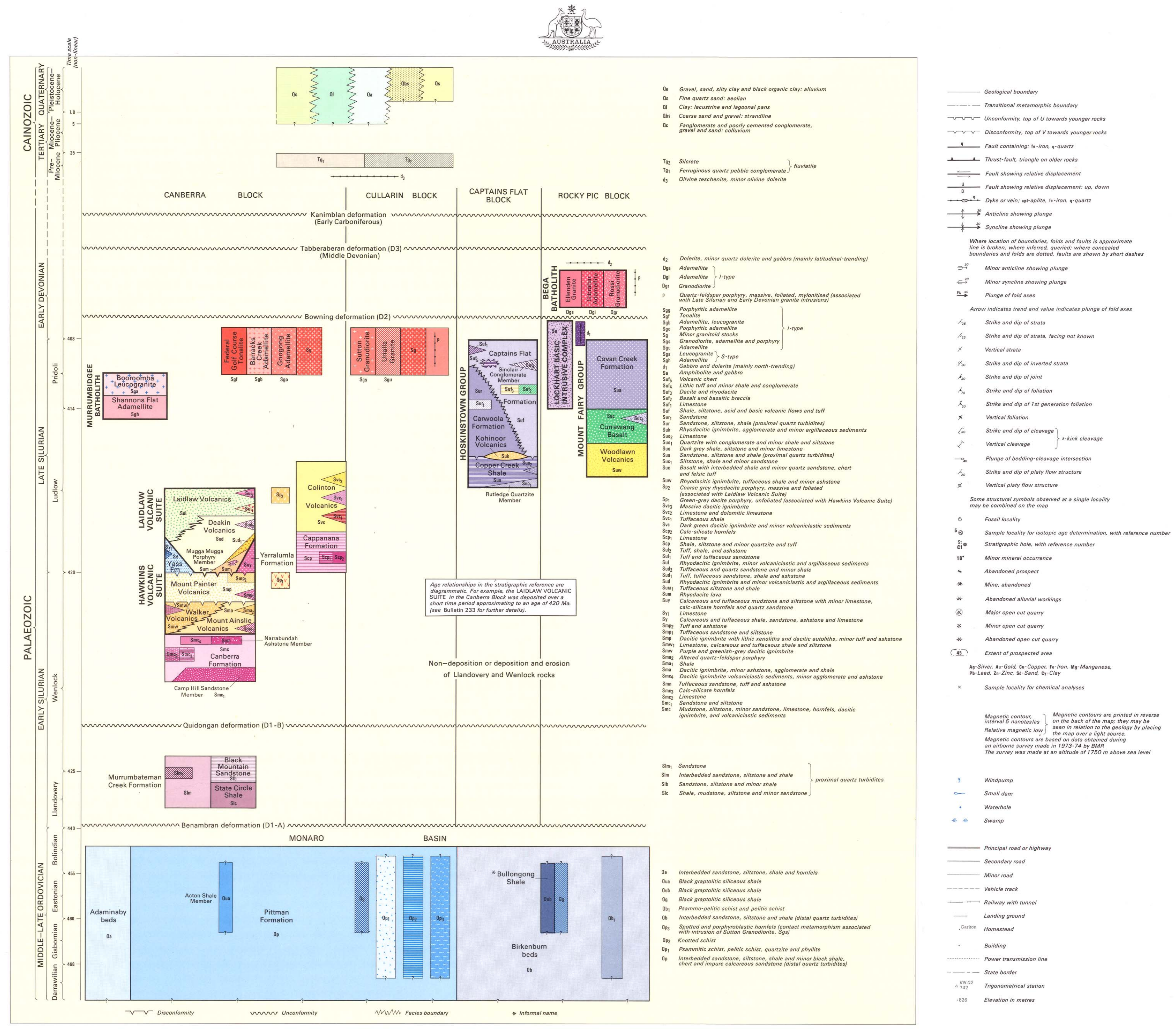
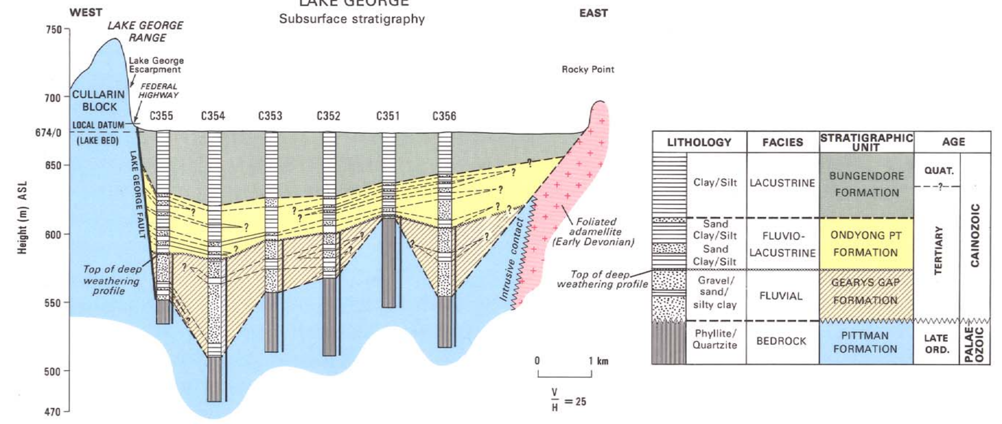


LAKE GEORGE
Subsurface stratigraphy



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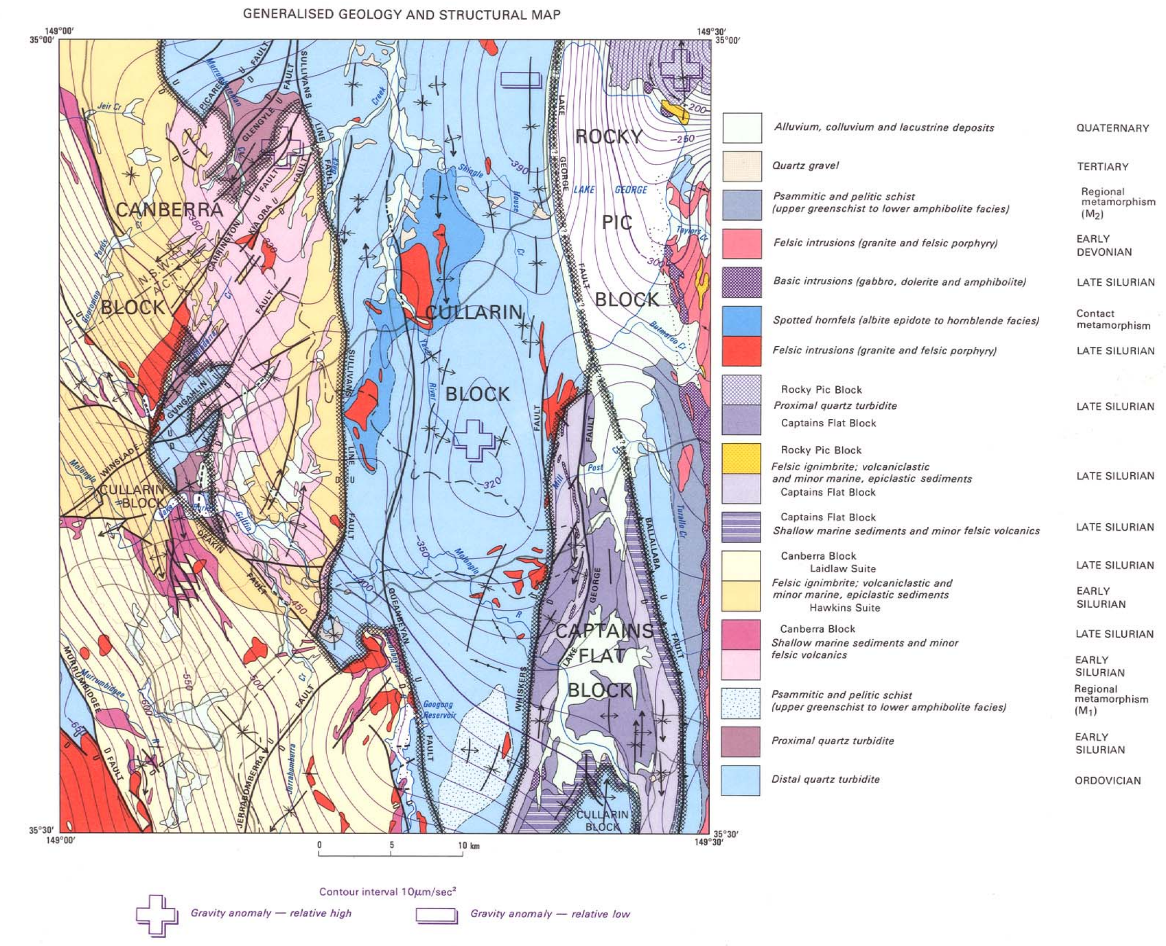

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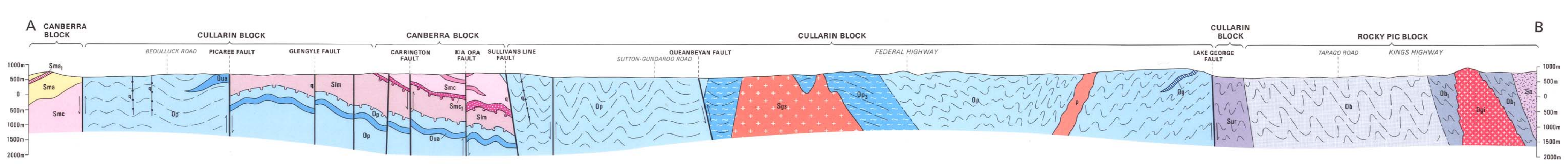
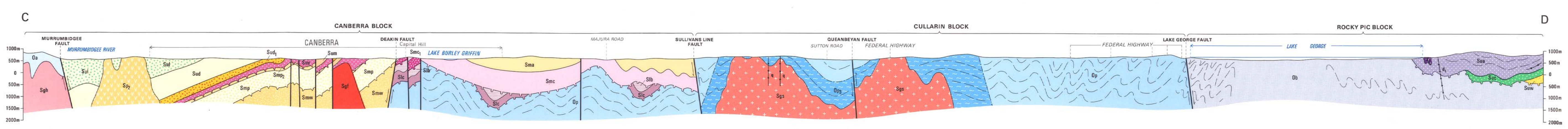
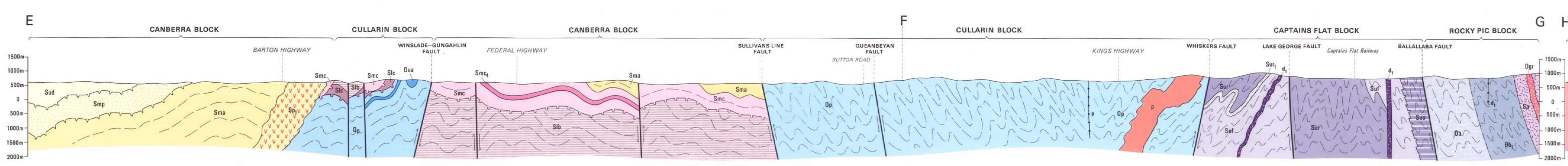
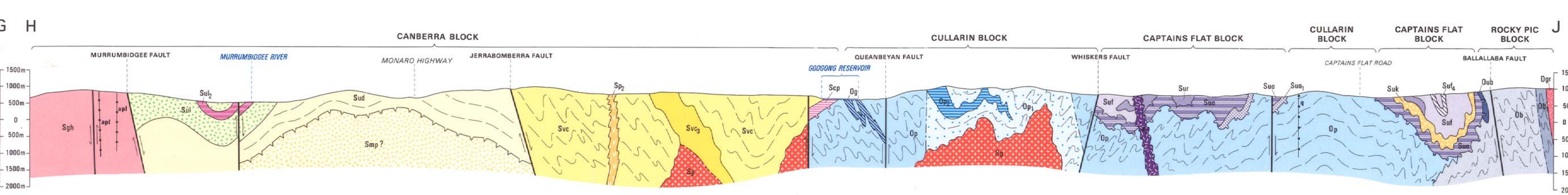
Cainozoic sediments omitted
Scale: $\frac{V}{H} = 1$









STRATIGRAPHIC DRILL HOLES

Reference number	Depth (m)	
C5	137.2	Silurian/State Circle Shale
C145	300.0	Silurian/Canberra Formation
C155	240.4	Silurian/Yass Formation
C158	50.0	Silurian/Canberra Formation
C284	30.0	Silurian/Canberra Formation (Narrabundah Ashstone Member)
ANU BORE	64.0	Silurian/State Circle Shale
C1	120.0	Quaternary/Tertiary?/weathered Ordovician bedrock
C4	71.3	Quaternary/Tertiary
LG4 (ANU)	36.0	Quaternary/Tertiary
C294	84.5	Quaternary/Tertiary?/weathered and fresh Ordovician bedrock
C295	47.8	Quaternary/Tertiary?/weathered and fresh Silurian bedrock
C296	61.1	
C297	65.3	
C298	37.3	Quaternary/fresh Silurian bedrock
C351	131.5	Quaternary/Tertiary/weathered Ordovician bedrock
C352	163.0	
C353	160.2	
C354	197.5	
C355	139.5	
C356	157.0	Uncored
C357	168.5	
C358	129.0	Quaternary/Tertiary/weathered Ordovician bedrock
C359	84.5	
C360	74.0	
C361	96.4	Uncored
C362	132.8	

ISOTOPIC AGE DETERMINATION

	Sample Number/Name	Age (Ma)	Method
1	76460348	397±6	Rb-Sr
2	76460145	407±4	Rb-Sr
3	76460258	410±4	Rb-Sr
4	ANU bore	435±7	Rb-Sr
5	76460262	422±6 417±8	K-Ar Rb-Sr
6	Mugga quarry	414±9	Rb-Sr
7	GA 2811	425±4	Rb-Sr
8	87840566	382±3 387±3	K-Ar Rb-Sr
9	76460350	400±6	Rb-Sr

All ages corrected using current isotopic age constants

MINERAL DEPOSITS

10		Cu
11	Gooda Creek gold prospect	Au, Cu
12	Hall copper prospect	Cu, Au
13	Gold Creek gold prospect	Au
14	Glenesk gossan	Fe, Zn, Pb, Cu
15	Spring Range alluvial gold prospect	Au
17	Murrumbateman Creek gold workings	Au
18		Mn
20	Black Maria gold mine	Au
21	Back Creek gold prospect	Au
22	Goorooyarro gold prospect	Au
23		Fe
24	Shinglehouse Creek alluvials	Au
25	Cartwrights claim	Au
26	Williams reef	Au
27	Little Wonder reef	Au
28	Macs reef	Au
29	Lone Hand mine	Au
30	Coolgardie mine	Au
31	Millyn and party claim	Au
32	Clancy and East claim	Au
33	Erenshaw, Whalan and party claim	Au
34	Lowe and party claim	Au
35	Robbins, Cartwright and party claim	Au
36	Bywong reef (Johnstons reef)	Au
37	Walshs copper lode	Cu, Ag
38	Johnston and party claim	Au
39	Cox and Kershaw claim	Au
40		Au (alluvial)
41		Au
42		Au (alluvial)
43		Au
44	Dawsons reef	Au
45		Au (alluvial)
46	Brooks Creek alluvials	Au
47	Clare prospect	Fe, Au?
95		Pb
97		Au (alluvial)
100	Valley Creek	Cu, Pb, Zn
101		Au
102	Carwoola Copper prospect	Cu
103	The Briars mine	Cu, Pb, Ag
104		Au (alluvial)
105	Woodlands	Au

Mineral deposit numbers refer to the mine data sheets which accompany the Canberra 1:250 000 metallogenic map (Gilligan 1974, 1975)

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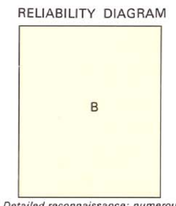

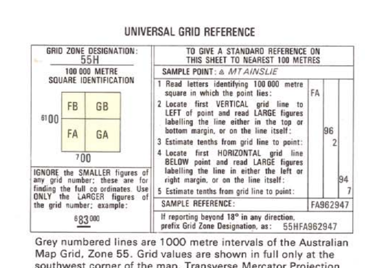

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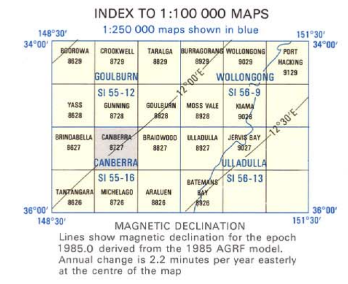
INDEX TO 1:100 000 MAPS



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