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GEOLOGY OF TENNANT CREEK 1:250 000 SHEET AREA, NORTHERN TERRITORY

by

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ABSTRACT

The Tennant Creek 1:250 000 Sheet area was mapped by the Bureau of Mineral Resources in 1970-71. High-grade metamorphic rocks, tentatively classified as Archaean, form sparse outcrops about 30 km west-southwest of Tennant Creek. Early Proterozoic shale, siltstone, greywacke, and interbedded volcanics of the Warramunga Group occupy much of the central part of the Sheet area. The Warramunga Group is considered to be a geosynclinal sequence deposited in a shallow to moderately deep marine environment; the interbedded volcanics show features associated with submarine extrusion. Warramunga Group rocks are intruded by small lamprophyre dykes and sills, diorite, a dolerite, and porphyries. The porphyries appear to be associated with granite. Numerous small outcrops of granitic rock are concentrated in a broad belt. Twenty lithologically distinct types, ranging in composition from adamellite to granodiorite, have been distinguished in the Sheet area.

The Tomkinson Creek Beds rocks, which overlie the Warramunga Group and are probably of Carpentarian age, consist of up to 9100 m of sediments and volcanics of the Blanche Creek Member, the Hayward Creek Formation, Whittington Range Volcanics, Morphett Creek Formation, Short Range Sandstone and the Attack Creek Formation. They are believed to have been deposited in a shallow marine basin, with conditions of sedimentation ranging from intertidal to neritic. The Hatches Creek Group forms small outcrops in the southern part of the Sheet area. On lithological, structural, and stratigraphic grounds, the Hatches Creek Group is correlated with the Tomkinson Creek Beds. The Proterozoic rocks are overlain by flat-lying Cambrian rocks: the Helen Springs Volcanics, the Gum Ridge Formation, and the Anthony Lagoon Beds.

Mining in the Tennant Creek area commenced in 1933, and has continued to the present. Although more than 120 mines of various sizes have been exploited in the Tennant Creek field, by 1974 six mines were in operation: Peko, Orlando, Juno, Warrego, Gecko, and Nobles Nob; by 1977, Peko Orlando and Juno were closed, but two small deposits, the Golden Kangaroo and the Golden Forty were being developed, their high grade ore used for blending with lower grade ore from Nobles Nob. The Tennant Creek field is an important source of copper, gold and bismuth.

INTRODUCTION

The Tennant Creek 1:250 000 Sheet area was mapped by geologists of the Bureau of Mineral Resources (BMR) in the spring of 1970 and the autumn of 1971. This Record describes the geology of that area, and is complementary to the published reports of Crohn & Oldershaw (1965) and Dunnet & Harding (1967) on the Tennant Creek and Mount Woodcock 1-mile Sheet areas, respectively. Modifications have been made to the interpretation of the northern part of the Mount Woodcock 1-mile area and to the soil/rock boundary on the Tennant Creek 1-mile Sheet area. Some changes in the stratigraphy of the Warramunga Group are tentatively proposed, although the original divisions of Crohn & Oldershaw (1965) and Dunnet & Harding (1967) are essentially retained. The Tomkinson Creek Beds have been sub-divided into a number of formations.

The mapping was carried out using 1:46 000-scale aerial photographs (flown in 1947); 1:85 000-scale aerial photographs flown in 1961 by Adastra Airways Pty Ltd were used for navigation and general positioning where the older photographs were inadequate for these purposes.

During the course of the survey three drill holes were put down by the BMR to try to solve structural and stratigraphical problems.

Location and Access

The Tennant Creek Sheet area lies between latitudes 19°S and 20°S, and longitudes 133°30'E and 135°00'E, almost in the centre of the Northern Territory of Australia. The township of Tennant Creek, which has a population of about 2200 (1977), is on the Stuart Highway, which runs north to Darwin (1026 km) and south to Alice Springs (508 km). This road is the major line of communication for the area. Access from the east is by the Barkly Highway, which joins the Stuart Highway at Flynn's Monument, 23 km north of Tennant Creek township. The Barkly Highway runs to Mount Isa (655 km) in Queensland. Regular air services to Tennant Creek from Darwin and Alice Springs serve the town almost daily. Sealed roads serve the major mines, with the exception of Nobles Nob and Golden Forty, which are served by well-formed gravel roads. Except for short periods following heavy rain, a large number of minor tracks and gravel roads give good access to much of the area. The Short Range makes access to the northwest of the Sheet area difficult; the only track into this area at present runs northwest from the Last Hope Mine.

The township of Tennant Creek has hospital, post office, hotel, garage, and shopping facilities. A swimming pool is open in all seasons except winter. Minor centres of population in the Sheet area are the Threeways Roadhouse, the settlements at the Nobles Nob, Peko, Gecko, and Warrego Mines and two small pastoral stations, Phillip Creek and Tennant Creek.

Climate and Vegetation

As the region lies about 400 km north of the Tropic of Capricorn, the climate is hot in summer and mild in winter. The average monthly maximum temperature is nearly 38°C in summer and about 24°C in winter (Table 1). Temperatures of up to 43°C are common in summer; frosts have been only rarely recorded in winter. Rainfall is virtually restricted to the summer months, although it is unreliable. A southeasterly wind blows for much of the year, and the humidity is low except for short periods in the summer.

The vegetation of the area is governed by the semi-arid climate. Soft spinifex (*Triodia pungens*) is abundant over most parts of the Sheet area, with scattered *Eucalyptus papuana* (ghost gum) and *Eucalyptus brevifolia* (snappy gum). *Triodia basedowii* (hard spinifex) occurs sparsely in the lower areas, particularly in places occupied by rocks of the Warramunga Group. *Acacia aneura* (mulga) forms thick scrub on low-lying clay flats, and numerous acacia species grow on the more sandy areas. Patches of perennial tussock grass, such as *Eragostis eriopoda* woollybutt), grow on the wetter sandy areas. Along the shallow valleys and in the floodout areas *E. papuana* (ghost gum) and *E. camaldulensis* (river red gum) are common.

Previous Investigations

W.G. Woolnough (1936) compiled the first geological report on the Tennant Creek Goldfield. He described the general geology and in particular he discussed the origin of the ironstones. The first magnetic survey was carried out in 1935 (Rayner & Nye, 1936; Richardson, Rayner & Nye, 1936; Richardson & Rayner, 1937) and proved to be the most effective exploration method for detecting the iron-rich gold and copper lodes.

Ivanac (1954) carried out a comprehensive study of the mines and regional geology of the Tennant Creek Goldfield and summarized the earlier work.

TABLE 1

AVERAGE TEMPERATURES AND RAINFALL - TENNANT CREEK

Month	Annual	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Rainfall (mm)	326	90	86	49	14	12	7	6	3	6	14	25	50
Mean Temp. (^{o}C)	25.3	30.6	29.8	28.5	25.3	21.3	18.2	17.4	19.8	23.7	27.5	29.7	30.9
Max. Temp. (^{o}C)	32.0	37.0	36.0	34.7	31.6	27.6	24.4	24.1	27.5	31.4	35.1	36.8	37.6
Min. Temp. (^{o}C)	18.5	24.4	23.6	22.3	18.9	15.0	11.8	10.6	12.3	16.0	19.9	22.6	24.2

A review of work on magnetic prospecting was carried out by Daly (1957), and in 1958 the BMR produced a series of 1:63 360-scale maps showing total magnetic intensity over much of the Sheet area. In 1962 a revised and extended version of the magnetic map, which also showed radioactive anomalies, was published by the BMR. Geochemical work was carried out in 1955-57 (McMillan & Debnam, 1961) and further work is being undertaken by BMR at present.

In 1965, BMR published a report on the detailed geology of the Tennant Creek 1-mile Sheet area (Crohn & Oldershaw, 1965). A report on the geology of the Mount Woodcock 1-mile Sheet area, including a description of a geochemical survey, was published in 1967 (Dunnet & Harding, 1967). Whittle, in 1966, submitted a thesis for a Ph.D to the University of Adelaide on the genesis of gold and base metal deposits in the Lower Proterozoic rocks of the Tennant Creek area.

Numerous specialised investigations have been carried out in the Tennant Creek area. These include company investigations (Geopeko Ltd and Australian Development Ltd), and a series of CSIRO Mineragraphic Reports which deal mainly with compositions, textures and paragenesis of ore from Peko and Nobles Nob Mines. Hays (1958) and Crohn (1961) described the hydrology and subsurface geology of the Cabbage Gum Basin, which in 1974 supplied about 30 percent of the water for Tennant Creek. The Kelly Well Basin supplied about 70 percent of the water requirements (Faulks, 1965).

History of Mining and Production

The early history of the field is discussed by Ivanac (1954), and developments up to 1963 were dealt with by Crohn & Oldershaw (1963). The major developments from 1963 to 1977 were: the commencement of production from the Ivanhoe, Juno, Gecko, and Warrego Mines, and the closing of the Orlando, Ivanhoe, Peko, and Juno mines. Small scale mining started at the two small prospects, the Golden Forty and the Golden Kangaroo. Most of the gold produced is converted to bullion; the remainder is recovered during the treatment of copper concentrates in Japan.

Numerous smaller mines have been worked for gold since production started in 1933; by 1971 only the Blue Moon and Last Hope Mines were being sporadically worked, and in 1977 the Hopeful Star east was the only small mine being exploited. The more important of the smaller mines were Eldorado

(3353 kg), Whippet (574 kg) and Blue Moon (490 kg). In 1977 Exploration Licences or government reserves were held over much of the Sheet area.

Acknowledgment

M.R. Daly, of the Geological Survey of the Northern Territory contributed to the Record by offering valuable suggestions and providing important statistical and geological information about the Sheet area.

PHYSIOGRAPHY

The physiography of the Tennant Creek and Mount Woodcock 1-mile Sheet areas has been described by Crohn & Oldershaw (1965) and Dunnet & Harding (1967) respectively.

The present drainage of the Tennant Creek 1:250 000 Sheet area is developed on an uplifted peneplain, which lies at an average height of about 300 m above sea level. The general relief in the Sheet area is about 60 m, and the maximum about 100 m, in the Mount Samuel area.

The Warramunga Group sediments form groups of mesas and buttes in the central part of the Sheet area; elsewhere they weather to low rocky outcrops. The mesas and buttes are commonly capped by lateritic crusts. The mesas are separated by low flats, up to several kilometres wide, covered by wind-blown and, more rarely, flash-flood deposits. The slopes of the mesas are commonly covered by ferruginous rubble. Residual vein-quartz gravel is common on both the slopes and the 'bulldust' flats adjacent to outcrops. The volcanic beds within the Warramunga Group crop out as low hills, and the more massive or cherty beds form strike ridges. Quartz veins, whose distribution is controlled by the major faults, commonly form sharp ridges which can be followed for several kilometres (e.g. Quartz Hill Fault).

The mesa-flat topography is in strong contrast to the large rounded tors developed on porphyritic granite. The tors are particularly well-developed in an area 10 km north-northwest of Tennant Creek. The non-porphyritic, aplitic, and fine-grained granites, however, form low rounded hills, commonly covered with coarse quartz sand.

The Short and Ashburton Ranges in the north and on the northern edge of the Murchison Range in the south are composed mainly of quartz sandstone. The massive, blocky, and in places silicified beds in the sequence form steep-sided strike ridges separated by silty, feldspathic, or fine-grained sandstone and in many places sills of highly lateritised diorite/dolerite. Calcareous beds weather to areas of low relief. The Whittington Range Volcanics which lie within the Tomkinson Creek Beds are very strongly weathered, and outcrops are rare.

A large area of blacksoil plain is developed on the Cambrian Anthony Lagoon Beds in the northeast. The Lower Cambrian Gum Ridge Formation forms low hills; bedded chert and limestone form low ridges. Outcrops of Anthony Lagoon Beds are rare: the ground is mostly covered by chert rubble.

In the east and west, the topography is typified by gently undulating hills and extensive plains. Low rises in the east are formed by extensive consolidated sand dunes. In the southwest, travertine is developed in several areas. The western part of the Sheet area is semi-desert and typified by nearly featureless gently undulating topography. In the northwestern corner of the Sheet area weathering of the Tomkinson Creek Beds sediments has resulted in the deposition of extensive sand plains.

The flat-topped mesas and buttes and the strike ridges of the Short and Ashburton Ranges lie between 360 m and 440 m above sea level. They are the remnants of an uplifted peneplain on which laterite was extensively developed during the Cainozoic. The levels slope at low angles in various directions; this may be due to later warping or to incomplete planation of the pre-existing surface.

The few streams in the area are seasonal, and only a few waterholes persist into late winter and spring. The streams are incised into alluvial deposits, commonly 3-5 m thick, but up to 15 m in the flood plains of the Gosse River and Tennant Creek. All drainage terminates on low-lying areas within the Sheet area. Except for Kelly Creek in the extreme south and the creeks near Warrego Mine, which flow to the south, all streams flow north and east.

? ARCHAEAN

One small outcrop and several areas of sub-outcrop of hematite-rich quartzite were found in an area about 30 km west-southwest of Tennant Creek. Diamond drilling in this area intersected high-grade gneiss below superficial cover. These rocks may extend as far east as the Cabbage Gum Basin, as gneissic and schistose rock has been found associated with granite in the basin (Whittle, 1966). These rocks are thought to be older than the Warramunga Group because of their higher grade of metamorphism. Judging from their composition, grade of metamorphism, and possibly, their stratigraphic position, they are probably correlatives of the Arunta Complex, and as such, Lower Proterozoic. However, until the age of these rocks is established, they are tentatively classified as Archaean.

The metamorphic rocks are overlain by up to 25 m of poorly consolidated grit and sand. Their relation to the sediments of the Warramunga Group is not known, but because of the differing metamorphic nature of the two units the contact is believed to be unconformable. There remains, however, the possibility that these rocks belong to the Warramunga Group, but have undergone a higher grade of metamorphism than that known elsewhere. Geophysical and borehole evidence suggest that gneiss may be bounded by a faulted contact along the northeastern edge of the metamorphics. The northern contact is with granite. The metamorphics are intruded by adamellite, alkali microgranite, microdiorite dykes, and sulphide-bearing quartz dolerite and gabbro (Whittle, 1966). Some of the acid intrusives show evidence of garnet-grade metamorphism, but most of the intrusives post-date the early metamorphism. Fresh massive basic intrusives cut the fold structures, and if they can be correlated with the Short Range dolerite/diorite, they postdate the Carpentarian or Early Proterozoic folding of the Warramunga Group.

Whittle (1966) recognized garnet-mica gneiss, grunerite-garnet gneiss, and plagioclase gneiss. The rocks lie within the almandine-amphibolite facies or more specifically, the sillimanite-almandine-muscovite subfacies of regional metamorphism (Turner & Verhoogen, 1960). Lit-par-lit injection of layers composed of graphically intergrown quartz and feldspar is common within the gneiss. Andalusite occurs within limited zones in the Archaean rocks, although this may be attributable to later contact metamorphic effects of the basic intrusives. Hornblende-diopside-garnet gneiss and tremolite schist were intersected in one drill hole. In the most westerly drill hole (DDH 161 - Whittle, 1966) slightly lower-grade metamorphics of the staurolite-almandine sub-facies are present: quartz-biotite-garnet gneiss and hornblende-tremolite-garnet-quartz rock. Sodic plagioclase is also present, and some parts of the rock contain up to 10 per cent graphite. Total-rock samples from core of amphibolite indicated a Rb-Sr age of 1920 $\pm$ 60 m.y. (Black, 1977).

Outcrops of the metamorphic rocks consist of distinctly banded limonite quartzite. The bands are commonly irregular; they are 0.5 mm to 1 cm wide, and average 3 to 4 mm. They consist of linear concentrations of limonite within the quartzite. In thin sections the rock can be seen to consist of bands of finely divided limonite-stained hornblende in a mosaic of unstrained equigranular quartz. Minor muscovite is present.

EARLY PROTEROZOIC

WARRAMUNGA GROUP

Sediments and interbedded volcanics of the Warramunga Group underlie much of the central part of the Sheet area. Outcrops of the Group extend as far north as Hayward Creek and south onto the adjoining Bonney Well Sheet area. The major development of the Group lies in a roughly ovoid zone stretching between the Gosse River in the southeast and the Last Hope Mine in the northwest. This zone, which covers about 1500 km^2, is the major area in which the central part of the sequence, comprising shale, siltstone, greywacke, and interbedded volcanics, crops out. The older part of the sequence, which consists dominantly of shale, is exposed in the west, and the younger beds crop out in the north along the base of the Short Range.

The Warramunga Group is folded into a large westerly plunging anticlinorium with abundant intermediate and small-scale folds. The small-scale structures are particularly marked in the fine-grained sediments. Secondary folding and subsequent faulting have considerably modified the original geometry of the fold pattern.

The Warramunga Group is composed of interbedded sediment and volcanic lenses. The writers have tentatively subdivided the Warramunga Group into ten units, including seven units, Ew_1 - Ew_7, not necessarily in stratigraphic order. It must be emphasised, however, that this subdivision cannot be substantiated with confidence in the field. Dunnet & Harding (1967) and Crohn (in Dunnet & Harding) have used different correlations for the Warramunga Group rocks. It is doubtful if the thickness of the Warramunga Group sequence exceeds 3000 m, but a composite section may be drawn to give a maximum of 6000 m. The true thickness of the sequence is difficult to calculate in many areas, owing to the high degree of folding, lack of marker bands within the sequence, and sparse outcrop. The sediments consist of tuffaceous greywacke, siltstone, shale, minor sandstone, and interbedded acid volcanics in all parts of the sequence. A distinctive hematite-rich shale occurs in the central part of the sequence. The upper 750 m of the Group consists of feldspathic sandstone and several pebble bands, and shows both ripple marks and festoon cross-bedding (Dunbar & Rodgers, 1957). These rock types are transitional between the eugeosynclinal facies of the central part of the Warramunga Group and the shallow-water marine environment of the overlying Tomkinson Creek Beds. This relation is particularly evident in the Last Hope mine area, where the upper part of the Warramunga Group attains its maximum development.

Shale from the Ꝑw$_6$ unit and volcanic rock from the Bernborough Formation were dated at 1766 ± 80 m.y. and 1753 ± 40 m.y. respectively by Black (1977).

Unit Ꝑw$_1$

Distribution

The unit Ꝑw$_1$, composed mainly of siltstone and shale, crops out around the Gosse River from about 13 to 22 kms east southeast of New Hope mine; east of the Stuart Highway, northeast of Flynn's Monument; and in the White Hill area. It is the oldest exposed unit of the Warramunga Group in the Sheet area.

Stratigraphic relationships

The unit conformably underlies the siltstone, greywacke, and sandstone of unit Ꝑw$_5$. It is intruded by several stocks of massive granite, quartz-feldspar porphyry dykes, and other quartz porphyry bodies. The porphyries were emplaced during two periods; the older porphyries are cleaved and apparently folded with the sediments, whereas the later intrusives, which are associated with the granite, are massive, and post-date the cleavage.

Contact-metamorphic effects are visible for up to 200 m from the granite and later-generation porphyries. The metamorphism has resulted in the recrystallization of clastic micas to form larger non-aligned muscovite books in the siltstone. At grid reference 450819 a quartz actinolite vein has caused metasomatism of the surrounding pink to purple coarse-grained siltstone. Small radiating actinolite aggregates about 4 mm across are found in the siltstone up to 8 m from the vein.

Lithology

Owing to sparse outcrop and the presence of numerous faults, no estimate of total thickness can be given for the unit in the area around the Gosse River. It forms numerous scattered outcrops southeast of the Gosse River crossing. The rocks lie along the southeastern extension of the Rocky Range fault zone, and show evidence of much shearing. They are grey to fawn and red-brown to pink, consist of fissile to flaggy, rarely blocky to massive coarse to fine siltstone and subsidiary shale, and are commonly silicified.

In the area north of Channingum Creek a series of tuff, silicified lava, and ashstone is intruded by porphyry and granite. The volcanics are underlain by purple to white, flaggy, fine-grained siltstone with some thin tuff(?) bands. The oldest volcanics exposed in the eastern part of the outcrop area consist of purple, medium-grained lithic tuff and minor interbedded red acid lava. These are succeeded by white, pink, and purple banded chert and kaolinitic bands. The purple chert commonly contains irregular (feldspathic?) inclusions, and shows wavy irregular banding. Thin, highly vesicular zones are found within these beds, and rare small fragments of vesicular lava are enclosed in the fine-grained matrix. To the west, the volcanics interbedded with flaggy ferruginous shale and siltstone are more tuffaceous. Hematite is very abundant in these beds; pure hematite bands up to 4 mm thick commonly occur within the sequence.

At grid ref. 450826, pink and purple blocky chert (ashstone?) and pink, coarse-grained, felspathic tuff overlie purple, flaggy to fissile siliceous shale and fine-grained siltstone. These volcanics are probably related to the more southerly outcrops, described above.

At grid ref. 445813 the uppermost part of the unit is exposed. Lilac, fissile to flaggy, cleaved shale and fine to medium-grained siltstone crop out beneath the basal, massive, thick-bedded greywacke of the Ew_5 unit. Within the shale a 15-cm hematite-rich zone is concordant with the bedding.

In the area around White Hill silicified shale and fine-grained greywacke and siltstone are intruded by granite. It is probable that these beds are truncated to the southwest by a concealed continuation of the Bernborough Fault.

Dunnet & Harding (1967) describe the beds northeast of Flynn's Monument as greywacke and shale. These are tentatively assigned to unit Ew_1.

Bernborough Formation and Whippet Sandstone Member

Distribution

These two units are restricted to the Mount Woodcock 1-mile MSheet area, and were defined and described in detail by Dunnet & Harding (1967). No further detail has been added by the present authors.

The units crop out over an area of about 42 km^2 in a crescent stretching southwest from the Whippet mine to Bishop Bore. Outcrops are discontinuous along this zone, the maximum development being in the type area, a group of low hills northeast of the Bernborough mine. The unit also crops out in two small hills 2.5 km southeast of Flynn's Monument.

Stratigraphic relations

The Bernborough Formation is inferred to conformably overlie unit Ew_1. The Whippet Sandstone Member is commonly at the base of the Bernborough Formation, but where sandy interbeds are present higher in the volcanics, these are also termed the Whippet Sandstone Member. Both units are intruded by purple, banded, quartz-feldspar porphyry.

Lithology

The Bernborough Formation reaches a maximum thickness of 800 m in the type area. It consists of acid lava, tuff, and tuffaceous greywacke interbedded with shale, siltstone, and minor ashstone. Northeast of the Bernborough mine three sediment interbeds are present in a sequence of purple acid lava and crystal tuff. The volcanics typically contain epidote and quartz 'phenocrysts' in a hematitic hemicrystalline to fine-grained matrix.

The Whippet Sandstone Member ranges in thickness from 180 m in the area of Whippet trigonometrical station to 120 m in the Bernborough mine area. It consists of white to grey and fawn, massive to blocky and flaggy, quartz and feldspathic sandstone. Grit and pebble bands occur locally in the sequence. Acid porphyry pebbles have been reported in the sandstone interbeds in the volcanics, suggesting penecontemporaneous erosion of the volcanics.

Unit Ᵽw_2

Unit Ᵽw_2 includes unit Ᵽw_1 described by Crohn & Oldershaw (1965) and unit Ᵽws described by Dunnet & Harding (1967). It may be equivalent to the lower shaly part of Ᵽw_3, which crops out only west of the Phillip Creek lineament, and north of the Great Western Syncline.

Distribution

The unit Ᵽw_2 crops out in a wide arc in the north of the McDougall Ranges, from a point 5 km east of Mount Cleland to the Orlando mine. Numerous smaller outcrops occur to the north, between Butchers Waterhole and the Whippet mine. The total area of outcrop is about 112 km^2. The outcrops form a westerly plunging anticlinal trace around the major fold within the Warramunga Group.

Lithology

The unit crops out only on the Mount Woodcock and Tennant Creek 1-mile Sheet areas, and has previously been described by Crohn & Oldershaw (1965) and Dunnet & Harding (1967). It is estimated by Crohn & Oldershaw (1965) to have a maximum exposed thickness of 780 m. The unit is composed of shale and siltstone and, in the sequence at Mount Cleland, pebble beds 2 m thick. The pebble and shale fragments are up to 7 cm in diameter. About 3 km south of Station Hill, slate and minor siltstone crop out. The shale consists mainly of sericite flakes, but also contains flat lenticular aggregates of fine grained quartz and martite euhedra (Whittle, 1966).

In the Bernborough area (Mount Woodcock 1-mile Sheet area), Dunnet & Harding (1967) estimated unit Ᵽw_2 to be 1200 m thick; it consists of thin-bedded buff to red and brown siltstone, and hematite-rich shale. At the Edna Beryl mine, hematitic siltstone and shale 60 m thick are believed to be near the base of the sequence.

Near the Orlando mine, shale containing thin sandy intercalations shows two sets of cleavage - a primary east-west slaty cleavage, and a secondary fracture cleavage parallel to the axial plane of sinistral S_3 kink folds. Zones of intense shearing have caused boudinage of the more competent arenaceous beds, which are recrystallized into quartz porphyroblasts; an example can be seen at the Orlando mine, where it has the appearance of a pebble bed.

Elliston (1960, 1965) described the rocks as a 'pelletoid conglomerate' which he considered was formed by colloidal accretion in a thixotropic slurry.

Three and a half kilometres northwest of Quartz Hill brick-red to purple, flaggy to fissile, fine-grained siltstone and shale are affected by at least two phases of folding. An early vertically dipping S_2 cleavage strikes at 135^o, and a later S_3 cleavage, axial planar to the numerous small scale kink folds, strikes at 165^o and dips at 80^oE. Further west, near the Gecko mine, flaggy to blocky medium-grained siltstone is interbedded with the shale.

Stratigraphic relations

Contacts between both the overlying unit Ew_6 and the underlying lenticular unit Ew_7 are gradational. However, the contact with the underlying Bernborough Volcanics in the Bishop Creek area is sharp. In the vicinity of the Mary Lane mine, fissile micaceous fine greywacke passes vertically upwards into more blocky coarse greywacke, and downwards into siltstone. The contact with the underlying unit is exposed in the area north of the Orlando mine in a complex faulted anticline. The underlying unit Ew_7 consists of interbedded greywacke and shale, and this passes upwards over a narrow vertical interval into dominant shale.

The Gecko Volcanics (Ewg) form a thin conformable layer within unit Ew_2 in areas 2.5 km southwest and 6.5 km southeast of the Gecko mine. Unit Ew_2 is intruded by granite, quartz-feldspar porphyry, and quartz porphyry.

Gecko Volcanics

The Gecko Volcanics comprise several lenses of tuff, lava, and volcanic greywacke, and are exposed south and southeast of the Gecko mine. They were described by Dunnet & Harding (1967), and were defined by Ivanac (1954). The Olive Wood lens in the eastern part of the exposed volcanics, described by Dunnet & Harding as 'coarse porphyritic quartz-felspar rock to massive tuffaceous greywacke', was mapped as a quartz-feldspar porphyry lens.

Derivation of name

The name is taken from the Gecko mine.

Distribution

The volcanics form a series of small lenses within the unit Ew_2. They cover a total area of less than 3 km^2. The lenses stretch in a rough line from 2 km northeast of the Gecko mine to 6 km southeast of the mine. They lie alongside the track from Quartz Hill to the Marion Ross and Orlando mines. At Mount Argo (grid ref. 488844) the volcanics comprise two distinct beds which are folded into a northwest-plunging antiform.

Lithology

The Gecko Volcanics consist of grey-green and purple tuff, quartz and feldspar porphyry, and greywacke mostly derived from volcanic rock. Compared with quartz and quartz-feldspar porphyry, which they resemble, the volcanics are notable for their lack of quartz veins.

On the southwestern limb of the Mount Argo antiform the unit consists of two parts divided by a thin shale band. What is believed to be the lower part consists of well-jointed blocky, purple to grey, vesicular lava with quartz and feldspar phenocrysts, as well as tuff. Small rounded clear quartz and euhedral feldspar phenocrysts lie in a sheared fine-grained sericite-feldspar-quartz matrix. The uppermost part of the unit consists of sheared quartz-feldspar and feldspar porphyry interbedded with shale of unit Ew_2.

Blocky to massive, medium-grained volcanogenic greywacke crops out south of the Quartz Hill-Gecko Mine track. The rock contains rare quartz, and epidote grains in a fine-grained grey-purple matrix. About 1 km west of this large outcrop is a small hill composed of purple-grey quartz porphyry with small rounded clear yellow or white quartz phenocrysts in a weathered, ferruginous, fine-grained groundmass.

The quartz-feldspar porphyry of the Olive Wood lens contains large ovoid blue quartz phenocrysts and weathered remnants of large feldspar crystals. It is apparently discordant.

Thickness

The maximum thickness of the [illegible] m.

Stratigraphic relations

The Gecko Volcanics are overlain and underlain conformably by shale of unit Ew_2, but they range laterally both in thickness (about 200 m to 300 m), and composition. They are bounded in several places by faults.

Warrego Volcanics

The Warrego Volcanics have not been previously defined as a unit, as they are restricted to the previously unmapped Marion Ross 1-mile Sheet area. Dunnet & Harding (1967) briefly described the volcanics. They correlated the upper part of the Volcanics and the lower part of the unit Ew_3 with pink 'volcanic' chert that crops out 3 km north of Orlando mine on the Mount Woodcock 1-mile Sheet area.

Derivation of Name

The name is taken from the Warrego mine which lies 11.5 km west southwest of the type area of the unit. No type section can be measured for the unit, as exposure is poor and the lithology different from place to place. The outcrop on the northern limb of the Great Western Syncline may be regarded as the type area for the unit.

Distribution

The Warrego Volcanics crop out over 21 km^2 between the Orlando and Warrego mines. The largest single area of outcrop lies 11 km east-northeast of the Warrego mine, where the volcanics define the Great Western Syncline. They are folded into a westerly plunging open syncline; the corresponding anticlines are poorly exposed to the north and south. Numerous faults complicate the areal distribution of the unit, both in the Great Western Syncline and in the Black Angel mine area. Directly southwest of the Black Angel mine the volcanics are exposed in a faulted block. Further west the upper part of the volcanics is again exposed in an anticline.

Lithology

The volcanics range in thickness from about 550 m in the type area down to about 200 m at about 7 km southwest of the Warrego mine. They consist of purple banded rhyolite, grey ignimbrite, pink ashstone and tuff, and grey banded hematite shale interbedded with siltstone, greywacke, and shale. The sequence is best developed in the Great Western Syncline between 8 and 14 km east-northeast of the Warrego mine. The basal units are dark purple to cream and pink, brittle, silicified, irregularly banded, rhyolitic lava. The rock contains lenticular fragments, believed to be siltstone, and quartz-feldspar aggregates.

The dark purple lava consists of angular quartz, secondary(?) muscovite and hematite aggregates in a groundmass of hematite, kaolin, and sericite. Irregular glass fragments are abundant in the groundmass. Purple tuffaceous siltstone with small, roughly rectangular hematite inclusions underlies the volcanics.

Further to the southeast grey to pink and purple claystone and tuffaceous siltstone are overlain by a distinctive grey, flaggy to blocky, well-jointed, finely banded hematite shale. The hematite shale crops out in several localities on the southern limb of the Great Western Syncline. It consists of finely crenulated, broadly lenticular hematite-rich bands in a matrix of very fine-grained quartz, sericite, and hematite. Small quartz crystals and sericite flakes are present in the hematite-rich bands. The hematite shale is lithologically identical to a bed used by Crohn & Oldershaw (1965) as a marker horizon cropping out in the vicinity of the Kathleen mine. Overlying the hematite shale are pink and purple lava, ashstone, and rare coarse-grained greywacke.

In the western part of the Great Western Syncline flaggy to blocky tuff and leached white tuffaceous siltstone are interbedded with pink and cream cherty ashstone. Slump folding in the blocky tuff suggests that their provenance was to the east.

On the northern limb of the Great Western Syncline the whole sequence is exposed; the upper blocky tuff and greywacke overlie cream, pink, and purple ashstone. Hematite shale crops out at three stratigraphic levels in the lower part of the sequence. The purple lava crops out near the base of the sequence. The pink ashstone is fractured by irregular micro-cracks, and mottled by veins.

Six kilometres southwest of the Warrego mine a small outcrop of Warrego Volcanics consists of fine-grained cream to pink tuff and tuffaceous siltstone containing small, fine-grained feldspar in a siliceous matrix. Lenses and irregular bands of chert breccia are enclosed by the shale directly overlying the volcanics. The brown chert fragments are angular, and have an average length of 0.5 cm; the breccia lenses are possibly derived from agglomerate. About 1 km northwest of the outcrops, angular uncleaved greywacke and siltstone fragments up to 10 cm long (average 4 cm) in a weathered hematitic quartz-feldspar matrix may be sediments brecciated during extrusion of the volcanics.

Eight and a half kilometres southwest of the Warrego mine more volcanic rocks are exposed in an upfaulted block. The sequence is considerably thinner than in the type area, but retains some of the characteristic features of the unit. At this outcrop a band of hematite-rich shale 3 m thick crops out against blocky to flaggy, highly feldspathic tuff. Dark red and pink, finely-banded tuff and rhyolitic lava with 'flattened' feldspar and minor quartz inclusions overlie the hematite-rich shale. Greywacke and siltstone make up a greater proportion at this exposure than in the Great Western Syncline.

The Warrego Volcanics also crop out in a crescent-shaped area south of the Black Angel trigonometrical station. The lower contact of the volcanics is well exposed on the southern margin of the flat-topped hills 0.5 to 1 km south of Black Angel trigonometrical station. Breccia zones up to 3 m long, and consisting of angular chert and greywacke fragments in a hematite-clay-quartz matrix, are present in the upper parts of unit Ew_7 and the lower parts of the volcanics. The breccia zones commonly disrupt the bedding in the sediments. A 'breccia' bed 25 cm thick, believed to be an agglomerate, is interbedded with tuffaceous siltstone and greywacke at the base of the volcanics. One kilometre south of Black Angel trigonometrical station, a tuffaceous siltstone passes laterally into weathered ferruginous quartz porphyry.

Pink to yellow and grey, fissile, silicified tuff and lilac shale are interbedded with orange coarse-grained angular tuff and agglomerate in a series of small rocky hills, 1 km south of Black Angel trigonometrical station. Parallel layers of hematite grains and zones of shale flakes are common in the volcanics. At grid ref. 389845 a 1-m band of grey-purple to pink, coarse-grained tuff is composed of angular, dark-grey vesicular lava fragments up to 5 cm long and small pink feldspar(?) fragments in grey clay matrix. The fragments are apparently flattened in the plane of the bedding. In addition to being abundant in the rock itself, hematite occurs in 2 mm-thick bands. Weathering, devitrification and, possibly, metasomatism of the rock have erased any diagnostic features. The matrix consists of a mosaic of tiny anhedral quartz, feldspar, and hematite grains. Locally associated with this lava are massive, jointed, grey, coarse greywacke, pink cleaved, and fissile to flaggy tuff, and green chert.

About 700 m southeast of Black Angel trigonometrical station, quartz porphyry intrudes a 1-m thick grey chert/kaolin bed which exhibits distinctive flow structures. The bed is thought to have been a viscous acid lava, later altered to its present composition. The chert/kaolin bed is interbedded with lava, sedimentary breccias and dark red, cleaved, shaly tuff.

In the area adjacent to the Peko mines copper smelter, fawn to red-grey, medium to coarse-grained feldspathic tuffaceous siltstone and fine-grained greywacke are intruded by quartz-feldspar porphyry. Small dykes and apophyses of quartz-feldspar porphyry have intruded the volcanics near the contact. Large feldspar 'clots' up to 1.5 cm across are present in the tuff and greywacke (B. Williams, personal communication). Half a kilometre southwest of the smelter, grey-purple to pink, fissile to blocky, thin to medium-bedded tuffaceous siltstone, ashstone, and shale are intruded by quartz-feldspar porphyry. Black martite crystals are abundant in the volcanics.

Three and a half kilometres northeast of the smelter, further pink, purple, feldspathic greywacke and flaggy jointed cherts are also intruded by quartz-feldspar porphyry. Dark grey-purple finely banded chert containing small feldspathic inclusions occurs within the beds.

Relationships and boundary criteria

The Warrego Volcanics conformably overlie the greywacke and shale of unit Ew_7. The contact zone is well exposed in the area 5 km northwest of Great Western trigonometrical station where purple cleaved shale and mottled red-purple fine-grained greywacke are interbedded with pink claystone and chert. The chert is brittle and closely jointed, and has an irregularly scalloped bedding surface. The rocks grade from greywacke, siltstone and shale to volcanics; the lower boundary is somewhat arbitrary. The base of the formation is considered to be the lowest volcanic bed. The lower contact zone is well exposed in the sides of the Warrego No. 2 Dam, where pink, blocky to flaggy, compact finely banded silicified ashstone overlies purple to white flaggy siltstone. The volcanics contain thin hematite-rich bands stained with limonite.

The upper contact of the Warrego Volcanics grades into unit Ew_3, and is marked by the highest tuff, ashstone, or lava in the sequence. The volcanic sequence is thinner in the area 7 km southwest of Warrego Mine than in the Great Western Syncline.

The unit is intruded by dykes and irregular bodies of quartz porphyry and quartz-feldspar porphyry. The Red Bluff Adamellite probably intrudes the unit south and southwest of its southern limit of outcrop, but the contact is not exposed. The volcanics show extensive silicification.

Unit Ew_3

Distribution

Unit Ew_3 crops out over about 100 km^2 in the Sheet area. It extends from the Whippet mine in the east to the area of the Last Hope and Warrego mines in the west. A further outcrop lies 20 km west of the Last Hope mine. The unit is also well-exposed near Red Bluff.

Lithology

Where it is thickest the unit consists of a lower shale interval and progressively greater amounts of greywacke and siltstone higher in the sequence. Greywacke near the top of the unit is succeeded by a thin shale or siltstone band. The sequence thickens westward from a minimum of about 300 m in the Whippet area to a maximum of over 3000 m about 8 km southeast of the Last Hope mine. In the Whippet area, at the eastern edge of the unit's outcrop it consists of grey-purple to white, laminated, blocky fine-grained siltstone and shale. To the west, the unit is concealed over much of the Mount Woodcock 1-mile Sheet area, and only the lower more shaly parts are exposed in contact with the underlying unit Ew_2.

Northwest of Butchers Waterhole, however, interbedded shale and greywacke are exposed. Grey to brown and purple, flaggy to massive, dominantly blocky, fine to medium-grained greywacke is interbedded with purple to grey, flaggy to blocky mudstone. Greywacke units show graded bedding, and range in thickness from 7 cm to 1 m, and some contain angular shale fragments from 0.5 cm to 10 cm long. Flute casts are well defined at the base of some units, and they indicate a constant direction of origin of 160^o.

The lower shale unit which crops out in an east-west zone 2-3 km wide, about 6 km north of Great Western trigonometrical station, consists of pink to purple, fawn, and white, fissile to massive, laminated to flaggy shale, siltstone, and claystone. The beds are tightly folded into a series of plunging anticlines and synclines. Minor blocky to massive coarse siltstone and greywacke bands are present near the top of the shale unit. Limonitic banding, which may define small-scale cross-bedding, occurs commonly in the siltstone beds. More rarely small ovoid quartz-hematite concretions have distorted the fine limonitic bands. The concretions formed before the main f_2 folding, as they are flattened and elongated along the cleavage.

Rocks of unit Ew_3 form small outcrops below unit Ew_4 next to the basal conglomerate of the Tomkinson Creek Beds, 10 km west of Phillip Creek. These consist of grey to purple, blocky to fissile, thin-bedded to laminated siltstone and minor finely cross-bedded shale.

The lower shale is succeeded by an interbedded greywacke-shale zone. The beds consist of purple to pink and grey, massive to flaggy, fine-grained greywacke and thin-bedded to laminated shale and siltstone. Cross-beds are larger in these beds, reaching 0.5 m in foreset length, and 15 cm in height. Pseudo-ripples are found on the upper surface of a greywacke unit (grid ref. 388860). The 'ripples' have a wave length of 0.5 cm, and are sinuous and symmetrical in form. The size and range of orientation of the 'ripples' make it difficult to assess their mode of origin. Cross bedding in the upper blocky to massive greywacke units indicates an easterly origin for the unit. The cross-beds range from 1 m to 5 m in foreset length, and from 0.5 to 1.3 m in height.

The upper parts of unit Ew_3 are also well exposed in the area north of the Last Hope mine where they consist of alternating blocky fine-grained greywacke and flaggy siltstone. White, blocky to massive, compact, well-jointed, lithic sandstone and minor siltstone form a prominent ridge 1 km northeast of the Last Hope mine. The succeeding fine-grained siltstone has been eroded to form a valley. Fawn to white, blocky to flaggy, medium-bedded fine-grained lithic sandstone and coarse-grained siltstone overlie the siltstone. Small, white, rounded quartz pebbles (0.5 cm diameter) are abundant near the top of the beds. Further fine-grained siltstone and a thin greywacke zone with well developed load casts succeed the pebble beds.

In a belt stretching 3.2 km south of the Last Hope mine, shale, siltstone and minor greywacke strike north-south, and are strongly folded about east-west axes. The sequence is stratigraphically equivalent to the lower part of unit Ew_3 in the area 6 km north of Great Western trigonometrical station, well exposed in the sides of the Warrego No. 3 dam. Large flute casts are seen at the base of blocky fine-grained greywacke. The dominant cross-bedded coarse-grained siltstone sequence contains a zone of small quartz-hematite concretions in a finely limonite-banded siltstone. This zone is correlated with an equivalent zone at the locality north of Great Western trigonometrical station. Much of the sequence exposed in the area north of the Warrego No. 3 dam consists of purple to cream, lilac, grey, and orange, flaggy to laminated siltstone and minor shale. Greywacke horizons are more abundant both above and below the siltstone. Rare claystone beds occur in the siltstone sequence.

Five and a half kilometres southwest of the Warrego mine, dark purple to grey, fawn and cream, cleaved siltstone and shale are intruded by many quartz porphyry and quartz-feldspar porphyry bodies.

One kilometre southeast of Black Angel trigonometrical station, the lower shale unit has been silicified by the adjacent granite, and crops out as numerous small rocky hills. The highly cleaved, grey to pink and purple, fissile phyllitic shale shows abundant Liesegang banding on cleavage planes.

The unit also crops out on the southern margin of the granite in the Red Bluff area. The beds dip steeply south-southwest, and apart from rare minor folds the sequence is very uniform along its outcrop length. It consists of a lower shale and siltstone unit and an upper greywacke unit, which contains some shale towards its top.

The shale-siltstone sequence is grey to purple, pink, and white, flaggy to fissile, thin-bedded to laminated and shows abundant kink folding. Progressively more blocky siltstone and fine-grained greywacke beds succeed the shale. A graded greywacke unit 5 m thick is present in the upper part of the sequence. The coarse-grained base of the unit, which crops out for 1 km, looks similar to the intrusive quartz-porphyry. On examination in thin section, however, it can be seen to consist of sub-angular to sub-rounded quartz and weathered feldspar(?) grains 1 to 3 mm in diameter, with abundant mud flakes up to 5 mm across in a matrix of fine-grained quartz, hematite, sericite, and possibly feldspar.

Flaggy to blocky, fine and coarse-grained greywacke and thin to medium-bedded siltstone succeed the thick greywacke bed. A 6 cm white claystone bed crops out at several localities in the Red Bluff area at the base of the flaggy zone. Laminated, medium-grained siltstone containing bands of mud flakes crops out above the flaggy, medium-bedded siltstone. A further shale sequence crops out south of Red Bluff, but the beds are highly silicified by the nearby quartz-feldspar porphyry.

A large outcrop of cleaved siltstone and shale of unit Ꝑw$_3$ lies 12.5 km northwest of the Warrego mine. The rock types exposed include hematitic spotted shale, pink flaggy chert with minute sulphide (pyrite?) grains, and cream to purple and pink siltstone and fine-grained greywacke. Graded bedding is common in the greywacke, and the penetrative cleavage can be seen to be deflected some 10^{o} in the coarser-grained parts of the turbidite units. The units are generally finer-grained than the rocks to the east, and it is thought that they represent deposition in the central part of a 'flysch' basin.

Stratigraphic relations

Unit Ꝑw$_3$ conformably overlies unit Ꝑw$_2$ in its eastern area of outcrop. The lower boundary represents a lithological change from a dominantly shale sequence to an interbedded greywacke, shale, and siltstone sequence.

Unit Ꝑw$_3$ is intruded by adamellite and aplitic granite, and dykes and irregular bodies of quartz porphyry and quartz-feldspar porphyry. Small lamphrophyre dykes and sills also intrude the unit in areas next to the large granite masses. Dolerite and/or diorite sills intrude the unit at three localities causing spotting (pseudomorphs after andalusite?) in the adjacent shales, e.g., grid ref. 396863.

To the west the unit thickens, and a lower shale parting is well-developed in the area 8 km northwest of Great Western trigonometrical station. The shale zone is cut off to the south by a large fault trending west-northwest. Half a kilometre southwest of the Black Angel mine a much reduced thickness of Warrego Volcanics is conformably overlain by the lower shales and siltstones of the unit Ꝑw$_3$.

Unit Ꝑw$_3$ is overlain conformably by unit Ꝑw$_4$. The boundary is marked by a change from interbedded shale and greywacke to massive greywacke with quartz pebbles.

Unit Ew$_4$

Distribution

Unit Ew$_4$ crops out over a total area of about 55 km^2 in a narrow crescent-shaped belt between the headwaters of Hayward Creek and the western end of the Short Range. It crops out discontinuously along the base of the Short Range, and at the base of a group of hills north of Whippet trigonometrical station.

Lithology

The unit consists of greywacke, lithic and feldspathic sandstone, and rare siltstone, claystone, and conglomerate. The sequence has a maximum exposed thickness of about 1450 m, north of the Last Hope mine, but is considerably reduced in the Hayward Creek-Whippet area and in the western part of the Short Range.

The generalized sequence in the area north of the Last Hope mine is shown in Section 1 (Appendix). The cherty claystone horizon crops out only north and northwest of the Last Hope mine. The chert was examined in thin section, and found to consist of a very fine-grained mosaic of quartz and feldspar with minor sericite and larger inclusions of volcanic glass(?). The bed forms a useful marker horizon, from which the unconformable nature of the Warramunga Group-Tomkinson Creek Beds contact may be determined.

The pebbly sandstone near the top of the sequence consists of pebbles composed of vein quartz in a matrix of interlocking, angular, unstrained and slightly strained quartz and about 40 percent of feldspar grains. Some of the feldspar is orthoclase; most is altered to sericite and clay minerals.

Grain sorting in the feldspathic sandstone increases westward. The lower part of the unit, composed of mottled grey-green, blocky, fine-grained greywacke, is intruded by dolerite about 6.5 km north northwest of Last Hope mine. The greywacke is overlain to the north by purple siliceous ferruginous siltstone with cross-beds of an average foreset length of 35 cm, and a height of 12 cm. Higher in the sequence in this area, layers of grit and pebbles lie in a coarse-grained matrix of quartz, feldspar, and minor lithic fragments. The conglomerate bands contain abundant sub-rounded white quartz pebbles up to 5 cm across and rare, dark grey, small siltstone pebbles. Blocky sandstone overlies the conglomerate zone and this grades upwards into purple, blocky to flaggy, coarse-grained hematitic siltstone, and flaggy, white to pale grey, quartz siltstone. A bed of green-grey chert and white claystone 3 m thick succeeds the siltstone, and is in turn overlain by flaggy to fissile, thin-bedded quartz siltstone and fine-grained sandstone.

To the east, in the area 9 km northwest of Butchers Waterhole, greywacke grades into the overlying clean sandstone. The lowest part of the unit in this area is flaggy to blocky, fine to medium-grained, medium-bedde quartz greywacke. Graded bedding is common, and inverted dips are seen in many planes. The overlying grey massive, fine to medium-grained, greywacke is resistant to erosion, and forms prominent ridges. At grid ref. 393864 the greywacke is well exposed, and contains several grit bands and pebble lenses. A feature of the greywacke throughout the outcrop area is the presence of isolated white quartz pebbles. The greywacke consists of 45 percent of angular quartz grains in a matrix of sericitized and kaolinized feldspar, rock fragments, and hematite.

Grit and pebble beds succeed the greywacke, and in turn are overlain by poorly sorted feldspathic sandstone and blocky to flaggy fine-grained sandstone. The sandstone at grid ref. 394864 contains abundant hematite, locally concentrated in the bedding planes and emphasising the cross bedding.

Further east, at about 9 km west of Phillip Creek, purple, flaggy to blocky, fine-grained greywacke with minor siltstone underlies massive to flaggy grit. Quartz pebbles, locally stained by iron oxide are common in the rocks. North of the grit horizon weathered grey fragmented tuffaceous(?) rocks are associated with grey to purple fissile laminated tuffaceous siltstone. The tuffaceous rock consists of rounded, commonly corroded, quartz phenocrysts with rims of phlogopite(?) in a matrix of sericite, kaolin, phlogopite, limonite, magnetite, quartz, and volcanic fragments. Some altered feldspar(?) fragments are also present. The tuffaceous rock is overlain by the basal conglomerate of the Tomkinson Creek Beds.

In the upper Hayward Creek area unit Ᵽw$_4$ consists of grey-green, blocky to massive, medium-grained greywacke and lithic sandstone.

Stratigraphic relationships

Unit Ᵽw$_4$ is the youngest in the Warramunga Group. It conformably overlies unit Ᵽw$_3$, is disconformably overlain by the Blanche Creek Conglomerate Member and the Gibson Creek Formation in the eastern Short Range, and overlain with slight angular unconformity by the Blanche Creek Conglomerate Member in the central and western parts of the Short Range. In the ridge 9.5 km northwest of the Warrego mine the stratigraphic relations are obscured by faulting, but it is thought that there is some angular discordance between unit Ꝑw$_4$ and the basal Tomkinson Creek Beds. The unit is intruded by sills and dykes of diorite and/or dolerite.

Unit Ꝑw$_5$

Unit Ꝑw$_5$ consists of coarse-grained siltstone, fine to medium-grained lithic and silty sandstone, and minor shale, greywacke, and quartz sandstone. Many shallow-water depositional features are common within the sequence. The unit corresponds to unit Ꝑlw$_3$ of Crohn & Oldershaw (1965).

Distribution

Unit Ꝑw$_5$ forms a crescentic outcrop of about 35 kms^2, immediately east of the New Hope mine, and is composed largely of coarse-grained sediments. It is resistant to erosion, and forms extensive flat-topped mesas and ridges with a relief of about 70 metres. Strike ridges are common above the general level of the countryside.

Lithology

The unit was described by Crohn & Oldershaw (1965), who estimated the maximum thickness to be about 1000 m. A thin conglomerate near the base of the sequence was mapped at several localities. The present survey has shown that the maximum exposed thickness is approximately 2100 m in the area south of the Last Hope mine.

Two to five kilometres south of the Golden Mile mine, grey to purple, massive to blocky, fine to medium-grained silty sandstone is exposed at the base of the sediments. A band of conglomerate about 1 m thick, and consisting mainly of rounded vein quartz and siltstone pebbles in a silty sandstone matrix, lies near the base of the sediments. Flute casts are well developed on the base of the sandstone and conglomerate. Similar basal beds are seen 4 km to the southeast of the exposures south of the

Golden Mile mine, across a large northwest-trending fault which appears to have a relative right lateral displacement of about 3 km.

The basal beds of the unit are also well exposed at grid ref. 444813. A generalized sequence is shown in Section 2 (Appendix). Between grid refs. 443815 and 443816 the upper parts of the sequence are well exposed in an open syncline. The lowest beds exposed in this section are grey-purple massive to blocky coarse-grained siltstone and fine-grained lithic and silty sandstone. Poorly defined interference ripples are seen on some bedding surfaces. Flaggy, medium to coarse-grained quartz siltstone with rare blocky sandstone overlies the more massive beds. The sediments are weakly graded, and in the upper part hematite-rich layers form distinctive bands. A leached fine-grained siltstone horizon lies within the coarse-grained siltstone. Longitudinal ripples are abundant on the upper bedding surfaces of the siltstone. Rare, small-scale flute casts are also seen at the base of several units in this part of the sequence. Grey, well-bedded, blocky thin-bedded to laminated shale with siltstone nodules and irregular bands overlies the siltstone.

The same horizon is exposed about 1 km to the southwest, where purple to grey and red fine-grained mottled siltstone and shale contain 'pillows' of coarse-grained siltstone, ranging from 0.5 m to 1 m high and from 0.3 m to 0.8 m across; the bedding can be seen to be disturbed between the 'pillows;. The 'pillows' are thought to have been formed by the argillaceous envelope remaining thixotropic after deposition, while the more competent silt enclosed in the claystone was insufficiently supported and consequently broke up into isolated rafts before compaction.

North of the New Hope mine - Gosse River track, there are further extensive outcrops of unit Ew_5. Southwest of the Rocky Range fault, the beds dip south and consist of grey to purple, blocky to massive, fine-grained silicified silty sandstone, siltstone, and minor greywacke.

Further southeast, purple flaggy to blocky and rarely fissile siltstone and fine-grained silty sandstone have well developed interference and longitudinal ripples, some with sinuous crests. Overlying these beds are flaggy to blocky siltstone, fine-grained silty sandstone, and several coarse-grained massive greywacke bands. The greywacke, 1 to 2 m thick, consists of black chert, quartz, hematite, and shale fragments up to 5 mm long in a hematitic siltstone matrix. The quartz is subrounded to sub-angular and 1 mm to 2.5 mm in diameter. The shale tops of the greywacke are 0.5 m thick, and show abundant small-scale cross bedding. Large-scale flute casts are common in this part of the sequence.

Further north, a monotonous sequence of grey to purple, flaggy to massive, coarse-grained cross-bedded siltstone and fine to medium-grained silty sandstone is exposed. Hematite-rich banding is very abundant in this area. The banding commonly defines cross-beds, typically 15 cm thick and with a preserved foreset length of about 50 cm.

Stratigraphic relations

Unit Ꝑw$_5$ is considered to be a lateral shallow-water equivalent of parts of unit Ꝑw$_2$, which is composed dominantly of shale and siltstone. It may also be broadly correlated with the Whippet Sandstone Member (Ꝑww) which crops out to the north and northwest. Unit Ꝑw$_5$ conformably overlies the shale and siltstone of unit Ꝑw$_1$, and reflects a shallowing of water in the area. The base of unit Ꝑw$_5$ is marked by the first massive sandstone or greywacke that appears in the sequence. Greywacke and shale of unit Ꝑw$_6$ conformably overlie unit Ꝑw$_5$. Medium-grained quartz-feldspar porphyry and fine-grained quartz porphyry discordantly intrude the sandstone of the unit. Lamphropyre sills 0.5 to 1 m thick are common in the lower beds of the sequence.

Unit Ꝑw$_6$

Unit Ꝑw$_6$ corresponds to unit Ꝑlw$_2$ of Crohn & Oldershaw (1965), and may be laterally equivalent to parts of the Ꝑw$_3$ unit which occur in the northern and western parts of the Sheet area. Little additional work was carried out on unit Ꝑw$_6$ during the present survey. Whittle (1966) carried out a detailed petrographic, geochemical, and stratigraphic study of parts of the unit.

Distribution

Unit Ꝑw$_6$ crops out in an area of about 110 km^2 between the New Hope mine and the Ivanhoe mine, and is thus restricted to the central part of the Sheet area. It forms steep-sided mesas and plateaux, which are well developed in the vicinity of Tennant Creek township. Individual outcrops are separated by dust plains strewn with ferruginous fragments of the rock. Crohn & Oldershaw (1965) estimated that the minimum thickness of the unit is 775 m.

Lithology

Crohn & Oldershaw (1965) gave a general description of the unit, listing it as Elw_2, Whittle (1966), presented a detailed lithological description.

During the present Survey rock was examined in the Peko and Juno mines, where it is fresh and unoxidized. The sequence in the Peko mine consists of moderately folded greywacke, shale, and siltstone; rare folded jasper bands are also seen. A massive greywacke-grit band about, 2.2 m thick, containing apparently orientated fragments of shale, 5-20 cm long, in its upper part, has large flute casts at its base. These features are typical of flysch greywacke (e.g., Carpathian geosyncline - Marschalko 1970).

The grit consists of sub-rounded to angular unstrained quartz grains, commonly embayed and containing inclusions, set in a muscovite-quartz-feldspar matrix. The quartz grains show poor sorting, but a distinct bimodal size distribution. Small rounded volcanic fragments, consisting mainly of hematite and quartz, are present.

Calcareous phyllite is exposed in the Peko mine. It is a grey, slaty rock with flattened rounded calcite porphyroblasts up to 3.5 mm across showing an apparent diablastic texture. The calcite is strained, is very commonly twinned, and contains very small irregular inclusions. It also has associated pressure shadows, which suggests that the main folding occurred subsequent to or during the calcite crystallization. The rock also contains rounded to angular unstrained quartz grains in a matrix of muscovite flakes, which show a distinct preferred orientation. The apparently early age of the calcite suggests that it was formed before folding and copper-gold mineralization. The mineralization post-dates the folding and the early faulting.

In the Juno mine well-graded, blocky, fine-grained greywacke is interbedded with shale and minor jasper lenses. The greywacke contains quartz and minor feldspar in a sericite-chlorite matrix. The sericite shows a strong preferred orientation. Irregularly rounded grains of chalcopyrite are present throughout the rock, but are finer-grained in the shaly bands.

Crohn & Oldershaw (1965) placed great emphasis on the use of the hematite shale within unit Pw_6 as a marker bed. Whittle (1966) included the shale bands in his 'specific horizon'.

In the Eldorado mine area, hematite shale is overlain by pink and purple banded siltstone. Pink blocky laminated chert is also present. In a similar stratigraphic position on the southern limit of the outcrop, cream claystone is present. The sediments are believed to be at least partly of volcanic origin.

In the area northeast of the Kathleen mine hematite shale is well exposed in two distinct horizons, where it forms the fine-grained tops of massive to blocky turbidite units. Individual beds are up to 1 m thick, and the associated greywacke beds are 60 cm to 1.3 m thick. Shale accounts for up to two-fifths of the turbidity units. Fluid folding and lensing is very common in the beds, and the shale forms inclusions in the overlying greywacke, indicating that the shale was in a mobile state when the succeeding turbidite was deposited. Microscopic examination of the shale shows that the hematite is probably primary, although there is evidence of secondary iron staining. It is suggested that the shale was deposited from a volcanic source in moderately deep water between periods of turbidity. Minor pink tuffaceous beds are associated with the shale in this locality.

In the area of the Golden Mile mine the hematite shale consists of thin hematite laminae alternating with red lenticular jasper bands. Fragments of jasper are commonly included in the basal parts of the overlying bed. The presence of martite throughout the hematite shale (Whittle, 1966) is consistent with a volcanic origin. Whittle has emphasised the tuffaceous nature of this essentially greywacke unit, and has cited as evidence the following: the abundance of martite, trace element distribution, and the minor ashy content of many horizons. The present authors spent some time looking for the ash beds mentioned by Whittle in the areas near Kathleen mine, Rocky Range, and west of the Red Terror mine. We consider that the evidence from these localities is somewhat vague and no beds of definite volcanic origin could be found. Silicification is abundant in the unit, and silicified shale appears very similar to the more westerly volcanics. However, the unit near the Red Terror mine consists of pink to purple, grey, and cream, flaggy to blocky tuffaceous siltstone with martite euhedra. Angular tuff or lava fragments are found in several siltstone horizons commonly closely associated with martite concentrations.

The greywacke of unit Ᵽw$_6$ contains numerous flute casts. The plunge of these structures was recorded at two localities near the Bees Knees and Gibbert mines. All the structures indicate an easterly origin for the unit, the direction being nearer to northeast in the more westerly locality. Sand volcanoes were noted in unit Ᵽw$_6$ by Crohn & Oldershaw (1965). They are common in the Mount Samuel area where they were formed in grey coarse-grained greywacke-siltstone. The volcanoes are indicative of rapid deposition and subsequent dewatering of an underlying water-charged sandy bed through the overlying siltstone. On dewatering, sand is carried upwards to the surface above. The ovoid and flattened shapes show the effect of f_2 deformation on the structure.

Stratigraphic relations

Unit Ᵽw$_6$ conformably overlies unit Ᵽw$_2$, the contact being gradational in the Mary Lane mine area, and to the east it apparently overlies conformably the more arenaceous unit Ᵽw$_5$. The successions exposed at each area can be correlated with one another. The unit is unconformably overlain by the Adelaidean(?) Rising Sun Conglomerate (Crohn & Oldershaw, 1965) and by the Lower Cambrian Helen Springs Volcanics near the Blue Moon mine.

Unit Ᵽw$_7$

Distribution

Unit Ᵽw$_7$ crops out over an area of about 21 km^2, west of the Phillip Creek lineaments, and may be equivalent to unit Ᵽw$_8$, which crops out extensively further east.

The unit consists of greywacke, shale, siltstone, and minor acid volcanics, but facies changes are typical over a short distance. The unit is best exposed in the Black Angel trigonometrical station - Black Eye mine area, 12 km east southeast of the Warrego mine. It is also exposed on the limbs of a large anticline west-southwest of the Great Western mine, and around the margins of the Great Western syncline.

Lithology

The lowest Ew_7 beds crop out in a group of mesas near the Great Western trigonometrical station. Purple-grey, pink, grey, cream, and yellow fissile to flaggy shale is interbedded with minor flaggy to blocky, and, rarely, massive siltstone and claystone. Minor folding and Liesegang banding are common. The upper beds composed mainly of shale and siltstone, contain some fine-grained greywacke with low-amplitude longitudinal ripples and flute casts.

One kilometre south of the Black Eye mine the unit is folded into a broad westerly plunging anticline. Red shale and siltstone in the east of the area are succeeded by flaggy to massive, fine- to coarse-grained greywacke to the north and west. Hematite-quartz segregations up to 3 m across are common in shale. Several bands have been completely silicified and hematitized, apparently before folding. Banded jasper is also common within the upper shale-siltstone beds.

The flaggy to massive greywacke beds commonly contain martite euhedra. At one locality (grid ref. 390849) a 2.5 m turbidite unit is well exposed. Flute casts at the base of the unit indicate an easterly provenance for the turbidite. Low-amplitude longitudinal ripples are developed in the shale of the upper part of the sequence. The ripple crests strike roughly eastwest.

Flute casts and current lineations are well developed in similar greywacke beds that are well exposed 0.5 km southwest of the Black Eye Mine. The beds also contain numerous sheared concretions, which range from 15 cm to 1 m across, around quartz-hematite nuclei about 3 cm in diameter. The hematite pseudomorphs magnetite (i.e., martite) or pyrite. The greywacke is locally underlain by purple to dark red siltstone, which is tuffaceous in part.

At the Black Eye mine, cream, flaggy to blocky, fine to medium-grained siltstone with abundant martite crystals up to 3 mm across is overlain by blocky to flaggy greywacke and shale; flute casting is common in the greywacke. The greywacke beds are at the highest stratigraphic level seen in the Black Eye area.

Further north, unit Ew_7 is exposed around the margins of the Great Western syncline. Mottled grey-red to pink siltstone, shale, and claystone are interbedded with blocky to massive coarse-grained greywacke. The beds directly underlie the Warrego Volcanics. Kink folding is common in the more shaly bands.

In the area south of the Black Angel mine flaggy to blocky fine to medium-grained greywacke, siltstone, and shale are intruded by numerous dykes and irregular bodies of quartz porphyry and quartz-feldspar porphyry. Concordant lenses of porphyry in the sediments commonly contain brecciated fragments of sediment. In the west, the beds grade upwards into tuffs of the Warrego Volcanics.

The upper and middle parts of unit Ew_7 are well exposed in the area adjacent to Black Angel trigonometrical station. Immediately north-west of Black Angel trigonometrical station, a mudflow conglomerate is interbedded with grey to purple, blocky medium-bedded siltstone and fissile iron-oxide-banded shale. The conglomerate is up to 3 m thick, and consists of pebbles and boulders, commonly of siliceous greywacke, up to 12 cm in diameter, and abundant light grey and cream mud flakes in a matrix of fine-grained siltstone and shale. The bed shows medium-scale folding, and the conglomerate is well-exposed in a small westerly plunging syncline. A similar, though thinner bed of conglomerate crops out at scattered localities up to 1 km south of the Black Angel trigonometrical station.

The conglomerate is overlain by flaggy to blocky siltstone and shale, succeeded by massive to flaggy, fine-grained greywacke and siltstone. This is well exposed 1 km south of the Black Angel trigonometrical station. Within the greywacke and siltstone are numerous lenticular 'shale breccia' lenses or pods. The pods show no evidence of shearing, and are 5 cm to 3 m long and up to 1 m wide. They are generally enclosed by bedded greywacke, and are conformable with the bedding. The fragments in the pods are commonly angular, and lie in random orientations. The matrix ranges from coarse to fine-grained, and is highly ferruginous. The breccia pods are seen in several outcrops in the Black Angel trigonometrical station - Warrego mine area, and are also found in the lowermost Ew_3 beds southwest of the Warrego mine.

Overlying the breccia zone at grid ref. 388845 is a thin band of grey to pink and purple ferruginous shale with thin hematitic laminae. Small-scale cross bedding is seen in several horizons. The shale is overlain by a pink, fissile thin-bedded tuff and tuffaceous siltstone, which contains agglomerate pods. The pods reach 3 m in length, and resemble quartz porphyry, but have irregular lumps of tuffaceous material within them.

Fissile siltstone and fine-grained greywacke overlie the tuff, and these contain numerous siliceous concretions up to 2 cm in diameter. Slump folds, with a small amplitude are also abundant in this horizon. The folds indicate a northeasterly provenance for the unit. The greywacke contains a large amount of tuffaceous material, and is thought to lie near the top of unit Ew_7.

About 1 km to the northeast (grid ref. 389845), the uppermost beds of unit Ew_7 are well exposed. They consist of pink to purple and cream tuffaceous siltstone and shale with tuffaceous and volcanic interbeds. The surrounding sediments do not show any thermal metamorphic effects, but the lava has chilled margins in many places. The flows range from 3 cm to 20 m thick.

Hematite shale is also commonly associated with the tuffaceous beds; in places the lava pods appear to grade into hematite shale. A 90 cm-thick agglomerate horizon may be traced for several hundred metres around medium-scale folds. The lava lenses interbedded with the tuffaceous beds indicate that the shale breccia lenses, which lie in beds stratigraphically below this sediment-volcanic zone, may have been formed by lava or tuff extrusion in a marine environment. This would account for the features seen in the shale breccia lenses.

Stratigraphic relations

The base of unit Ew_7 is not exposed. The lowermost sediments exposed are shaly; judging from their composition and distribution, they may be laterally equivalent to unit Ew_2, which crops out to the east of the Phillip Creek lineament.

The sediments exposed are of uniform thickness. The upper parts of the unit are characterized by progressively higher content of volcanic material; the boundary between unit Ew_7 and the overlying Warrego Volcanics is transitional in the Black Angel trigonometrical station area. Further north in the Great Western syncline, hematite shale marks the base of the volcanics.

Ew (undifferentiated)

Ten to fifteen kilometres south and southwest of Red Bluff are many small scattered outcrops of red-brown, highly cleaved, fissile shale and fine-grained siltstone. The outcrops generally lie near quartz reefs or aplite veins. Some parts of the shale have well developed sericite along the cleavage. Slate pencils have formed in one outcrop by the interference of the dominant east-west trending S_2 cleavage with a strong southeast-northwest trending S_3 cleavage. The beds have not been assigned to any unit of the Warramunga Group as it is thought that they may represent deposition in a more distal part of the "geosyncline" (or "flysch" basin), and correlation with other units was therefore not possible.

Palaeogeography and Sedimentation of the Warramunga Group

The Warramunga Group may be termed an eugeosynclinal sequence as it is composed of greywacke, shale, siltstone, and volcanics. Sandstone, presumably formed in a shallow to moderately deep marine environment, crops out in the east and northeast parts of the area, indicating that the margins of the basin are relatively close in these directions.

The long axis of the major basin in which the thick greywacke shale sequence was deposited was probably aligned either east-west or southeast-northwest. The greywacke-shale sequence shows features typical of turbidite deposition. Graded bedding, flute casts, convolute bedding, and rock fragments are all abundant in the greywacke beds. The thickest single turbidite beds are in the central zone of the geosyncline between Mount Rugged and the Black Angel mine. The bands are up to 3 m thick.

In one such band at the Peko mine, large shale fragments, some of them orientated roughly parallel to the direction of turbidite flow (deduced from very large flute casts on the base of the unit) are present. Marschalko (1970) considers that such fragments result from the impact of a turbidity current on the shaly substratum causing the shale to be ripped up and carried along by the current. He considers that this feature is restricted to proximal or marginal parts of the geosyncline. The presence of boulder beds (e.g., Caroline Boulder Bed - Crohn & Oldershaw, 1965) and mud-flow conglomerates in the centre of the basin suggests that the axial areas were not a great distance from the point of generation of the turbidites. Flute-cast directions indicate a provenance to the east for the turbidites. The exception to this is in the upper parts of the sequence at the Butchers Waterhole-Last Hope mine area where flute casts and crossbedding foresets indicate southerly provenance for the sequence. This suggests that the depositional basin may be arcuate or that current direction varied in the more distal parts of the basin.

The presence of Lower Proterozoic or Archaean gneiss to the south-west of the major area of outcrop indicates that this area probably acted as a foreland forming part of the southern or south-western margin of the geo-syncline. The inclusion of shale fragments in the conglomerate bands and epidote in the feldspathic sandstones of unit Ew_4, and the presence of acid porphyry, hematite-jasper, and hematitic shale fragments in the basal cong-lomerate of the Tomkinson Creek Beds all indicate rapid uplift of the area soon after deposition. It is known that at least some of the granite in-trusions and porphyries were emplaced early in the tectonic history of the geosyncline. If the intrusions were accompanied by uplift then the lower Warramunga Group sediments and the intrusives could be source rocks for the upper part of the sequence.

Volcanic rocks interbedded with greywacke and shale commonly show features (e.g., slump folding in tuff) that are considered indicative of extrusion in an aqueous environment. The presence of pebble bands contain-ing fragments of acid volcanics in parts of the Whippet Sandstone Member interbedded with the Bernborough Formation (volcanics) suggest penecontem-poraneous erosion of the volcanics - that is, the volcanics were extruded into shallow water, or possibly, a littoral environment.

Hematite shale crops out at several localities. The shale is very lenticular in places and shows signs of 'fluid' folding. The folding is believed to be due to the effect of slumping of the overlying turbidite on the underlying soft, finely banded hematite-rich shale. The hematite in the shale is considered to be a replacement of martite, for which a volcanic origin is proposed. The presence of the hematite shale interbedded with tuff and lava and in zones apparently laterally equivalent to volcanics strongly supports such an origin for the martite. The martite commonly occurs as cubes and octrahedra in tuffaceous beds of the Warramunga Group. This is well seen in the areas around the Black Eye mine (4.5 km west of Great Western trigonometrical station and the Red Terror mine.

EARLY PROTEROZOIC OR CARPENTARIAN

GRANITE

Under the general term granite are included the potash granite which lies in the northwestern part of the granite belt, and the adamellite and minor granodiorite which are abundant in the central and southeastern part of the belt. The most notable features of the granite in the Sheet area are its unweathered nature and textural diversity: twenty lithologically distinct types were distinguished. However, the distinctions were based on minor mineral and textural differences between granitic rocks in isolated outcrops. If the granitic rocks were better exposed, it is possible that at least some of the types would be found to belong to larger single masses. For convenience the main granite types have been informally named.

Distribution

The granite lies in a northwesterly trending zone extending from the southeastern corner of the Sheet area to the sandstone ridge 23 km west northwest of the Warrego mine. Outcrops range from 1-2 km across (New Hope Granite - Ꝑgo) up to about 20 km (South Gosse Granite - Ꝑgm). Lack of exposure commonly makes it impossible to assess the true shape and size of the granite bodies. Many of the porphyritic units crop out as series of isolated tors. Fine-grained granite, however, weathers deeply, and forms low hills. Granite extensively underlies many of the flat 'bulldust' plains of the Sheet area. In the area south and west of the Nobles Nob - Mount Samuel ridge, adamellite and gneissic granite have been proved by drilling to underlie much of the Cabbage Gum basin. Several small aplite outcrops occur 21 km south of Red Bluff, indicating that granite may underlie parts of this area. Whittle (1966) has reported borehole intersections of granite intrusions in Archaean(?) rocks.

Lithology

The granite ranges from fine-grained adamellite to coarse-grained porphyritic potash granite. It is commonly foliated parallel to the regional cleavage, but in places there also appears to be a flow foliation.

The 'Warrego Granite' comprises three major granite types:-

Ꝑgw - This massive, widely-jointed, coarse-grained muscovite granite forms several scattered weathered outcrops northwest of the Warrego mine. Much of the granite is covered by residual quartz sand. The granite consists of large muscovite and pink euhedral plagioclase crystals in a groundmass of grey orthoclase and quartz. Large inclusions of fine-grained muscovite granite are present in the rock. Quartz veins striking north-south cut the granite. Grey Cambrian quartz grit and gravel, and fawn Tertiary silcrete are extensively developed over the granite.

Ꞓgy - This unit crops out only in the northeastern part of the 'Warrego Granite'. It is fine-grained and composed of dark green muscovite in a quartz-orthoclase groundmass with minor hornblende. The granite is cut by north-striking 3-metre wide quartz veins, except at grid ref. 379866, where it forms a 0.6 m wide dyke striking 145^{o}.

Ꞓgx - The western part of the 'Warrego Granite' is a massive, pink to red, medium-to coarse-grained aplitic granite. The rock is composed of orthoclase, plagioclase, blue opalescent quartz, and ferromagnesian minerals mostly replaced by chlorite. Marked foliation strikes between 110^{o} and 135^{o}. Quartz veins commonly follow cleavage. Fine-grained aplite dykes and basic xenoliths are present in the most southwesterly outcrop.

The 'Red Bluff Granite' is composed of two major types:-

Ꞓgj - Red-brown, medium to coarse-grained massive adamellite accounts for the major part of the 'Red Bluff Granite'. It consists of 1 to 2-cm long euhedral orthoclase phenocrysts in a mottled brown-green to black groundmass. The orthoclase is perthitic in part, and the plagioclase inclusions are commonly altered to clinozoisite. Microcline twinning is present in some of the orthoclase. The groundmass consists of anhedral quartz, euhedral oligoclase - partly altered to sericite and epidote - minor orthoclase, and clusters of biotite flakes, partly replaced by chlorite. Irregular grains of hematite and magnetite and minor small zircon grains and blue tourmaline are present in the groundmass. The adamellite is strongly jointed and is also cut by shears.

Ꞓgk - The northwestern part of the 'Red Bluff Granite' consists of a pink medium-grained closely jointed granophyric aplitic granite. It consists of orthoclase, quartz, minor plagioclase, and secondary limonite. At grid ref. 389844 a 7-m thick northerly aligned quartz vein cutting the aplite contains minor chrysocolla and hematite.

The Tennant Creek Granite Complex has been described in detail by Crohn & Oldershaw (1965) and Dunnet & Harding (1967). A connection between the main outcrops, which occur around Station Hill and White Hill, and the larger poorly exposed mass, which lies south of the Whippet trigonometrical station and north of the Barkly Highway, is tentatively assumed. The rock types at the various outcrops are very similar, and there is a magnetic low saddle between the two major anomalies which mark the granite.

For convenience the Tennant Creek Granite has been divided into three major types:

Ꝑgu - Distinctive leucocratic to melanocratic coarse-grained porphyritic granite, locally strongly foliated. A specimen from the well-exposed area 2 km northeast of Station Hill consists of rounded orthoclase phenocrysts 1 to 1.5 cm across in a groundmass of blue opalescent quartz, plagioclase (altered to clinozoizite and sericite), biotite, and minor euhedral pyrite, magnetite, and small rounded zircon grains. The phenocrysts, whose degree of roundness increases with the strength of foliation, are perthitic in part, and also show some cross-hatched twinning. The quartz crystals commonly show slight undulose extinction, indicating post-crystallisation straining. Quartz is also present as small equigranular mosaics. Crohn & Oldershaw noted that in parts of the granite, ovoid quartz crystals had their long axes plunging steeply southwards. In much of the granite, the quartz crystals are elongated and bent around feldspars. There are two generations of biotite in the granite; the older crystals are in part corroded, whereas the younger euhedral biotites, which cross-cut many of the earlier crystals show no corrosion.

Ꝑgt and Ꝑgv - Fine-grained and coarse-grained granite in the complex were only briefly examined; they were described by Crohn & Oldershaw (1965) and Dunnet & Harding (1967).

The 'New Hope Granite' is composed of two units:-

Ꝑgo - Grey, massive coarse-grained leucocratic adamellite forms large exfoliated tors, up to 20 m high, in a wide sandy plain 2.5 km northeast of the New Hope mine. The adamellite consists of large white euhedral oligoclase-andesine (An_{30}) and rounded perthite crystals up to 3 cm across in a groundmass of strained blue opalescent quartz, plagioclase, biotite - in part altered to chlorite - minor orthoclase, and accessory magnetite. The small biotite flakes form thin trains and small clusters in the adamellite. The plagioclase is partly replaced by epidote and sericite. The rock contains rare aplite xenoliths up to 30 cm across.

Ꝑgp - Small exfoliated boulders of pink to orange, fine to medium-grained leucocratic adamellite lie scattered across a plain, 3.5 km east of the New Hope mine. The adamellite is bounded by a quartz-feldspar porphyry zone, and may be unconnected with the adjacent Ꝑgo intrusion. It consists of sparse, rounded microcline microperthite phenocrysts (about 1 cm across) in an equigranular groundmass of anhedral orthoclase, corroded quartz, euhedral plagioclase, and irregular flakes of biotite, partly replaced by chlorite. Chlorite and magnetite replace an amphibole. Rutile, fluorite, and minor pyrite are accessory minerals. Irregularly shaped biotite-rich xenoliths up to 5 cm across are sparsely distributed through the adamellite.

The 'Channingum Granite' is readily divisible into two rock types: fine to medium-grained micro-porphyritic granite and massive porphyritic granite.

Ꝑga - Orange and grey coarse-grained porphyritic granite crops out as a series of exfoliated tors, west of the northern part of the Gosse River. The granite consists of euhedral perthite phenocrysts, 1 - 2 cm across, in a groundmass of quartz, biotite, rounded and euhedral plagioclase (largely altered to clinozoisite and sericite), and minor orthoclase. Chlorite has replaced much of the biotite. Accessory zircon, pyrite, magnetite, and fluorspar are present.

Ꝑgb - Fine to medium-grained porphyritic biotite granite, typically very closely jointed, forms cubes about 40 cm across, some of which show spheroidal weathering. The granite consists of small round potash feldspar phenocrysts in a medium-grained groundmass of blue quartz, orthoclase, plagioclase and biotite. The unit becomes finer-grained towards its margin, and grades into quartz-feldspar porphyry.

The 'Gosse River North Granite' may be subdivided into two types: massive medium-grained granite and porphyritic granophyre.

Ꝑgg - Massive, medium-grained leucocratic biotite granite is an orange-brown equigranular rock which weathers white. Plagioclase phenocrysts up to 1 cm long are rare. The rock consists of large unstrained orthoclase grains, which are rarely perthitic, quartz, and andesine (in part altered to sericite and clinozoizite). Large corroded biotite flakes, partly replaced by chlorite, constitute about 3 percent of the rock. Irregular fluorite crystals, up to 0.4 mm across, small magnetite crystals, and minor hematite veins constitute the accessory minerals. The granite is extensively jointed in several directions (045^{o}, 065^{c}, 150^{o}). Aplite dykes fill many of these joints (e.g. at grid ref. 455818).

Ꝑgh - Massive porphyritic granophyre crops out in the central part of the Ꝑgg granite (grid ref. 458819). It is more closely jointed than the surrounding granite, and is typified by rounded orthoclase phenocrysts 1 - 3 cm long and plagioclase up to 2 cm long. Quartz and orthoclase form micrographic intergrowths in a groundmass of plagioclase altered to clinozoizite and sericite, anhedral quartz, large biotite flakes and accessory chlorite.

The 'Gosse River East Granite' (Ᵽgr) crops out sparsely for about 20 km east-southeast of the junction of the Gosse River and Channingum Creek. It discordantly intrudes shale and siltstone of unit Ᵽw_1 at its western margin. It may be a ferruginized and weathered fine-grained equivalent of the Ᵽgg granite. It is a pink and brown mottled, closely jointed, fine to medium-grained granite, composed of anhedral orthoclase with subsidiary euhedral plagioclase, partly altered to sericite and epidote, biotite, partly altered to chlorite, and anhedral quartz. In parts the quartz is opalescent.

The 'Cabbage Gum Granite' complex (Ᵽgc) is the most poorly exposed granite in the Sheet area. A few boulders of red, medium-grained, non-porphyritic 'granite' were found by the authors about 2 km south southwest of Cabbage Gum Bore. Crohn & Oldershaw (1965) listed a few exposures of porphyritic adamellite at grid ref. 416818, and in a report on the results of the extensive hydrological drilling in the Cabbage Gum basin, they described medium-grained adamellite with rounded potash feldspar phenocrysts, augen granite, and gneissic granite with subsidiary aplite, quartz-feldspar porphyry, and dolerite. The granite is weathered to 30 m below the surface. Warramunga sediments form a series of highly sheared and recrystallized inliers in the granite complex. The Peko Lineament, a large northeasterly striking photogeological feature, crosses the Cabbage Gum Granite complex. A wide shear zone containing many quartz veins has been shown by drilling to coincide with the feature in this region. A sample of the porphyritic adamellite from the Cabbage Gum complex has been dated by the K-Ar method at 1630 m. years (Walpole & Smith, 1961).

The 'North Seismic Adamellite' in the area some 10 km southeast of Nobles Nob can be divided into two units: coarse-grained mottled adamellite and massive medium-grained adamellite.

Ᵽgd - Coarse-grained pink to orange and green mottled biotite adamellite forms low rubbly hills and only rarely exfoliated boulders. The adamellite consists of rounded potash feldspar phenocrysts, up to 2 cm across, in a groundmass of quartz, plagioclase, biotite, and minor orthoclase. Well developed foliation strikes 085° and dips 75°N. Rare xenoliths of biotite and quartz are conformable with the foliation. The adamellite has a well-developed joint system; the joints are only rarely infilled with quartz. The granite is finer-grained towards its western and northern margins of outcrop.

Ᵽge - Black and white mottled, massive medium-grained biotite adamellite crops out as a series of tors northwest of the Ᵽgd adamellite. The boundary with unit Ᵽgd is a linear shear zone striking 095^{o}. The foliation of unit Ᵽge strikes 095^{o}, and dips steeply north. The adamellite consists of white ovoid Carlsbad-twinned orthoclase, which is perthitic in part, in a groundmass of anhedral quartz, andesine, biotite and accessory sphene and magnetite. The quartz commonly forms myrmekitic intergrowths with andesine which is largely altered to clinozoisite and sericite. Brown and green biotite forms irregular clusters, and shows only minor alteration to chlorite. Quartz-biotite xenoliths, commonly about 25 cm long, are conformable with the foliation. Quartzite and quartz-tourmaline pods with rare chalcopyrite are also contained in the adamellite. Migmatitic banding is present in several of the xenoliths, and in one large micaceous aplite xenolith, 15 m long and 5 m wide, banding is parallel to the foliation. Aplite dykes are rare.

The 'Gosse River South Adamellite' (Ᵽgm) crops out as a series of broadly jointed exfoliated corestones in a roughly circular area of about 450 km^{2}, around the southern end of Gosse River. The adamellite is foliated in its southwestern part; the foliation dips steeply and ranges in strike between 090^{o} and 130^{o}. It is a very coarse-grained pink, green and black mottled rock with 1 to 4-cm fawn potash feldspar phenocrysts in a groundmass of quartz, plagioclase, biotite, and accessory muscovite and zircon. The phenocrysts are Carlsbad-twinned perthite, and are rimmed by small highly altered plagioclase crystals. The biotite forms large flakes, and is partly altered to iron-rich yellow epidote and chlorite. Rounded and elongated biotite-quartz xenoliths are very common, and rare fine-grained granite inclusions are also present. This adamellite may be termed a Rapakivi granite according to the definition of Turner & Verhoogen (1960).

Ᵽgn - Grey medium to coarse-grained massive biotite granite crops out as a series of corestones near a track from the Stuart Highway to Morgan Creek south of Gosse River. The granite is considered to be a related, less sodic phase of the 'Gosse River Adamellite'.

General Comments

Granites intrude sediments of the Warramunga Group, but their relationships to the Tomkinson Creek Beds and the Rising Sun Conglomerate are not known. Lower Cambrian siltstone unconformably overlies weathered aplitic granite at grid ref. 355849. In this area the Tomkinson Creek Beds are faulted against the granite. Dunnet & Harding (1967) reported that the Tomkinson Creek Beds rest unconformably on sheared porphyritic granite in the same area, but this was not noted by us. In many areas where the upper surface of the 'Warrego Granite' is exposed, an angular poorly sorted quartz grit, commonly with a clay matrix, has developed from the weathering of the granite. The grit forms the lowest member of the Cambrian sequence, and may reach up to 2 m in thickness.

Crohn & Oldershaw (1965) described low-grade metamorphism of the Warramunga Group sediments at and near the granite margins. The metasediments commonly dip radially off the granite, and, although thin quartz-(feldspar)-tourmaline veins are developed in places, the rocks are merely baked or silicified. Crohn & Oldershaw also noted that there were few xenoliths of country rock in the marginal granite areas, suggesting that little or no assimilation of the Warramunga Group sediments has taken place.

A zone of muscovite development surrounds the 'Gosse River North' Granite, where flaggy to fissile siltstone and shale have a schistose appearance.

A common feature of the granite in the southwestern quarter of the Sheet area is that it forms the centre of larger composite intrusions. Porphyritic granite is surrounded by medium to fine-grained granite which is in turn surrounded by quartz-feldspar and quartz porphyry. The pattern, however, is rarely complete.

Genesis

The granites show many textural and mineralogical similarities, and may be assumed to have a common source. They range in composition from the potash-rich granites to adamellites.

Most of the economic deposits lie relatively close to the potash-rich granites. The possible exceptions to this are the Peko-Nobles Nob-Juno group of mines. The composition of the granite which lies immediately south of these mines is not known. Tourmaline has been found in the lower levels of Peko mine, indicating metasomatic introduction by granite; this prompts the question as to whether the gold/copper mineralization of the field is related to the granites.

Recent studies of Tertiary granites in Saudi Arabia and the Sierra Nevada, U.S.A., have shown that the granite will rise through overlying sediments to within 1 km of the surface. Porphyries are commonly emplaced at the margins of these intrusions, which are associated with zones of cataclasis. In these recent granites the circular bodies have a characteristic radius of 5 km. Fyfe (1973) has suggested that if the depth of granite formation is around 30 km (the base of the crust) temperature should be about 900°C, and pressure 7 to 10 kilobars. As a temperature of 900°C would result in anatexis, even at a low partial pressure of water, granite would have the excess heat necessary to assimilate some of the country rock, and to enable the granite to rise to a shallow depth. If the rock had the initial composition of an amphibolite, then, dependent upon the depth of formation, the product would range in composition from granite to granodiorite.

PORPHYRY

The term porphyry is meant to encompass all intrusive acid igneous rocks which contain feldspar and quartz phenocrysts in a fine-grained groundmass. Two distinct types are present: quartz porphyry, in which quartz phenocrysts lie in a hematitic fine-grained groundmass, and quartz-feldspar porphyry, in which quartz and feldspar phenocrysts lie in a similar groundmass. The latter type includes the quartz-Baveno feldspar porphyries of Crohn & Oldershaw (1965), which are quartz feldspar porphyries in which the alkali feldspars are considerably larger than in the typical porphyry. Euhedral plagioclase crystals are abundant in some of the quartz-feldspar porphyries. The porphyries commonly crop out near granite margins, and in such cases they are mineralogically and chemically related to the adjacent granite.

Quartz-feldspar porphyry (Ꞓfp)

Distribution

Quartz-feldspar porphyry crops out abundantly in the Sheet area, particularly in a wide northwest-trending zone of granite between the Gosse River and the Warrego-Last Hope mine area.

Lithology

The porphyry consists typically of large rounded microcline or perthite phenocrysts and, commonly, embayed ovoid quartz phenocrysts in a fine-grained granitic groundmass. Euhedral andesine is locally present, and flow structure is seen in some thin sections. Quartz-feldspar porphyry intrudes the Warramunga Group sediments in numerous forms - sills, dykes, pipes, bosses, and irregular masses.

A sill of quartz-feldspar porphyry may be traced around several folds in the Peko-Nobles Nob-Red Terror area. Oriented rafts of cleaved siltstone and shale up to 5 m wide occur within the sill 0.5 km west of the Golden Forty mine. The upper contact of the sill is well exposed about 1 km west of the Golden Forty mine. The contact locally cuts across bedding and cleavage, but its boundary appears to be controlled to some extent by cleavage planes. The sediments are hard and baked adjacent to the contact. The sill is composed of massive, dark brown to grey and pink quartz-feldspar porphyry with pink euhedral andesine phenocrysts and large pale pink ovoid, cracked and corroded K-feldspar phenocrysts in a fine-grained groundmass.

The K-feldspars are extensively altered to clinozoizite and sericite. They are also cracked, and permeated by the groundmass material. Perthite is rarely seen. The andesine is glomeroporphyritic in part, and the crystals show only minimal corrosion effects. The quartz occurs in clear, ovoid grains 0.3 mm to 5 mm in diameter; they are commonly cracked and permeated by the matrix material, and may show embayed outlines. The quartz phenocrysts are commonly surrounded by small quartz crystals. The groundmass consists of a mosaic of quartz, feldspar, green biotite, and small euhedral andesine crystals. Radiating aggregates of chlorite (penninite) and anhedral green biotite are abundant in the groundmass. Irregular aggregates of leucoxene and euhedral magnetite crystals are also present. The rock ranges locally in composition from granodiorite to adamellite, depending on the presence of potassium feldspar phenocrysts.

Dykes of quartz-feldspar porphyry are rare, but two 15 m dykes are seen to intrude volcanics 10 km east of the New Hope mine. The rock consists of pale grey potassium feldspar crystals (up to 0.5 cm across) and clear quartz ovoids in a fine-grained groundmass.

The porphyry forms circular vertical pipes which cross-cut sediment boundaries at a high angle in the area adjacent to the Golden Forty mine and the Black Angel trigonometrical station. Sediment inclusions are present near the margins of the pipes. In the area of the Black Angel trigonometrical station the porphyry pipes are 30 to 50 m in diameter.

Bosses and irregular masses of quartz-feldspar porphyry up to 5 km in diameter are the most common forms of intrusion. Near the Peko smelter a large boss consists of fawn and pink, massive, jointed porphyry with ovoid pink microcline crystals (Spry, in Carey, 1963) up to 2 cm across (average 7 mm) and embayed, round to ovoid quartz crystals up to 7 mm across (average 2-3 mm). Small euhedral plagioclase crystals are also present. The phenocrysts lie in a pink to fawn fine-grained granitic-textured groundmass. The large potassium feldspar crystals (microcline-Spry, in Carey, 1963) have weathered out of the rock in one locality. Further southwest, about 5 km south-east of the Warrego mine, numerous northwesterly trending lenses of quartz-feldspar porphyry intrude shale of unit Ew_3. The rock ranges from grey to red, purple, and pink, and is cleaved. Blue ovoid quartz phenocrysts and large pink potash feldspar crystals lie in a highly altered ferruginous sericitic groundmass.

The large ovoid microcline crystals and small euhedral plagioclase crystals are almost completely altered to sericite or groundmass-like material; outlines and small remnants of the original material are all that remain. The quartz crystals are cracked and extensively embayed by the matrix, which consists of fine-grained quartz and sericite with limonite and euhedral magnetite. In the area 1 km north of Great Western trigonometrical station, purple folded cleaved quartz-feldspar porphyry is intruded in its western part by pink to purple and grey massive quartz-feldspar porphyry.

In the Red Bluff area, two generations of quartz-feldspar porphyry are present. The older consists of weak to strongly cleaved, grey-green to pink and purple quartz-feldspar porphyry, which shows lateral variation to quartz-porphyry and no apparent contact effects. The younger generation is represented by pink, massive quartz-feldspar porphyry which is finer-grained towards its margin, and shows extensive contact effects.

The intrusive relations of the quartz-feldspar porphyry and the presence of microcline and embayed phenocrysts imply an igneous origin. Rare shattered quartz crystals also indicate inversion from beta to alpha quartz (Whittle, 1966). The lack of contact effects, particularly in the cleaved (i.e., early generation) porphyries is unusual, and suggests that intrusion took place at a low temperature (about 600^{o}C). Judging by the degree of permeation and embayment, many of the quartz and potassium feldspar phenocrysts were not in equilibrium with the melt. It is suggested that early formed quartz and potassium feldspar phenocrysts were absorbed by a later melt, and that before or during intrusion, chemical corrosion of the phenocrysts occurred. The composition of the porphyries is complementary to the granites (Whittle, 1966) is that the granodioritic varieties are associated with the more potash-rich granites.

Elliston (1964) described the highly porphyritic varieties of quartz-feldspar porphyry as 'porphyroids'. He suggested that the porphyroids were formed authigenically from a colloidal suspension of fine sediment, and that the process was set in operation by pre-consolidation slumping. Nashar (*in* Carey, 1963) has attributed the porphyroids of quartz-feldspar porphyries to metasomatism of the sediments. Spry (*in* Carey, 1963), however, refers extensively to their mineralogical and textural characteristics, and concludes that they are igneous rocks.

Contact Relations

In many localities the porphyries cross-cut the bedding, and have caused much silicification of the adjacent sediments, especially in an area 1 km southeast of Red Bluff where massive, uncleaved quartz-feldspar porphyry discordantly intrudes yellow, cleaved silicified shale. The quartz phenocrysts are more abundant near the margins of the intrusion, and several phenocrysts lie within the silicified shale.

However, massive, weakly cleaved quartz-feldspar porphyry lies parallel to the strike of the sediments 0.5 km north of Red Bluff. It contains feldspar phenocrysts 2-5 cm in diameter and quartz phenocrysts up to 1 cm in diameter. The body has no apparent associated contact effects, and predates cleavage.

Quartz Porphyry (Ep)

Distribution

The quartz porphyry forms numerous outcrops commonly associated with granite, and stretching from the area around Boon Hill in the southeast corner of the Sheet area to the hills 20 km west-northwest of the Warrego mine. It also forms numerous smaller dykes and bodies which concordantly and discordantly intrude the Warramunga Group sediments between the larger porphyry outcrops.

Lithology

The unit may be divided into an older porphyry which is strongly cleaved and a younger porphyry related to the granite and younger quartz-feldspar porphyry, and which appears to postdate the cleavage.

The younger prophyry is restricted to small outcrops such as at grid ref. 389846 where uncleaved quartz porphyry forms the major part of a circular intrusion. The pink, massive porphyry has caused slight silicification and gentle doming of the surrounding sediments, and consists of clear quartz phenocrysts in a granular feldspathic matrix.

The older porphyry is much more abundant, and is notable for its cleavage and ferruginous alteration. It crops out with a characteristic rough weathering surface, typically in lenses ranging in length from several metres to several kilometres. The ovoid quartz phenocrysts may give the rock the appearance of a grit. At grid ref. 359857, blue quartz ovoids up to 2 cm long (average 4 mm) lie in a purple to red mottled, foliated iron stained groundmass.

In the Red Bluff and Great Western areas, small intrusions of cleaved quartz porphyry are chevron-folded with the sediments. The porphyry consists of quartz ovoids 1 to 3 mm long and 0.5 to 1 mm wide in a highly cleaved ferruginous groundmass.

In an area 3.5 km north of Boon Hill (grid ref. 449805), scattered quartz porphyry outcrops are heavily veined by quartz, the major vein reaching 15 m in width. The porphyry consists of blue quartz phenocrysts in a silicified ferruginous groundmass. The phenocrysts are sheared and stretched to a length of 1 to 2 cm. Their width, however, is only 1 to 2 mm. There appears to have been a locus of shear along a narrow zone.

One kilometre south of Boon Hill, pink highly sheared quartz porphyry, which consists of small blue quartz ovoids in a pink feldspathic groundmass, is kink-folded about axes plunging 70° to 030°. The porphyry is cross-cut by the unsheared fine-grained marginal phase of the 'South Gosse Adamellite'. Thus the porphyry in this area was emplaced and folded before the adamellite intrusion.

In the area 5 km northwest of the Gosse River crossing (grid ref. 450823), two distinct generations of porphyry, which are lithologically dissimilar, crop out widely. The older porphyry consists of clear ovoid quartz phenocrysts set in a dark red-brown ferruginous groundmass. It forms small sills, dykes and circular plugs in the sediments, and is strongly cleaved. The younger porphyry, however, is restricted to a zone around the 'Channingum Granite', and consists of irregular small clear quartz phenocrysts set in a purple, commonly silicified, feldspathic groundmass. This porphyry is uncleaved and clearly discordant with the surrounding sediments.

Similar, although commonly orange or grey, uncleaved porphyry is associated with the 'North Seismic Granite'. One outcrop of grey, massive, brittle, silicified porphyry occurs at grid ref. 435815. It consists of clear quartz phenocrysts set in a dark grey feldspathic matrix containing small biotite flakes. The rock is unique for its unweathered appearance and blue-grey colour.

Quartz porphyry can be shown in many places to be discordant with the surrounding sediments, and is therefore intrusive. Contact effects are slight, and, in the case of the older porphyries, may have been obscured by subsequent metamorphism, weathering and iron enrichment.

The similar mineralogy, and in places the continuity of outcrop of the two main porphyry types (quartz and quartz-feldspar) indicates a genetic relationship. The occurrence of quartz phenocrysts in the sediments close to the contact suggests that free silica was very abundant in the intrusion, and diffusion into the surrounding sediments occurred. The presence of quartz phenocrysts in joint planes in the adjacent sediment indicates that the sediments were in a lithified state when fluids from the intrusives diffused into them.

Contact relationships

The quartz porphyry is in many places marginal to granite or quartz-feldspar porphyry bodies and cross-cuts the bedding traces of the Warramunga Group. It also forms dykes (e.g., at grid ref. 380861) which transgress the bedding of the sediments and cause minor silicification. However, in several localities there is little or no apparent contact effect on the surrounding sediment, and the porphyry is commonly concordant with the bedding.

Within the Peko mine quartz-chlorite porphyry occurs in a series of 'folded' lenses and isolated irregular fragments in the surrounding sediments. Quartz phenocrysts are concentrated around its margins, and in the surrounding sediments, where they form ovoids at several places. This indicates that diffusion of quartz into the sediment took place at the time of intrusion.

Similarly, a fine-grained quartz porphyry body forms a marginal phase to a large quartz-feldspar porphyry intrusion about 0.5 km southeast of Peko smelter. The quartz porphyry forms a small dome 7 m in diameter which is discordant with the surrounding sediments; several lenses of quartz porphyry also occur within the sediments. Silicification has taken place at many of the contacts. Quartz phenocrysts up to 1 mm across are concentrated adjacent to the porphyry, and then there is a 'barren' zone for 7 to 10 mm followed by a 10-mm zone of quartz pods 1-2 mm across. Zones of permeation (e.g., minor joints) are also marked by a line of quartz phenocrysts.

In several areas (e.g., near the Gecko mine) the porphyry-sediment contact consists of porphyry, shale, and siltstone showing complex intermixing. Shear zones are abundant in the contact zones.

UNDIVIDED PROTEROZOIC

DIORITE AND DOLERITE

Diorite and rare dolerite sills and dykes intrude the lower parts of the Tomkinson Creek Group and the upper parts of the Warramunga Group. Diorite is more common in outcrop. A few diorite/dolerite dykes also intrude granite, near the Mary Lane, Gecko, and Orlando mines. Whittle (1966) records the intersection of dolerite intruding Archaean gneiss in the area 3 km northwest of No. 3 Bore (grid ref. 385820). It has been suggested by Whittle, and Dunnet & Harding (1967), that the dolerite is the source of the gold-copper mineralization within the Tennant Creek Goldfield. The diorite/dolerite postdates the major folding and faulting, and the acid intrusives in the Goldfield.

The diorite is heavily lateritized to hematite, limonite, goethite, clay, and minor quartz in nearly all localities, and up to 8 m of pisolitic laterite has been observed on weathered diorite. Limonite veining is common in the larger weathered intrusions, and spheroidal weathering is seen in many of the outcrops.

Distribution

Diorite crops out sparsely within the Warramunga Group, and the only large outcrop covers an area of about 0.4 km^2 3 km northwest of the Mary Lane mine (Crohn & Oldershaw, 1965). However, small intrusions have been found during the present survey in the upper parts of the Warramunga Group. Near the basal beds of the Tomkinson Creek Beds, diorite occurs as a series of large coarse-grained sills and irregular masses which discordantly intrude the sediments. The intrusives show up as large crescentic magnetic anomalies on the aeromagnetic map of the Sheet area.

Most of the valleys in the Short Range are the result of the weathering out of diorite sills. Outcrop of diorite in these valleys is rare; the presence of diorite must be inferred in some cases from lateritized rubble with an igneous texture, and from aeromagnetic data.

Diorite/dolerite bodies are known in shear zones within the Warramunga Group. A Northern Territory Geological Survey drillhole at grid ref. 392854 intersected, at 80 m depth, quartz diorite containing up to 15 per cent magnetite (M.R. Daly, pers. comm). BMR No. 1 hole (1970) was drilled 0.5 km east of this borehole, and intersected weathered diorite at 17 m.

The dolerite dykes intruding granite are fine-grained, and form regular tubular bodies unlike the many larger intrusions, which are sills or have an irregular shape.

Lithology

The diorite commonly crops out as soft brown limonitic masses with an igneous texture. Quartz is seen only rarely in outcrop, except where the diorite has been heavily leached, leaving only quartz and limonite.

Plagioclase changes on weathering from pink to grey, whereas the orthoclase changes from pink to fawn and white. Further ferruginisation and leaching turn the kaolin, etc. into an iron-rich homogeneous clay, commonly with residual magnetite grains.

A small outcrop of fresh diorite was found 2 km east of the Last Hope mine. The diorite is a mottled dark green and pink, coarsely crystalline rock. It consists of laths of green to brown hornblende showing minor alteration to chlorite aggregates, in a groundmass of anhedral orthoclase, euhedral andesine, and irregular aggregates of magnetite partly altered to hematite. Minor augite is present as small cracked crystals in part converted to hornblende. Small blebs of quartz are present in the orthoclase.

Quartz veining is not common in the diorite, but is found along some contacts with the upper parts of the Warramunga Group.

Contact relations

The diorite cuts the Tomkinson Creek Beds and the Warramunga Group. Sills of diorite are regionally concordant with bedding, but locally the diorite cuts across the bedding.

At grid ref. 397869 diorite cuts blocky sandstone at a low angle. The sandstone is indurated for 15 cm, and is heavily iron stained. The diorite becomes fine-grained towards the contact, and is truncated against a fault to the northwest. In many places faults cut the diorite, but in some areas there is no regular displacement pattern along the faults and the diorite intrusion may be merely have been controlled by the fault pattern.

At grid ref. 397867, a 6-m fine-grained diorite dyke fills a north-south fault, and angular silicified sandstone fragments are included in the marginal parts of the dyke. The sandstone is indurated for 10-20 cm from its regular boundary with the diorite. Wedges of diorite penetrate the sandstone. Diorite dykes commonly lens out laterally.

LAMPROPHYRE

Small lamprophyre dykes and sills intrude the sediments of the Warramunga Group near three granite masses in the Sheet area.

Three kilometres south of the margin of the 'Tennant Creek Granite', around the Mary Lane mine, many lamprophyre dykes intrude the Warramunga sediments. The lamprophyre forms lenses which range in width from 1 m to 40 m, averaging 4 m, and are commonly about 60 m long (Crohn & Oldershaw, 1965). The dykes are controlled by local faults and shear zones.

West of the 'Warrego Granite', several dykes of coarse-grained lamprophyre, 7 to 40 cm wide and striking roughly north-south, intrude shale and siltstone of unit Ew_3. The dykes are associated with small pegmatitic veins.

East of the 'Warrego Granite', about 1 km southwest of Last Hope mine, lamprophyre dykes and sills intrude the Ew_3 shale and siltstone. A 3m-wide sill, broadly concordant with the sediments, but locally crosscutting is folded along axes plunging 40^{o} to 110^{o}.

South and east of the 'Channingum Granite', small sills of lamprophyre 0.3 to 3 m thick intrude unit Ew_5 of the Warramunga Group. The sills can be traced for a maximum exposed length of 100 m. In several exposures, particularly where they intrude coarse-grained greywacke, they lens out rapidly, and may be only 3 m long.

The lamprophyre is deeply weathered, and Crohn & Oldershaw (1965) found it to be commonly covered by dolomitic travertine. The lamprophyre may be recognized by its large somewhat altered biotite flakes in a ferruginous feldspathic groundmass. Some of the mica has been replaced by chlorite, some is highly altered.

Lamprophyre from near the 'Channingum Granite' consists of large biotite crystals in a limonite, hematite, and feldspar groundmass with minor quartz. The groundmass shows no preferred orientation. Crohn & Oldershaw report the presence of amphibole and pyroxene lamprophyre (camptonite) as well as the more common biotite lamprophyre (minette).

The distribution of the lamprophyres in the Sheet area indicates that they may be genetically associated with granite. Their composition is related to the adjacent granite bodies and around the 'Warrego Granite' they occur in association with pegmatite veins.

?CARPENTARIAN

TOMKINSON CREEK BEDS

Introduction

The Tomkinson Creek Beds were previously called the Ashburton Sandstone (Ivanac 1954) and Hayward Creek Beds, and were named the Tomkinson Creek Beds by Randal, Brown, & Doutch (1966). Dunnet & Harding (1967) continued the use of this term . The nomenclature of this group is discussed by Randal, Brown, & Doutch (1966).

The Tomkinson Creek Beds crop out extensively in the Short Range and the southern end of the Whittington Range in the Sheet area. There are also isolated outcrops in the northwest corner of the Sheet area, on a north-south ridge west of the Warrego mine, northeast of Meerie Waterhole, and 8 km south-west of No. 11 bore. The Tomkinson Creek Beds reach their maximum thickness of 9100 m at Attack Creek. At Hayward Creek, the measured thickness is 7450 m. This is considerably less than the 50 000 feet (15 000 m) cited as the total thickness of the Group by Randal, Brown, & Doutch (1966). However, it is probable that beds higher in the sequence in the Helen Springs 1:250 000 Sheet area are absent in the Tennant Creek Sheet area. Ivanac (1954) gives 11 000 feet (3 300 m) as the thickness for the Ashburton Sandstone, a figure too low if the whole of the Tomkinson Creek Beds was being considered, but acceptable for the quartz sandstone (Gibson Creek Formation) near the base of the Beds.

There is no type section, but the best exposed and most complete sequence is along Attack Creek in the extreme north of the Sheet area.

Previous workers have considered the Tomkinson Creek Beds to be of Early Proterozoic age (Randal, Brown, & Doutch, 1966), and early Late Proterozoic age (Ivanac, 1954). Potassium-argon dating on glauconite from sandstone in the sequence indicates an age of 1700 m.y. (Early Carpentarian) for the Tomkinson Creek Beds (H.F. Doutch, pers. comm.). Although this date is based on only one sample, it is consistent with the age previously supposed, and, to date, can be taken to be a satisfactory estimate.

The Tomkinson Creek Beds overlie the Warramunga Group with a slight angular unconformity which is best exposed in the range west of the Last Hope mine. Twenty five kilometres west-north-west of the Warrego mine a drillhole (BMR 2) was put down to a depth of 76 m to intersect the contact between flaggy and blocky sandstone of the Tomkinson Creek Beds and the underlying folded and cleaved shale of the Warramunga Group. The hole terminated in porous limonitic rock, which may represent either a fault zone or a weathered horizon at the top of the Warramunga Group.

The Beds have been divided into six formations within the Sheet area:

Formation	Thickness
Attack Creek Formation	800 m
Short Range Sandstone	200 - 880 m
Morphett Creek Formation	2500 - 4200 m.
Whittington Range Volcanics	200 - 450 m.
Hayward Creek Formation	3000 - 6000 m
Blanche Creek Member	Up to 150 m (not on Tennant Creek 1:250 000 Sheet)

Generalized sections are shown in the Appendix.

The units of the Tomkinson Creek Beds consist dominantly of cross-bedded and ripple-marked quartz sandstone (orthoquartzite) (about 70 per-cent). Pebbly sandstone, shale, siltstone and limestone account for a smaller proportion of the Beds (about 25 per cent), and a thin layer of basalt and minor acid volcanics, about 5 per cent.

The quartz sandstone contains about 0.1 per cent of heavy minerals - blue or green tourmaline and zircon. Some acicular apatite inclusions are also present in quartz grains, possibly indicating a granitic source for the sediments (Keller & Littlefield, 1950). The degree of rounding and sorting makes it more likely that the sediments were derived from older sedimentary rocks, and that these are composed of truly polycyclic grains (Blatt, 1967). The underlying Lower Proterozoic Warramunga Group rocks provided some of the source material for the Tomkinson Creek Beds sediments, especially in the basal Blanche Creek Member and the lower half of the Hayward Creek Formation. Argillaceous material in the Morphett Creek Formation may also have been derived from uplifted Warramunga Group sediments. The bulk of the arenaceous sediments probably came from a relatively distant sedimentary source area. Cross-bedding measurements in the Short Range Sandstone indicate that the provenance was to the west.

The environment of deposition is that of a shallow to very shallow marine basin, the conditions of sedimentation ranging from inner neritic to intertidal. Deposition took place, it is believed, in a slowly subsiding marine basin (the so-called 'Ashburton Geosyncline') (Brown, Campbell, & Crook, 1968) in which the rate of infill exceeded the rate of subsidence to produce a gradually shallowing marine environment. The presence of basaltic volcanics (non-spilitic) and shallow-water features such as symmetrical ripple marks, littoral cross-beds, and mud-cracks, attests to the near-shore environment of deposition for these sediments.

Blanche Creek Member

Derivation of name

The name is derived from Blanche Creek on the Tennant Creek 1:250 000 Sheet (lat. $19^{o}02'$S, long. $134^{o}09'$E).

Distribution

The Blanche Creek Member forms scattered outcrops along the eastern side of the Whittington Range as far south as Gibson Creek, and along the southern edge of the Short Range. Its outcrops are not, however, shown on the Tennant Creek 1:250 000 Sheet. The member is up to 150 m thick.

Type section

The type section for the unit lies in the vicinity of grid reference 411885.

Lithology

The unit is a poorly sorted pebbly sandstone and conglomerate, consisting of 20-30 per cent subrounded pebbles, 6 to 8 cm across, in a lithic sandstone matrix. At Hayward Creek, pebbles 1-6 cm across account for up to 20 per cent of the rock, and at Phillip Creek, the pebbles range from 2-5 cm, and account for about 50 percent of the conglomerate. The pebbles are mostly white quartz; about 10 per cent of the total pebbles are black chert, red jasper, acid igneous rocks (quartz porphyries), and rarely, dark red-purple siltstone and shale fragments. Many of these pebbles are very similar to the outcropping Warramunga Group sediments to the south.

The quartz-porphyry pebbles consist of about 25 per cent of resorbed quartz phenocrysts 1-2 mm across, and the groundmass is made up of shreds and patches of hematite, quartz, altered feldspars, and sericite. Some pebbles are composed of altered feldspar phenocrysts entirely decomposed to clays and sericite.

About 60 per cent of the matrix consists of moderately well-sorted sub-angular quartz grains 0.1 to 0.2 mm in diameter set in a clay-sericite cement. A few highly altered feldspar grains are characteristically lath-shaped, and show faint albite twinning. Locally the matrix consists of quartz grains and small particles of chert, shale, siltstone, and quartz-mica schist. Grains of fine-grained basalt? are rarely seen. Zircon and, less frequently, green tourmaline are present in the matrix. Some rocks cropping out are indurated.

The Blanche Creek Member shows characteristic high-angle cross-bedding (20^{o}-40^{o}). The cross-bedding indicates a consistent direction of origin from the east. In coarse-grained beds, poorly developed graded bedding is rare.

Stratigraphic relations

The Blanche Creek Member disconformably overlies the Lower Proterozoic Warramunga Group in many parts of the area, locally with slight angular unconformity. It is conformably overlain by the Hayward Creek Formation.

Palaeogeographic significance

The poor sorting of the basal member and the high-angle ("torrential") cross-bedding in the sandstone matrix suggest that the unit was deposited fairly close to its source area, and by swiftly flowing currents (Joplin, 1965).

The Blanche Creek Member is probably of fluvial origin as it contains sub-angular pebbles, has a poorly sorted sandstone matrix, and shows evidence of abundant current action during sedimentation (Conybeare & Crook, 1968). With the uplift of the source area, streams would have transported material down to a floodplain or coastline, where the coarse gravelly sediment was deposited over a large area. Most of the rock types forming the pebbles in this unit can be recognized in the underlying Warramunga Group rocks. These include acid igneous rocks, quartz, shale, and black chert. The presence of the quartz and acid igneous pebbles in the Blanche Creek Member indicate that the Warramunga sediments were consolidated and lithified before a new uplift and cycle of sedimentation. The beginning of the Tomkinson Creek Beds' sedimentation must have post-dated the first granite intrusive into the Warramunga Group rocks, assuming that the porphyries were associated with this phase of igneous activity. Most of the large quartz outcrops are associated with the granites.

The overall picture is that of a substantial hiatus between the end of sedimentation in the 'Warramunga Geosyncline' and the beginning of the sedimentation that produced the Tomkinson Creek Beds. Diagenesis of the Warramunga sediments, and intrusion of acid porphyry bodies and quartz and jasper veins, occurred before uplift and renewed sedimentation. Evidence of any tectonic activity which occurred during the hiatus has been obscured by the two later folding episodes which post-date the deposition of the Tomkinson Creek Beds.

Hayward Creek Formation

Derivation of name

The name is derived from Hayward Creek, lat. $19^{\circ}10^{\circ}$S long. 134° 09'E. The type section is from G.R. 410883 to G.R. 408883.

Distribution

The Hayward Creek Formation constitutes a large part of the Whittington Range and the Short Range, and it also crops out in the north-west corner of the Sheet area. The isolated outcrop centred 8 km south-west of No. 11 bore and the outcrops northeast and northwest of Meerie Waterhole are also composed of rocks of the Hayward Creek Formation. The unit ranges in thickness from about 3000 m in the southern part of the Whittington Range to about 6000 m in the Short Range.

Lithology

The Hayward Creek Formation shows a gradation from pebbly lithic sandstone into clean quartz sandstone. In the basal 500 m there are a few pebbly beds consisting of subrounded white quartz and pink and grey silicified orthoquartzite pebbles 3-4 cm across in an orthoquartzite matrix. The pebbly beds are usually only 15-30 cm thick, but within these beds pebbles constitute up to 70 percent of the rocks. In the north-south outcrop 22 km west of Warrego mine, white quartz pebbles 1-2 cm across account for about 10 percent of the sandstone near the base of the formation, and north of Butchers Waterhole, pebbles and cobbles of white quartz are up to 10 cm across. In the upper parts of Hayward Creek red jasper pebbles account for about 1 percent of the beds a few hundred metres from the base of the formation. A few black chert pebbles are also seen in the lower part of the formation at the outcrop southwest of the No. 11 bore. The pebbles are less abundant higher in the sequence, up to about 100 m from the base, where there are only scattered pebble and grit bands with included white quartz pebbles

0.5-1 cm across. The sandstone in the basal part of the Hayward Creek Formation is commonly torrentially cross-bedded on a small scale.

The topmost 2000 m of the unit in the type section are clean quartz sandstone (orthoquartzite) and feldspathic sandstone consisting of 85-98 percent quartz grains. The sandstone ranges in colour from cream to red and is generally silicified to produce a hard, compact rock which weathers into rounded boulders and, in places, walls up to 10 m high. The beds range from thin to thick bedded and flaggy to massive. Cross-bedding is widespread. Where the beds are not silicified, the sandstone weathers readily.

The quartz grains have authigenic overgrowths, and form an interlocked mosaic. 'Dust rings' around the original grains show that they were 0.4 to 0.6 mm across, rounded to sub-rounded, and were moderately clear to well sorted. The grains have undulose extinction, and are commonly streaked with or are full of 'dust'. Some sandstone contains up to 15 percent white feldspar grains. Small (0.05 mm) grains of zircon, apatite needles, and green or blue tourmaline are also present. The interstices are filled with clay or, more rarely, sericite and limonite. Near the base of the formation there is up to 5 percent of muscovite or sericite in the matrix.

Distinguishing features of the unit are the abundance of cross-beds and ripple marks in the basal parts of the formation. Small voids 1-2 cm across the sandstone probably represent shale clasts which have weathered out at the surface. Cross-bedding is of the festoon type (Dunbar & Rodgers, 1957), ranging from 5 cm high by 30 cm in foreset length to 15 cm high by 1 m in foreset length. A generalized section of the lower part of the Hayward Creek Formation is shown in the Appendix.

Stratigraphic relations

The unit is overlain conformably by the Whittington Range volcanics, and conformably overlies the Blanche Creek Member.

Palaeogeographic significance

The Hayward Creek Formation orthoquartzites were probably deposited as shallow-water coastal marine sands of the sub-littoral or inner neritic zones. The medium-scale cross-beds indicate marine conditions, and the presence of a few symmetrical ripple marks near the base of the formation indicate shallow-water conditions. The grains constituting the orthoquartzites are medium-grained, well rounded and sorted, and non-argillaceous; these features indicate deposition in marine conditions (Conybeare & Crook, 1968).

A marine transgression probably followed the initial uplift and commencement of sedimentation of the Blanche Creek Member, the strand line moving over previously deposited gravels (Shaw, 1964). Deposition of the marine sands would probably have occurred in the shallow marine environment. The presence of quartz pebbles towards the base of the formation suggests that fluvial material was still being derived from the uplifted source area of Warramunga Group rocks to the south and east. However, the predominant quartz sand content of the unit was probably derived from a larger source area of quartz sandstone, possibly to the west. The orthoquartzite pebbles in the lower pebble beds of the Hayward Creek Formation are probably less-abraded fragments from the westerly source area.

Whittington Range Volcanics

Derivation of name

The formation name is derived from the Whittington Range, which extends into the northern part of the Tennant Creek Sheet area from the Helen Springs 1:250 000 Sheet area. The type section is in the vicinity of grid ref. 407892.

Distribution

The Whittington Range Volcanics form six small outcrops in the central southern part of the Whittington Range, and two outcrops in the eastern part of the Short Range, about 7.5 km northwest of Phillip Creek station. The volcanics typically form low mesa-like outcrops, invariably capped with about 3 m of Tertiary silcrete. Elsewhere, evidence of the volcanics may be found amongst the angular rubble on valley floors. This consists mostly of quartz sandstone fragments, but also includes pebbles and angular fr[illegible] of vein quartz, blue-green rhyolite, epidotized basalt, and red jasp[illegible]

Lithology

The sequence is from 200 - 450 m thick. Because of severe weathering and alteration, it is not possible to obtain fresh specimens of the volcanics at the surface. However, fresh specimens were obtained from drill-cores. The lowest few metres of the formation consist of interbedded ortho-quartzite and lateritized basalt 4 to 10 cm thick. Above this, about 40 m of coarse-grained, highly weathered ?basalt consists of small, white feldspar laths in a red, friable, ferruginous groundmass. This is succeeded by about 20 m of cream micaceous quartz sandstone and red-brown micaceous siltstone. The quartz sandstone is flaggy and thinly cross-bedded, and contains a few green and cream shale clasts; it is moderately well sorted with subrounded quartz grains 0.2 - 0.3 mm across, and with authigenic quartz overgrowths on each grain. The rock contains 5-10 percent of altered feldspathic grains, and a small amount of clay minerals, sericite, and muscovite flakes. Small brownish green to bluish green tourmaline grains make up to 0.1 percent of the rock. The micaceous siltstone beds are commonly leached.

Above the sandstone is the main sequence of volcanics, which is 100 - 350 m thick and composed of vesicular and non-vesicular basalt, commonly epidotized, and a few spherulitic ?rhyolite flows. Where weathered and lateritized, as in most surface exposures, the fine-grained non-vesicular non-epidotized basalts are light grey to cream and brown, and almost wholly composed of kaolinitic material. Small quartz-filled vesicles are rare. Weathered vesicular and coarse-grained varieties are rusty red and contain amygdales up to 0.5 cms across filled with quartz enclosing white feldspathic centres. Epidotized basalt with or without quartz-filled vesicles is less prone to weathering and lateritization. The rhyolitic flows range in colour from cream to red-brown and blue-green, the last colour possibly due to secondary copper staining. Some varieties show a flow-banded structure with alignment of small feldspar microlites. Quartz phenocrysts up to 4 mm across are locally corroded. All the volcanics are cut by jasper and quartz veins, the latter up to 6 cm wide. Though calcite veins were not seen, patches of quartz in the veins appear to be pseudomorphs after calcite.

Petrographic examination of surface samples showed that they were basalts and rhyolites. The following descriptions illustrate the typical rock types.

Rock 70861002 - Weathered amygdaloidal basalt. A reddish-brown clayey rock with poorly defined vesicles. The rock has a basaltic texture; altered plagioclase laths 0.1 mm long make up about 60 percent of the rock by volume. The amygdales, consisting of clay with a quartz margin, range from 3-5 mm in diameter and constitute 25 percent of the rock. The groundmass is a mixture of iron oxide and clay.

Rock 70861024 - Epidotized amygdaloidal basalt. The rock is almost entirely altered to epidote, but contains 20 percent of quartz amygdales (1-3 mm) rimmed with jasper. A few unaltered patches retain relict basaltic texture, with plagioclase laths 0.2 - 0.3 mm long in a groundmass of iron oxides and epidote.

Rock 70861029 - Weathered amygdaloidal basalt. A greenish grey rock with vesicles filled with white feldspathic material, quartz, or rarely chlorite. Amygdales are 2-5 mm across, and make up about 3 percent of the rock. The groundmass consists of clay minerals and iron oxides and highly altered plagioclase laths.

Rock 70861027 - Rhyolite. A white to reddish brown very fine-grained cherty rock with microspherulitic texture; the spherules are composed of radiating quartz or orthoclase. The centres of the spherules are mostly occupied by finely crystalline quartz. Hematite accounts for about 3 percent of the rock, and quartz is abundant in the groundmass.

A drillhole (BMR 3) put down at lat. 19° 03' 17"S, long. 134° 07' 27"E to a depth of 72.5 m produced fresh rock samples suitable for detailed petrographic work.

The drill-core samples are vesicular and non-vesicular basalts. The vesicular basalts consist of a dark greenish grey groundmass, commonly containing small spots of chlorite-pumpellyite, with up to 40 percent of vesicles, 0.3 - 3 cm across, filled with quartz, epidote, jasper, chlorite-pumpellyite, calcite, pink albite, quartz rimmed with jasper, or quartz rimmed with chlorite. The non-vesicular varieties are similar, but contain about 10 percent of 1-2 mm spots of chlorite-pumpellyite in a grey-green groundmass. Both types are mostly epidotized, the groundmass in each case being completely replaced by epidote.

If vesicular basalt represents the top of a particular flow, the log of the drill-hole shows there are seven flows represented in the 72.5 m drill-core, ranging in thickness from 2 to 22 m.

Specimens from the drill core contain 30-40 percent of andesine (An_{34}), 0.05 - 0.1 mm wide and 0.3 - 0.9 mm long, the crystals showing both Carlsbad and albite twinning. Patchy alteration of the feldspars to clay minerals and sericite has occurred. The rock contains up to 5 percent of small (0.1 mm or less) augite crystals, partly altered to chlorite and iron oxides. Pyroxene grains with a very low 2V are probably pigeonite. A fine groundmass makes up about 50 percent of the rock; it consists of magnetite, hematite, chlorite, clay minerals, and rare feldspar microlites. With increasing depth chlorite is less common in the groundmass. About 10 percent of the rock is composed of 1-2 mm wide amygdales containing a mixture of chlorite, pumpellyite, and rarely a little calcite, arranged in concentric bands. Calcite is also present as small veins and patches in the rock mass itself.

The presence of pigeonite and the nature of the groundmass indicate that these basalts have tholeiitic affinities. The epidotization is probably the result of late-stage deuteric alteration, and not a change brought about by regional metamorphism. It is too localized in certain flows to be general alteration under metamorphic conditions. The log of Tennant Creek Bore 3 in the Whittington Range Volcanics is shown in the Appendix.

Stratigraphic relations

The formation conformably overlies the Hayward Creek Formation and is conformably overlain by the Morphett Creek Formation.

Basalt of the Whittington Range Volcanics and amygdaloidal basalts found in the Murchison Range, in the Bonney Well 1:250 000 Sheet area to the south, are similar. In the Murchison Range, basalt and acid lava are interbedded with sandstone of the Hatches Creek Group. From petrographic descriptions (Walker, in Smith , Stewart & Smith, 1961) the amygdaloidal basalt from the Murchison Range appears to be similar to that of the Whittington Range. Basalt examined in the field near Kurundi Homestead in Bonney Well Sheet area contains amygdales of calcite and pink albite rimmed with epidote. Small specks of chalcopyrite, similar to those present in the drill core from the Whittington Range basalt, were also seen. As the rock types are similar in both areas, and both are found as lava flows in Lower Carpentarian sandstones that can be correlated stratigraphically (the Hatches Creek Group and the Tomkinson Creek Beds), it is possible to correlate the two sets of volcanics and postulate that they originated from the same source.

Basic volcanics crop out in valleys in sandstone of the Tomkinson Creek Beds in the Helen Springs 1:250 000 Sheet area. They have been described as part of the Lower Cambrian Helen Springs Volcanics: 'The basalts and basal sediments occupy valleys eroded into soft siltstone units of the Precambrian Tomkinson Creek Beds' (Randal, Brown & Doutch, 1966 p 15). They form mesas capped by thick laterite or lateritized sediments. However, there is a striking similarity between these Lower Cambrian Helen Springs Volcanics and basalt of the Whittington Range Volcanics. Randal, Brown & Doutch also make reference to sandstone that has been melted or contact-metamorphosed by the basalt flows, consisting of coarsely recrystallized quartz with 'abundant sillimanite(?) or mullite(?) needles'.

It is suggested that at least some of the basalt mapped as Helen Springs Volcanics in the Helen Springs 1:250 000 Sheet area is probably of Lower Carpentarian age, and can be directly correlated with the Whittington Range Volcanics. Randal, Brown & Doutch admitted that it was difficult to demonstrate that the volcanics were not conformable with the surrounding sediments.

Morphett Creek Formation

Derivation of name

The name of the formation is derived from Morphett Creek, in the Helen Springs 1:250 000 Sheet area, at lat. 18°53'S, long. 134°05'E. The type section is between G.R. 407893 and G.R. 403891.

Distribution

This formation crops out poorly, because it is composed of soft shale and siltstone, which are eroded relatively rapidly. It is exposed in places in the central southern part of the Whittington Range and in some areas along the north side of the Short Range. It can probably be correlated with quartz siltstone cropping out in the north-west of the Sheet area.

Lithology

The formation ranges from 2500 to 4800 m in thickness, being thickest in the Whittington Range and thinning southwards in the Short Range.

The lowermost 700 to 900 m consists of feldspathic sandstone containing from 10 to 50 percent of altered feldspar grains, and up to 10 percent muscovite. It is a moderately well-sorted sandstone with sub-rounded grains about 0.2 to 0.3 mm across. These sandstones are unsilicified, and are light grey to pink. Some sandstone contains up to 10 percent limonite, and a few small grains of green tourmaline and zircon are commonly found as accessories. Several bands of rounded quartz pebbles 1-2 cm across occur near the base of the formation. The sandstone is fissile to flaggy and locally massive and thick-bedded. Ripple marks, cross-beds, and shale clasts are common. The lower 100 to 150 m is characterised by abundant iron oxides and 20-30 percent of jasper, either as detrital grains or as a cementing material around the quartz grains. The rock has a deep, rusty brown colour, and is readily discernible on aerial photographs as a dark bed immediately overlying the Whittington Range Volcanics. The most probable explanation for the high iron content of the sandstone is that the detrital quartz grains were intermixed with weathered material from the underlying volcanics. Jasper veins are common in the Whittington Range basalt, and provided the source of jasper in the lowermost beds of the Morphett Creek Formation.

Siltstone, shale, and minor interbedded sandstone overlie the basal sandstone. A thin boulder conglomerate lens between Gibson and Hayward Creeks, stratigraphically above the sandstone sequence, is about 5 m thick and stands up to 10 m high as a resistant wall. The conglomerate consists of 75-95 percent boulders, 6 - 15 cm across, in a quartz sandstone matrix. The boulders are well-rounded, have a high degree of sphericity, and consist of white quartz, pink and cream orthoquartzite, and boulders of pebble sandstone (orthoquartzite with 20-40 percent of white quartz pebbles). Both the orthoquartzite and pebbly sandstone boulders were probably derived from the underlying Hayward Creek Formation, the pebble sandstone coming from the basal 1000 m of the Tomkinson Creek Beds.

Exposure of the shale and siltstone is poor, because of lack of silicification. The only places where the unit crops out are creek beds and gullies, and in isolated hills and ridges on the sand-covered plain. The shale and siltstone are light grey and red, and commonly micaceous, and form beds 4-6 cm thick. Opposite Gibson Creek on a major fold axis, deep red hematitic shale is partly leached. Within these beds irregular ironstone and minor cherty siltstone were possibly formed by lateritization of iron-rich shale and siltstone. A few travertine boulders and fragments formed on the calcareous beds of the Morphett Creek Formation.

Near the top of the formation are interbeds of coarse quartz siltstone and feldspathic sandstone. They are light grey or cream, weathering to rusty brown on the surface. The beds contain 10-50 percent of feldspar grains (rarely identifiable as plagioclase) or have a decomposed feldspar matrix. The rock contains up to 10 percent limonite cement and up to 5 percent muscovite. The sandstone is fissile, splitting readily into slabs 1 - 8 cm thick. Light green shale clasts are present in the sandstone and siltstone, but these generally weather out leaving voids. Ripple-marks and cross-beds are rarely present.

Stratigraphic relations

The Morphett Creek Formation conformably overlies the Whittington Range Volcanics, and is conformably overlain by the Short Range Sandstone. There is a distinct break in lithology at the top of the Morphett Creek Formation, where it passes abruptly from shale and siltstone into the resistant Short Range Sandstone.

Palaeogeographic significance

The lower 1000 m of sediments was deposited in a near-coastal (inner neritic) marine environment. The increasing abundance of shale clasts, mica flakes, and ripple marks, and the preponderance of thin bedding, suggest that the basin became progressively more shallow. The Morphett Creek Formation sandstone was probably deposited in part in a sub-littoral or pre-delta environment. Randal, Brown & Doutch (1966) record glauconite in this formation, indicating a marine environment. Randal, Brown & Doutch (1966, p 9) also note: 'the occurrence of halite pseudomorphs, mud cracks, and primary current lineation, and the presence of significant quantities of siltstone and carbonates with algae' - features which point to very shallow water conditions with periods of sub-aerial exposure, indicating a deltaic or tidal flat environment. Carbonate beds observed in this formation in the Tennant Creek Sheet area confirm the very shallow marine environment. There is evidence of penecontemporaneous uplift of both the source area and the edges of the marine basin, where sediments of the Tomkinson Creek Beds had already been deposited. This uplift probably caused the gradual shallowing of the marine basin, also exposing older beds of the Tomkinson Creek Beds to erosion. The evidence for this uplift and marine regression comes from the boulder conglomerate lens above the sandstone sequence, which contains pebbles of white quartz and orthoquartzite, and also fragments of conglomeratic and pebbly sandstone. Almost identical rock types are found in the underlying Hayward Creek Formation.

In the upper part of the formation, the rock types become predominantly micaceous; shale and siltstone with interbedded flaggy quartz sandstone containing shale clasts are the dominant rock types. With uplift, the Warramunga Group rocks, re-exposed to erosion, would again have become important as a source area. The large amounts of mud and silt in the upper part of the unit were probably derived from erosion of Warramunga Group rocks to the south and east. The presence of shale clasts in the quartz sandstone indicates intermittent periods of sub-aerial exposure during deposition.

Short Range Sandstone

Derivation of name

The name is derived from the Short Range, in the Tennant Creek Sheet area, lat. $19^{\circ}12'$S long. $134^{\circ}05'30$E. The type section for the formation is in the vicinity of grid ref. 401894, where a southern tributary of Attack Creek cuts through the Short Range Sandstone.

Distribution

This formation crops out only on the western side of the Whittington Range in the Tennant Creek 1:250 000 Sheet area. It is easily discernible on aerial photographs as a thin, prominent ridge running north-south from grid refs. 388898 to 397877, and as ridges and small hills up to 7 km west of this main ridge.

Lithology

The Short Range Sandstone is 200 - 800 m thick, and generally thickens northwards. It consists of pink, light grey, cream and purple massive to blocky orthoquartzite, composed of well-sorted and rounded quartz grains 0.3 to 0.4 mm across. The quartzite is silicified, compact, and resistant to weathering. Some beds contain a few percent of decomposed feldspar grains and muscovite flakes. Almost all the quartz grains have authigenic overgrowths, giving the rock a mosaic-like fabric. Some grains contain small needles of apatite. Blue-green tourmaline grains 0.05 mm across are rare. Limonite constitutes up to 5 percent of the rock. Voids left by the weathering out of shale clasts account for up to 10 percent of the rock's volume. The voids are sub-rounded and from 1-2 cm across.

Crossbeds range from up to about 5 cm thick near the top of the formation to about 1 m thick in the lower half of the formation. Ripple marks are common throughout the sandstone. They are symmetrical and longitudinal in form. Each ripple is typically straight and continuous for several metres. Rarely, they are bifurcated and slightly sinuous. Some interference ripples are also present. The ripple index - i.e., the ripple width divided by its height - ranges from 8 to 15, and the continuity index - the total length of a ripple divided by its width - is always over 50.

The low-angle (10^{o} to 15^{o}), medium to large-scale cross-beds within the formation indicate shallow-water marine conditions (Conybeare & Crook, 1968). The lower half of the Short Range Sandstone is characterised by very long, low-angle cross-beds, which probably indicate a littoral environment. The well-sorted, well-rounded quartz grains also indicate a shallow-water environment of deposition. The change from the argillaceous sediments of the Morphett Creek Formation to the prominent Short Range Sandstone may be due to shallow basin conditions; the geological boundary may coincide with a strand line. The sand was probably part of a beach deposit in a zone shallow enough for wave action to become the dominant factor in the sorting and abrasion of the incoming sediments.

Eighty-seven cross-bedding attitudes were measured, and their bedding poles plotted on a stereo net and then rotated back to the horizontal to remove the effect of folding, assuming that such folding is cylindrical. In this way, the beds at two localities in the Whittington Range were rotated 50^{o} about an axis bearing 010^{o}, and 35^{o} about an axis bearing 160^{o}. The results indicate the dips of the foreset beds of the cross-beds and these, when plotted on rose diagrams, indicate that the sedimentation was from the west (Fig. 1).

The upper half of the formation is characterised by numerous shale clasts, abundant wave-formed ripple marks and small to medium-scale cross-beds. These sedimentary structures indicate a shallow water origin, probably in a littoral or sub-littoral environment.

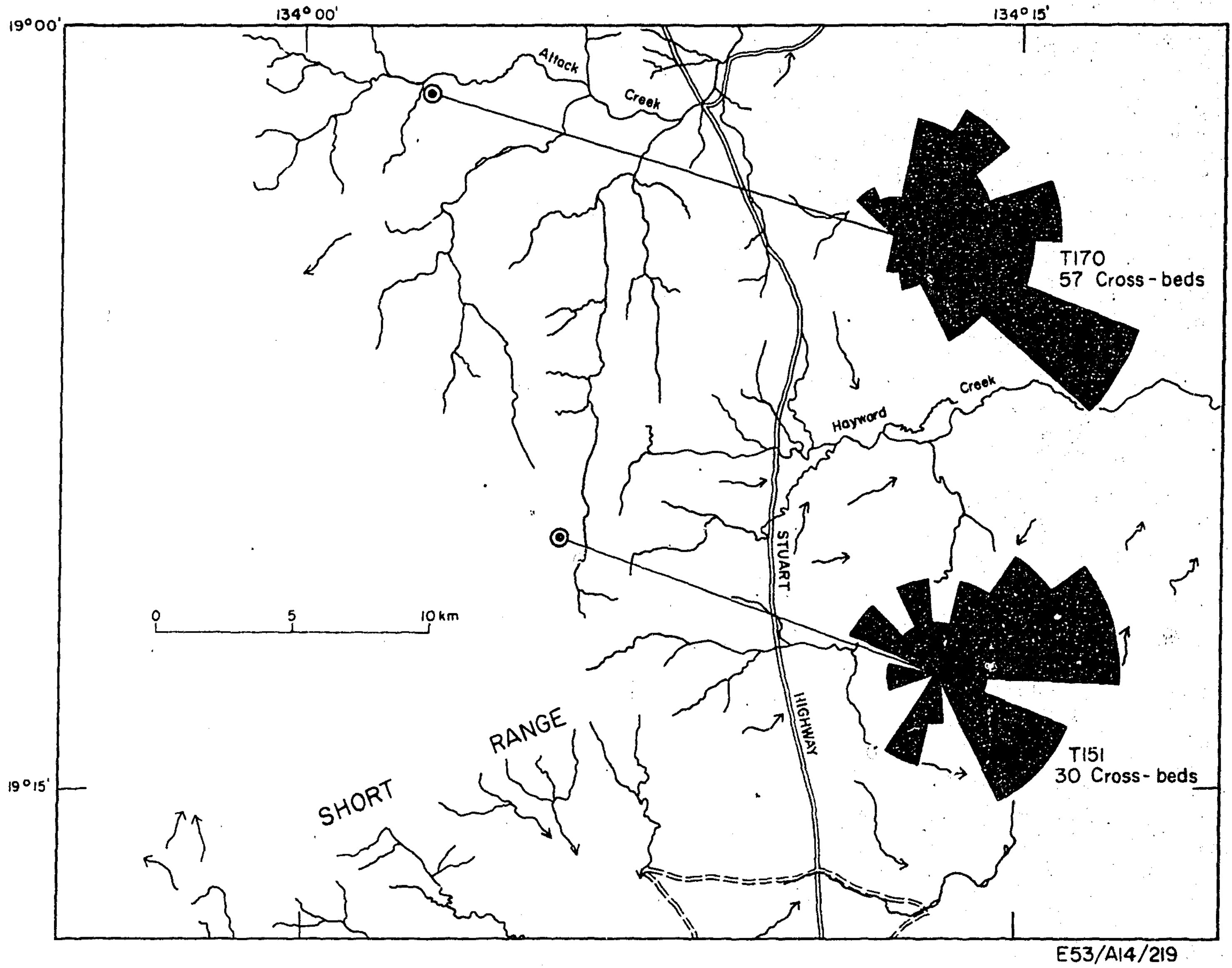

Fig. 1 Cross-bedding directions in the Short Range Sandstone.

Stratigraphic relations

The unit conformably overlies the Morphett Creek Formation, and is itself conformably overlain by the Attack Creek Formation. The boundaries with the continuous formations are very distinct.

Attack Creek Formation

Derivation of name

The name for the formation is derived from Attack Creek in the Tennant Creek Sheet area, lat. 19°03'30"S, long. 134°03'E. The type section is between grid refs 401893 and 398892.

Distribution

The formation crops out over a limited area immediately west of the prominent north-south ridge formed by the Short Range Sandstone.

Lithology

The formation is the youngest exposed part of the Tomkinson Creek Beds in the Sheet area. Its thickness cannot be precisely determined because its top is not seen in the Sheet area, but it is at least 800 m thick. A limestone unit ranges in thickness from 450 to 550 m. At the top of the Short Range Sandstone, there is a distinct change in lithology to the basal cream or buff calcareous siltstone of the Attack Creek Formation, which ranges in thickness from about 50 to 100 m. The beds are medium to thick-bedded, and commonly contain small manganese dioxide dendrites. These beds are succeeded by 450-550 m of dark grey limestone, commonly silicified. This weathers on the surface to a white, banded travertine. The limestone is flaggy, and thin (1 cm or less) calcareous siltstone or shale layers separate 8-10-cm layers of limestone. Some limestone contains shaly clasts, siliceous nodules, and concentrations of oolites. The limestone is a fine-grained sparite containing up to 60 percent ovoid or rounded lenticular clasts composed of micrite, fine clay, or silt, and manganese and iron oxides. The clasts commonly have a 'bent ovoid' shape, and some show an attenuated structure, being thick and bulbous at each end and thinned out in the middle.

Limestone of the Attack Creek Formation contains about 75 percent $CaCO_3$ and only about 1 percent $MgCO_3$. The remainder is fine mud and silt, with small amounts of iron and probably manganese oxides. No algal remains were identified in the limestone.

The limestone is richer in clay and iron oxide towards the top, where it grades into beds of concretionary ironstone, calcareous black mudstone, and brown and black mottled chert. The black calcareous mudstone is readily leached. Its colour is due mainly to the presence of manganese. Chemical analysis of a mudstone from grid ref. 401888 gave Mn, 24.0%; Cu, 0.09%; Co, 0.09%; Zn, 0.02%; Pb, 0.008%; Ni, 0.005%; Cd, 0.005%; Fe, 0.50%, Mo, 3 ppm; Ag, 1 ppm.

Overlying these beds is a sequence of feldspathic quartz sandstones and compact silicified orthoquartzite up to 200 m thick. The lowest sandstone consists of about 80 percent of subangular, well-sorted quartz grains 0.2 - 0.4 mm across, and about 10 percent of altered feldspar grains in a clayey or siliceous cement. Minor iron oxides and sericite are also present. Rare zircon and more abundant olive-green tourmaline grains (0.05 mm or smaller) account for about 0.1 percent of the total. Higher in the sequence the sediment is orthoquartzite, consisting of about 98 percent subangular to subrounded quartz grains with authigenic quartz overgrowths. Above this is a sequence of softer rocks, believed to be friable sandstone or siltstone. The uppermost beds exposed in the Sheet area are light-grey to cream, massive, thick-bedded orthoquartzite, containing voids left by weathered-out shale clasts. The sandstone is characterised by well-rounded pink orthoquartzite pebbles, 3-5 cm across, making up 1-2 percent of the rock. No white quartz pebbles or other rock types are present.

Stratigraphic relations

The formation has a sharp boundary with the underlying Short Range Sandstone.

Palaeogeographic significance

The limestone beds of the Attack Creek Formation represent the shallowest water environment of the Tomkinson Creek Beds. They were probably deposited in very shallow marine lagoonal conditions. Oolitic sparite is diagnostic of a shallow marine tidal environment (Conybeare & Crook, 1968; Hatch & Rastall, 1965).

The concretionary ironstone and manganiferous calcareous mudstone represent a quieter depositional environment, where sediments were laid down in more euxinic conditions, and subjected to bacterial action. The high metal content of the mudstone is ascribed to bacterial activity, the sulphide-producing bacteria fixing metal ions from sea water. The manganese deposits of Muckety, west of Renner Springs in the Helen Springs 1:250 000 Sheet area, are similar, and hence may be stratigraphically correlated with the manganiferous mudstones of the Attack Creek Formation. The Muckety deposits are the result of secondary surface enrichment of siltstones replaced by or impregnated with manganese oxides (Randal, Brown & Doutch, 1966).

The recurrence of sandstone above the calcareous beds is probably the result of a marine transgression or an increased rate of subsidence within the marine basin. The well-rounded orthoquartzite pebbles in the massive sandstone in this part of the sequence are either derived from the main source area or, more probably, from the underlying Short Range Sandstone or Gibson Creek Formation as the result of erosion of uplifted and lithified sediments.

HATCHES CREEK GROUP

The Hatches Creek Group forms small outcrops 26 km and 16 km west and about 3 km north of Kelly Well, and in the extreme south of the Sheet area centred 8 km east of the Stuart Highway, on the northern edge of the Murchison Range.

The Hatches Creek Group was estimated to be about 8000 m (24,000 ft) thick by Smith, Stewart & Smith (1961) and is composed largely of cross-bedded and ripple-marked orthoquartzite, which is pebbly near the base. The beds are lithologically similar to orthoquartzite of the Hayward Creek Formation and the Short Range Sandstone of the Tomkinson Creek Beds, and, like these units, contain accessory green tourmaline and zircon. At the outcrop 16 km west of Kelly Well, 1-cm thick interbeds of brownish purple shale near the base of the sequence are very similar to the shale of the underlying Warramunga Group and, they are possibly derived from the older rocks.

The Hatches Creek Group is regarded as being early Carpentarian, as it is intruded by granite with a K-Ar age of 1450 m.y. and unconformably overlies granite 1800 m.y. old. It crops out more extensively on the Bonney

Well 1:250 000 Sheet area, described in more detail by Smith (1967) and Smith, Stewart & Smith (1961).

Smith tentatively suggested a correlation between the Hatches Creek Group and the Tomkinson Creek Beds because of their similar composition and age.

The present survey has resulted in a considerable amount of new information about the Tomkinson Creek Beds, and we believe that the Tomkinson Creek Beds and the Hatches Creek Group may be correlated for the following reasons:

- Both directly overlie the Lower Proterozoic Warramunga Group rocks, disconformably and with local angular unconformity.
- Both are probably Lower Carpentarian.
- The rock types of each group are almost identical: clean quartz sandstone, cross-bedded and ripple-marked, with pebbly beds near the base of each group; minor shale and siltstone.
- The quartz sandstone contains the same heavy mineral accessories (up to 0.1 percent of green tourmaline and zircon).
- Basic lavas, and to a lesser extent acid lavas, are found as thin interbeds in each group. The basic lavas are commonly amygdaloidal basalt, the amygdales containing quartz, calcite, epidote, chlorite pink albite, and quartz. The basalt within each group also contains small grains of chalcopyrite, and the plagioclase in both basalts is less calcic then usual - i.e., andesine in the Tomkinson Creek Beds basalts, and oligoclase or andesine in the Hatches Creek Group basalts.
- Both groups are structurally similar, since they have undergone two phases of deformation, and are moderately folded in similar styles.

?ADELAIDEAN

Rising Sun Conglomerate

This unit crops out in a strip about 0.5 km wide, from about 0.5 km south of Nobles Nob mine, east-southeast for some 10 km. A minor outlier lies 2 km north of Rocky Range. The unit consists of conglomerate, quartzite, and grit with sandstone, siltstone, and mudstone in its upper part. It rests with angular unconformity on weathered quartz porphyry and Warramunga Group sediments. Details of thickness and lithology of the unit were described by Crohn & Oldershaw (1965).

The unit is folded along approximately east-west axes and forms a syncline, which is fault-bounded to the south. Dips reach 20° to 30° on the north limb of the syncline, and are locally overturned on the southern limb. The structures cannot be correlated with any that affect the Warramunga Group.

The basal parts of the unit are conglomeratic, and consist of rounded orthoquartzite boulders and cobbles in a sandy matrix. The conglomerate is not lithologically similar to the Blanche Creek Member of the Tomkinson Creek Beds, as suggested by Crohn & Oldershaw (1965). We believe that the boulders were derived from beds of the Hatches Creek Group or the Tomkinson Creek Beds or both, and that the Rising Sun Conglomerate, therefore, post-dates the lithification, folding and uplift of these groups.

CAMBRIAN

Helen Springs Volcanics

Distribution

The Helen Springs Volcanics of Early Cambrian age (Noakes & Traves, 1949) form a few small outcrops in the Sheet area. The outcrops lie 29 km east-northeast of Tennant Creek township; 18 km northeast of the Whippet mine (Ivanac, 1954); at Kelly West trigonometrical station; 21 km west of the Warrego mine and on each side of the Gosse River, north from Channingum Creek to the Barkly Highway.

Lithology

The outcrops are generally highly weathered and lateritized, making recognition of the rocks difficult. The maximum thickness of the unit is recorded as 15 m by Crohn & Oldershaw (1965). The volcanics are 6 m thick at Kelly West and 5 m thick in the outcrop 4 km east of the Golden Mile mine; a thickness of only 2 m is visible in the outcrop 21 km west of the Warrego mine.

Locally, the unit includes a few metres of basal quartz sandstone, as in the outcrops east of the Golden Mile mine and 18 km east of the intersection of Channingum Creek and the Gosse River. Elsewhere, the sandstone is absent. Overlying the sandstone is a sequence of extensively lateritized volcanics, described by Ivanac (1954) as fine-grained to coarse-grained vesicular basalts with lenses of tuff and agglomerate. The 'basalts' are generally too weathered to identify. Moderately fresh brick-red tuff, 21 km west of the Warrego mine and at Kelly West rock, consists of about 40 percent of angular quartz fragments 2-5 mm long and about 10 percent of lithic fragments, some possibly composed of devitrified glass, in a highly decomposed matrix of clay and iron oxide. The volcanics occupying valleys in the Tomkinson Creek Beds sandstone, described by Randal, Brown & Doutch (1966) as Helen Springs Volcanics, are considered by us to be Whittington Range Volcanics of early Carpentarian age. (See Appendix for generalized section of the Helen Springs Volcanics and the Gum Ridge Formation).

Stratigraphic relations

The Helen Springs Volcanics unconformably overlie the Warramunga Group, and are apparently conformably overlain by the lower Middle Cambrian Gum Ridge Formation.

The Gum Ridge Formation

Distribution

The Gum Ridge Formation was described by Ivanac (1954) and Crohn & Oldershaw (1965). It crops out extensively over much of the Sheet area, although exposure typically consists of low hills covered by angular chert rubble. The most prominent outcrops lie in a north-south belt, about 15 km wide, extending from the intersection of Channingum Creek and the Gosse River along the west side of the Gosse River to north of the Barkly Highway, and about 25 km from the eastern margin of the Sheet area. The unit is also extensively exposed near Kelly West trigonometrical station and about 21 km west of the Warrego mine. A few minor patches of chert rubble occur in topographic lows within the Tomkinson Creek Group sandstone and also on the sandy plain in various parts of the Sheet area.

Lithology

The maximum thickness of the formation is probably about 25 m; Ivanac (1954) gives the maximum thickness as 13.5 m, around Gum Ridge trigonometrical station. The age is definitely established as Ordian (earliest Middle Cambrian) on fossil evidence (Ivanac 1954).

The rock types of the Gum Ridge Formation exposed in the Tennant Creek 1 mile Sheet area were described by Ivanac (1954). Most of the isolated outcrops on the sandy plain and in depressions in the Tomkinson Creek Beds consist of angular chert rubble and rare fragments of silicified siltstone or limestone. The chert is cream, light to dark grey, brown, and commonly finely banded. Chert fragments may be cemented together into silcrete with a sandy or siliceous matrix. Where in situ, as at Kelly West and 21 km west of the Warrego mine, the formation consists of interbedded chert, siltstone, and limestone and minor sandstone and mudstone beds. In the section measured 21 km west of the Warrego mine, about 5 m of siltstone and mudstone is overlain by up to 10 m of chert breccia. About 10 km north, 7-8 m of partly silicified limestone overlies the chert breccia. The limestone is granular or saccharoidal and blocky to massive. Weathered surfaces show a peculiar polygonal 'mud-crack' pattern, caused by either a surface shrinkage effect or silicification of the carbonate. Similar limestone crops out near No. 2 bore and 5 km south of the Barkly Highway near the eastern margin of the Sheet area. The limestone is interbedded with and overlain by further flaggy banded, but unfossiliferous, chert.

The outcrop at grid ref. 442872 shows a well-exposed unconformity between the Gum Ridge Formation and the Warramunga Group rocks. The Cambrian rocks in this area are commonly cream chert, siltstone, and scattered biostromal limestone, the latter consisting of about 90 percent fossil fragments (brachiopods, trilobites, and biconulites) cemented by a ferruginous matrix. Thin beds of chert interbedded with the siltstone contain good load-cast structures.

Crohn & Oldershaw (1965) described a composite stratigraphic section through the Gum Ridge Formation.

Stratigraphic Relations

The formation apparently conformably overlies the Helen Springs Volcanics, and is conformably overlain by the Cambrian Anthony Lagoon Beds in the northeast part of the Sheet area. In many parts of the area the Gum Ridge Formation is the youngest unit exposed.

Palaeontology

The chert and siltstone are richly fossiliferous. Bioconulites is abundant in the chert breccia and in some silicified siltstone. Trilobite and phosphatic brachiopod fragments are also fairly abundant, and a fragment of the gastropod Stenotheca sp. was found in the biostromal limestone at grid ref. 442872. A detailed list of the fossils in this formation is given in Ivanac (1954).

Anthony Lagoon Beds

The Anthony Lagoon Beds occur as scattered rubble and scree only in the northeast corner of the Sheet area, within the black soil areas. No information regarding thickness or stratigraphic position can be obtained because of the absence of good outcrop. The areas marked on the map as Anthony Lagoon Beds were delineated from aerial photograph interpretation.

According to Randal, Brown & Doutch (1966), this formation is Middle Cambrian and overlies the Gum Ridge Formation: 'part of the widespread Middle Cambrian sequence of the Barkly Tableland' having a thickness of 'probably several hundred feet'.

The only rock types seen in the Tennant Creek Sheet area are angular chert and sandstone fragments occurring as rubble on the sand and black soil plains. The chert is light grey to red-brown. Quartz sandstone rubble is less abundant, and the sandstone consists of about 90 percent of moderately sorted angular to subangular quartz grains in a cream clay matrix. Deep red ferruginous varieties are also common.

Further information on the rock types of this formation is given in Randal, Brown & Doutch (1966).

MESOZOIC

The only outcrops classified as Mesozoic consist of conglomerate and claystone which fill depressions in the Short and Whittington Ranges. These are tentatively assigned to the Cretaceous, as it is known that sedimentation took place during that time on the adjacent Helen Springs Sheet area (Randal, Brown & Doutch, 1966). The conglomerate is a local deposit derived from adjacent high-relief areas.

CRETACEOUS(?)

Cretaceous(?) sediments form mesas in the upper reaches of Attack Creek, and are overlain by Tertiary silcrete, 7.5 km west of the junction of Blanche and Attack Creeks. A small outcrop also occurs 9 km west of Phillip Creek, where the sediments fill a valley in the Short Range.

The Cretaceous(?) sediments unconformably overlie the Tomkinson Creek Beds. They were deposited in areas with marked relief as they generally fill topographic lows eroded in the Carpentarian Hayward Creek Formation. The sediments are flat lying and are overlain by Tertiary silcrete and laterite.

In the area 7.5 km west of the junction of Blanche and Attack Creeks, Tertiary silcrete overlies about 4 m of massive flat-bedded friable feldspathic sandstone. The sandstone is well jointed and consists of moderately sorted quartz grains in white clay (feldspar?) matrix.

Further west, Tertiary silcrete overlies Cretaceous(?) siltstone and sandstone in several mesas. White, massive, micaceous siltstone and claystone with a conchoidal fracture are interbedded with 10 to 30-cm thick beds of light grey, fine-grained, poorly sorted, micaceous quartz sandstone. Some poorly preserved plant(?) remains are present at this locality.

Nine kilometres west of Phillip Creek, 4 m of brown to yellow and white, flaggy to blocky siltstone underlies about 3 m of pebbly, poorly sorted coarse-grained sandstone and conglomerate. The conglomerate is flat-bedded, and covers an extensive area in the present valley. No fossils were found in the conglomerate. The sub-rounded boulders and pebbles in the conglomerate, which are up to 30 cm in diameter, are composed of grey to pink orthoquartzite and white quartz.

CAINOZOIC

Laterite (Czl)

Pisolitic laterite exposures are the remnants of a previously more widespread cover of thin laterite. In many places the laterite has been largely eroded and redeposited in nearby valleys and depressions. Such deposits show on aerial photographs as very dark-toned patches.

At grid references 398869 and 396868, thin laterite is developed on medium-grained diorite. The diorite is itself completely altered at the surface to limonite and clay minerals.

Further southwest, at grid. ref. 397864, 10 to 15 m of nodular quartz-rich laterite is well exposed. The upper 2 m consists of pisolitic laterite. Fluvial erosion of this and other outcrops, and deposition downstream, have resulted in the formation of up to 8 m of reconstituted pisolitic laterite partly cemented by chalcedony. The laterite is overlain by up to 8 m of fawn silcrete.

Thin laterite deposits are common throughout the Sheet area, and notable deposits occur at the following localities: grid ref. 465816, where ferruginous Lower Cambrian sandstone pebbles and pisolitic laterite form a thin veneer; grid ref. 466811, where pisolitic laterite rubble up to 1 m thick is developed on granite; grid ref. 429815, where 1 m of pisolitic laterite overlies partly ferruginous granite, in which limonite pseudomorphs of Carlsbad-twinned potassium feldspar are prominent.

Travertine (Czt)

Travertine fragments are found scattered on black soil plains, and in a north-south-trending belt in the southwest quarter of the Sheet area. The thickness of travertine, where in situ, is never over 1 m. Travertine overlies Cambrian limestone a few metres east of the claypan near No. 2 bore, about 27 km southwest of Tennant Creek. It occurs as a cream or light brown rock consisting of about 60 percent of subangular dolomite fragments, less than 1 cm across, in a light brown calcareous matrix.

On the black soil plains in the northeast corner of the Sheet area, the travertine fragments are cream to pink and consist of fragments of limestone or dolomite in a calcareous matrix. Dolomitic travertine commonly overlies lamprophyres in the Sheet area.

Black soil (Czb)

Black soil occurs mainly in the northeast corner of the Sheet area. There are minor areas of it near No. 2 bore and from 24 to 30 km west of the Warrego Mine.

The nature and origin of the black soil is fully described in Randal, Brown & Doutch (1966); briefly, the soils are believed to have developed in situ from clay, silt and sand deposited under water. The soils are characterised by a high clay content.

Silcrete (Ts)

Tertiary(?) silcrete, ranging in thickness from 3 to 8 m, is fairly widespread over the northern part of the Sheet area. It forms mesa-like cappings on the Attack Creek Limestone and Whittington Range Volcanics, and also on many other rock types, particularly in the Short Range. Stratigraphically, it overlies both Mesozoic (Cretaceous?) beds and the Cainozoic laterite.

The silcrete consists of subangular to rounded fragments of quartz, orthoquartzite, and chert, ranging in size from 1 cm to over 40 cm across. The pebbles and cobbles are cemented in a siliceous matrix, usually of a light grey to fawn colour. Locally, the matrix contains small quartz grains and pebbles with concentric overgrowths of silica. The matrix has a characteristic flinty appearance, breaking through the quartz grains with a subconchoidal fracture. At one locality, about 9.5 km west of Philip Creek Station, a coarse siliceous conglomerate containing pink and white quartzite boulders up to 1 m across lies in a valley in the Gibson Creek Sandstone. This is a Tertiary deposit which grades in places into the more typical silcrete.

The silcrete was probably deposited on an earlier Tertiary landsurface. After uplift and dissection of the new landsurface, the silcrete is now limited to cappings on mesas of older rocks.

STRUCTURE

Almost all the Precambrian rocks which crop out in the Tennant Creek 1:250 000 Sheet area have been affected to some extent by folding, faulting, and low-grade metamorphism. The late massive granites and porphyries are the exception to this. The early granites (e.g., Tennant Creek Granite) show a tectonic foliation, defined by biotite flakes, in addition to a primary flow foliation (Crohn & Oldershaw, 1965). Dunnet & Harding (1967) studied the structural geometry of the Mt Woodcock 1-mile Sheet area. We have extended this study to the adjacent Marion Ross 1:50 000 Sheet area and other parts of the Tennant Creek 1:250 000 Sheet area. The major structural features of the Tennant Creek 1:250 000 Sheet area are shown in Figure 2.

Figures in this chapter showing normals to bedding, cleavage, or fold axes are plotted on a stereographic projection (equal-area net) on the lower hemisphere. Concentrations are contoured to show percentages of poles per percent area.

Folding

Three distinct fold phases can be defined in the Warramunga Group rocks. A further phase (f_1), has been postulated by Dunnet & Harding (1967) by considering the structural geometry of the phase 2 (f_2) folding and the structural position of the granites. Figure 3 shows the total number of bedding poles measured in Warramunga Group rocks. Although most bedding poles define a great circle with a corresponding B_2 axis plunging 25^o to 284^o, there is an ill-defined spread of poles in the southern half showing the effect of later f_3 and f_4 fold phases. Figure 4 shows stereograms of bedding poles for the sub-areas marked on Figure 2. On these stereograms, in sub-areas 5, 8, 9, and 10, the f_2 deformation phase shows a remarkable geometrical consistency throughout the Tennant Creek 1:250 000 Sheet area.

If an original folded surface existed before the f_2 folding it must have had a sheet dip of about 25^o to the northwest, since folded surfaces in the axial zones of f_2 folds have this orientation (e.g., Black Angel anticline, Great Western syncline). However, it is not uncommon for areas of major folds in orogenic belts to have a regional plunge. This may be the result of an original sedimentary dip to the northwest and/or the intermediate and least principal stresses of the superimposed stress field not lying in planes related orthogonally to the Earth's surface. Any initial sedimentary dip would probably be accentuated by later folding. No evidence was seen by us to confirm that granite intrusion occurred before the deposition of the Tomkinson Creek Beds, as suggested by Dunnet & Harding (1967, p. 29), although this may perhaps be inferred from the presence of quartz porphyry pebbles in basal conglomerate of the Tomkinson Creek Beds. It is suggested that granite was intruded early in the tectonic history of the area, during f_2 deformation. Recent studies in California and Saudi Arabia (Fyfe 1973) have shown that granite can rise to within about 1 km of the Earth's surface in active orogenic zones. The resultant foliation would thus be related to the regional stress field at the time of intrusion. We

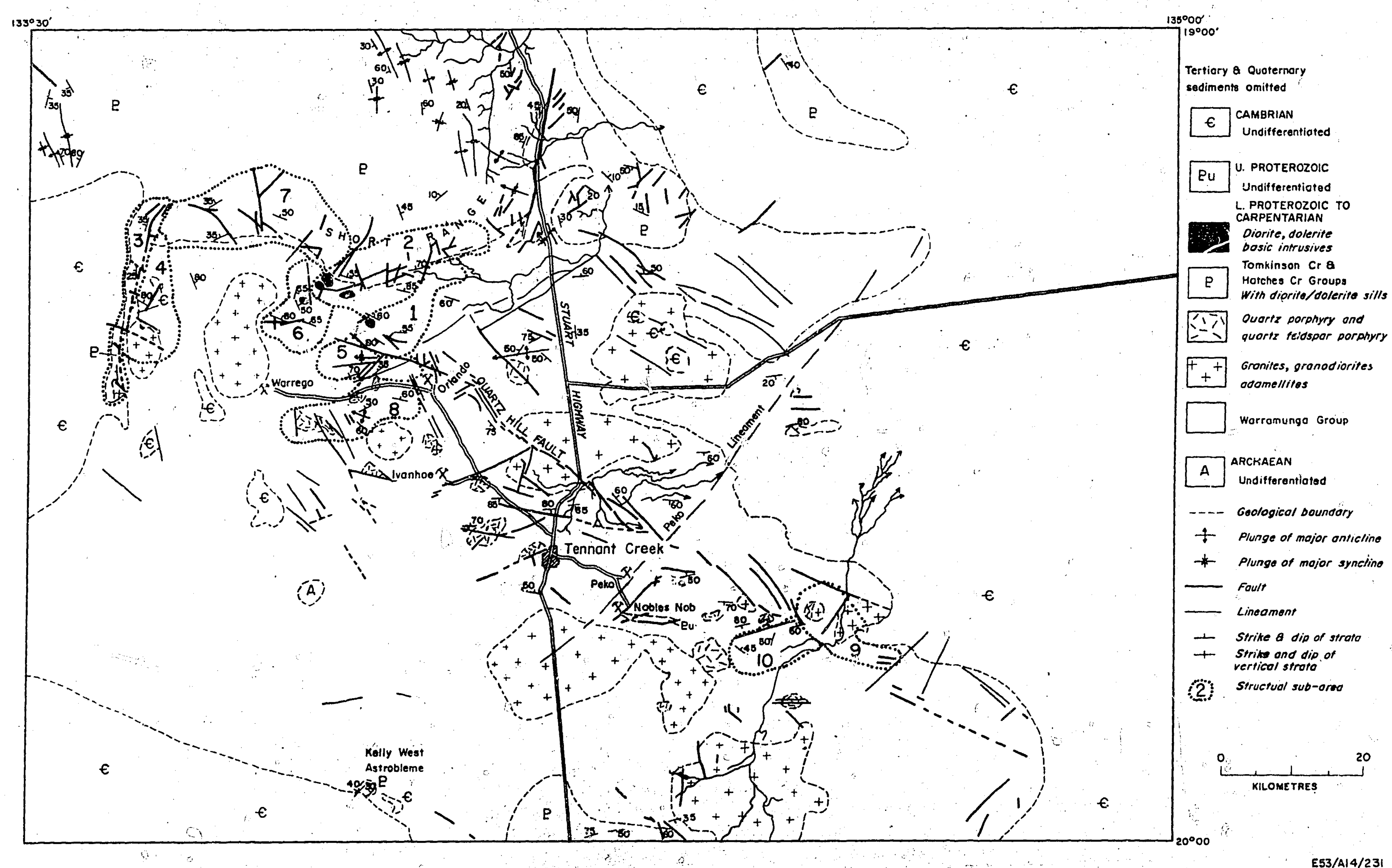

Fig. 2 Sketch map of the structu›ₐ' features of the Tennant Creek 1:250 000 Sheet area.

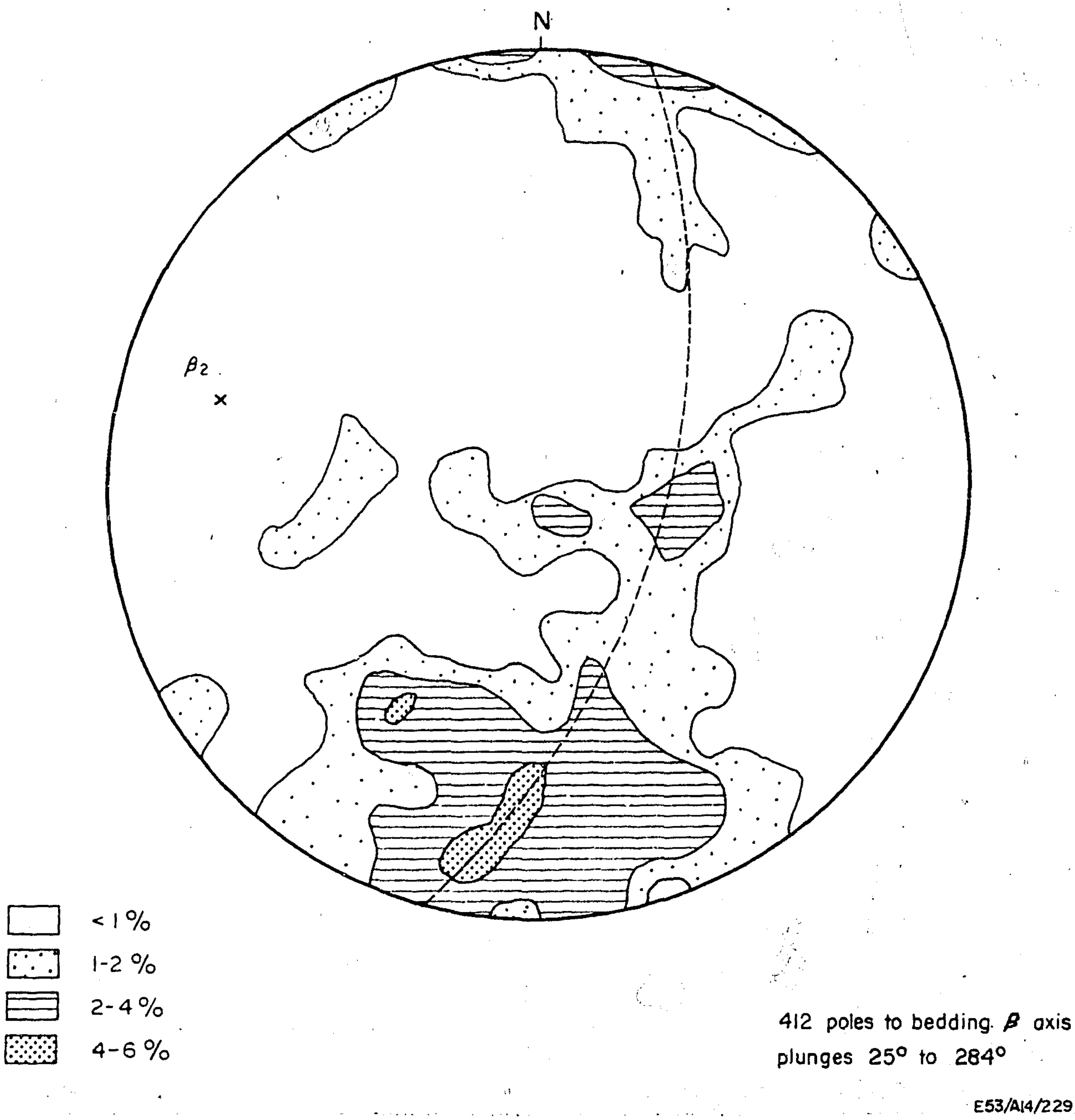

Fig. 3 All measured bedding poles plotted on equal area projection.

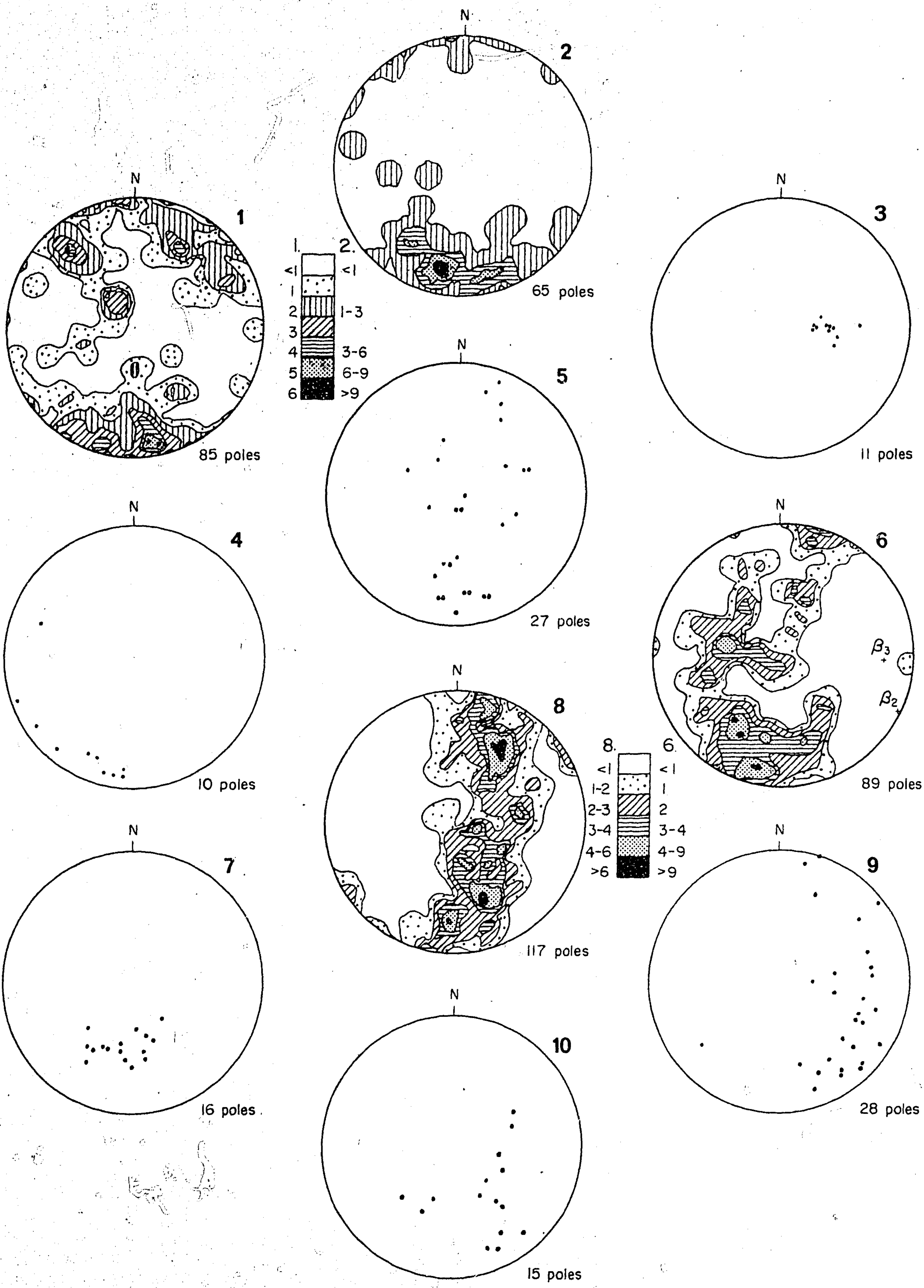

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Fig. 4 Poles to bedding for the structural sub-areas 1-10 shown in Fig. 2.

question the change in plunge of f_2 folds assigned by Dunnet & Harding (1967) to the presence of a pre-existing f_1 folded surface. It is difficult to see how a gently northwesterly plunging fold could cause a change in plunge from 15° east to 45° west within a few hundred feet. The f_1 and f_2 fold axes in the Orlando area differ in plunge direction by only about 10° or 20°. In our view this change may also be explained by the mutual interference of f_2 and later f_3 and f_4 folds or the effect of inhomogeneous compressive strain along the length of a fold (Ramsay, 1967, p. 436). No first fold areas or related cleavage, lineation, or strain features were noted by us and the existence of an f_1 deformation phase is doubted. The nomenclature of Dunnet & Harding (1967) is retained, however, to avoid confusion.

The Tomkinson Creek Beds show the effects of two phases of folding which may be related to the f_2 and f_3 phases in the Warramunga Group. As the Tomkinson Creek Beds are composed largely of competent massive sandstone, they have reacted differently to stress than have the shale and greywacke of the Warramunga Group. The folds are open in style, and large-scale interference patterns are present. Cleavage is poorly developed, even in the more shaly parts of the sequence.

Some decollement has probably occurred between the Warramunga Group and the Hatches Creek Group. Thirteen kilometres south of the southern margin of the Sheet area, moderately tightly folded, purple flaggy siltstone is overlain by uniformly dipping, massive to blocky, fine-grained quartzitic sandstone. Apart from a few fissile zones in the vicinity of the apparent unconformity, no obvious structural dislocations were seen in the sequence. This unconformity (Smith, Stewart & Smith, 1961) must have acted as a local slip surface, however, to allow the deformation styles of the two different rock types to be accommodated. In the Short and Ashburton Ranges the differing fold styles in rocks of the Warramunga Group and Tomkinson Creek Beds generally change gradually, in keeping with the lithology. It is only in areas such as that 22 km west of the Warrego mine and 11 km west-southwest of Phillip Creek, where shale and siltstone are in proximity to massive orthoquartzite, that some evidence of decollement, such as sheared and fractured zones, is found.

f_2 phase

The f_2 fold phase has affected all the formations within the Warramunga Group and the Tomkinson Creek Beds. In the siltstone, shale, and fine-grained greywacke of the Warramunga Group a penetrative slaty cleavage is present. In the coarse-grained greywacke and more rarely in rocks of the Tomkinson Creek Beds a fracture cleavage is present. Figure 5 shows a stereogram of poles to cleavage planes in the Sheet area (data were obtained from the sub-areas marked in Figure 2). There is a well-defined elongate maximum which has an average value for cleavage of 107/89^o, expressed as strike/dip and direction. However, a spread of strike values from 091^o to 121^o, may be attributed to local strain variations within the overall relatively uniform pattern. It is significant that the average regional cleavage value lies symmetrically about the great circle of poles to bedding (Fig. 3), suggesting that the two features are genetically related.

Cleavage fanning is seen in f_2 folds at grid ref. 379862 near the Last Hope mine. Cleavage and orientations change from 080/65^{o}S on the overturned northern limb of a minor anticline plunging 35^o to 100^o, to 085/80^{o}S at the axis. This suggests that in this area cleavage formation was in part synchronous with the f_2 folding. As the intermediate and maximum (X) strain axes are known to lie within the cleavage plane in areas of slaty cleavage, this suggests that the f_2 folds and cleavage are closely related and were formed in a similar stress field.

A lineation caused by the intersection of bedding on cleavage planes is commonly visible in the Warramunga Group. In some cleavage planes, particularly those in fine-grained tuff, iron staining has caused banding which should not be mistaken for bedding. This banding results from deposition from circulating iron-bearing solutions.

Rare boudinage of jasper bands is seen in the Juno mine, and boudinage and subsequent folding can be seen in the tectonic pseudo-conglomerate in the Orlando mine.

Some measure of the finite strain in the siltstone of the Warramunga Group may be obtained from measurements of flattened and elongated quartz-hematite concretions. The average value for three concretions (measured at grid ref. 390857) gives X:Y:Z = 1.29:1.15:0.67. Deformed limonitic-hematitic siltstone concretions (with pseudomorphs after pyrite) are well exposed in a prominent butte at grid ref. 388848. These give strain values in the cleavage plane (X, Y plane) with relative ratios for X:Y averaging 2:1 and reaching a maximum of 3:1. These values are greater than those measured on the quartz-hematite concretions. This may indicate that the concretions have acted partly as relatively competent bodies during deformation. The

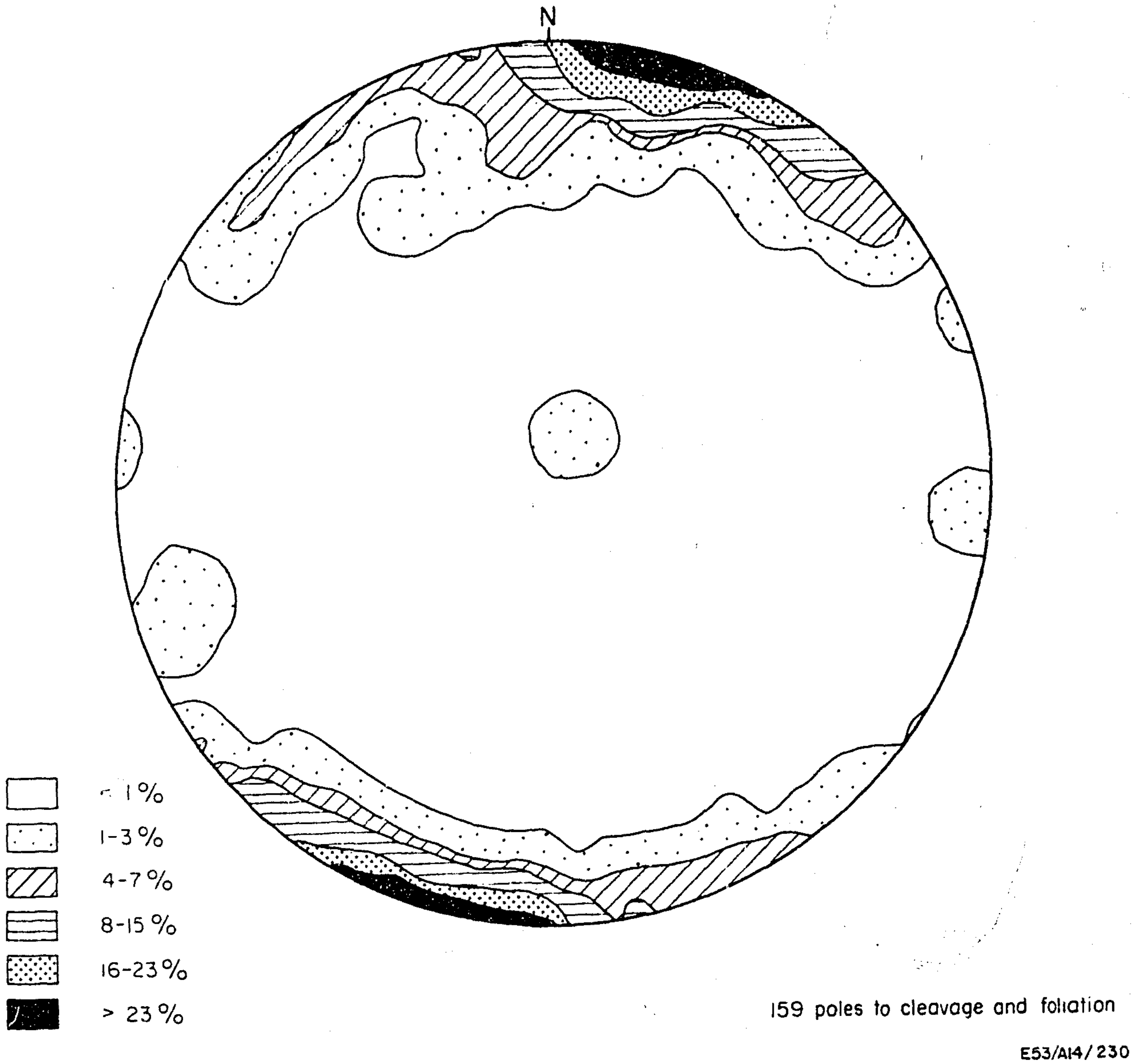

Fig. 5 Poles to cleavage and foliation of Warramunga Group.

orientation of the maximum strain axis (X) lies horizontally in the cleavage plane, and the intermediate axis (Y) at right angles to it. The minimum strain axis lies normal to the cleavage plane. These relations appear to be constant in the Warramunga Group sediments. Although strain values show that the deformation lies in the apparent flattening field ($Y > 1$; $0 < k > 1$) (Flinn, 1962), it is probable that there has been some volume loss. This loss, of about 15-20 percent, would cause the field of true flattening to decrease, but would still include the strain values obtained for the concretions. There may possibly be scope for further strain studies using the ellipsoidal quartz phenocrysts of the quartz porphyries, provided that their shape is due solely to tectonic effects.

The f_2 folds have limbs dipping generally between 50° and 80°. There are several orders of fold size, which range in wavelength from 1 metre to 50 km, with maxima about 200 m and 9 km. The amplitude of folds ranges from 0.5 m to 8 km, the average values being about 90 m and 4 km, corresponding to 200 m and 9 km wavelengths, respectively. Large folds have smaller-scale folds of similar style on their limbs. The folds have a regional plunge of 25° to 284°, as discussed in the preceding section. Fig. 6 shows a stereogram of f_2 fold axes; these may be seen to lie roughly in the plane of the cleavage. The effects of the large-scale f_3 and f_4 folds may in part account for the spread of axes. They show a maximum concentration plunging 10° to 280°; this is roughly coincident with the B_2 axis derived from the poles to bedding figure (Fig. 3). At grid ref. 390852, in the Great Western syncline, the cleavage/bedding lineation plunges 9° to 095°, whereas the B_2 fold axis plunges 70° to 280°. This illustrates that the fold geometry cannot be related to the total regional strain ellipsoid in this area, and that the bedding dipped steeply westward before fold formation. This dip may have been related to early fault movements.

Near Great Western trigonometrical station, well-developed cleavage shows late shear movements with displacements along the cleavage planes accentuating the pre-existing folds. The displacements are discrete and irregular.

Cuspate structures are well developed at the junction of lamprophyre dykes and Warramunga Group Ew_3 siltstone in the area of the Last Hope mine (grid ref. 380862). The structures have developed by shortening normal to their axes where a competency difference exists at the boundary of two rock types. Three such axes were measured at this locality. These give an average plunge of 42° towards 110°. The pointed lobes face towards the lamprophyre,

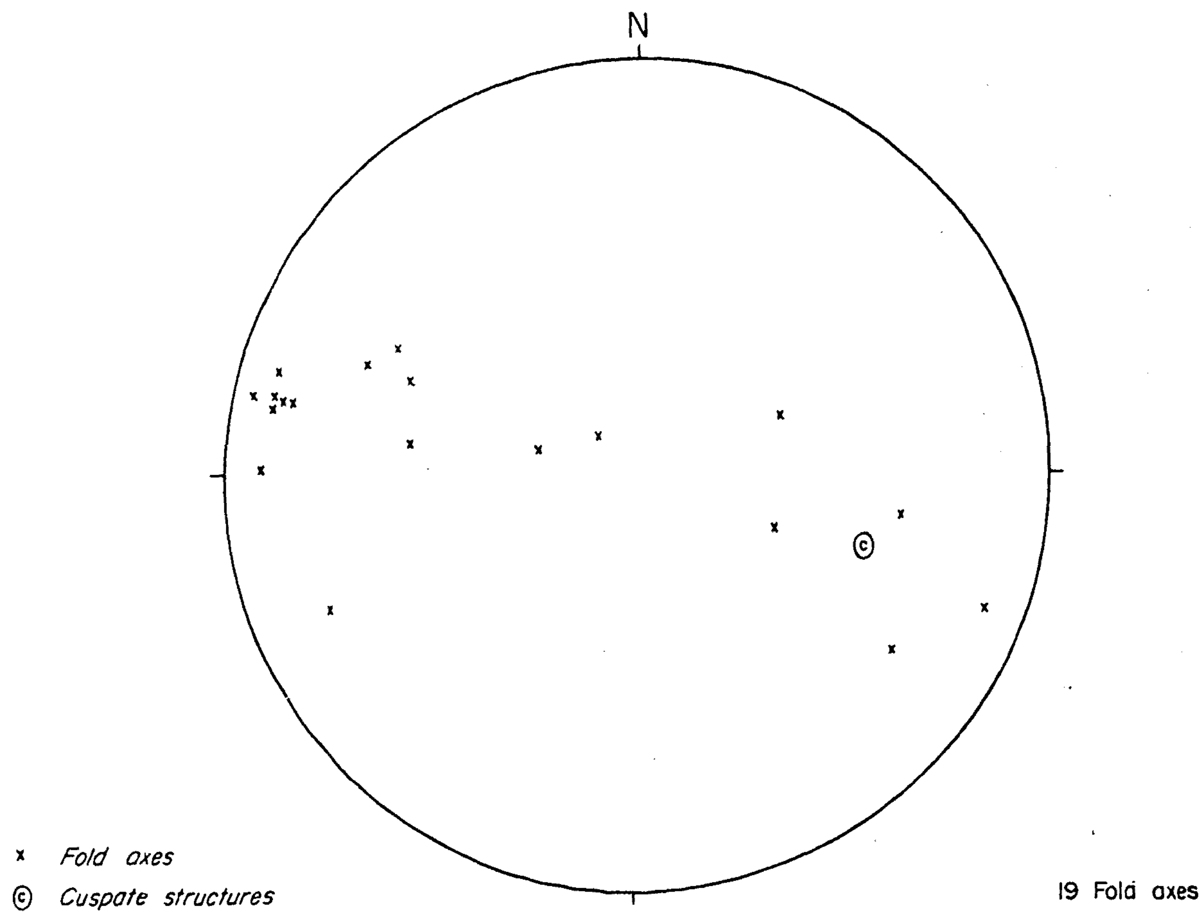

Fig. 6 f_2 fold axes plotted on a lower hemisphere equal area projection showing that this was the more competent rock during the period of deformation. The cuspate structures are related to the f_2 deformation phase, as they are geometrically related to the S_2 cleavage. The present plunge of the structures is attributed to the effects of large-scale f_3 deformation, which in this area has resulted in the formation of a large sinistral kink fold with sub-vertical axes.

$\underline{f_3/f_4}$ phase

These phases of folding are best developed in the Quartz Hill, Black Angel, and Red Bluff areas, and appear to be virtually restricted to the area west of the Stuart Highway. They broadly correspond to the f_3 and f_4 phases of Dunnet & Harding (1967). Folds are generally chevron or markedly asymmetrical, and straight-limbed. They have wavelengths ranging from 100 m to 1 cm - commonly about 1 m. Their amplitude is about half the wavelength. There are geometrical limits to the amount of shortening that can be achieved by this style of folding. The fold will tend to lock up after the limbs have reached a dip of 60^o to 80^o, depending on stress conditions and layer thickness (Ramsay, 1967).

Figure 7 shows the plunge of f_3 and f_4 fold axes plotted on a lower hemisphere equal-area stereogram. These axes have variable trends in the area, depending on the pre-existing bedding orientation controlled by f_2 structures. The f_3 folds have a Z profile when viewed down their northwesterly plunge, in contrast to f_4 folds, which have an S profile when viewed down-plunge. Kink folds are related to these structures, because they occur in areas where true folds are absent, and also possess a similar structural geometry. Kinks result from deformation under a low confining pressure, and can be seen to fold S_2 cleavage and B_2 cleavage/bedding intersection. Kink bands and folds commonly show a constant local movement sense, but are regionally variable. The f_3 and f_4 structures are in many areas distinguished only by their trends, f_3 kinks and folds plunging NW-SE, and f_4 folds and kinks plunging NE-SW. The formation of the two structures is considered to be roughly synchronous. Rare conjugate kinks imply shortening in a NNE-SSW direction. The overall f_3-f_4 pattern may also be related to a superimposed N-S stress system.

In some areas f_3 folds have an associated axial-plane cleavage, striking NS-SE; this is well developed in the Quartz Hill area (Dunnet &

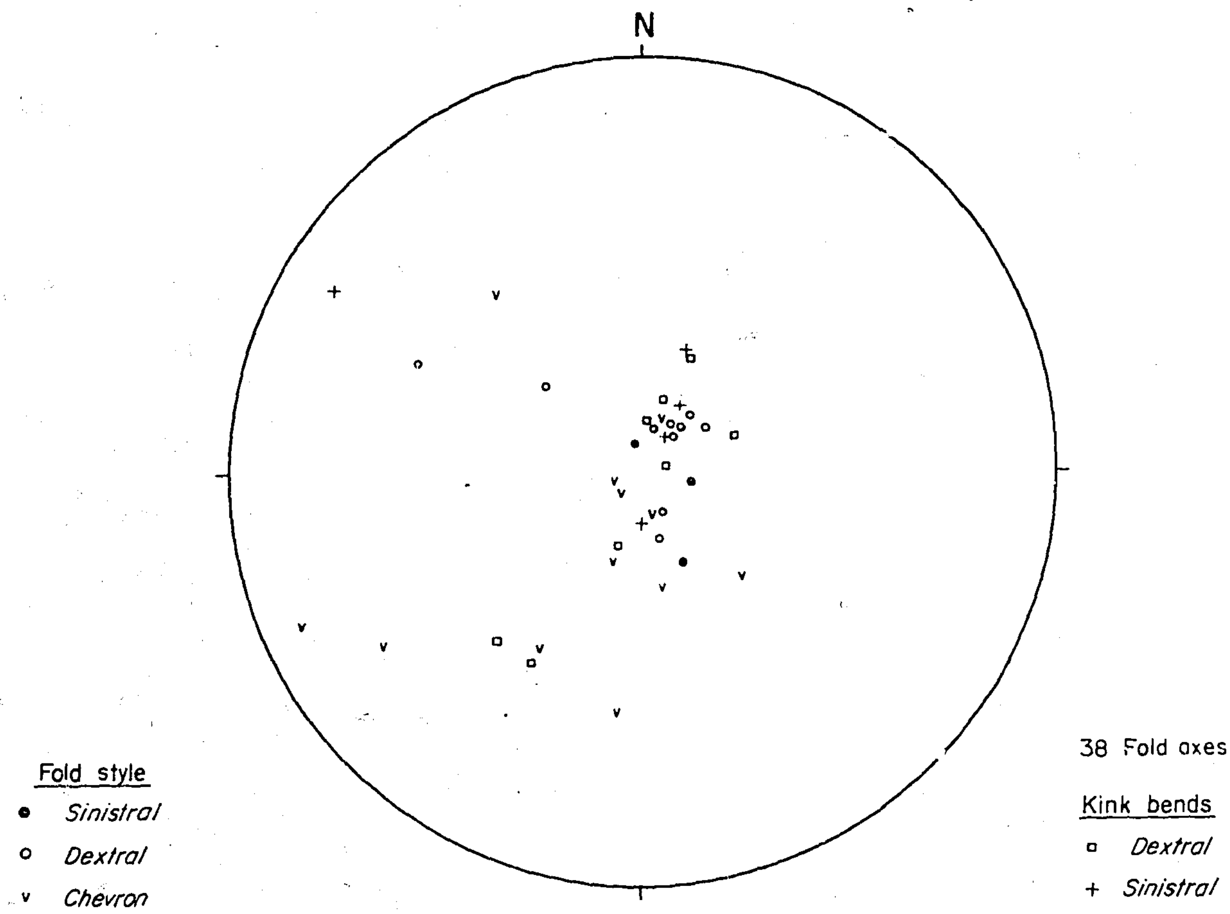

Fig. 7 f_3 and f_4 fold axes plotted on a lower hemisphere equal area projection

Harding, 1967). In places this has become a very penetrative structure, obliterating earlier S_2 structures. In strikes 140^o to 160^o, and generally dips sub-vertically. A subsidiary sub-vertical S_3 cleavage, striking 120^o to 130^o (Dunnet & Harding, 1967), is also present in the Quartz Hill area. This combination of cleavages has produced slate pencils.

The f_4 folds have an associated closely spaced fracture cleavage in area of the Warrego and Black Angel mines, and at grid ref. 379845 a sub-vertical cleavage striking 035^o combines with a folded S_2 cleavage to give slate pencils. S_4 fold axes plunge 80^o to 200^o, owing to the influence of subsidiary S_2 structures associated with the Black Angel anticline.

Near the Black Angel mine, an S_2 cleavage is cut in several places by a later S_4 cleavage striking 060^o-065^o and dipping about 60^oSE. The cleavage is developed only in shale beds of the Warramunga Group. Late quartz-feldspar porphyries cut discordantly across all the structures. In the poles to bedding diagram for the area of the Black Angel anticline (No. 8, Figure 5), there is a spread of poles in the B_2 girdle, which is due to the later f_3 and f_4 folds. It is significant that the two distinct maxima coincide roughly with the fold axis plunge directions of the f_3 and f_4 deformation phases.

As two well-defined geometrically unrelated cleavages (S_2, S_3/S_4) occur in favourable rock types, this implies that two distinct deformation phases are involved - an early f_2 phase and a later f_3/f_4 phase. Although the f_3/f_4 structures appear to be complementary, they rarely occur in the same areas of outcrop. In the Quartz Hill area, however, a crenulation cleavage, which may be assigned to the f_4 phase, affects S_3 structures. S_4 structures generally show movement in a sinistral sense and the large strike swing around the Last Hope mine is probably on an S_3 kink fold. This is shown by the pole to bedding diagram (sub-area 6 - Fig. 14) for the Last Hope mine area, in which the two distinct great circles give the corresponding B_2 and B_3 axes. The large-scale f_3 folds have caused some rotation of the B_2 axes.

Faulting

Faults are common throughout the Tennant Creek 1:250 000 Sheet area; they were a feature of the geological fabric before the f_2 deformation, and commonly show evidence of repeated movements. Cambrian sediments are extensively faulted. Many fractures and faults contain vein infillings commonly composed of quartz and/or jasper, but containing abundant magnetite, hematite (limonite), and more rarely dolomite, talc, pyrite, copper and bismuth minerals, and gold. No detailed analysis of the fracture patterns was carried out during the present survey, and the reader is referred to the relevant sections in Crohn & Oldershaw (1965) and Dunnet & Harding (1967) for more detailed information on Tennant Creek and Mount Woodcock 1-mile Sheet areas.

Quartz and jasper veins are folded by f_2 structures, and affected by S_2 cleavage. There was thus considerable fracturing before the main fold episode, and it is possible that faults were active during sedimentation. This type of environment (greywacke sedimentation - volcanism) is at present associated with seismically active areas.

Crohn & Oldershaw (1965) have depicted the fracture pattern in the Tennant Creek 1-mile Sheet area, and show that it is symmetrical about W-E axes. The pattern may be related to a roughly N-S directed compressive stress field, and hence the folding and faulting may be related to similar stress conditions.

The major faults and veins trend NW, the prime example being the Quartz Hill-Rocky Range fault system, which is marked by discontinuous quartz reefs up to 20 m wide. Several other major NW-trending faults can be identified on the Tennant Creek 1:250 000 Sheet area, but many of these are represented only by photogeological lineaments and rare linear quartz reefs. A complex system of northwest-trending faults between the Warrego mine and the Cabbage Gum Basin forms prominent lines of quartz reefs and photogeological lineaments. These faults may reflect some pre-existing lines of weakness in the crust, which have been rejuvenated at several periods. It is doubtful if movements, on the Quartz Hill fault for example, can be expressed in terms of a single movement, although the major movement is thought by us to be subhorizontal and dextral in sense. This is in accord with all the evidence (en echelon shear patterns, lateral bed correlations) quoted by Crohn & Oldershaw (1965) and Dunnet & Harding (1967), except for the boundaries of the Station Hill Granite. However, the initial form of this granite body may have been fault-controlled in part. Minor relative vertical movements have probably occurred locally along the fault system, which has had only relatively minor effects on the stratigraphy when compared to major faults in other tectonic areas (e.g., Tasman geosyncline, New Zealand, Alps, etc.).

As a result of the recent mapping, several approximately north-trending strike and oblique slip faults have been recognized in the Tennant

Creek 1:250 000 Sheet area. The course of the Stuart Highway north of Gibson Creek in part follows the trace of a large oblique slip fault, which in its southern part has an apparent dextral horizontal movement of about 5 km. The eastern block has moved south and down relative to the western block. Along the Short Range there are several smaller, approximately north-trending faults, which commonly show apparent dextral horizontal movement and, more rarely, sinistral strike-slip movement. Several of these faults have little or no vertical movement on them. Near the western boundary of the Short Range a large, dominantly dextral strike-slip fault displaces the Warramunga Group-Tomkinson Creek Beds unconformity by at least 4.5 km. Inspection of the map shows that these north-trending faults are restricted mainly to the northwestern part of the Tennant Creek 1:250 000 Sheet area. A notable exception is at the Peko mine, where a north-trending dextral strike-slip fault has been mapped. As all the remaining structural features on the map may be explained in terms of an applied stress system with the greatest compressive stresses acting in the direction 015^{o} - 195^{o}, it is suggested that these strike-slip faults may follow the line of pre-existing zones of weakness which were reactivated after the deposition of the Warramunga Group and Tomkinson Creek Beds. The resulting dominantly dextral, strike-slip movement is thus explained by this hypothesis. This faulting may be related to the f_3/f_4 fold deformation phase.

A further deep structure is the Peko lineament, a strong northeast-trending regional photogeological lineament, which extends from the Cabbage Gum Basin, where drill holes have shown it to be a wide shear zone, to near the Peko mine, Pigeon Holes, and lineaments at grid references 458864 and 465869. No effects of this lineament are found in the workings at the Peko mine, however.

Kelly West Astrobleme

What appears to be an astrobleme was discovered at a locality about 40 km south-southwest of Tennant Creek (Tonkin, 1973) (see Fig. 8). The structure consists of a roughly circular outcrop about 2 km in diameter, and is composed of quartzite of the Carpentarian(?) Hatches Creek Group. Shatter cones were found in most parts of the quartzite, and locally it is fractured and finely jointed. Cambrian sediments fill the structure, thereby dating the impact at between Carpentarian and early Cambrian.

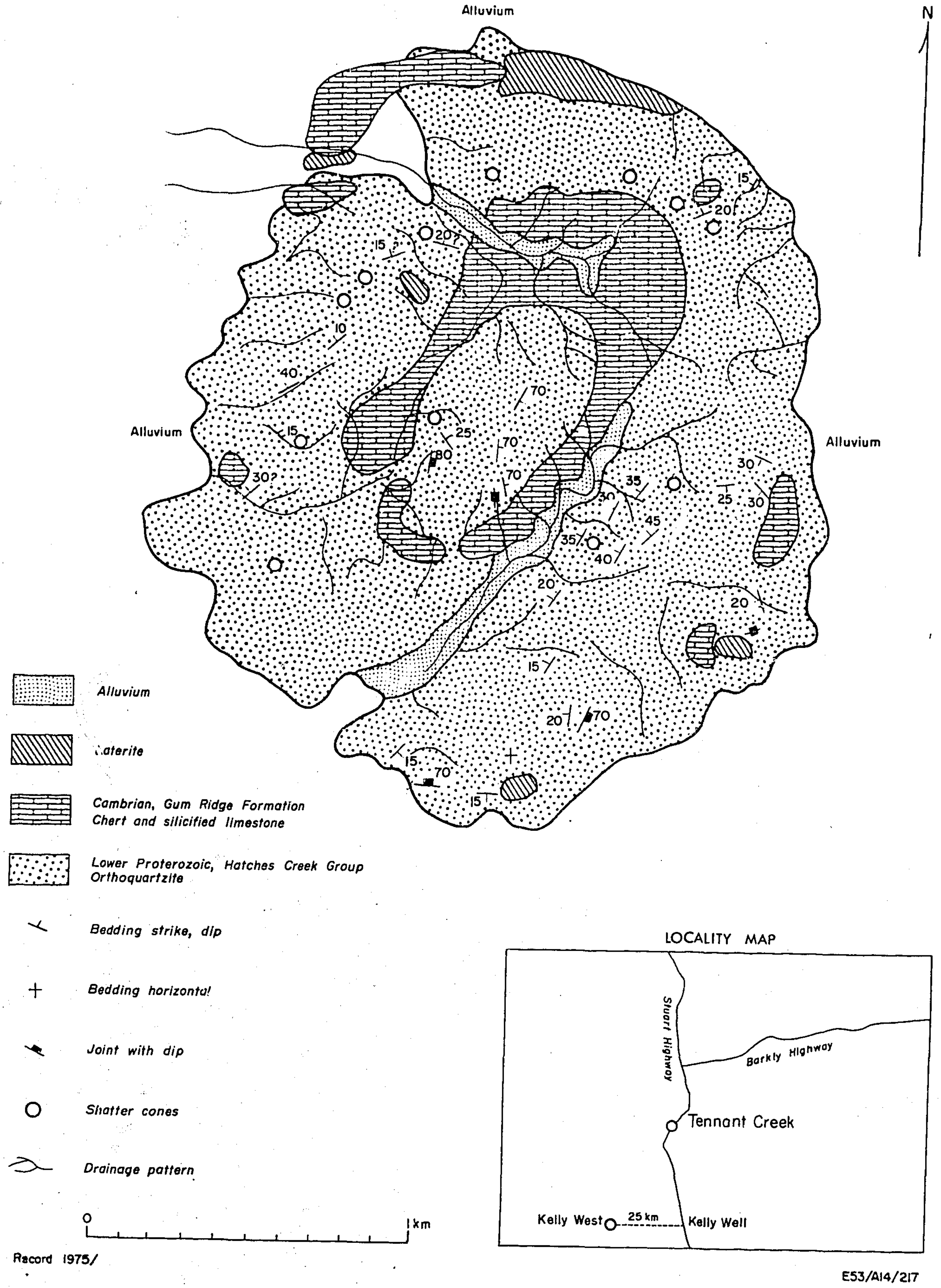

Fig. 8. Geological sketch map of Kelly West Astrobleme

The maximum elevation of outcrop above the surrounding plain is 30 m; elsewhere the relief is as low as 16 m above the plain. The Hatches Creek Group quartzite is massive to blocky, and composed of 90-95 percent of well-sorted quartz grains in a siliceous matrix. Because the astrobleme has been largely eroded away, it is difficult to determine its exact structural nature. The sandstone crops out well only on the northern and eastern sides of the structure. Only about 30 bedding measurements could be taken accurately, and these were mostly on the eastern side of the structure. The sandstone strikes roughly northeast, and dips 20^{o} to 40^{o} to the west, except in the centre where dips are 70^{o} to the east; there is no obvious circular arrangement of dips. It is improbable that the Hatches Creek sandstone was horizontal at the time of impact as it had been affected by at least one major phase of folding before the Cambrian. A number of strikes and dips do not conform to the general trend of the structure: these are measurements of bedding made on large isolated blocks that are probably detached from their original positions.

Disruption and tilting of the strata at the time of impact were superimposed on rocks already gently folded about a northeast-trending axis. At depth, below the impact site, there is likely to have been only slight disruption of the strata, negligible rebound effect, and the development of shatter cones and mild induration. What now remains at Kelly West is probably the remnant of the astrobleme, representing the central zone well below the original level of impact. The strata have more or less retained their original attitudes, but were still affected by the impact to the extent that shatter cones, fracturing, and related jointing are developed.

As outcrop is so poor, it is not possible to measure enough shatter cone orientations to determine the position of the centre of impact. The shatter cones are found in loose boulders, and are fairly evenly distributed about the structure.

A thin section of a shatter cone in quartzite showed the presence of minor cleavage cracks in many of the quartz grains, and planar lamallae were seen in a few grains. This together with the presence of the shatter cones provides good evidence that the rocks in the area have been subjected to very high stress caused presumably by the high velocity impact of some extra-terrestrial body (Dietz, 1959).

METAMORPHISM

Whittle (1966) is the only worker to have investigated metamorphic assemblages in any detail; little systematic work has been carried out by us. Whittle concluded that 'Archaean' rocks intersected in drillholes about 32 km west-southwest of Tennant Creek were metamorphosed to amphibolite facies. Deep weathering of most of the shale and siltstone members of the Warramunga Group precludes any regional surface study of metamorphism. Fresh specimens may be obtained by drilling below the oxidation level, or from the many mines in the area, although hydrothermal alteration is widespread in the mines and many rocks show evidence of calcium and magnesium metasomatism.

Sericite flakes are abundant in fine-grained greywacke, siltstone, and shale of the Warramunga Group. The flakes range from 0.05 mm to 0.1 mm long, and are broadly aligned along the S_2 cleavage. Chlorite flakes are abundant, and their colour and birefringence suggest that this is penninite. The chlorite shows that the rocks lie in the lower greenschist facies. The metamorphism is probably synkinematic with the S_2 cleavage formation. Later tectonic events have had little effect on the mineral assemblages.

In the Peko mine, phyllite contains calcite porphyroblasts up to 3 mm in diameter. The calcite is strongly twinned, and pressure shadows are present. This shows that the calcite was present in the rock before the f_2 fold phase to which the phyllitic texture is related. The calcite may have formed small nodules in the fine-grained siltstone before folding and metamorphism.

ECONOMIC GEOLOGY

Mining in Tennant Creek commenced in 1933. Production has been recorded for 134 mines and prospects, but by 1974 only six mines were in operation: Peko, Orlando, Juno, Warrego, Gecko and Nobles Nob. In 1977 Warrego, Gecko and Nobles Nob were still being mined, but two small deposits, the Golden Kangaroo and the Golden Forty were being developed, their high grade ore being used for blending with lower grade ore from Nobles Nob.

The area is an important source of copper, gold, and bismuth. Minor lead and zinc mineralisation is associated with the copper orebodies in many of the mines. Bismuth was an important product at the Juno mine and is also extracted from the Warrego ores. Selenium is recovered from the Gecko, and Warrego ores. Minor uranium mineralisation is known at several localities in the Sheet area.

Ivanac (1954) and Crohn & Oldershaw (1965) have described the mine geology and production within the Tennant Creek Goldfield in detail, up to 1951 and 1963, respectively. Dunnet & Harding (1967) have described the geology of Orlando and Northern Star mines.

Much of the following information on the mines was supplied by Peko Mines N.L.

The Peko mine is developed on a westerly pitching mineralised pipe dipping steeply west on the southern limb of a westerly plunging syncline. The pipe contains seven orebodies, and is cut by a steeply dipping normal fault which offsets the westerly orebodies 45 m to the north. On the footwall side of the major pipe, between 240 m and 400 m below ground level, two further orebodies and several smaller pods are located. The mineragraphy of the orebodies was described by Edwards (1955). Whittle (1966) noted that anthophyllite, talc, and tourmaline are present in the lower parts of the mineralised zone; he concluded that they were the product of boron and magnesium metasomatism. The mine was closed in 1975.

The Golden Forty mine (Aust. Development Ltd) is being developed near the site of the old Golden Forty workings. The small orebody with moderate to high grades of gold lies in a discordant magnetite body in a shear zone.

The Ivanhoe mine is in a vertical tabular chlorite-magnetite body with a strike length of 215 m and a width of up to 10 m. The minerals are disseminated through the body and as fracture fillings in the magnetite. Native gold, bismuthinite, galena, and spahalerite are present in minor amounts. Reserves in 1971 were estimated to be about 30 000 tons. The mine was closed in 1972.

The Orlando Mine is sited on a mineralised east-west shear zone in shale and siltstone of the Warramunga Group. Dolomite and talc are present near the margin of the mineralised zone. Oxidation extends locally down to 200 m below the surface. The gold occurs as discrete particles in the mineralised zone, and ore grades are unpredictable. To date, seven narrow orebodies have been defined; four gold orebodies, two copper orebodies, and a lead-zinc orebody. The mine was closed in 1975.

The Juno was a small mine which produced gold (average 100g/tonne), bismuth (average 0.69 percent Bi), and copper (average 0.51 percent Cu). Shaft sinking commenced in late 1965, and production commenced in mid 1967. Native gold, bismuthinite, and chalcopyrite are the major economic minerals. These are present in two orebodies in a wedge-shaped magnetite-chlorite mass, whose apex is about 180 m below the surface. The mass is represented by only a small surface magnetic anomaly. The No. 1 orebody has a strike length of 150 m, is up to 15 m wide, and dips about 85^{o}N. It cuts across a 1-m thick hematite shale band. Liesegang-banded dolomite and, rarely, jasper are present in the upper levels and at the eastern end of the body. The No. 2 orebody is irregular, 75 m long, and up to 30 m wide. The orebodies only locally extend down to the 242 m level. However, the magnetite-chlorite host rock extends to that depth. The mine was closed in 1975.

The Warramunga greywacke and shale (Ew_6) are gently folded and generally subhorizontal in the mine area. Minor folds are developed in the more incompetent beds, and boudinaging of jasper bands has taken place. Numerous chloritized shears are present in the mine.

The Warrego mine is a large mine from which it is planned to produce 500,000 tons of ore per year. The orebody pitches southeast, and dips steeply northwest. It cuts greywacke and interbedded siltstone of the Warramunga Group, which dip moderately to steeply south. The top of the orebody lies 140 m below the surface, and ore intersections are proved to a depth of over 600 m. A fracture cleavage dipping about 45^{o} east is associated with the numerous faults and shears in the mine area. Fault zones are commonly filled with mylonite, quartz, calcite, or chlorite, and commonly strike NW or NNE. Quartz porphyry and quartz-feldspar porphyry lenses intrude the sediments above the hanging wall of the orebody. Lamphrophyre dykes intrude the rock types in the mine, including the orebody. The ore minerals are chalcopyrite, bismuthinite, and gold. The host minerals are magnetite-pyrite (pyrrhotite?) and hematite. The geothermal gradient in the mine is high (1^{o} C per 33 m), possibly due to the oxidation of pyrrhotite intermixed with pyrite. Published ore reserves of Warrego are: 5 m tonnes ore containing 7 g/t gold, 2.6 percent copper and 0.3 percent bismuth.

Drilling of the Gecko mine area has shown that three copper orebodies lie in an ironstone body 120 m thick and with a strike length of over 185 m. The body lies 93 m below the surface. The ironstone body lies within a sub-vertical, east-west breccia zone consisting of fragmental, granular, and chloritized sediments. The breccia cuts across the surrounding Ew_7 sediments - greywacke, shale, and hematite shale. The ore consists of chalcopyrite and rare bismuthinite; the gangue minerals are magnetite, quartz, hematite, and pyrite, except in the upper part where chloritised sediment is associated with chalcopyrite. A dolomite body has been located beneath the major ironstone body. Published ore reserves of Gecko mine are: 2.4 m tonnes ore containing 0.6 g/t gold, 3.4 percent copper and 0.1 percent bismuth.

At the Last Hope mine filiform and nodular gold occur in veins of quartz and hematite, which lie parallel to the bedding of cleaved, white to pink and purple, flaggy to fissile siltstone (unit Ew_3). The siltstone is rarely kink folded. Pegmatite and diorite intrude the sediments near the mine.

Mineralisation and ore genesis

Known ore concentrations are restricted to a north-western trending ovoid zone extending from the New Hope mine (grid ref. 441820) to the Last Hope mine (grid ref. 381862). This coincides with the major area of outcrop of the Warramunga Group. All the economic deposits are associated with hematite and/or magnetite bodies, most of which are discordantly emplaced in shear zones. Crohn & Oldershaw (1965) analysed three samples of ironstones for trace element concentrations, from the Mount Samuel-Skipper area. Dunnet & Harding (1967) found from analysing 480 ironstone samples that elements present in significant quantities included copper, lead, zinc, cobalt, bismuth, and molybdenum. The association of some ironstones with hematite shale is stressed by Crohn & Oldershaw (1965) and Whittle (1966). The shale is easily leached and brecciated in shear zones. As a large part of the area is covered by superficial deposits the amount of hematite shale present in the Warramunga Group may be greater than previously thought. Whittle (1966) proposed that many of the ironstones were formed by precipitation in favourable structures of iron derived from surface waters. The lateral and vertical lenticular form of many ironstones strongly supports a local secretion hypothesis.

The orebodies are associated with pipe-like structures situated on large-scale shear zones. Unit Ew_6, composed of interbedded shale and greywacke, appears to be a favourable host rock. The orebodies are structurally controlled, and many occupy major faults. The Peko and Juno mines lie on the Peko lineament, a very prominent photogeological feature, which can be traced southwest into a major shear zone in the Cabbage Gum Granite (Hays, 1958; Crohn, 1961); however, there is little sign of major shearing in the two mines. Orebodies are commonly associated with a plunge reversal of minor folds, but they are uncommon in shale belts where minor folding is well developed.

Edwards (1955) considered that the orebodies are the result of several generations of epigenetic mineralisation. Introduction of iron has occurred repeatedly in the major orebodies. The gold and copper mineralisation succeeded the major iron deposition. The gold commonly occurs as very fine-grained disseminations within magnetite, and very rarely (e.g., Last Hope and Hopeful Star mines) in filiform and nodular shapes. The copper occurs as irregular aggregates of chalcopyrite associated with pyrite and phyrrhotite. Chlorite, quartz, magnetite, hematite, and talc are the common gangue minerals. Dolomite is present in some of the major mines. The dolomite contains traces of lead, zinc, nickel, and molybdenum, and is considered to be epigenetic. Anthophyllite and tourmaline are present in the deeper levels of Peko Mine. Sericite is abundant in minor mines (e.g., Black Eye Mine), adjacent to granite or porphyry bodies.

The granites which crop out in close proximity to the mines have been proposed as the source of mineralisation by Ivanac (1954), and fractures in most of the mineralised areas can be traced to granite masses. The Station Hill granite, which lies on the northern side of the goldfield, is potash-rich, with prominent accessory pyrite. The Ivanhoe shear may be traced northeast from the mine to the granite. The Peko-Juno lineament and the Golden Forty-Nobles Nob fault may similarly extend into the Cabbage Gum Granite which lies about 12 km to the south. The Warrego lode lies on a large fault which extends northwest to the 'Warrego' granite. The granites range in composition from rare granodiorite to adamellite and potash-rich granite. Accessory minerals include fluorite, tourmaline, sphene, and rarely pyrite. The low trace element concentrations of copper recorded from the granites (Whittle 1966) do not exclude them from being the source rocks. Numerous examples occur in Australian mineral fields (e.g. Herberton-Mount Garnet Tinfield/Elizabeth Creek Granite; King Island Scheelite/Bold Head Adamellite) of granites acting as metal sources, and yet having low trace element concentrations.

The porphyries have been proposed as a source of metals by Elliston (1964, 1965). He envisages 'porphyroid' forming by accretion in a colloidal suspension which formed when water-laden sediment became thixotropic, owing to earth movements or slumping. He believes that the liquid expelled by synaeresis, the process during which fluid is separated from a colloid, would be enriched in metal ions. Preliminary trace element studies (A.D. Haldane, BMR, pers. comm., 1977) show that the sediments and porphyries do not have anomalously high levels of copper. Although porphyry is present near the major orebodies, there is no apparent direct connection between the porphyries and the mineralisation. Some of the porphyries, particularly the quartz porphyries, were intruded before the formation of the S_2 cleavage which appears to be a control of the copper-gold mineralisation. The quartz-feldspar porphyries are considered to be very closely related to the granites, and therefore are grouped with the granites for the purpose of explaining ore genesis.

The basic rocks (dolerite/diorite suite) in the Sheet area have been proposed as the source material for the copper and gold mineralization by Whittle (1966) and Dunnet & Harding (1967). Whittle examined core from Archaean rocks, and found that minor chalcopyrite mineralisation is associated with the basic intrusives in this area. It is now known that a gabbro complex lies concealed in the central western part of the Sheet area (Whittle, 1966). Basic to intermediate rocks commonly occur in shear zones, particularly near the Orlando Mine. However, in the Peko-Juno-Nobles Nob area, no basic intrusions were found - basic dykes previously recorded (Ivanac 1954) are chlorite-filled shears, e.g. The Pinnacles, Juno mine. In the area where basic rocks crop out abundantly - along the Warramunga Group-Tomkinson Creek Beds contact - no significant mineralisation has been found. Although the basic rocks have a high trace element copper content, this is not unusual, and is probably of little significance. The basics are known to intrude the lower levels of the Tomkinson Creek Beds and, therefore, may be of a similar age to the copper-gold mineralization (1810 m.y. Late Carpentarian; Black, 1977). The presence of tourmaline in the lower levels of Peko mine, however, would suggest that granitic source is more likely, at least for the Peko orebody.

Meyer & Henley (1967) have investigated the solubility of sulphides in hydrochloric acid in the presence of silcates. They showed that the wall rock composition played an important part in determining the composition and solubility of the various sulphide ions. Henley extended this work to include gold solubility, and showed that in the presence of muscovite, potash feldspar, quartz, potassium chloride and water at between 400 and 600^{o}C, gold readily passed into solution as H_3AuCl_6 (typically 0.1 ppm). The solubility is proportional to the partial pressure of HCl to the power 6 and the partial pressure of oxygen to the power one and a half. Hence, since we know that as temperature drops, the partial pressure of oxygen and HCl falls off exponentially, the solubility of gold decreases extremely rapidly. This major change in solubility decrease occurs at a temperature of 300^0-400^0C and from this Henley predicted that gold deposits should occur in greenschist facies terrains. He envisaged the gold passing into sodium rich solutions in the underlying amphibolite facies rocks and thence being precipitated in the overlying greenschist rocks. This hypothesis is applicable to the Tennant Creek goldfield. The gold would not require an igneous source, but would be concentrated through leaching of the underlying rocks (average Au content of crust - 0.002 ppm. The change from magnetite to hematite would create a high partial pressure of O_2 in these sediments. The gold would have been deposited in places where introduction of mineralised solutions was possible: into shears or other structural zones within greenschist grade rocks.

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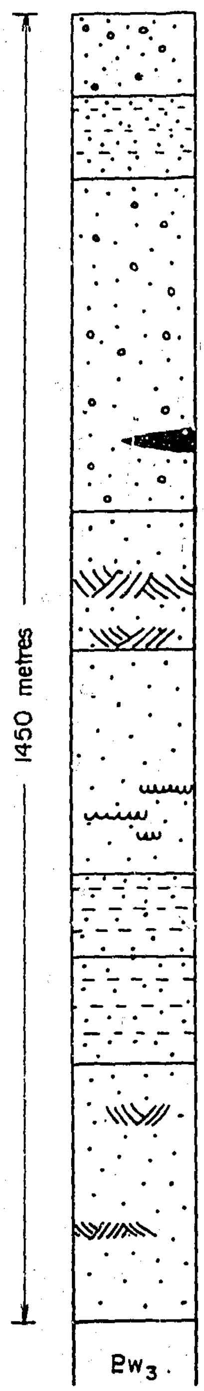
APPENDIX



Flaggy, thin bedded, lithic and feldspathic sandstone. Rare quartz pebbles

Light purple, fissile, laminated, micaceous siltstone

Blocky, medium to coarse-grained feldspathic sandstone. Poor to medium sorting with sub-rounded white quartz pebbles common (average 1·5cm diameter ; maximum 5cm) Epidote and pink feldspar grains abundant. 4m grey to green chert and white claystone horizon present in some localities

Blocky to massive, highly cross-bedded sandstone. Cross-beds (average 4m in foreset length and 1m high) S. derivation of unit inferred

Blocky to flaggy fine-grained lithic sandstone

Flaggy, thin-bedded, fine-grained silicified sandstone and subsidiary shales. Interference ripples.

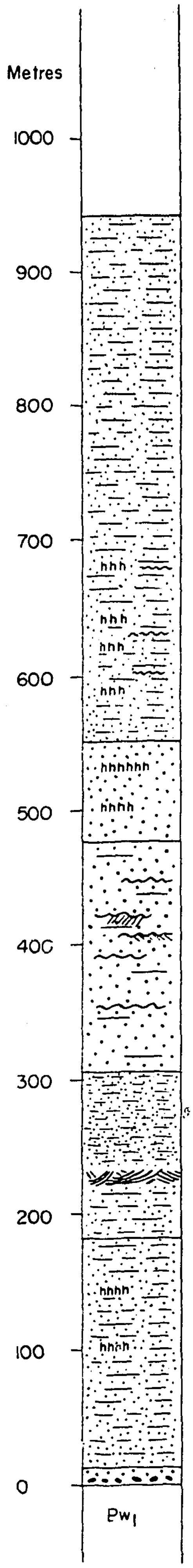
Massive thin to medium bedded, coarse-grained siltstones and fine-grained sandstones

Purple, flaggy and rarely blocky, coarse-grained siltstones

Grey, flaggy to massive, medium to thick bedded fine-grained greywacké and minor coarse-grained siltstones. Cross-beds (1m foreset length, 0·6 m high)

E53/A14/228

Section 1. Generalized sequence of Unit Ew_4 north of Last Hope Mine



Purple flaggy siltstone

Purple flaggy to blocky, thin to medium-bedded fine-grained greywacke and coarse-grained siltstone

Massive thick-bedded fine-grained lithic sandstone and coarse-grained quartz siltstone. Hematite banding

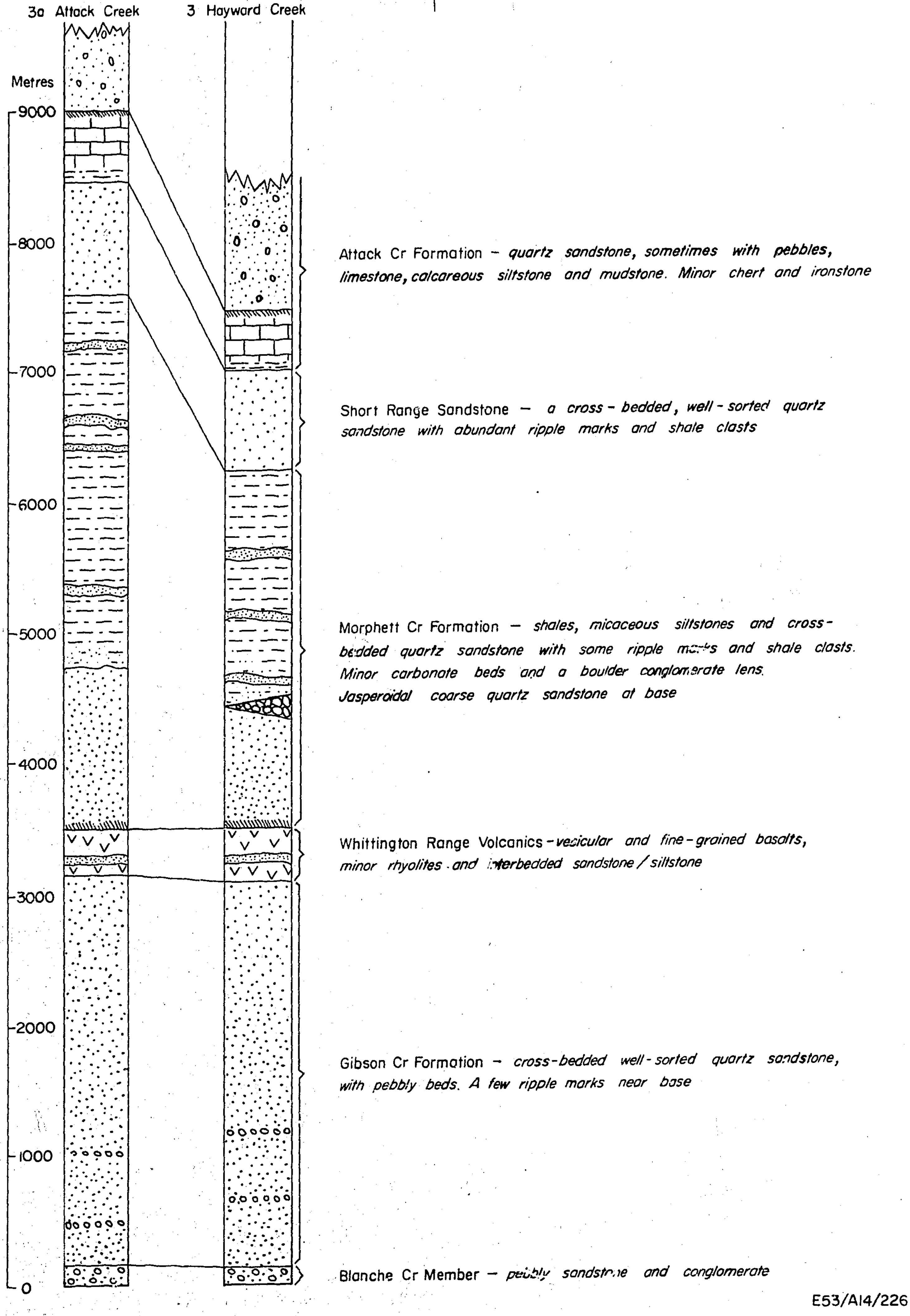
Blocky to flaggy, thin to medium-bedded, banded, commonly ripple marked and rarely cross-bedded quartz siltstone
Minor fine-grained sandstone. Interference and sinuous irregular ripples

Flaggy to fissile and rocky blocky, then to medium-bedded, fine to coarse-grained quartz siltstone. Cross-bedding

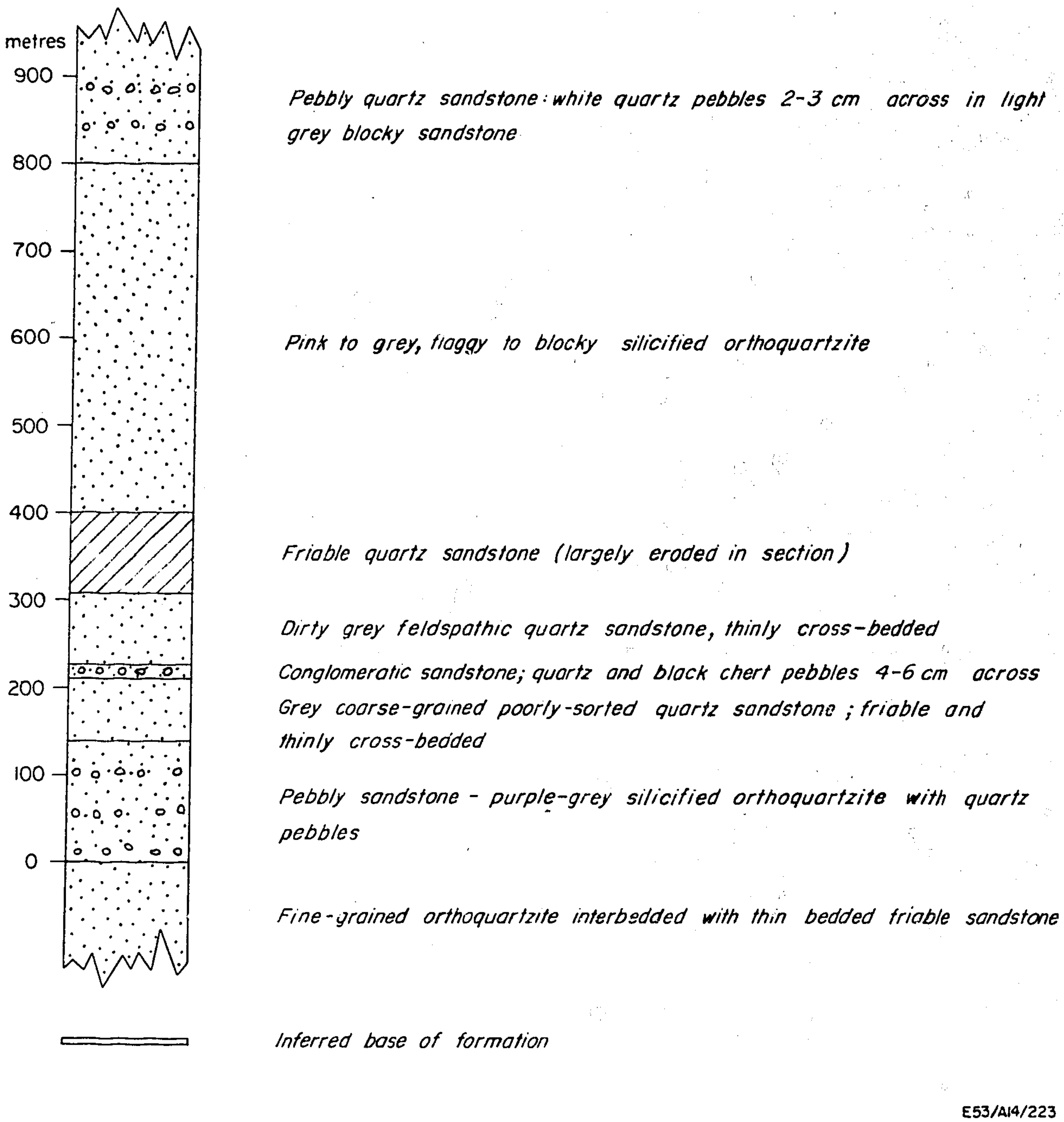
Purple, massive to blocky, rarely flaggy, fine grained greywacke and coarse-grained siltstone. Hematite banding

Section 2. Generalized Section of basal beds of unit Pw$_5$
6·5 km south east of New Hope Mine

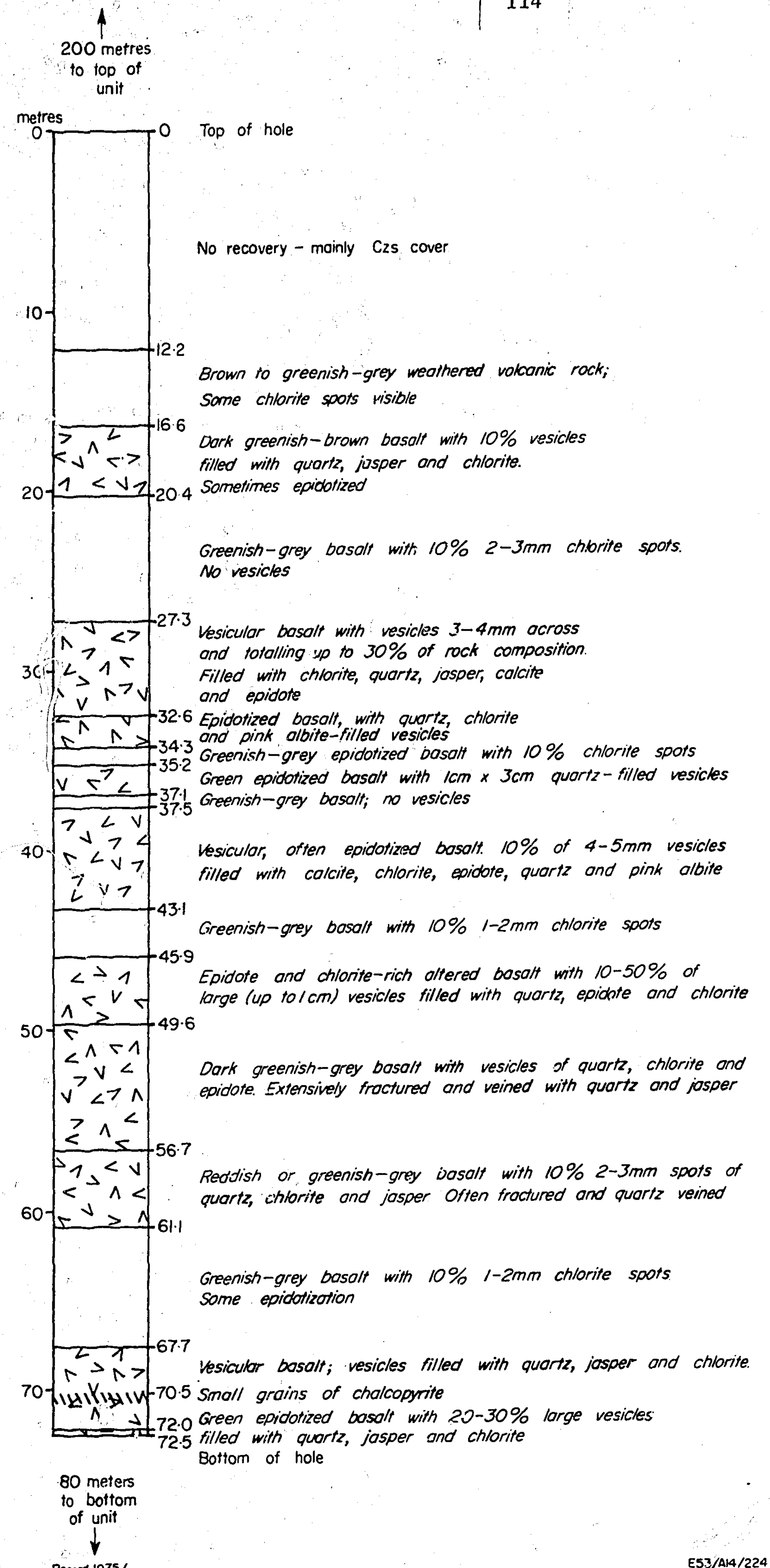
Purple, massive medium-grained lithic sandstone mud pellets



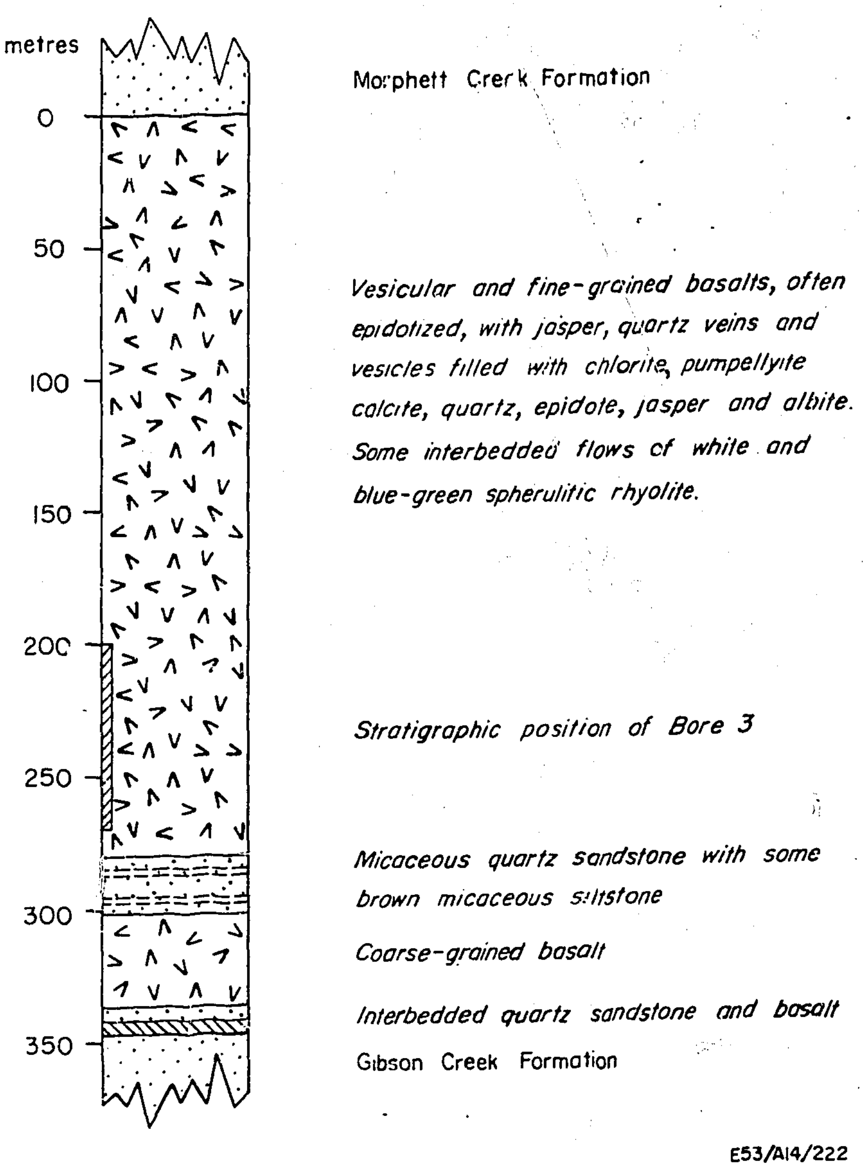
Sections 3, 3a of the Tomkinson Creek Group at Attack and Hayward Creeks



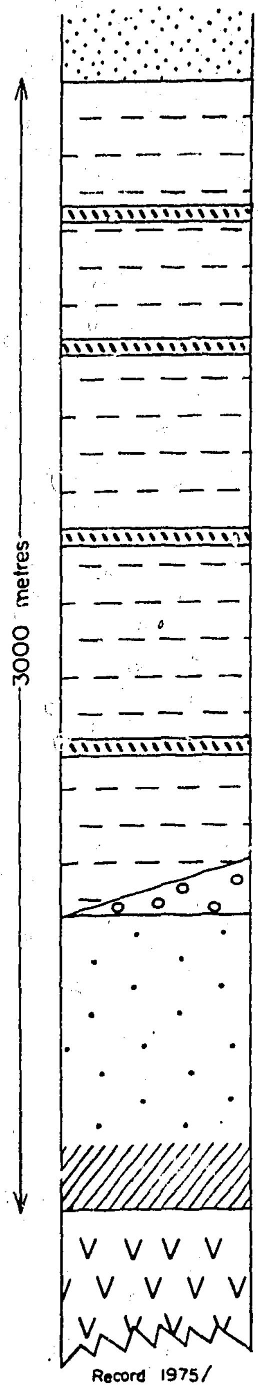
Section 4. Generalized section of lower part of Gibson Creek Formation at outcrop 8kms south-west of Bore 11



Log of Tennant Creek Bore 3 in Whittington Range Volcanics, with stratigraphic position of drill hole



Section 5. Generalized section of Whittington Range Volcanics (Type section locality)



Short Range Sandstone

Interbeded red and white shales and micaceous siltstones, some quartz siltstone and feldspathic quartz sandstone beds. Flaggy to laminated. Minor ironstone and calcareous beds

Boulder conglomerate lens-boulders consist of orthoquartzite, quartz and pebbly sandstone

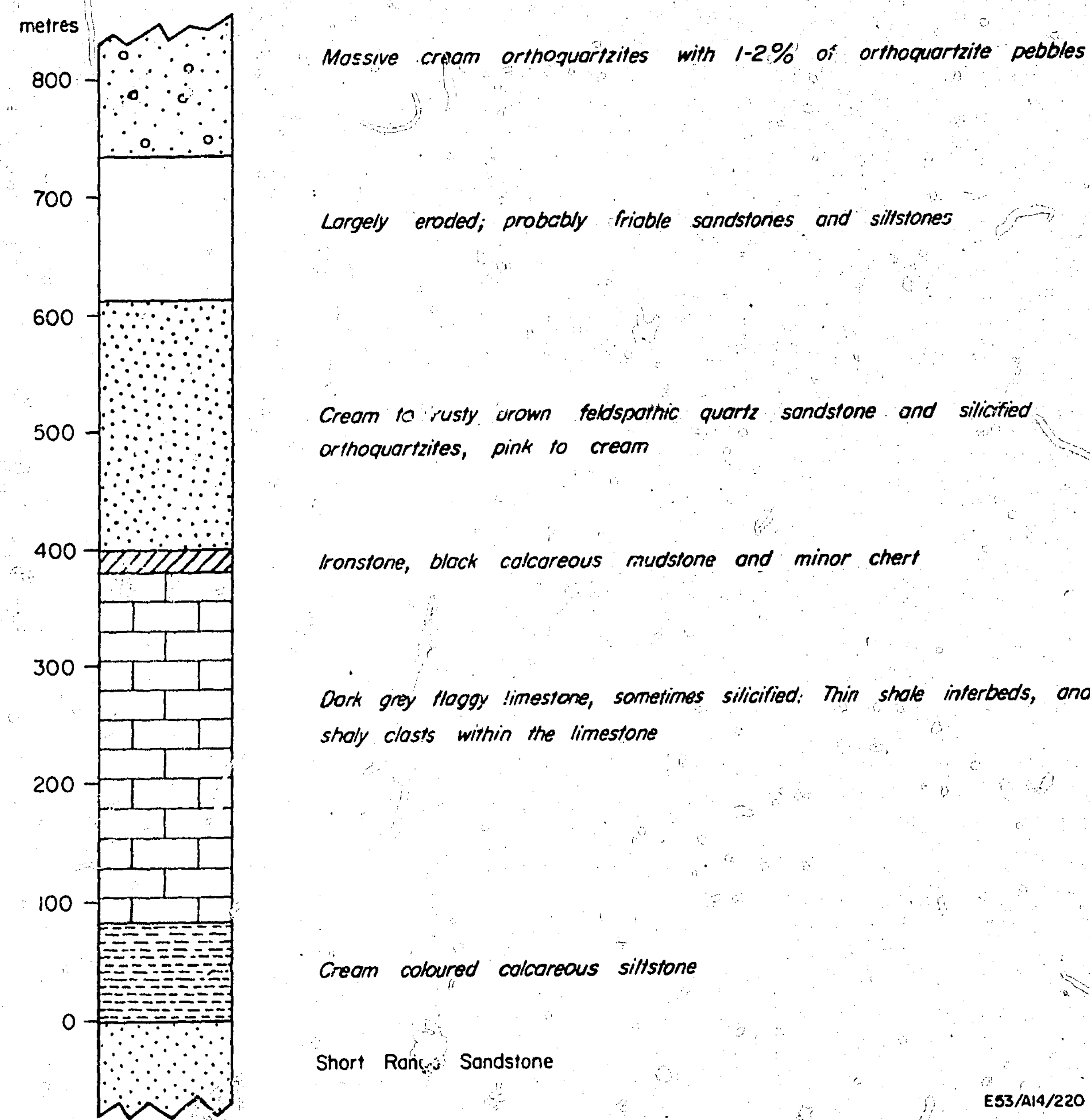
Flaggy to blocky feldspathic quartz sandstone, with ripple marks, mud-clasts and cross-bedding

Ferruginous quartz sandstone with jasperoidal cement

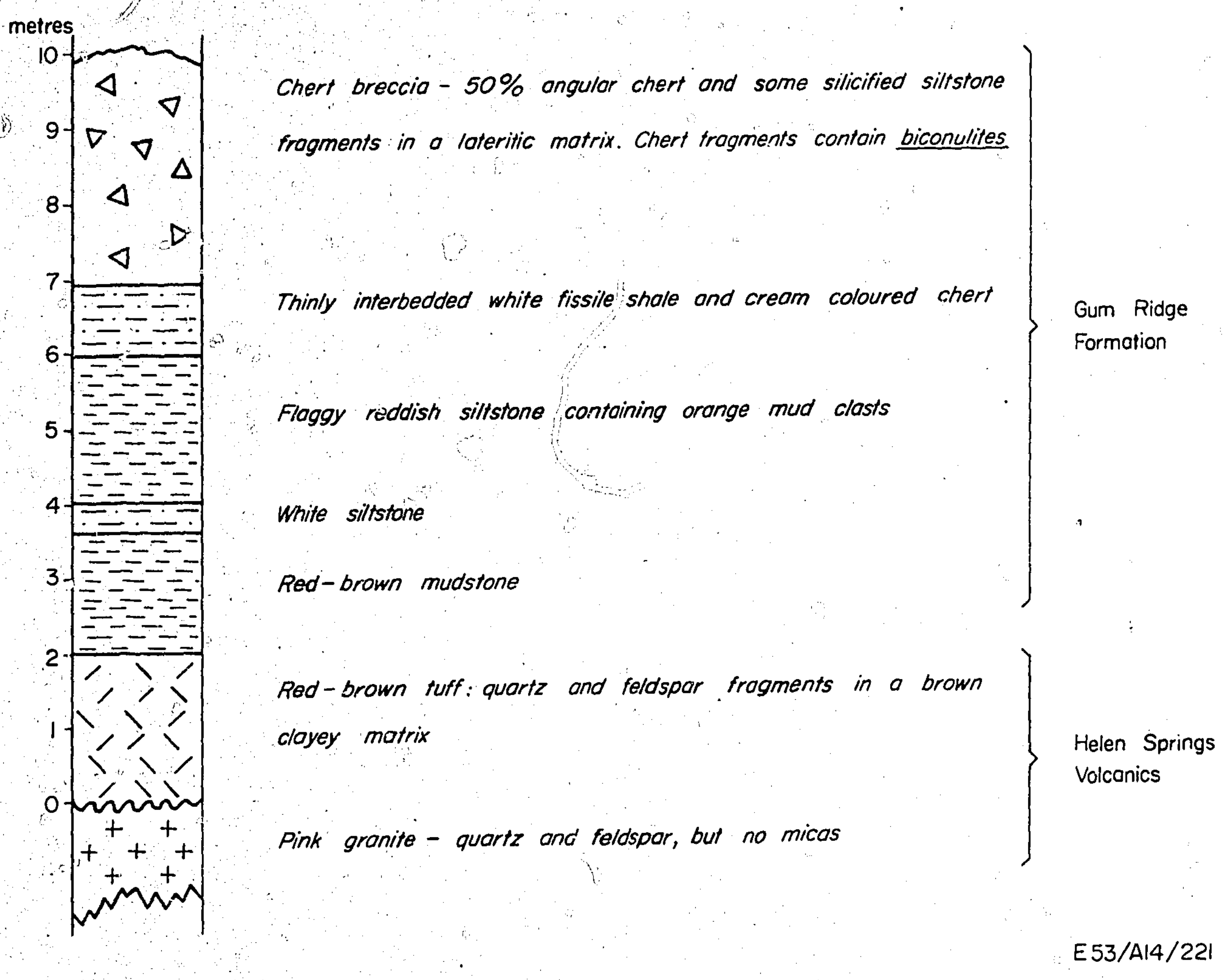
Whittington Range Volcanics

E53/A14/233

Section 6. Generalized section of Morphett Creek Formation



Section 7. Generalized section of Attack Creek Formation (at type locality).



Section 8. Generalized section of Helen Springs Volcanics and Gum Ridge Formation, 21 km. west of Warrego Mine