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MINERALOGY AND MAJOR ELEMENT ANALYSIS OF CAINOZOIC SEDIMENTS AT LAKE GEORGE, NEW SOUTH WALES.

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R.S. ABELL, J.L. FITZSIMMONS AND T.I. SLEZAK

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SUMMARY

Semi-quantitative clay and non-clay mineral data is reported for over 700 core samples from two drillholes in early Palaeozoic bedrock and Cainozoic fluvio-lacustrine sequences in the Lake George Basin.

Illite, kaolinite, montmorillonite and mixed-layer clays represent the main clay mineral groups. The clay minerals which may be detrital and/or authigenic occur as simple illite-kaolinite and complex illite-kaolinite-montmorillonite-chlorite and mixed-layer clay assemblages. These assemblages reflect source rock, lithostratigraphic and palaeoclimatic signatures in the basin. Detrital non-clay minerals are quartz, feldspar and traces of amphibole. Authigenic minerals are represented by halite, gypsum, iron oxides and hydroxides, calcite, siderite and traces of dolomite.

The mineralogy results from a complex depositional environment and post-depositional processes of diagenesis and weathering. Evaporitic sequences are absent.

Twenty major elements from drillhole C354 were identified by semi-quantitative emission spectroscopy. Initially the elements have been derived from bedrock in the catchment and then hydrogeochemically dispersed and concentrated in the lakebed sediments.

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INTRODUCTION

Coincident with a drought period, Lake George dried out briefly from July 1982 until May 1983, providing an opportunity for drilling on the dry lake bed. A drilling and downhole geophysical logging program obtained data on a Cainozoic sequence of fluvio-lacustrine sediments overlying Palaeozoic bedrock. Detail on the drillhole logs, lithostratigraphy and history of the Lake Geoge Basin are given in Abell (1985).

The core from two adjacent drillholes (C353 and C354) was sampled. The main objectives of the study were (a) to identify the clay and non-clay mineralogy of the fluvio-lacustrine sediments and weathering profiles, (b) determine the distribution of major elements, (c) interpret the clay mineral assemblages and chemistry.

The analysis and identification of the clay minerals was undertaken by J.L. Fitzsimmons. The analysis and identification of the major elements was undertaken by T.I. Slezak. The computer program devised to handle the chemical data for C354 was developed by R.S. Hill and D.G. Walton of the computer assisted cartographic group of the BMR drawing office. For reference purposes the X-ray diffractometer traces are held in the clay mineralogy section of the BMR Division of Petrology and Geochemistry.

Geography and climate

The Lake George drainage basin is an elongate, meridionally oriented basin of about 930 km^2 within the Southern Tablelands of New South Wales (Fig. 1). The lake lies at latitude 35°05'S and longtitude 149°25'E, about 40 km northeast of the national capital, Canberra, and about 100 km inland from the sea. The floor of the lake is about 674 m a.s.l. (above sea level).

The present warm, temperate, continental climate over the Lake George Basin is typified by hot summers and cold winters with altitude moderating summer and lowering winter temperatures. The mean January and July temperatures for the nearest meteorological stations - Canberra Forestry (581 m a.s.l.) and Yass (505 m a.s.l.) are 20.1°C/21.5°C and 4°C/4.9 respectively (Singh, Opdyke and Bowler, 1981). Prevailing winds are mostly from west to northwest. The proximity of the basin to the coast mean that onshore southeast humid sea breezes may reach inland to bring temporarily cooler or more humid conditions from January to March (McAlpine and Yapp, 1969). Frosts are common in winter, particularly along the sheltered lee side of the Lake George escarpment. The mean annual precipitation on Lake George is estimated as 750 mm based on records from two rain gauges in the catchment at Bungendore and Collector. Precipitation is distributed fairly evenly throughout the year with a maximum in October (Jacobson and Schuett, 1979). However arid and more humid climates are known to have existed during the history of Lake George (Coventry, 1976; Bowler, 1982).

Geology

A simplified geological map of the Lake George Basin is shown in Figure 2. The pre-Cainozoic bedrock geology comprises a thick pile of marine turbidite sediments of Middle to Upper Ordovician age overlain unconformably by late Silurian acid and basic volcanics and quartz turbidite units. The sediments have been invaded by different generations of Siluro-Devonian acid and basic intrusions. The sequence has been folded, faulted and weakly metamorphosed by a series of Palaeozoic earth movements which give a strong meridional trend to the geological structure. Late Palaeozoic and Mesozoic rocks have not yet been identified in the basin; it seems unlikely that Permo-Triassic sedimentation extended southwestwards beyond the confines of the Sydney Basin. Since the Permian the local region has remained sufficiently stable for an ancient landscape to have developed by the late Cretaceous.

In the Tertiary, the Lake George Basin originated by faulting, possibly rejuvenating late Palaeozoic faults (Abell, 1985). The Cainozoic sediments in the basin were deposited in a normal fault-angle basin. The extent and nature of Tertiary sedimentation is largely obscured by a cover of Quaternary sediments. Beneath Lake George, drilling has revealed the existence of more than 150 m of fluvio-lacustrine sediments which have so far been dated to the late Miocene (Singh et al, 1981; Truswell, 1984; Abell, 1985).

In an earlier investigation, the Cainozoic sequence in the lake area was divided into two lithostratigraphic units: a lower Gearys Gap Fomation and an upper Lake George Formation (Abell, 1985). The amended lithostratigraphy now shows a threefold division (Fig. 3). The Gearys Gap Formation is the oldest Cainozoic unit predating the Lake George basin. The Ondyong Point Formation is a fluvio-lacustrine unit representing the oldest sediments in the basin. The Lake George Formation has been renamed the Bungendore Formation in accordance with the reservation procedures of the Stratigraphic Nomenclature Committee. These units will be defined and reported in the geology of the Canberra 1:100 000 sheet (Abell in preparation). Pre-basin sediments in this report are defined as sediments existing prior to the formation of the Lake George Basin. Basin sediments, fill or sequence are sediments deposited during the formation of the basin.

The Gearys Gap Formation consists of deeply weathered fluvial sand and gravel with minor silt and clay. These early Tertiary? deposits were laid down unconformably on Palaezoic bedrock, burying a palaeotopography incised into bedrock and the remains of a prior drainage system which originally flowed northwest. The oldest unit of the basin sequence is the Ondyong

Point Formation. This unit consists of fluvial sand and lacustrine clay and silt deposited disconformably on deeply weathered pre-basin sediments. The Bungendore Formation comprises lacustrine clay and silt. The two basin units appear conformable and are separated by a laterally persistent layer of sand and silt. They represent deposition in a closed drainage basin where lithofacies is largely a function of climatic change. Preliminary palynology by E.M. Truswell (in Abell, 1985) dates the lake sediments to the late Miocene.

Quaternary sediments are recorded by colluvial deposits which have accumulated on the flanks of hills and along the Lake George escarpment. Lagoonal, lacustrine and aeolian deposits formed near the strandline. Ancient beach lines up to 37 m a.l.b (above lake bed) testify to some very large fluctuations of water level in prehistoric times. Above this height the lake would overflow through Gearys Gap into the Yass drainage system (Coventry, 1976). Since the Pleistocene, alluvial deposition has continued along major streams draining towards Lake George. With the advent of European settlement in the 19th century, land clearing, gully erosion and sand mining have modified natural land forms in the basin.

Geomorphology

The Lake George Basin is a small tectonic depression representing a base level of internal drainage. The basin margin is defined by the topographically subdued watershed of the Great Divide in the east and the Lake George range to the west. At its northern and southern limits, the margin comprises a subdued topography with low saddles, a complex of natural and artificial drainage lines and swampy lagoonal areas. Within the basin topographic relief commonly ranges from 680-900 m a.s.l.

Streams in the basin occupy wide open valleys in their upper reaches. They converge towards Lake George by meandering across flat alluvial plains and embayments. Morphotectonic evidence of faultline rejuvenation is demonstrated by the disrupted headwater system of the Yass river as indicated by elevated river gravels, the remnant of a broad topographic expression at Gearys Gap and the barbed drainage of creeks flowing into the northern end of Lake George (Taylor, 1907; Ollier, 1978; Abell, 1985).

Modern hydrologic regime

Lake George is an outstanding example of a lake in a closed drainage basin. It is estimated that the lake, when full, constitutes about 16% of the total area of the drainage basin. Several creeks and watercourses converge towards the lake; Collector from the north, Alliagonyiga, Taylor and Butmaroo from the east and Turallo from the south (Fig. 1). There is little direct runoff to the lake from the escarpment on the western side of the basin. Jacobson and Schuett (1979) have estimated from a water balance study that 50 m^3/year enters the lake from runoff.

Lake George is a shallow body of water which shows large fluctuations in level and salinity which are mainly attributable to relative changes in rainfall and evaporation. The hydrograph for Lake George is one of the oldest and most continuous water level records in Australia (Russell 1886). In historic times the lake has shown marked seasonal fluctuation in water depth and area. Over longer but less frequent periods, changes in the regional rainfall pattern has caused the lake to dry out (Jacobson & Schuett, 1979). Over the last 167 years (1818 to present) the hydrographic record shows that the water depth in Lake George has rarely passed 6 m and as far as is known has not exceeded 7.5 m. Commonly its depth is between 1.5-4.5 m and its area 130-160 km^2.

When the lake is about 4 m deep, the water is considered fresh (approx. 300 mg/l TDS) but as depth and volume decrease the water becomes progressively more saline with sodium chloride (Nacl) the dominant dissolved salt. A major problem associated with Lake George is the dispersion of salt. A lake of this size which has existed since the Tertiary should have accumulated large amounts of salt. Lack of surface salts suggests their removal from the lake by deflation (Jacobson et al, 1979) or an interchange of salt between the lake and the groundwater system (Singh et al, 1981).

The lake has a seiche which is induced by northerly or southerly winds spreading thin sheets of water across the lake bed (Burton 1972). This type of water movement gives visible changes in water level and area leading to water losses by increased evaporation or in filtration (Fig. 4). Torgersen (1984) notes that seiche movements are a necessary consideration in the estimation of water and salinity budgets. Other wind-induced movements on the water surface cause turbulence and current systems. Bottom sediments are disturbed and fine muddy sediment of often carried in suspension.

Little is known about the groundwater regime in the basin. At this stage it is assumed to be a closed system and mimic to some extent the surface water hydrology (Abell, 1985).

<u>Previous work</u>

Data is sparse on the clay mineralogy and geochemistry of the sediments in the Lake George Basin.

White clay deposits at Bungendore have been sampled to assess their suitability in the manufacture of bricks (Gibbons & Bunny, 1963). X-ray diffraction showed the clay contained quartz, kaolinite, sericite and traces of feldspar and chlorite.

Coventry (1967) took 29 soil samples from a series of soil stratigraphic units in the Shingle House catchment immediately west of the Lake George escarpment. The assemblage of clay minerals was kaolinite, illite and chlorite; montmorillonite was not identified.

At the northern end of Lake George, Singh et al (1981) report geochemical data for the upper 11 m of the lacustrine sequence in ANU drillhole LG4.

CLAY MINERALOGY

Analytical methods

Two drillholes (C353 and C354) in the central portion of Lake George (Fig. 1), were sampled for mineral analysis. Two hundred and thirty -one samples were taken from C353 and four hundred and eighty-three samples from C354. The core from C354 was selected because it was the deepest hole and had the best recovery. An adjacent drillhole (C353), one kilometre to the east was sampled for comparison. Cylindrical samples of core weighing 3-4 gms were taken at 25 cm intervals where recovery, lithology and state of core permitted. Prior to sampling and to avoid contamination, the core was sliced thinly along its length to remove a surface coating of drilling mud. In C353 samples covered a depth range of 1.3-149.0 m and in hole C354 0.25-168.0 m.

Clay minerals were ientified by X-ray diffraction using a Philips PW 1010 generator with a PW 1050/25 goniometer. The analysis was undertaken on a smear of a natural sample mixed with alcohol and mounted onto a stainless steel slide; a size fraction was not selected. A 40kV/20mA stabilised power source irradiated a Cu/Ni source to produce X-rays. The operating details required a time constant of 4, collimator slits of widths

1°, 0.2°, 1°, a scanning speed of 1°/min, a chart speed of 10mm/min and a vertical chart scale of 4×10^2 c.p.s. (counts per second). The clay minerals were only X-rayed in detail from 4-15°2θ; similar detail on rational sequences of secondary diffractions beyond 15°2θ is unavailable.

Thirteen samples were selected from hole C353 for tests to confirm illite, kaolinite, montmorillonite and chlorite. In these tests another portion of the core plug was sampled and a smear of the sample was mounted on two stainless steel slides. One of the slides was heated with ethylene glycol for two hours at 60°C (glycolation) and then X-rayed from 4-15°2θ at room temperature. The other slide was heated for a series of two hour periods at temperatures of 110°C, 300°C, 600°C and 750°C. After each temperature interval this slide was also X-rayed from 4-15°2θ at room temperature.

Quantitative aspects

The clay and non-clay mineralogy is depicted in a semi-quantitative manner as shown in drillholes C353 and C354 (Figures 5 and 6). An estimate of the relative abundance of some minerals was made by measuring and comparing the intensities of basal diffraction peaks above background levels. Following this approach, an arbitrary division of peak intensity for illite and kaolinite is given below:

Trace - small poorly defined peak less than 20 mm height.

Minor - distinct but moderate peak 2-35 mm in height.

Major - strong peak greater than 35 mm in height.

In the case of montmorillonite measurement of peak intensity was not attempted; an arbitrary division is taken to be:

Minor - some definite indication of presence i.e.:
broad shouldered hump.

Major - definite broad peak.

In other clay mineral groups such as chlorite and mixed-layer clays, semi quantitative categories were not applied and the minerals are shown as present or absent.

Quartz is always present. In clays, quartz in minor quantities is usually marked by two major peaks at 26.65°2θ and 20.8°2θ. In silty and sandy layers it is depicted in larger quantities where XRD traces show subsidiary peaks between 36.5-55°2θ.

Feldspar is given an arbitrary division into three categories:

Trace - some definite indication of presence ie. poorly defined peak.

Minor - a distinct peak not greater than 40 mm in height.

Major - a strong peak greater than 40 mm in height.

Other non-clay minerals were not quantitatively categorised as peak intensities were poorly developed. These minerals are shown as being present or absent.

In drillhole LG4, gypsum, carbonates (calcite and magnesite carbonate) and halite are known to occur in the upper 11 m of core (Singh et al, 1981). Their geochemical analysis shows gypsum averages 0.15%, carbonates 2% and halite not less than 0.5%. X-ray traces for the top 11 m of drillholes C353 and C354 show these minerals are unevenly distributed. Assuming they have similar percentage levels to those quoted for LG 4, then quantities below 1% are probably beyond the detection limits of XRD., The sporadic occurrence of gypsum suggests limits of 2-3%. Table 1 lists some of the lowest identifiable percentage levels of clay and non-clay minerals reported in the literature.

MINERAL	LOWEST % IDENTIFIABLE
Kaolinite	5%
Illite	5%
Montmorillonite	10%
Mg Chlorite	1%
Fe Chlorite	10%
Feldspar	5%
Calcite	5%
Dolomite	1%
Halite	5%

Table 1. Detection limits of clay and non-clay minerals (after Carroll, 1970).

IDENTIFICATION AND DESCRIPTION

The clay minerals were recognised by their characteristic basal spacings corresponding to X-ray diffraction maxima as outlined in Carroll (1970). The clay mineral assemblage identified consists of illite, kaolinite, montmorillonite, chlorite and mixed-layer clays. A summary of the distribution of clay minerals in drillholes C353 and C354 is given in figures 5 and 6.

ILLITE

A 2:1 layered potassic-rich clay mineral that is closely related to the micas (muscovite and sericite). Illite is easily identified on the X-ray diffraction chart by a strong, sharp, first order basal peak (001) at about 10A° (8.8°2θ). Illite was confirmed by maintenance of the (001) basal peak after heating to a temperature of 750°C.

Distribution

The relative abundance of illite and its association with kaolinite assists in defining lithostratigraphic units in the Lake George Basin (Table 2). In the deep weathering profile, illite is preserved in ferruginous bedrock but is subordinate to kaolinite in zones of leached sand and gravel in the Gearys Gap Formation. Illite is abundant in clay and silt of the basin sediments (Ondyong Point and Bungendore Formations).

Origin

Illite is a detrital clay mineral derived by weathering and erosion of late Ordovician and Siluro-Devonian turbidite sequences outcropping in the lake catchment. Lesser sources of illite come from the weathering of potash feldspar in acid volcanic and granitic rocks (Fig. 7).

The retention of illite in the basin sediments is attributed to the stability of muscovite and sericite in the weathering and erosion cycle. Illite degrades to kaolinite by removal of K^+ ions in leached zones of the deep weathering profile. Illite tends to to be preserved in alkaline environments. Water analyses from Lake George give average pH values of 8.6 (Jacobson and Schuett, 1979).

STRATIGRAPHIC UNIT		ILLITE	ILLITE/KAOLINITE ASSOCIATION	COMMENTS
BASIN SEDIMENTS	BUNGENDORE FORMATION	Major	I > K	
BASIN SEDIMENTS	ONDYONG POINT FORMATION	Major	I > K	Illite locally subordinate to kaolinite at 69.7-73.5m (C353) and 75.8-81.5m (C354).
	Top deep weathering profile			
PRE-BASIN SEDIMENTS	GEARYS GAP FORMATION	Variable (trace to minor)	I < K	Illite degraded to koalinite in leached zones; preserved in ferruginous bedrock.
PRE-BASIN SEDIMENTS	BEDROCK	Major	I > K	

Table 2. Distribution of illite

KAOLINITE

A stable 1:1 layer type clay mineral. Kaolinite shows a strong first order basal peak (001) at 7A° (12.6°2θ). The peak is somewhat broader than for illite. Kaolinite was confirmed by a collapse of the (001) peak when samples were heated to 600°C for two hours. Hallyosite (a member of the kaolinite group) has a similar (001) basal spacing to illite at 10A° (8.8°2θ). This mineral is normally distinguished from illite by a shift in its peak from 10A° to 7A° on heating to 110°C. It was concluded that hallyosite was absent since the peaks for kaolinite and illite were unchanged when samples were X-rayed after heating at this temperature.

Outcrop distribution

White and pale grey kaolinitic clays occur in any rocks e.g. quartz turbidite sediments, outcropping in low relief areas of the Lake George basin (Figure 7). Leached slates of Ordovician age are exposed in railway cuttings near Bungendore railway station (MR 225/958)*. Several shafts sunk to investigate the economic potential of the clay show it extends more than a kilometre south of Bungendore and to a depth of more than 20 metres (Lloyd 1960, Loughnan 1960 and Gibbons and Bunny, 1963). Kaolinitic clays are also exposed in a deep weathering profile on the watershed seperating the Lake George and Molonglo drainage systems (Abell, 1985). Kaolin is present in strongly leached Silurian shale and sandstone. The deposits are currently worked in brick shale pits south of Woodlands HS, close to the Bungendore - Hoskinstown road at MR 210/870. Similar outcrops occur in a disused brick shale pit close to the Bungendore - Queanbeyan railway line at MR 225/958.

Comparable kaolin deposits have been investigated in the Goulburn - Bungonia area. The clays in this area are typical of well ordered residual kaolin as they plot between 0.7-1.3 on Hinckleys crystalline index (Baker and Uren, 1982).

Distribution in drillcore

Kaolinite is generally abundant in bedrock and overlying fluvio-lacustrine sediments. The vertical distribution of kaolinite for drillholes C353 and C354 is shown by a plot of peak intensity heights on the (001) basal spacing at 12.6°2θ (Figures 8 and 9).

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*Map references given in the text refer to the Canberra 1:100 000 topographic sheet No. 8727.

In the pallid zone of the deep weathering profile kaolinite is the dominant clay mineral. The uniform distribution of kaolinite in this profile is well displayed by C354. The distribution is unrelated to lithological change and reflects a residual origin from the degradation of feldspar and other clay minerals.

Kaolinite is unevenly concentrated in basin sediments above the deep weathering profile. Local concentrations are denoted by a grouping of high peak intensities in hole C353 at 40-45 m and 68-72 m and in hole C354 at 30-32 m and 47-53 m. Kaolinite tends to be less abundant in some of the coarse sandy layers in the Ondyong Point Formation.

Stratigraphy

The relative abundance of kaolinite, cystallinity index (CI) and association with illite assist in defining lithostratigraphic units (Table 3). The commonly used "half peak width/peak height" is appropriate enough to define a crystallinity index for kaolinite as an aid to characterising the stratigraphy. Other methods such as Hinckleys Index (Baker & Uren, 1982) were not used as the clay minerals were only analysed in detail over the 4-15°2θ range.

Origin

Prior to basin formation kaolin formed as a residual clay mineral by alteration of feldspar in weathered shale, granitic rocks, acid volcanics, acid porphyries and fluvial sands and gravel of the Gearys Gap Formation (Fig. 7). In the basin sediments, kaolinite was deposited as a detrital clay mineral (recycled or transported kaolin) by weathering and erosion of pre-existing kaolinised bedrock in the catchment bordering Lake George.

The formation of kaolinite deposits by weathering is favoured by humid climate, acidic weathering conditions and good drainage allowing leaching of soluble products. Residual kaolin formed under these conditions is well ordered and crystalline (Baker & Uren, 1982).

When the Lake George Basin was formed in the Miocene, kaolinitic bedrock was uplifted in marginal areas of the catchment. Kaolin was weathered out and transported downslope towards the depositional area of Lake George. According to Baker and Uren (1982), detrital kaolin formed in this manner will be disordered and poorly crystalline.

Drillholes on the lake bed and alluvial plains bordering the lake show the subsurface preservation of the full thickness of the deep weathering profile (Abell 1985). This profile has been protected from erosion by a cover of late Tertiary-Quaternary fluvio-lacustrine sediments.

STRATIGRAPHIC UNIT		KAOLINITE	CRYSTALLINITY INDEX (CI)	COMMENT	ORGIN
BASIN SEDIMENTS	BUNGENDORE FORMATION	Major	Uniform (ave. 0.05)	Some kaolinite residual in weathering profiles; less abundant in coarse clastic sediments	Detrital (disordered)
	ONDYONG POINT FORMATION	Variable (trace to major)	Variable		
	Top deep weathering profile				
PRE-BASIN SEDIMENTS	GEARYS GAP FORMATION	Major	Uniform (ave 0.025)		Residual (ordered)
	BEDROCK	Major			

Table 3. Distribution and origin of kaolinite

MONTMORILLONITE

A 2:1 layered magnesian-rich clay mineral belonging to the smectite group with well known cation exchange properties.

Montmorillonitic clays display a broad range of peaks from 11-17A° (8.5-5.2°2θ) corresponding to the (001) basal spacing. Sharper peaks in this range at about 12.4A° (7.1°2θ) indicate sodium montmorillonite and at 15°A (5.7°2θ) may indicate the presence of calcium montmorillinite or sodium montmorillonite with 2 water layers (Deer, Howie & Zussman, 1966). Montmorillonite was confirmed by an expansion of the crystal lattice to 17A° (5.2°2θ) after glycolation. When heated to 300°C to remove the interlayer water, the 11 -17A° peak disappeared. The peak shift to 9 - 10A° (9.8°-8.8°2θ) sometimes enhanced the illite peak. Examples of X-ray diffractograms for montmorillonite are shown in Figure 10.

Distribution

Montmorillonite is commonly distributed in lacustrine clays of the basin sequence. In the top 74 m of hole C353 and top 71 m of hole C354, montmorillonite may occur in major quantities. Minor amounts are found in fine to coarse grained clastic sediments and in association with intermittent ferruginous weathering profiles (Figures 5 and 6). The relative abundance of montmorillonite assists in characteristising stratigraphic units (Table 4). It is a common clay mineral in the Bungendore Formation and in clays of the Ondyong Point Formation. Montmorillonite is absent from deeply weathered pre-basin sediments and bedrock.

Orgin

Montmorillonite maybe derived by weathering of basic igneous rocks. Intrusive rocks of the Lockhart basic complex, numerous dolerite intrusions and the Currawang Basalt provide sources of plagioclase, pyroxene and amphibole (Fig. 7). Montmorillonite can form by the weathering of these minerals which are rich in Ca and Na ions but deficient in K ions. Montmorillonite may be a primary detrital mineral in the lacustrine clays of the basin sequence. However authigenic montmorillonite in the lake sediments is favoured by high silica and cations, poor leaching and drainage conditions, and neutral to alkaline pH.

Decrease or absence of montmorillonite in some ferruginous weathering profiles has been recorded in hole C353 at 21.25-29.75 m; 62.5-66.0 m and in hole C354 at 4-6.5 m; 16-18.75 m and 25-32.5 m. Weathering and leaching (desilicification) converts montmorillonite to kaolinite (Ollier 1984). A similar conversion has been documented for the Morney deep weathering profile in the Winton Formation of southwest Queensland (Senior 1979).

STRATIGRAPHIC UNIT		MONTMORILLONITE	COMMENT
BASIN SEDIMENTS	BUNGENDORE FORMATION	Major	Degraded to kaolinite in weathering profiles
	ONDYONG POINT FORMATION	Variable (Minor and major)	
	Top deep weathering profile		
PRE-BASIN SEDIMENTS	GEARYS GAP FORMATION	Absent (trace)	
	BEDROCK		

Table 4. Distribution of montmorillonite

A post-depositional origin for some of the montmorillonite is suggested by its close association with mixed-layer clays. Sodic and calcic montmorillonite may form by cationic exchange processes during silification.

CHLORITE

A 2:1 layered clay mineral with a structure closely resembling the micas. Its identification is often obscured by the presence of the broader peaks of montmorillonite and montmorillonitic mixed-layer clays. Chlorite was distinguished from montmorillonite by the detection of a sharp (001) basal peak at 14A° (6.3°2θ). Examples of X-ray diffractograms for chlorite are shown in Figure 11. Attempts to confirm chlorite by glycolation and heating tests were unsuccessful. Difficulty reproducing the sharp basal peak in these tests may have been influenced by mounting procedures or absence in repeat samples. The position of the (001) basal peak is similar to vermiculite. However indentification of chlorite is preferred as it is an abundant constituent of Palaeozoic rocks outcropping in the catchment.

Distribution

Chlorite is most common in the lacustrine clays of the basin sequence. Its distribution follows a similar pattern to montmorillonite and associated mixed-layer clays, but it is less abundant and more random in occurrence. Chlorite is confined to the upper 70.5 m of hole C353 and upper 77.75 m of hole C354 (Figs. 5 and 6). The distribution of chlorite helps to substantiate the lithostratigraphy of the basin. It is common in the upper 16 m of the Bungendore Formation. Concentrations of chlorite near the bottom of this formation (41.5-46.75 m in hole C353 and 46.75 - 53.00 m in hole C354) provide a possible means for stratigraphic correlation. Sporadic chlorite occurs in clays of the Ondyong Point Formation. Chlorite is absent from deeply weathered pre-basin sediments (Table 5).

Origin

Chlorite is a common mineral constituent of basic and acid igneous rocks. It is formed mainly by the alteration of ferromagnesian minerals (biotite, amphibole and pyroxene). Chlorite is also derived from low grade regionally metamorphosed (greenschist facies) argillaceous sediments in turbidite sequences (Fig. 7).

Chlorite is primarily a detrital clay mineral in the fluvio-lacustrine sediments of the basin. Diagenetic chlorite may form as an authigenic mineral in close association with montmorillonite and mixed-layer clays if there is sufficient availability of Fe and Mg ions in the sediments.

STRATIGRAPHIC UNIT		CHLORITE	COMMENT
BASIN SEDIMENTS	BUNGENDORE FORMATION	Commonly present	Stratigraphic indicator at base of formation
	ONDYONG POINT FORMATION	Sporadic	
	Top deep weathering profile		
PRE-BASIN SEDIMENTS	GEARYS GAP FORMATION	Absent	
	BEDROCK		

Table 5. Distribution of chlorite

MIXED-LAYER CLAYS

These are clays in which certain clay minerals are regularly or randomly interstratified. In the Lake George Basin, mixed-layer clays are divisible into (a) montmorillonite mixed-layer clays and (b) illite mixed-layer clays (degraded illite). Gradations between these two types are illite - montmorillonite mixed- layer clays. X-ray traces of these clays do not show well defined peak intensities but are recognized as areas of higher intensity background over wide 2θ ranges. Examples of the three types of mixed layering are given in Figures 12, 13 and 14.

Montmorillonite mixed-layer clays appear as a broad zone of peak intensity between 17.6A° (5°2θ) and 11.1A° (8°2θ). Small subsidiary peaks often occurring in this zone indicate a large proportion of the mixing is due to various forms of montmorillonite and chlorite.

Illite mixed-layered clays are characterised by a narrow shoulder on the low 2θ side of the illite peak between 10A° (8.8°2θ) and 11.1A° (8°2θ).

Distribution

Illite mixed-layer clays are common in the deeply weathered pre-basin fluvial sediments and bedrock. In hole C354 these clays have a fairly even distribution which appears to be more or less independent of lithology. The restriction of these clays in hole C353 is probably due to poor sample recovery.

Montmorillonite mixed-layer clays are unevenly distributed in fluvio-lacustrine sediments above the deep weathering profile. They are markedly reduced in the Ondyong Point Formation which has a high proportion of coarse grained clastic sediments, but most common in the lacustrine clays and silts of the Bungendore Formation.

The lithostratigraphic distribution of mixed-layer clays is summarised in Table 6.

Origin

Mixed layering reflects the adjustment of clay minerals to post-depositional processes. The availability of Fe, Mg, Al, Ca, K and Na cations in the lacustrine sediments ensures that clay minerals with cation exchange properties will revert to mixed-layer complexes.

In the deep weathering profile clay mineral assemblages are more stable and there is less tendency to form mixed-layer complexes. Illite has low exchange capacity and kaolinite is a stable 1:1 layer clay mineral.

STRATIGRAPHIC UNIT		MIXED-LAYER CLAYS	ORIGIN
BASIN SEDIMENTS	BUNGENDORE FORMATION	Montmorillonite type with subordinate illite-montmorillonite type	Diagnetic
	ONDYONG POINT FORMATION		
Top deep weathering profile			
PRE-BASIN SEDIMENTS	GEARYS GAP FORMATION	Illite type	Diagnetic
	BEDROCK		

Table 6. Distribution and origin of mixed-layer clays.

NON-CLAY MINERALS

The non-clay mineralogy may be divided into two major groups:

- Detrital minerals introduced during the deposition of the fluvio-lacustrine sediments (allogenic minerals). These are quartz, feldspar, amphibole and trace minerals such as garnet.

. Secondary minerals formed at the time or shortly after deposition of the sediments (authigenic minerals). These are carbonates (calcite, dolomite and siderite), evaporites (halite, gypsum and traces of barytes) and iron oxides (hematite and traces of lepidocrocite).

The sample preparation for the non-clay minerals followed that for clay minerals, except the samples were mounted onto glass rather than stainless steel slides. The samples were X-rayed for non-clay minerals from 4°-60°2θ at a scanning speed of 2°/minute using Cu radiation and a graphite monochromator. The minerals were recognised by various X-ray diffraction peaks corresponding to their characteristic crystal structure. A summary of the distribution of non-clay minerals in drillholes C353 and C354 is given in Figures 5 and 6. As far as possible the identification of non-clay minerals followed the procedures in Brindley and Brown (1980).

DETRITAL MINERALS

QUARTZ

Quartz was identified by its major peak at 3.34A° (26.65°2θ) and its secondary peak at 4.27A° (20.8°2θ). Samples with minor quartz (normally clays) are denoted only by major peaks at 3.34 and 4.27A°. Subsidiary peaks in the 36.5° - 55.0°2θ range indicate quartz in major quantities (mainly silt, sand etc.). Hence the relative "peakiness" of X-ray diffraction traces in the 4-60°2θ range is an indication of the abundance of quartz. This technique can provide a rough method for distinguishing silts from clays in lacustrine sediments. X-ray diffractograms for quartz are given in Figures 15 and 16.

Distribution

Quartz is present in all samples. Its distribution in the sedimentary sequence is a function of lithology. Quartz varies sufficiently for its use as a stratigraphic indicator. Generally it occurs in minor quantities in clay and silt of the Bungendore Formation and is relatively more abundant in sand and gravel of the underlying Ondyong Point and Gearys Gap Formations (Figs. 5 and 6).

Origin

A detrital mineral transported into the depositional area by the weathering and erosion of quartz turbidite sediments and acid igneous rocks in the catchment. The abundance of quartz in the sediments reflects its long term stability in the depositional system of the basin.

There is no clear evidence for authigenic quartz in the basin sequence. However a silcrete exposed at the base of the Lake George escarpment about 1 km south of Gearys Gap (Abell 1985) indicates silica mobility has occured during the history of the Lake George basin.

FELDSPAR

Feldspars are framework silicates which can be divided into two main groups, potash feldspars and the plagioclases. Feldspar was identified by a consistent peak at about 3.19A° (28.2θ). In some samples feldspar shows an extra peak at 3.24A° (27.5° 2θ). This double peaked X-ray signature indicates the present of plagioclase and only occurs in samples from (fluvial) sands (Fig. 17). Confirmation of plagioclase was achieved by the recognition of a strong secondary reflection near 4.03A° (22.2°2θ). Potash feldspar was judged to be absent as the strong reflection in the spacing range 3.18-3.22A° was not found (Brindley and Brown, 1980).

Distribution

The distribution of feldspar assists in characterising lithostratigraphic units (Table 7). Feldspar may occur in trace amounts, but is usually absent in deeply weathered sediments of the Gearys Gap Formation and Palaeozoic bedrock. Feldspar is most abundant in basin sediments above the deep weathering profile. The mineral is most prominent in silt, sand and gravel of the Ondyong Point Formation, but reduced to trace and minor quantities in clay and silt of the Bungendore Formation.

Origin

Detrital feldspar is derived mainly from igneous rocks east of the depositional area of Lake George (Fig. 7).

The apparent dominance of plagioclase in the basin sediments is unusual as the mineral has low durability in the erosion cycle. The abundance of plagioclase in bedrock and closeness of the depositional site of Lake George to source areas, might explain its retention in the basin sediments. The mineral is available in outcropping basic intrusive and volcanic rocks and may have been derived from a more extensive Tertiary basaltic cover to the east now removed by erosion. However the apparent lack of potash feldspar in the basin sediments is even more problematic since the mineral is known to be durable and occur in acid intrusive and volcanic rocks outcropping extensively in the catchment.

In the deeply weathered, leached profile uniformly high kaolinitic peaks support a proposition of in situ weathering and almost total degradation of feldspar . The increased amount of feldspar retained in the fluvial sand and silt of the Ondyong Point Formation suggest a rejuvenated topography and drainage shedding increased amount of sediment into the basin.

<table>
<tr><th colspan="2">Stratigraphic Unit</th><th>Feldspar</th><th>Faulting →</th><th>Origin</th><th>Tectonic Environment</th><th>Climate</th><th>Sedimentary Environment</th></tr>
<tr><td rowspan="2">BASIN SEDIMENTS</td><td>BUNGENDORE FORMATION</td><td>Variable (trace to minor)</td><td rowspan="2"></td><td rowspan="2">Detrital feldspar (plagioclase)</td><td>Tectonic Quiescence</td><td rowspan="2">Fluctuating (humid with arid periods becoming seasonal)</td><td>Lacustrine</td></tr>
<tr><td>ONDYONG POINT FORMATION</td><td>Variable (minor to major)</td><td>Tectonic Activity (rejuvenation and increased erosion and deposition)</td><td>Fluvio-lacustrine</td></tr>
<tr><td colspan="8">TOP DEEP WEATHERING PROFILE</td></tr>
<tr><td rowspan="2">PRE-BASIN SEDIMENTS</td><td>GEARYS GAP FORMATION</td><td rowspan="2">Mostly absent (traces)</td><td rowspan="2"></td><td rowspan="2">Feldspar originally detrital (now degraded to kaolin by in situ weathering)</td><td rowspan="2">Tectonic Quiescence</td><td rowspan="2">Humid</td><td>Fluvial</td></tr>
<tr><td>BEDROCK</td><td></td></tr>
</table>

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Table 7. Factors affecting the lithostratigraphic distribution of feldspar.

Local increases of feldspar in silty lake sediments may relate to higher run off conditions in wetter climatic periods. The non-correlation of feldspar and kaolinite in the basin sequence suggests a detrital origin for kaolinite (Table 7, Figs. 8 and 9).

AMPHIBOLE

Amphiboles are chain silicates identified by a sharp (110) peak at 8.3A° (10.6°2θ) situated between first order basal peaks of illite and kaolinite. The amphibole peak is found most commonly on the clay mineral diffractogram. Sufficient amphibole was sometimes present for the peak to show at 3.08A° (28.95°2θ).

Distribution

Amphibole has only local occurrence in the sediments. Trace and minor quantities are found to depths of 51 m in C353 and 68.5 m in C354. The mineral is confined stratigraphically to the Bungendore Formation and uppermost portions of the Ondyong Point Formation.

Origin

The small quantities of detrital amphibole in the cores suggests local derivation from basic igneous rocks in the catchment. The instability and low durability of amphibole in the erosional cycle suggests it is unlikely to be retained in large quantities in the basin sediments.

GARNET

In drillhole C354 a single grain of spessartite garnet was found in lacustrine clay at a depth of 49.75m. X-ray traces of spessartite showed clear reflections at 2.61A° (34.3°2θ), 2.34A° (38.4°2θ), 1.6A° (57.5°2θ) and two other major peaks. The garnet is assumed to be detrital and to have been derived from igneous or sedimentary rocks in the catchment.

SECONDARY MINERALS

CALCITE AND DOLOMITE

Calcite ($CaCO_3$) is the commonest carbonate mineral and is identified by a small broad peak at 3.03A° (29.4°2θ). Small shifts in the peak position to 2.98A° (30.0°2θ) are due to small differences in spacings probably arising from the limited replacement of Ca by other divalent cations such as Mg. Dolomite [$CaMg(CO_3)_2$] which is much less common than calcite is recognised by its major peak at 2.90A° (30.85°2θ). X-ray diffraction results indicate magnesian calcite exceeds dolomite. Aragonite was not detected.

Carbonates are ubiquitous in the pre-basin and basin sediments. The size of the X-ray reflections suggests calcite and magnesian calcite only occur in trace quantities in the Lake George Basin. However strong peaks for dolomite show it is a common mineral in the upper 5 m of the Bungendore Formation, notably at 1.3 m (C353) and 1.5 m (C354).

Some primary calcium carbonate maybe derived from the breakdown of shell debris. Coxiella gastropod and ostracod tests are known to occur in the upper 11 m of drill core in LG4 (Singh et al, 1981 and De Dekker, 1982) and also in C354, C355, C358, C360 and C355 (Abell, 1985). However most calcite is authigenic in origin. Secondary calcite may form in pedogenic processes by leaching and reconstitution as calcareous segregations (Singh et al, 1981). Under low water or even dry lake conditions calcite might be precipitated by evaporation from carbonate-rich surface and subsurface waters. Chemical analyses for Lake George waters in low lake level stands in 1969 and 1973 showed a marked increase in HCO_3 and CO_3 ions (Jacobson and Schuett, 1979).

Dolomite is known to form under varied depositional settings (Folk, 1974; Leeder, 1982). Singh et al, (1981) note the absence of dolomite in the top 11 m of core in LG4. They note that Ca exceeds Mg by a ratio of about 10:1 and imply that dolomite will only form if lakewater salinities are greater than 100g/litre (100,000 mg/litre). In chemical analyses of lakewaters, Mg exceeds Ca with the ratio increasing markedly in times of low lake levels (Jacobson and Schuett, 1979). Major element analyses in drillhole C354 also confirm that Mg occurs in excess of Ca.

SIDERITE

Siderite ($FeCO_3$) was identified by its major peak at 2.79A° (32.0°2θ). The position of the siderite peak is similar to the major halite peak at 2.82A° (31.8°2θ). It was not possible to seperate both minerals if they were present because the scanning speed of the X-ray machine was 2°/min. In such cases confirmation of either or both minerals was achieved by finding their subsidiary peaks. In drillhole C354, siderite was confirmed by the analysis of a composite nodule, approximately 1 cm in diameter, from a sample of black clay at a depth of 48 m. Subsidiary reflections for siderite occurred at 3.59A° (24.8°2θ), 2.34A°(38.4°2θ), 2.13A° (42.4°2θ), 1.96A° (46.2°2θ) and 1.80A° (50.8°2θ).

Traces of secondary siderite detected in weathered bedrock and in parts of the Gearys Gap Formation probably formed after these sediments were inundated. Siderite is common in the Ondyong Point Formation where it appears to show some association with weathering profiles. The mineral only occurs in trace amounts in the Bungendore Formation. The formation of siderite is typical of the non-marine diagenetic conditions and sub-tropical weathering patterns in the Lake George basin.

GYPSUM

Gypsum ($CaSO_4 . 2H_2O$) is readily identified on the clay mineral scans by a sharp peak at 7.63A° (11.6°2θ) situated close to kaolinite.

In C354, gypsum is concentrated locally at a depth of 48.0-55.5 m, straddling the boundary between the Ondyong Point Formation and the Bungendore Formation. Gypsum is most common in the upper 16 m of the Bungendore Formation.

In the upper 11 m of the lakebed sediments, Singh et al. (1981) report that sulphates average 0.15%. In low lake conditions sulphate values in lakewaters increase well beyond 2,000 mg/litre (Jacobson and Schuett, 1979). Gypsum maybe precipitated from evaporating saline lakewater or shallow saline groundwater in local drought or prolonged arid conditions. The lack of gypsum in the lacustrine sediments suggests it is carried down and dispersed into the underlying groundwater system during and after periods of dessication (Singh et al, 1981).

BARYTES

In drillhole C354, barytes ($BaSO_4$) was found as a white inclusion within the clay matrix at 54.25m. X-ray traces for barytes showed strong reflections at 3.43A° (26.0°2θ), 3.31A° (26.95°2θ), 3.09A° (28.85°2θ), 2.12A° (42.65°2θ), 2.10A° (43.1°2θ) and other smaller peaks. Barytes is an authigenic mineral and appears to be associated with a local concentration of gypsum already reported at a depth of 48.0-55.5 m.

HALITE

Halite (NaCl) is more common in the basin and pre-basin sediments than gypsum. It is identified by its major peak at 2.82A° (31.8°2θ), but not confirmed by its subsidiary peak at 1.99A° (45.7°2θ). The subsidiary peak at this position is masked by clay minerals. Seperation was not clear because the scanning speed of the x-ray machine was 2°/min.

Occasional traces of halite occur in the pre-basin sediments and the Ondyong Point Formation. Halite is fairly well distributed through the

Bungendore Formation in trace quantities. Local concentrations of halite in C353 occur at 6.25-7.25 m and 31.00-31.5 m; in C354 they are at 2.00-3.75 m, 6.00-10.25 m, 11.5-14.75 m and 23.0-24.25 m.

Drill holes on the lake bed show little evidence for large scale precipitation of evaporitic salts in the sediments. Jacobson et al. (1979) note that the salinity of Lake George increases as the lake dries out. In a low level stand in February 1973, salinity reached 44,800 mg/l TDS (seawater is approx. 36,500 mg/l TDS). The presence of halite in the Bungendore Formation suggests that in dry periods it is precipitated by evaporation of lakewater or perhaps by evaporative pumping of shallow saline groundwater.

IRON OXIDES AND HYDROXIDES

In drill core iron is evident in weathering profiles where it is recognised by red and yellowish brown colour mottling, banding and small concretionary growths. The iron minerals occur in forms ranging from poorly structured (amorphous) oxides to the more crystalline hydroxides.

Hematite

Hematite (Fe_2O_3) proved difficult to identify by X-rays. The mineral sometimes shows a small peak in the vicinity of 2.70A° (33.2°2θ). Subsidiary peaks for hematite were not identified.

In drill hole C354, hematite is concentrated near the base of the Gearys Gap Formation and top of weathered bedrock at a depth of 159.5-165.25 m. X-ray data from drill hole C353 suggests hematite may occur in trace quantities in the Bungendore Formation, but in C354 it was not identified in the basin sediments.

The drill core logs indicate that hematite is probably more common in the Lake George Basin than is suggested by the X-ray analysis. It is taken to form as an authigenic mineral in the deep weathering profile and in pedogenic zones of intermittent weathering profiles in the basin sediments.

Lepidocrocite

In drillhole C354 lepidcrocite [FeO(OH)], was identified in a nodule at 48 m by peaks at 6.15 A° (14.4°θ), 2.46A° (36.5°2θ), 1.90A° (47.0°2θ) and 1.73A° (52.8°2θ). Iron in this form may occur where sediments are elevated enough to allow weathering processes to oxidise siderite.

RESULTS AND DISCUSSION

CLAY MINERALS

Assemblages and lithostratigraphy

The clay mineral assemblages outlined in Table 8, equate with (a) deeply weathered bedrock and fluvial sediments formed prior to the basin and (b) fluvio-lacustrine sediments deposited within the basin.

In the pre-basin sediments, a simple clay mineral assemblage of illite, kaolinite and illite mixed-layer clays probably reflects inheritance from sedimentary rocks and weathering processes. As Table 9 shows, illite is more evident than kaolinite (I> K) in ferruginous bedrock. However in leached sand and gravel of the Gearys Gap Formation, kaolinite exceeds illite (K> I).

The basin sediments are characterised by a complex assemblage of illite, kaolinite, montmorillonite, chlorite and montmorillonite mixed-layer clays. The kaolinite and illite are largely detrital; the montmorillonite and mixed-layer clays are authigenic.

Age		Formation	Lithology	Facies	Clay Mineral Assemblage	Source Area	Weathering Conditions	Hydrology	Climate	pH	Eh
LATE MIOCENE? → QUATERNARY	BASIN SEDIMENTS	BUNGENDORE FORMATION	Clay/silt	Lacustrine	COMPLEX Illite Kaolinite Montmorillonite Chlorite Mixed layer clays *(Montmorillonite type)*	Acid and basic igneous rocks & qtz turbidite sediments exposed in basin catchment	Intermittent weathering profiles Palaeosols form in dry lake conditions	Closed drainage system Lacustrine conditions Internal circulation of major elements. Groundwater system may be open at depth.	FLUCTUATING Humid/temperate interspersed with arid periods	Neutral ↓ Alkaline	Negative redox potential (locally positive in weathering profiles)
		ONDYONG POINT FORMATION	Sand/silt, clay	Fluvio/lacustrine							
						TOP	*DEEP* *WEATHERING*	*PROFILE*			
EARLY TERTIARY?	PRE-BASIN SEDIMENTS	GEARYS GAP FORMATION	Sand/gravel (minor silt/clay)	Fluvial	SIMPLE Illite Kaolinite Mixed layer clays *(Illite type)*	Bedrock in enlarged catchment areas extending east. Clay minerals mainly reflect weathering conditions.	Deep weathering profile Full thickness retained below basin sediments.	Open drainage system Fluvial processes dominant. Loss of major elements	UNIFORM Warm/humid High rainfall	Acid	Positive redox potential
EARLY PALAEOZOIC		BEDROCK	Qtz turbidite								

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Table 8. Clay mineral assemblages and depositional environment of Lake George Basin.

<table>
<tr><th rowspan="3" colspan="2">FORMATION</th><th colspan="8">CLAY MINERALS</th><th colspan="8">NON-CLAY MINERALS</th></tr>
<tr><th rowspan="2">Illite (I)</th><th colspan="2">Kaolinite (K)</th><th rowspan="2">K/I Relationship</th><th rowspan="2">Montmorillonite</th><th rowspan="2">Chlorite</th><th rowspan="2">Montmorillonite Mixed layer clays</th><th rowspan="2">Illite Mixed layer clays</th><th rowspan="2">Quartz</th><th rowspan="2">Feldspar</th><th rowspan="2">Amphibole</th><th rowspan="2">Carbonate+</th><th rowspan="2">Halite</th><th rowspan="2">Gypsum</th><th rowspan="2">Siderite</th><th rowspan="2">Haematite</th></tr>
<tr><th></th><th>CI Index</th></tr>
<tr><td rowspan="2">BASIN SEDIMENTS</td><td>BUNGENDORE FORMATION</td><td rowspan="2">Major</td><td>Major</td><td>Uniform</td><td rowspan="2">I>K</td><td>Major ●</td><td>Common ●</td><td rowspan="2">Common ●</td><td rowspan="2"></td><td>Variable (minor to major)</td><td>Variable (trace to minor)</td><td rowspan="2">Local</td><td rowspan="2">Common</td><td>Common</td><td rowspan="2">Local</td><td>Local</td><td rowspan="2">Very local</td></tr>
<tr><td>ONDYONG POINT FORMATION</td><td>Variable (trace to major)</td><td>Variable</td><td>Variable (trace to major)</td><td>Local</td><td>Major</td><td>Variable (minor to major)</td><td>Local</td><td>Common</td></tr>
<tr><td colspan="18">TOP DEEP WEATHERING PROFILES</td></tr>
<tr><td rowspan="2">PRE-BASIN SEDIMENTS</td><td>GEARYS GAP FORMATION</td><td>Variable (trace to minor)</td><td rowspan="2">Major ●</td><td rowspan="2">Uniform</td><td>K>I</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">Common ●</td><td rowspan="2">Major</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">Common</td><td rowspan="2">Local</td><td>Local</td><td rowspan="2">Local</td><td rowspan="2">Very local</td></tr>
<tr><td>BEDROCK</td><td>Major</td><td>I>K</td><td></td></tr>
</table>

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Detrital Minerals
- Illite
- Kaolinite
- Montmorillonite
- Chlorite
- Quartz
- Feldspar
- Amphibole

Authigenic Minerals
- Kaolinite
- Montmorillonite
- Chlorite
- Mixed-layer clays
- Carbonates
- Halite
- Gypsum
- Siderite
- Hematite

$$\text{CI Index} = \frac{\text{Width at 1/2 peak height}}{\text{Peak height}}$$

+ *Mainly calcite and magnesian calcite with traces of dolomite*

● *Units containing authigenic clay minerals.*

Trace minerals found include spessartite, lepidocrocite and barytes.

Table 9. Summary of clay and non-clay mineral distribution for Lake George Basin.

The lithostratigraphy is confirmed by the distribution levels of clay and non-clay minerals (Table 9). The Bungendore and Ondyong Point Formations maybe seperated on the distribution of montmorillonite, chlorite, quartz, feldspar, halite, siderite and the crystallinity index of kaolinite.

Weathering

A deep weathering profile predates the late Miocene formation of the Lake George Basin (Abell 1985). The top of this profile can be defined by a change in the mixed-layer clays, lack of feldspar and montmorillonite and presence of residual kaolinite with a uniform crystallinity index (Figs. 5, 6, 8 and 9). Although core recovery in sand and gravel was poor and samples were widely spaced, the top of the profile has been placed at 82 m in C353 and 106 m in C354.

Intermittent ferruginous weathering events in the basin sediments may relate to a depletion or absence of montmorillonite (Figs. 5 and 6) and marked accumulations of kaolinite (Figs. 8 and 9).

Palaeoclimate

Clay minerals in sediments are commonly used as indicators of palaeoclimatic change (Singer 1984). In the continental sediments of the Tarkarooloo basin, Callen (1977) used smectite rich sediments as an indicator of aridity to demonstrate a subtropical to semi-arid climatic trend from the medial Miocene to the Pleistocene. Similar changes within the same timescale have been documented by Thompson et al (1982) for intermontane basins in the northern Rockies.

Following the weathering model of Ollier (1984, pp 73-76), a warm humid climate will promote strong leaching and desilicification of clay minerals. In the deeply weathered pre-basin sediments where the hydrological system was open, kaolinite and iron oxides will form with removal of silica and cations in solution. Conversely for basin sediments deposited in a closed hydrologic system, silica and cations cannot easily move from the depositional site. The reverse process of silicification will lead to an accumulation of more complex clay minerals such as montmorillonite which are independent of climatic parameters.

In summary, kaolinite attests to a high leaching, humid climate. Montmorillonite (in soils) on the other hand maybe an indication of aridity in that leaching is reduced. However the montmorillonite in the Lake George sediments is mainly authigenic, deposited in a swampy environment and therefore reflecting humid conditions.

Post-depositional alteration

A literature survey of non-marine clay mineral data in Grim (1968), indicates that only slight diagenetic changes can be expected in freshwater lake sediments. However the listing of authigenic clay and non-clay minerals in Table 9, suggests that post-depositional alteration may influence the distribution pattern of clay and non-clay minerals in the basin sediments.

It has been noted that the mobility of silica and adequate amounts of K, Ca, Na and Mg ions will ensure alteration of clay minerals by depletion or accumulation of silica and cation exchange processes. Other factors such as pH conditions, salinity levels and release of porewaters during sediment compaction may have roles in post-depositional alteration that await investigation.

SECONDARY MINERALS AND GEOCHEMISTRY

Carbonates

Calcite, dolomite and siderite occur in small quantities in the Lake George sediments. Models for the genesis of these minerals maybe speculative but their presence is possibly evidence for climatic change and post-depositional alteration in the basin.

Dolomite can form from any natural solution providing the Mg/Ca ratio is over 1:1. It can also be precipitated by ionic dilution when Mg-rich saline water is diluted with freshwater (see figs 1 and 2 in Folk and Land, 1975). In the Lake George Basin dolomite may crystallise where there is an interaction of fresh (meteoric) lake water with saline groundwater (a process aided by seiche activity). The mixing zone is likely to be within the top few metres of the lake bed sediments where dolomite has already been identified in the cores. In another model phreatic groundwater recharging sandy sediments marginal to the lake and moving towards the centre of the basin may take up available Mg ions and precipitate dolomite. Such a model might explain the occasional dolomite lower in the basin sequence.

At Lake George, an environment may periodically exist for the formation of dolomite by evaporation of saline groundwater. Dolomite in the upper few metres of the lake bed sediments may form by evaporative pumping during relatively dry periods of climate. Dolomite has also been reported from the upper 2 m of lacustrine muds at Lake Keilambete in Victoria (Bowler, 1981).

According to Leeder (1982), siderite will form in diagenesis where low dissolved sulphide concentrations are coupled with high dissolved carbonate, high Fe/Ca ratios, low Eh and near neutral pH. Such geochemical conditions tend to restrict siderite to non-marine diagenetic environments low in SO_4 ions and where abundant Fe^{2+} is present as in subtropical weathering conditions. The mineral therefore is expected to form in deltaic swamp facies where there is restricted water circulation; similar conditions have existed locally in the fluvio-lacustrine environment in the Lake George Basin.

Evaporites

The poor development of evaporite salts is an unusual feature of the lake sediments. Since Lake George lies in a closed drainage basin evaporites might be expected in greater quantity in upper portions of the lake sediments. The lack of evaporites may be identified with observations that (a) the basin is not a groundwater discharge area, (b) the regional climatic system is such that the lake does not dry out seasonally; in fact as the modern hydrographic record shows, water remains in the lake over long time periods, (c) replenishment of the lake is by low salinity meteoric water (rainfall and run off) rather than high salinity brines, (d) the basin sediments do not show characteristics of a playa-like complex. Playa conditions only form temporarily during terminal phases of the lake.

A model is needed to explain the dispersal and long term accumulation of salt (halite and gypsum) in the basin sediments. Rain-bearing westerly winds from the interior of the continent and easterly winds from the coast deposit salt over the basin. Weathering and erosion of rocks in the catchment also releases salt which is carried towards Lake George by surface runoff. Presumably the result of these processes is a long term increase in the amount of salt trapped in the depositional system of the basin.

An interchange of salt between lake and groundwater bodies is postulated by Singh et al (1981). In dry phases, vertical diffusion carries halite and gypsum down to the groundwater body. The salt storage capacity of groundwater in the Lake George Basin will depend on the hydrogeologic regime, the permeability distribution of the basin sediments and the palaeohydrolgic behaviour of Lake George. A study of seiche activity on Lake George by Torgerson (1984) suggests that low salinity lake water may infiltrate the lake bed to moderate salinity levels in the groundwater system (see Fig. 4).

At present it is unclear whether the groundwater body in the Lake George Basin functions as an open or closed system (Abell 1985). The mineralogical evidence from drill hole logs C353 and C354 (Figs. 5 and 6) indicate that halite and gypsum decrease in the Ondyong Point Formation and pre-basin sediments. This maybe evidence for an open hydrologic system at depth. If there is slow groundwater leakage from the basin it can be expected that evaporite minerals will not be precipitated since groundwater salinities have not evolved enough for salts to remain in solution.

MAJOR ELEMENTS

Analytical techniques

The specimens from C354 were analysed for major elements by optical emission spectroscopy using a Hilger spectrograph. The analytical method employed was an adaptation of one used by Waring and Annell (1953).

A small portion of sample was oven dried at 120°C for 24 hours. The dry sample was ground to a powder in an agate pestle and mortar. The sample was loaded into a preformed graphite electrode (National Carbon Company Type L4206). The anode was arced for 60 secs using a 6 amp DC current, which drove off the more volatile elements such as Na, K, Li, Sn, Cu and Pb. Another arcing for 60 secs using a 12 amp DC current drove off the remainder of the elements. Two types of spectrum analysis plates were used for identification of the elements. The Kodak No. 1 plate had a range up to 4,300A° and the Kodak No. 3 plate, a range up to 5,500A°. The plates were developed over a 5 minute period at 20°C using Kodak D-19 developer. The spectrogram of the elements was identified using a Jarrel ash double beam comparator.

The total number of elements analysed ws 20. The relative abundance of the elements was estimated in a semi-quantitative manner by division into three groups as shown by a range of approximate percentages (Table 10). The semi- quantitative estimation of the percentage ranges for the elements was by visual comparison of the intensity and thickness of spectral lines. A computer program was devised to handled the spectrographic data. The distribution of major elements in drillhole C354 is shown by simplified histograms (Fig. 6).

Zinc is not listed among the major elements analysed as the optical emission method used in this investigation was unsuitable for the detection of zinc especially when sodium is present. It is assumed that zinc is present in the local geochemical environment. West of Woodlawn mine, Ryall & Nicholas (1973) describe zinc anomalies which show hydromorphic dispersion downslope of the ore zone.

RESULTS

The assemblage of major elements identified in C354, largely reflect their dispersion and retention characteristics in the natural geochemical environment of the Lake George Basin. Table 11 is an attempt to classify the elements in terms of their expected mobility in the secondary environment of weathering, erosion and sedimentation (data adapted from Levinson 1974 and Butt and Smith, 1980). The more important factors

Major elements	%	ppm	Distribution
Major	>0·5	>5000	Si, Ti, Al, Fe, Mg, (Na), (K), (Ca)
Minor	0·05—0·5	500—5000	Mn, Ca, Na, K, Ba, (Cr), (Sr)
Trace	<0·05	<500	(Ba) Sr, Li, V, Co, Ni, Cn, Sn, Pb, Cr, Mo

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Minerals in brackets may also occur frequently in another category.

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Table 10. Semi-quantitive distribution of major elements in C354.

Mobile elements		Immobile elements
Mg		Si
Ca	← →	Al
Na	Fe	Ti
K	Mn	Cr
Co	Ni	Ba
Sr	Li	Sn
V		Pb
Mo		
Cu		

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MOBILE ELEMENTS are dispersed easily in a geochemical environment.

IMMOBILE ELEMENTS are generally stable and retained in weathering profiles

Fe, Mn, Ni and Li may be mobile or immobile depending on the nature of the geochemical environment.

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Table II. Mobility of major elements

affecting the mobility of these elements in the natural geochemical environment will be pH, Eh, fluid media (surface and groundwater distribution), solubility of salts and the adsorption properties of various clay minerals and oxides. At this stage it has not been possible to evaluate the relative importance of these parameters with regard to the element data in C354. Further, since samples from only one drillhole were analysed only a very preliminary interpretation can be placed on the analysis.

In this investigation the distribution of major elements is interpreted as a function of the capacity of clay minerals and iron/manganese oxides to adsorb the more mobile elements dispersed in the geochemical environment. Distinct correlations are not possible with clay and non-clay mineralogy, weathering profiles and units of the lithostratigraphic sequence. Unfortunately there are no other element analyses of subsurface sediments in the basin available for comparison.

The quantitative distribution of the elements seems to be representative of normal geochemical background levels. For example values of Mn, Ba, Sr, Cr, Cu, Ni, Li Pb, Sn, Mo, V and Co compare favourably with the range of abundance of these elements in soils (Levinson 1957, table 2-1 and figure 3-13). There is no indication that these elements occur in anomalous quantities in the sediments of the Lake George Basin. It is expected that elements such as Si, Al, Fe, Mg, Ca, Na, K and Ti will occur in major quantities since they are common components of rock-forming minerals.

Elements showing the greatest degree of change in the sequence are Na, K, Mn and Cr. Sodium and potassium vary independantly of one another. Potassium is known to be a major element in illite, but the change in the intensity levels of illite as measured by peak height did not find any obvious consistency with variation in potassium shown by emission spectroscopy. Manganese and chromium have similar chemical properties and tend to be immobile in the geochemical environment. It is assumed that their variability relates to differing capacities for cation adsorption by clay minerals.

Titanium is found regularly in major amounts. It is derived from basic rocks containing oxides e.g. ilmenite, which are resistant to weathering. Titanium tends to be insoluble and poorly mobile and is enriched in the deep weathering profile. In the basin sediments titanium is depleted locally to minor levels.

Tin is strongly resistant to weathering and occurs as a detrital element in trace proportions in the Gearys Gap Formation (119.75-139.75m). Tin appears to have been remobilised and re-deposited in the younger formations of the basin sequence.

Iron is common as a major element, particularly in weathering profiles. However it is moderated locally in the leached kaolinitic portions of the deep weathering profile (130.25 - 134.75 m).

Molybdenum occurs in trace quantities in the Bungendore Formation. Its origin is not clear but according to Wedepohl (1978), molybdenum is a mobile element and can be enriched by adsorption in organic rich clays. Some of the black clays in the Bungendore Formation appear to be rich in organic matter, but there is a lack of supporting quantitative data.

A background level for copper is indicated by its consistent trace quantities throughout the sequence. These levels are exceeded where copper occurs locally in minor quantities near the top and bottom of the Bungendore Formation. Its concentration may be due to cation adsorption by montmorillonite after carriage as a chloride complex in subsurface saline groundwater.

Significance of the element analysis

The Lake George Basin maybe a useful study area to determine and perhaps monitor geochemical processes operating in fault-bounded drainage basin. Assuming for the most part that normal background levels of metals exist in surrounding bedrock, there must be potential for the redistribution and concentration of these metals into the closed depositional system of the Lake George Basin. Some of the factors expected to influence such a distribution of metal ions are summarised in Table 12.

At this stage there is no evidence of anomalous mineralisation in the basin sediments. A study involving subsurface sediment analysis and hydrogeochemical sampling could provide a conceptual model that outlines the geochemical parameters affecting metal deposition in the Lake George Basin. If the study was positive enough to show the basin was a potentially suitable environment for the entrapment of metals, if might find application as an exploration aid to other similar depositional environments in humid areas of Australia.

When the lakebed is again accessible for drilling, it is recommended that water samples are obtained to study the hydrogeochemical dispersion of elements in the ground water system. In the meantime a substantial amount of drillcore is stored in refrigerated premises at Fyshwick. The core has been packed in an attempt to retain as far as possible the original moisture content and condition of the sediments.

LAKE GEORGE BASIN	Rejuvenated terrain; partly fault bounded basin; truncation of surface drainage; reduced catchment area; deep weathering profile attenuated in catchment but full thickness preserved beaneath fluvio-lacustrine deposits. Distribution of elements in basin sediments will reflect nature of catchment bedrock, weathering and mineralisation (Woodlawn Mine). Complex hydrological and hydrogeochemical conditions; subsurface saline environment; ground water main transporting agent for accumulation of metals in sediments. Clay dominated lacustrine sediments and intermittant weathering profiles suggest accumulation of metals and major elements by cation adsorption (Cu, Mo etc.); rapid changes in pH and redox conditions; permeable paleodrainage lines in pre-basin terrain cut off from recharge maybe in a reducing environment favourable for uranium. Top deep weathering profile
PRE-BASIN TERRAIN	Moderately dissected palaeorelief. Open hydrological conditions; surface runoff in drainage lines directed NW, catchment areas large and extending E: heavy minerals (zircon, tourmaline, ilmenite, magnetite etc.) and metals (Sn, Au etc.) expected to occur as placer deposits in sands and gravels associated with drainage lines. In situ chemical weathering; oxdising environment with acid pH values; gossan formation; concentration of immobile elements (Al, Fe, Mn, Ti, etc.) in the weathering profile.

Table 12. Factors affecting the occurence of metals in in the Lake George Basin.

CONCLUSIONS

(1) A clay mineral assemblage of illite, kaolinite and illite mixed-layer clays equate with early Palaeozoic bedrock and early Tertiary? fluvial sediments formed prior to the Lake George Basin.

A younger and more complex clay mineral assemblage of illite, kaolinite, montmorillonite, chlorite and montmorillonitic mixed-layer clays is associated with late Tertiary and Quaternary fluvio-lacustrine sediments deposited within the basin.

(2) Clay and non-clay minerals (a) largely reflect a provenance of acid and basic igneous rocks and quartz turbidite sediments outcropping in the catchment to the east of the lake area and (b) confirms in a general way the late Miocene to Recent lithostratigraphic divisions proposed for the sediments in Lake George.

(3) Weathering processes and post-depositional diagenesis in the Lake George Basin accounts for the presence of authigenic mixed-layer clays, carbonate minerals, halite and gypsum. Evaporite sequences are absent.

(4) The clay mineralogy is not quantitative enough to be used as an index of palaeoclimatic change. Kaolinite in deeply weathered pre-basin sediments indicates warm, humid, leaching conditions prior to the late Tertiary. The presence of montmorillonite in the basin sediments also indicates humid conditions as it forms when the lake is full. Depletion of montmorillonite in weathering profiles suggests drier phases and a fluctuating climate in the late Tertiary and Quaternary.

(5) In the pre-basin sediments, uniformly high levels of residual kaolinite supports a proposition of in situ weathering and almost total degradation of feldspar. In the basin sediments a detrital origin for kaolinite is supported by its uneven distribution and non-correlation with feldspar.

(6) The distribution of major elements in drillhole C354 is a function of the capacity of clay minerals and Fe/Mn oxides to adsorb the more mobile elements. The semi-quantitative distribution of the elements seems to indicate normal geochemical background levels. There is no evidence of anomalous mineralisation in the basin sediments.

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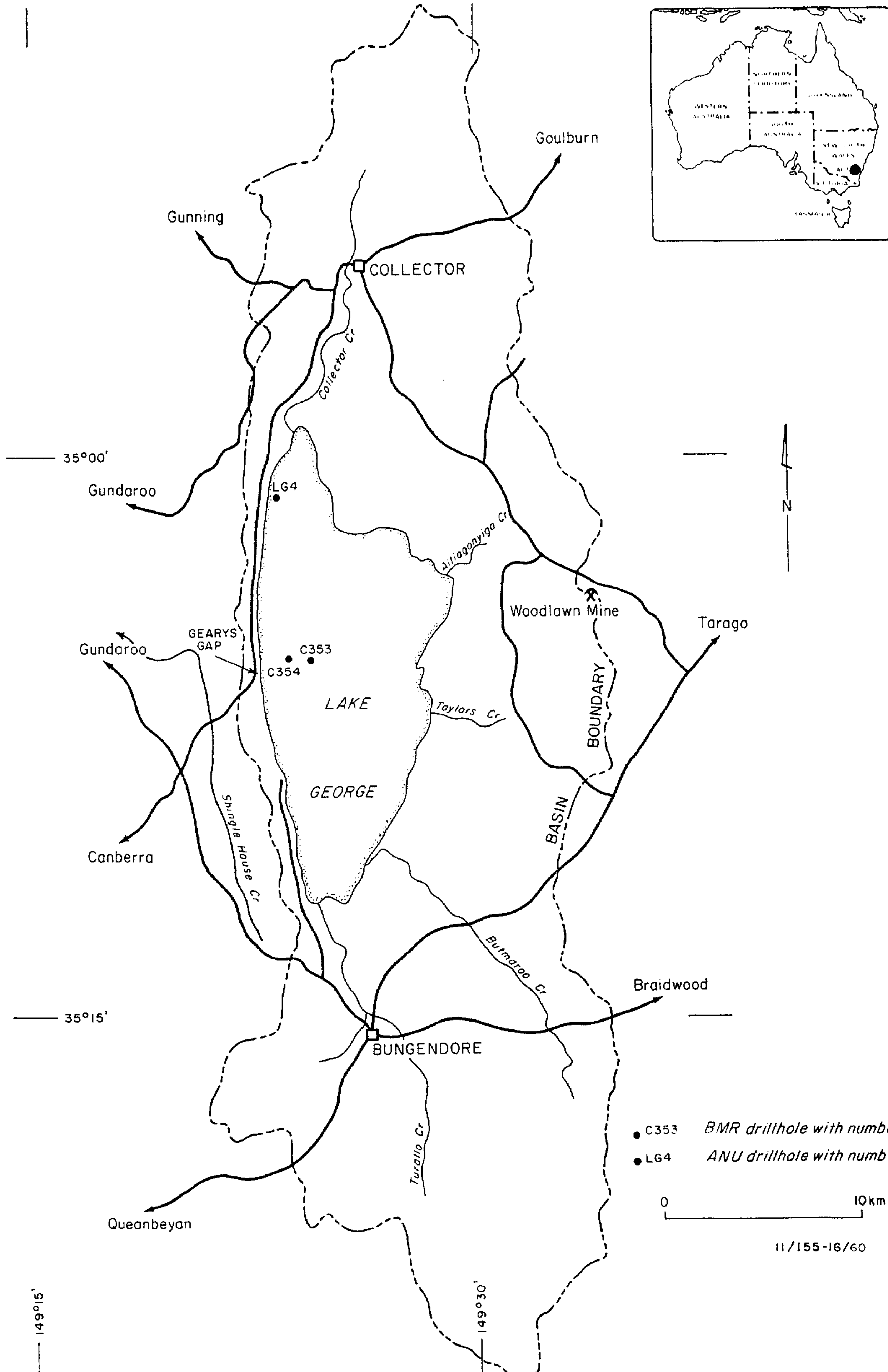

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Fig. 1 Lake George Basin and drillhole locations

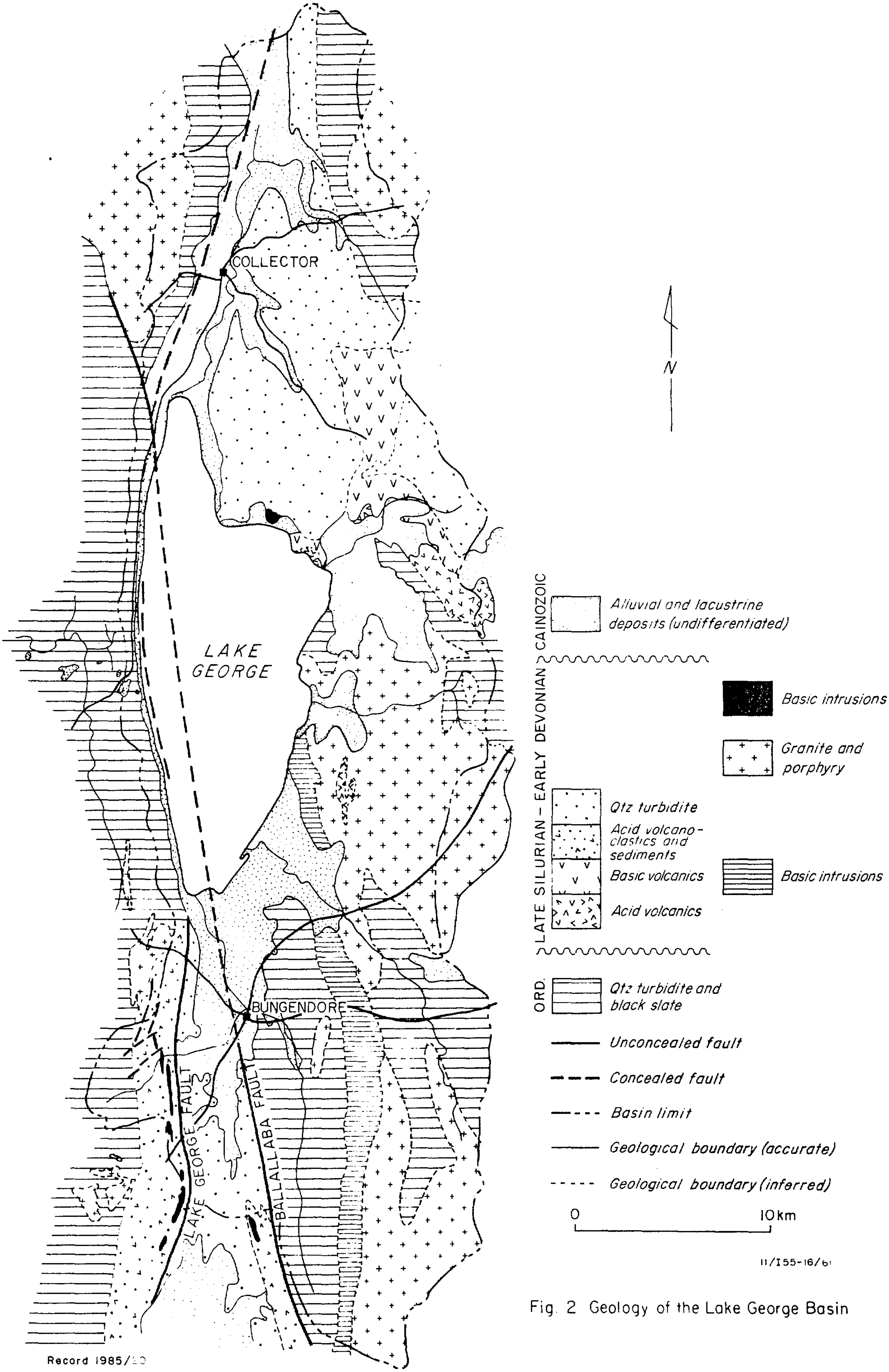

Fig. 2 Geology of the Lake George Basin

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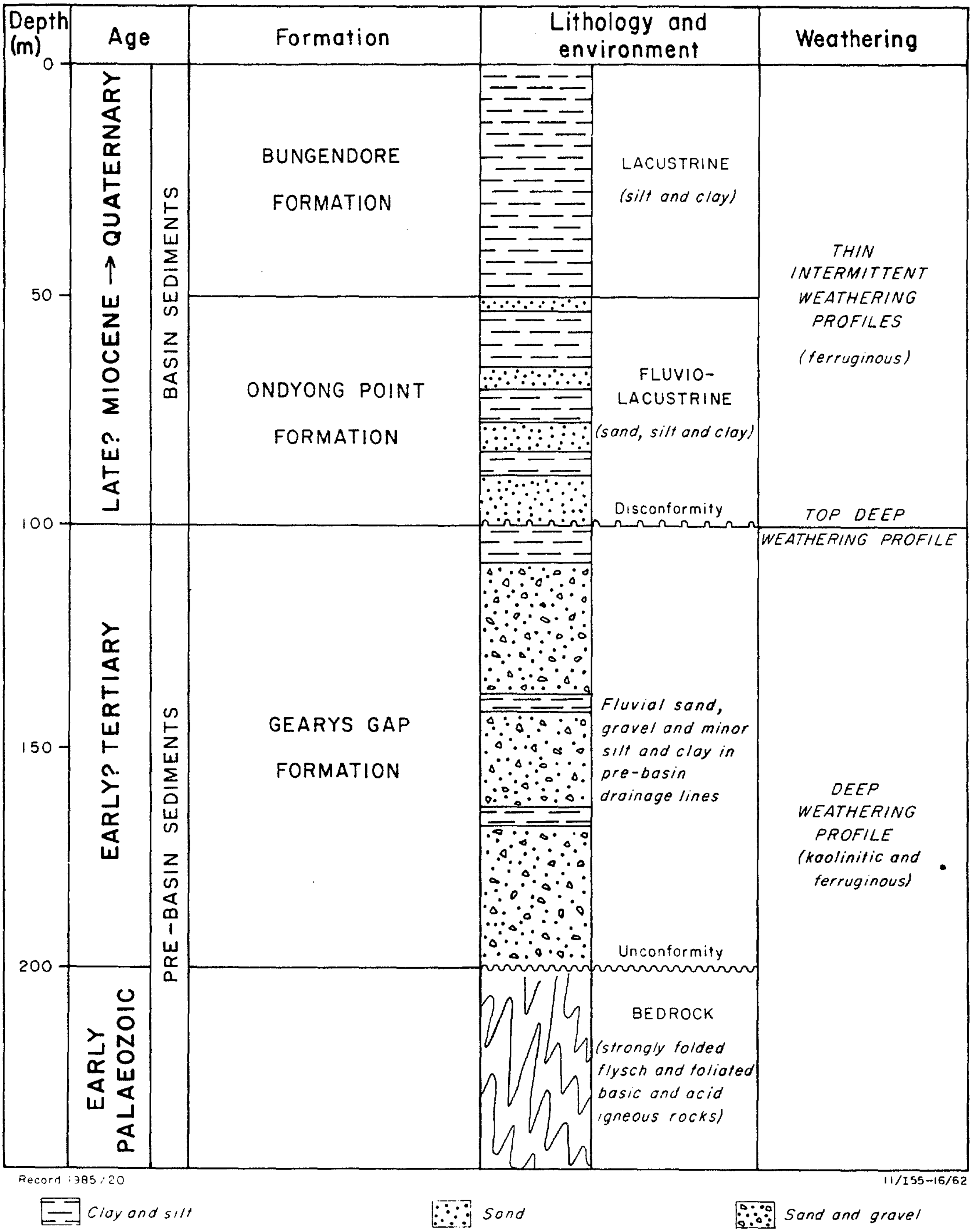

Fig. 3. Lithostratigraphic units

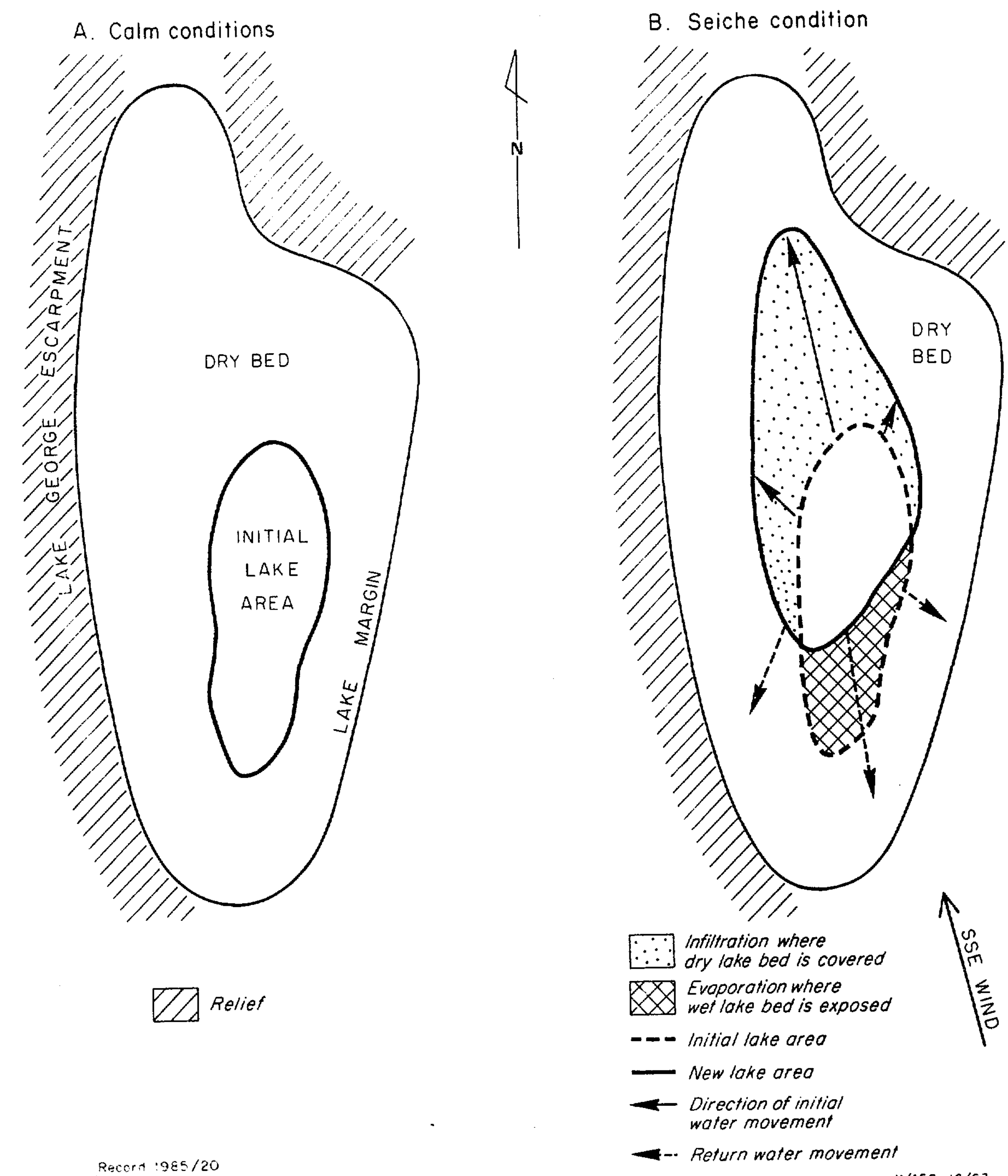

Fig. 4 Hydrologic effects of the seiche

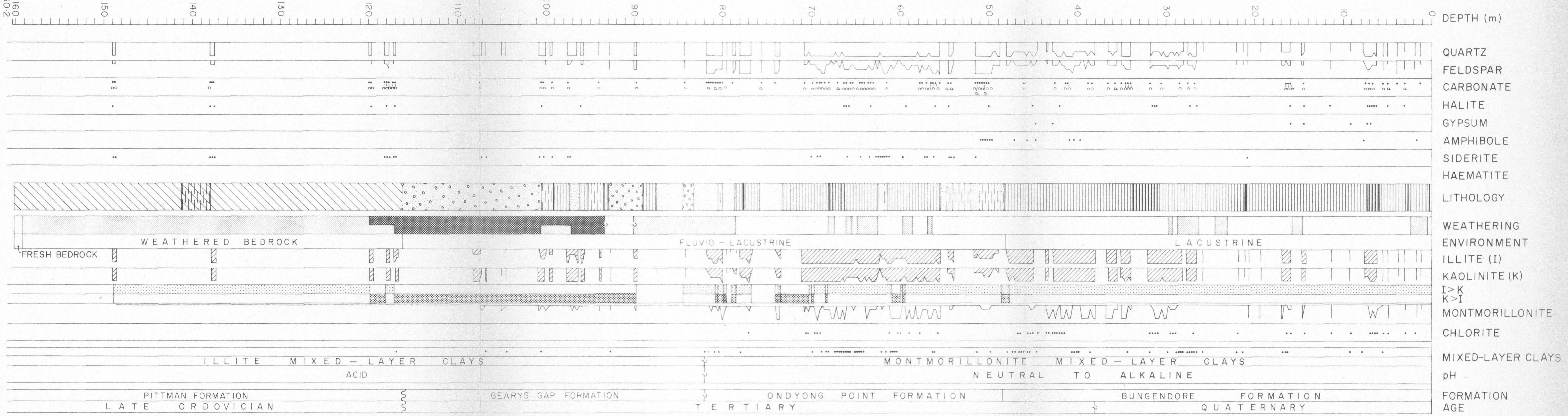

Fig.5 Composite log of the mineralogy in drillhole C353

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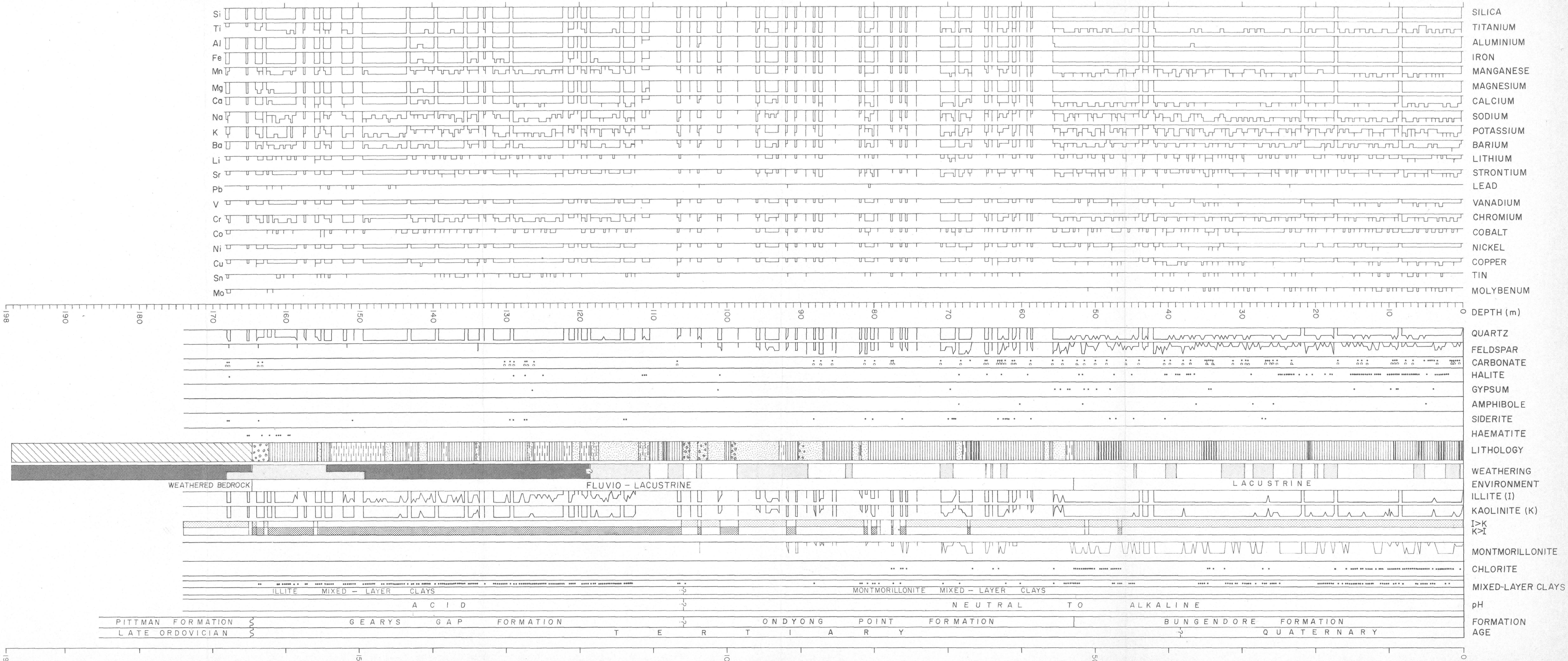

Fig 6 Composite log of the mineralogy and major elements in drillhole C354

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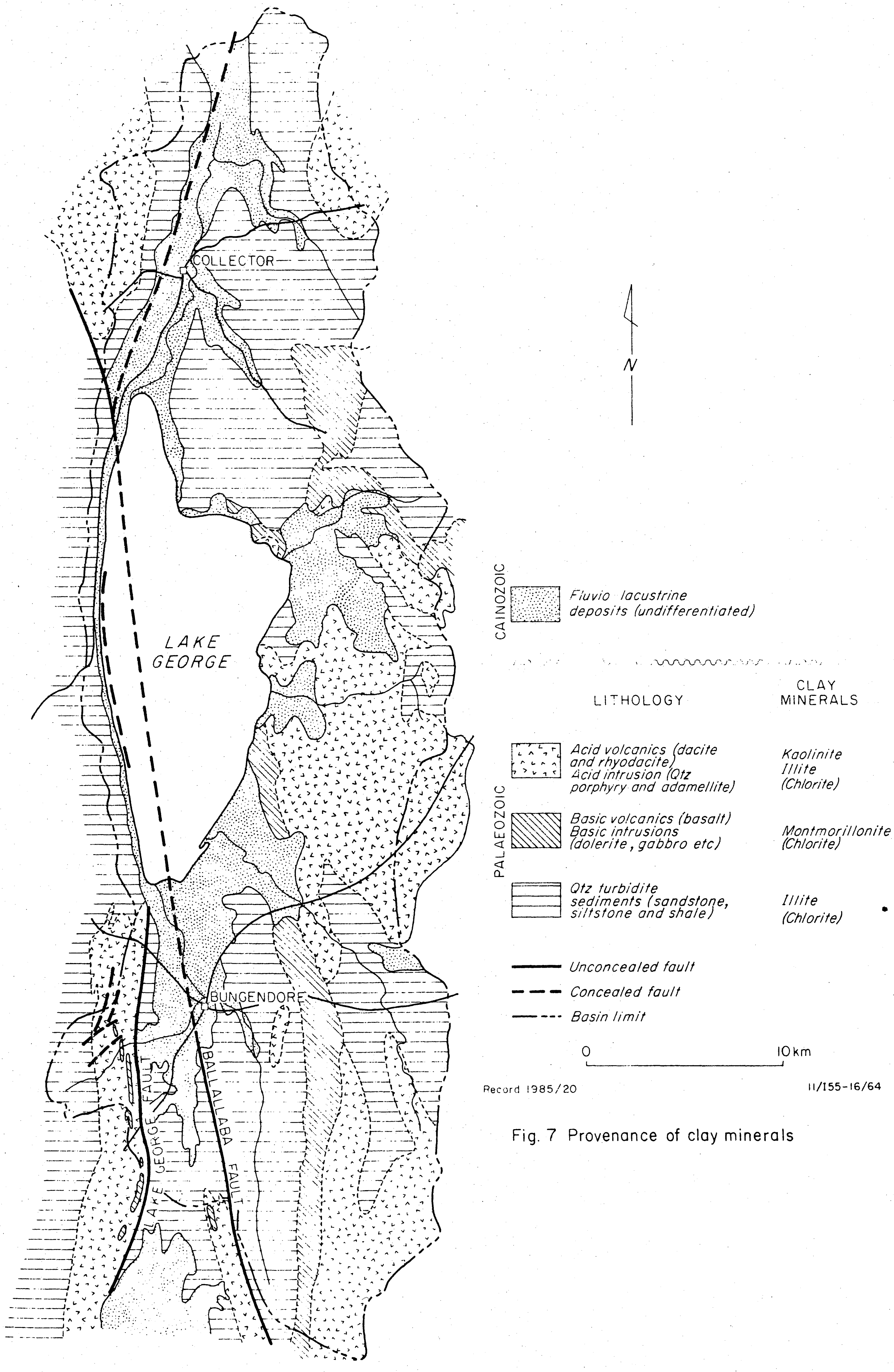

Fig. 7 Provenance of clay minerals

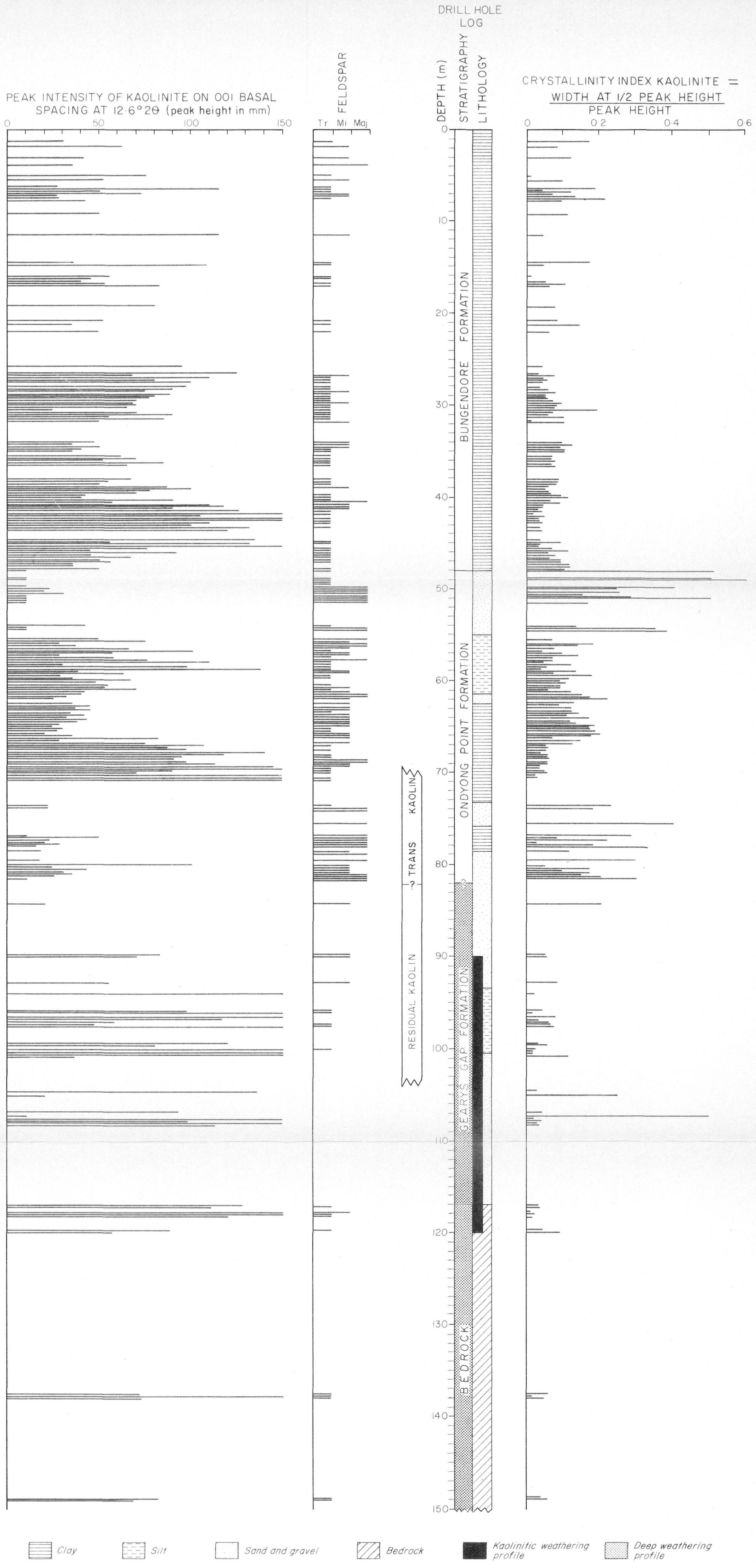

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Fig. 8 Vertical distribution and relationship of kaolinite and feldspar in drillhole C353

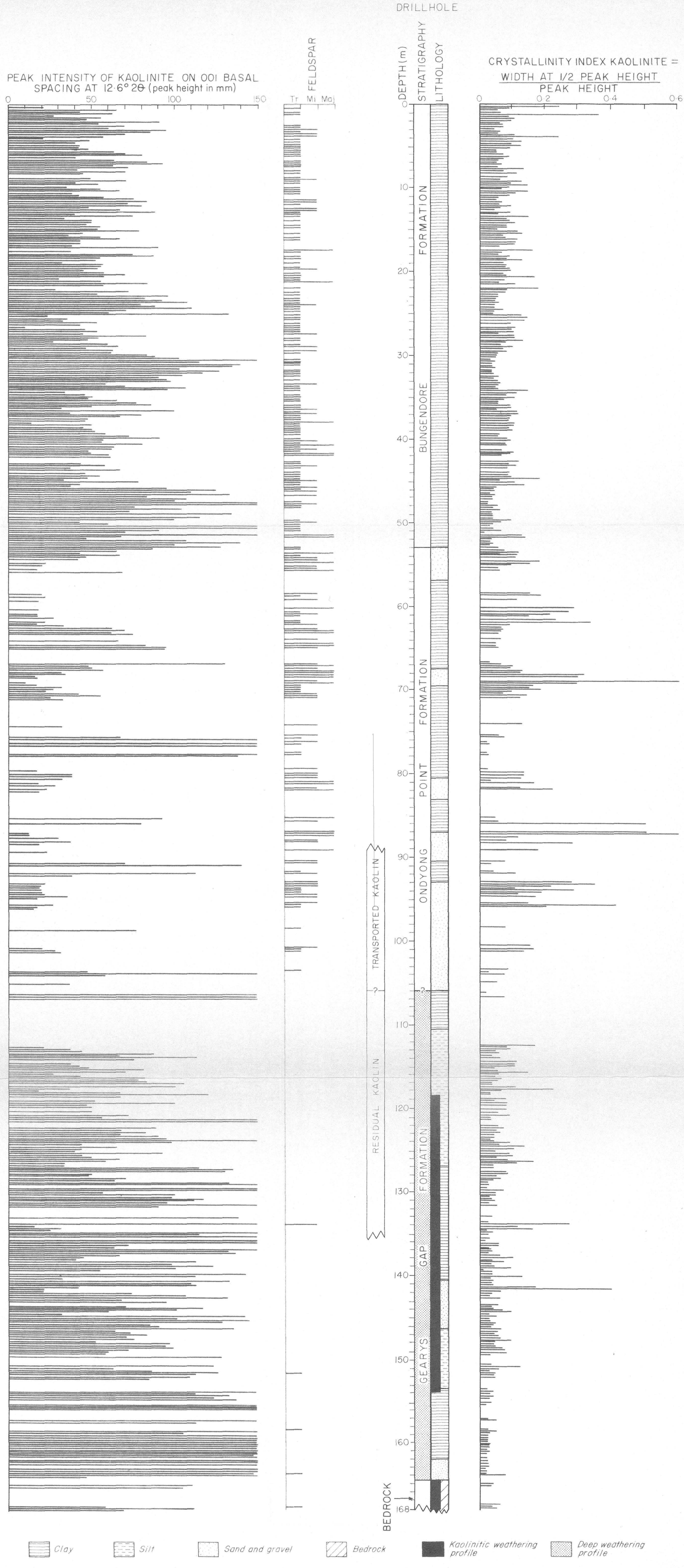

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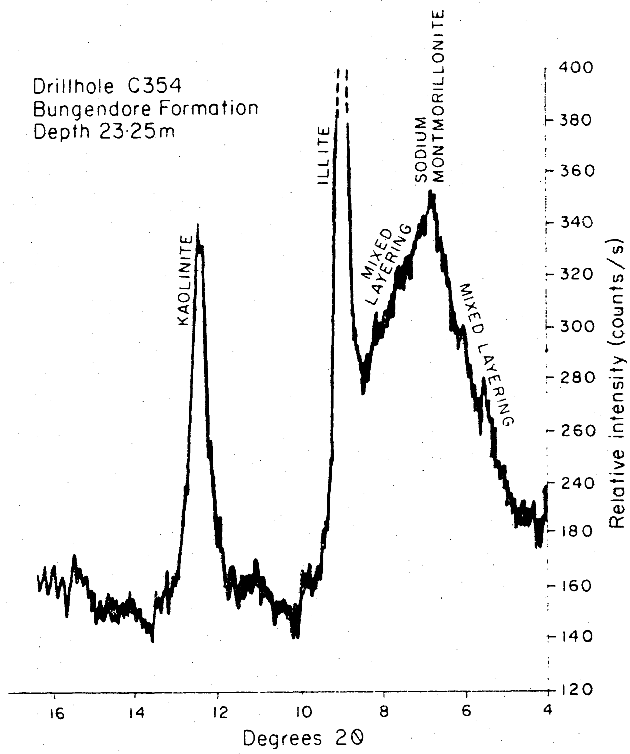
Fig. 9 Vertical distribution and relationship of kaolinite and feldspar in drillhole C354



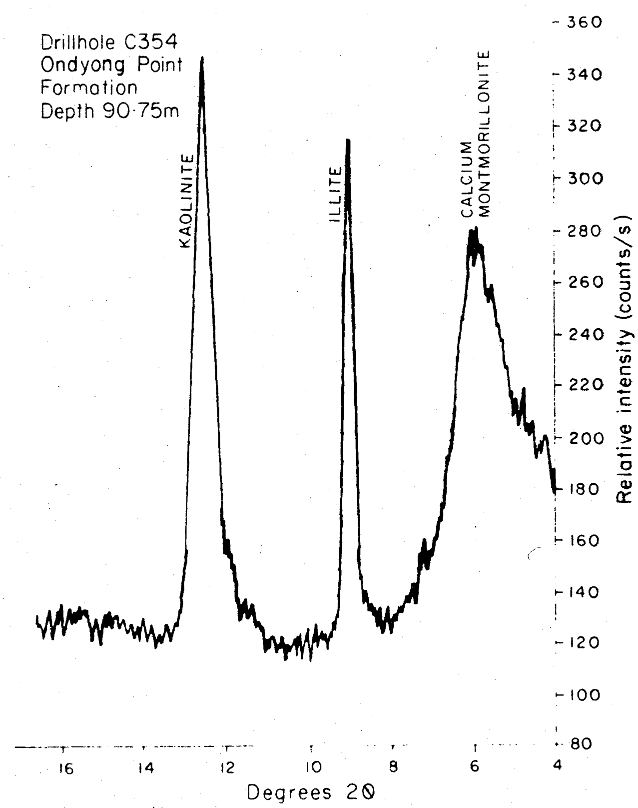


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Fig. 10 X-ray diffractograms for montmorillonite showing variation in peak character and position

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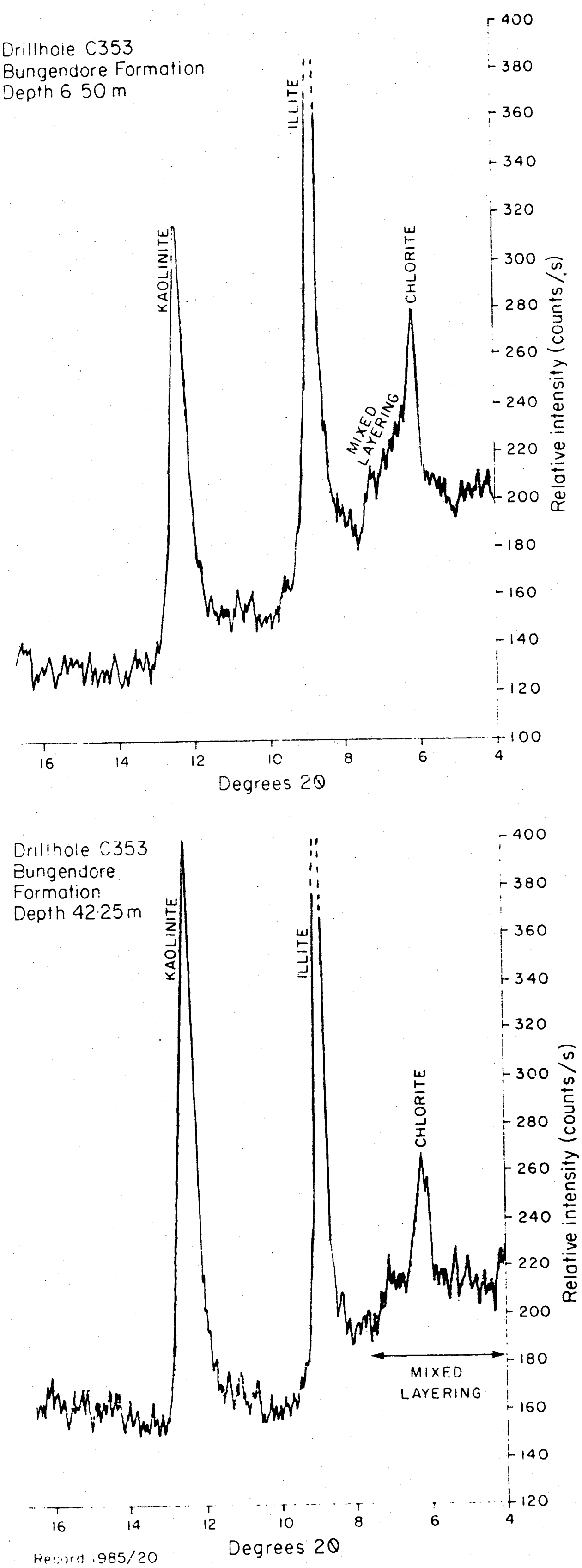

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Fig. 11 X-ray diffractograms for chlorite

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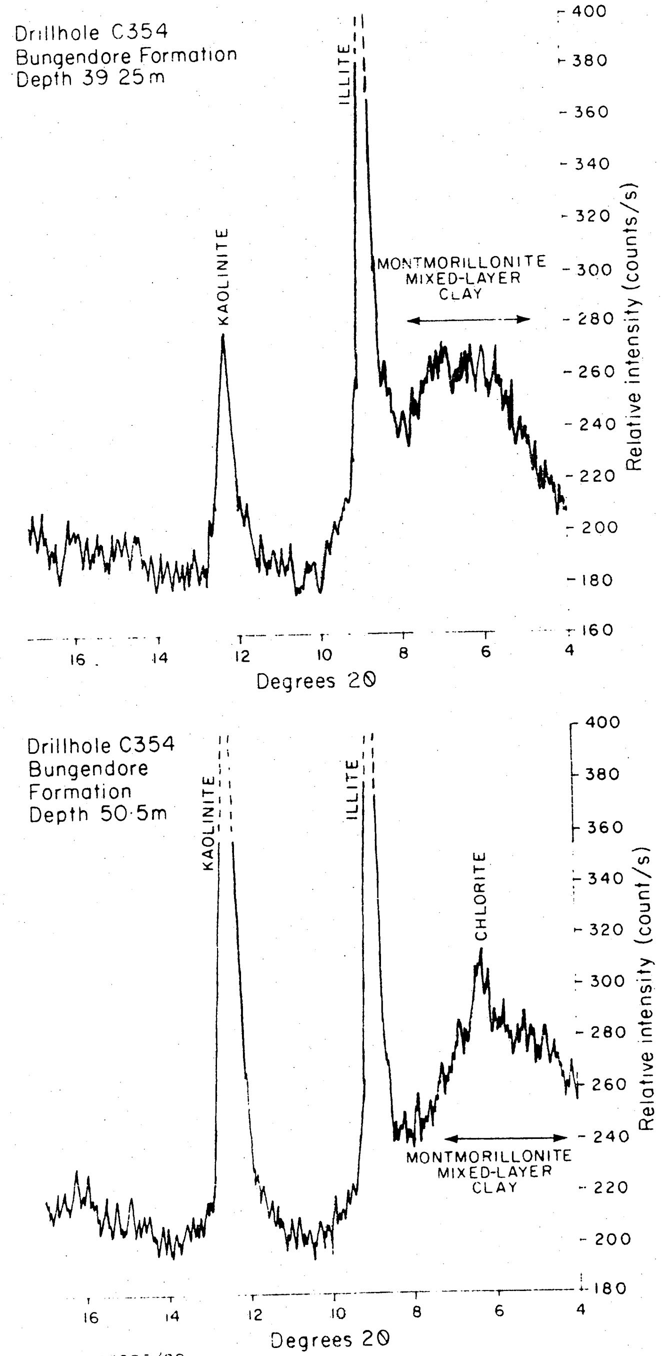

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Fig. 12 X-ray diffractograms for montmorillonite mixed-layer clays

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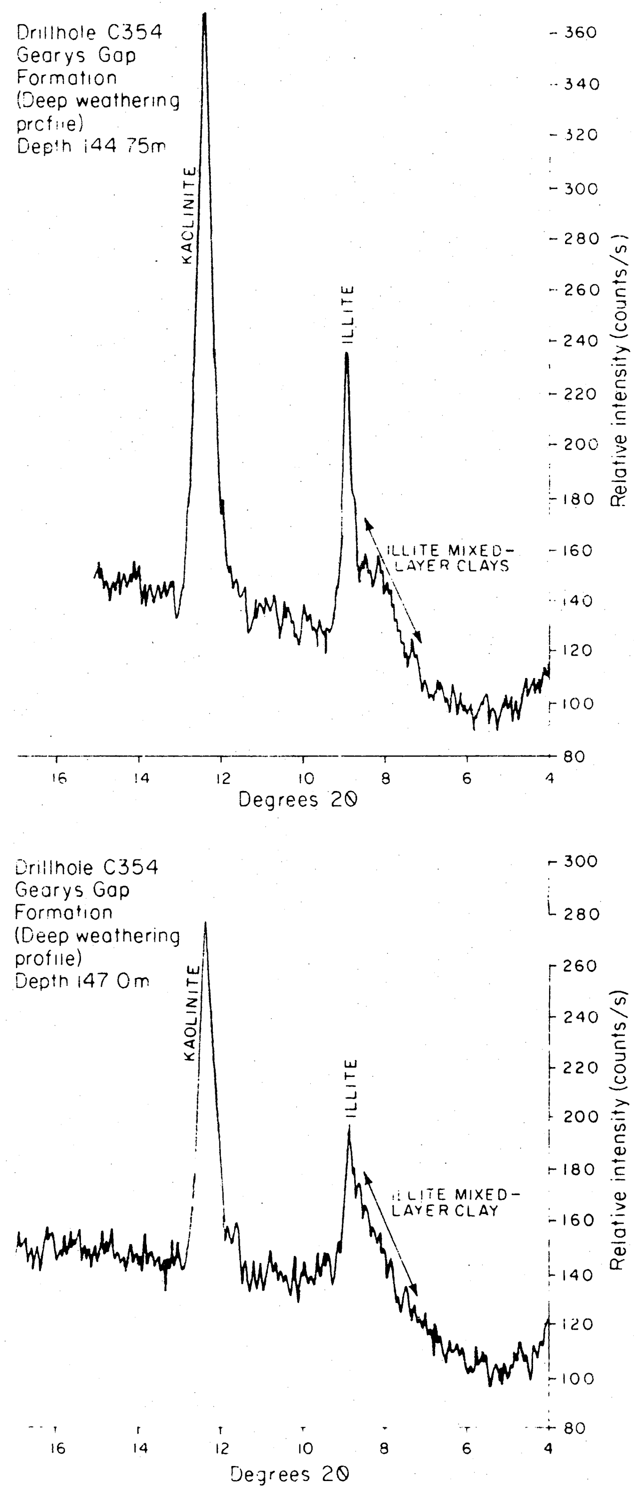

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Fig. 13 X-ray diffractograms for illite mixed-layer clays

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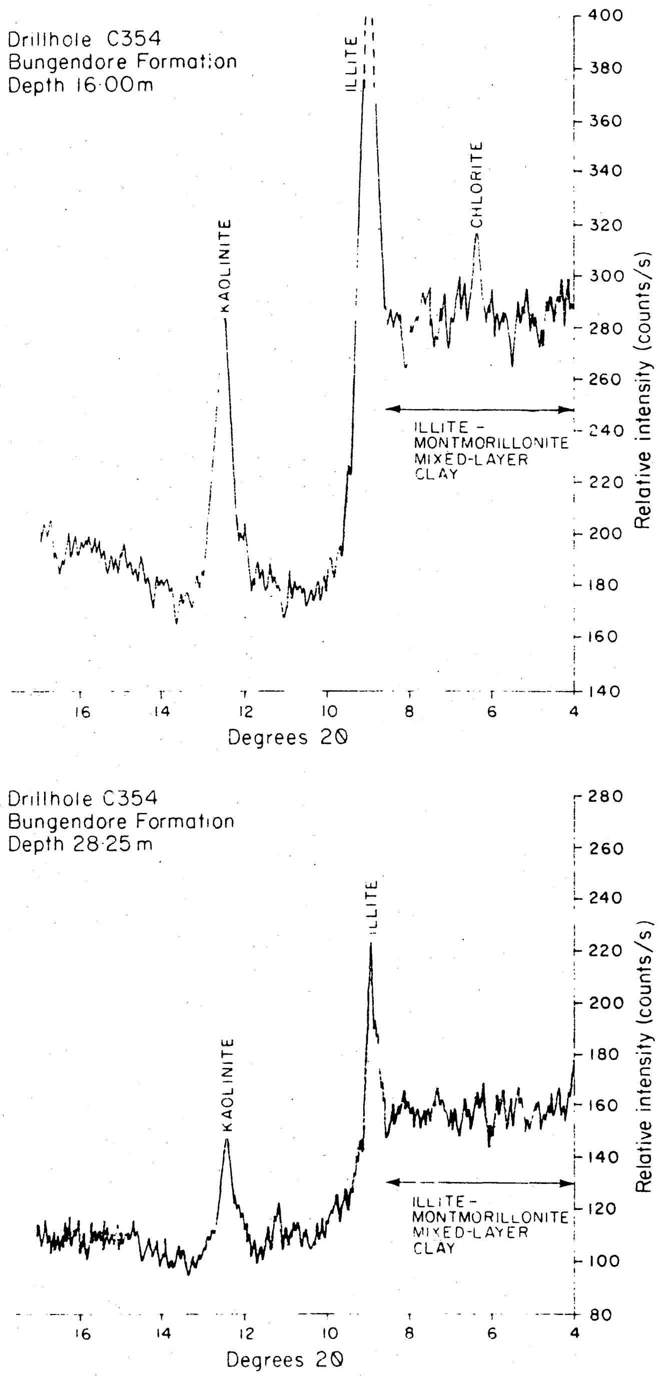

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Fig. 14 X-ray diffractograms for illite - montmorillonite mixed-layer clays

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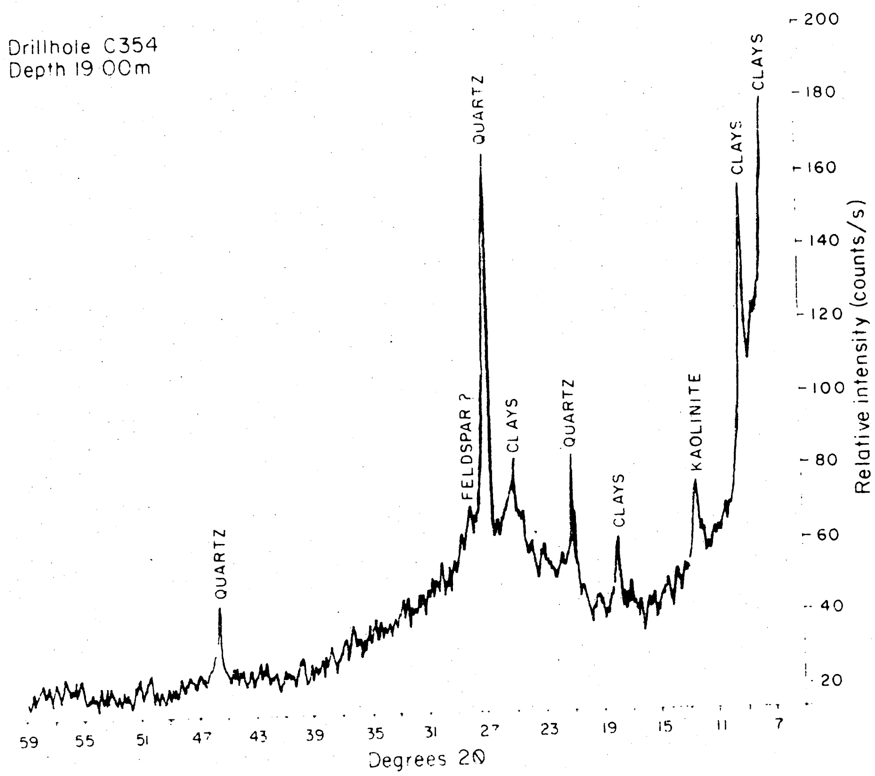

Fig. 15 Typical X-ray diffractogram of quartz from clay in the Bungendore Formation

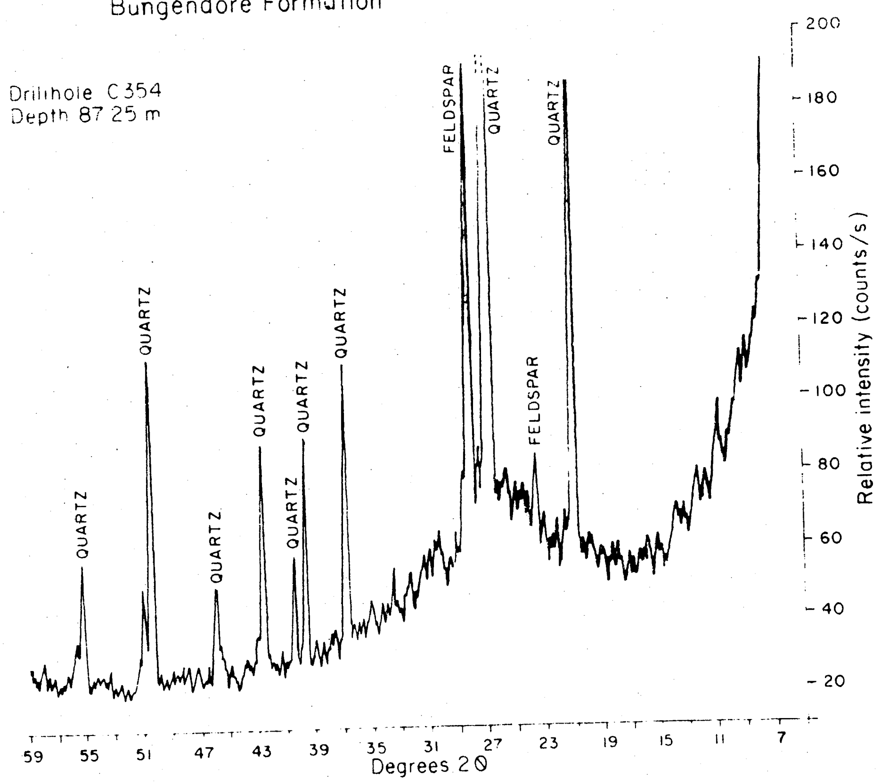

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Fig. 16 Typical X-ray diffractogram of quartz from sand in the Ondyong Point Formation

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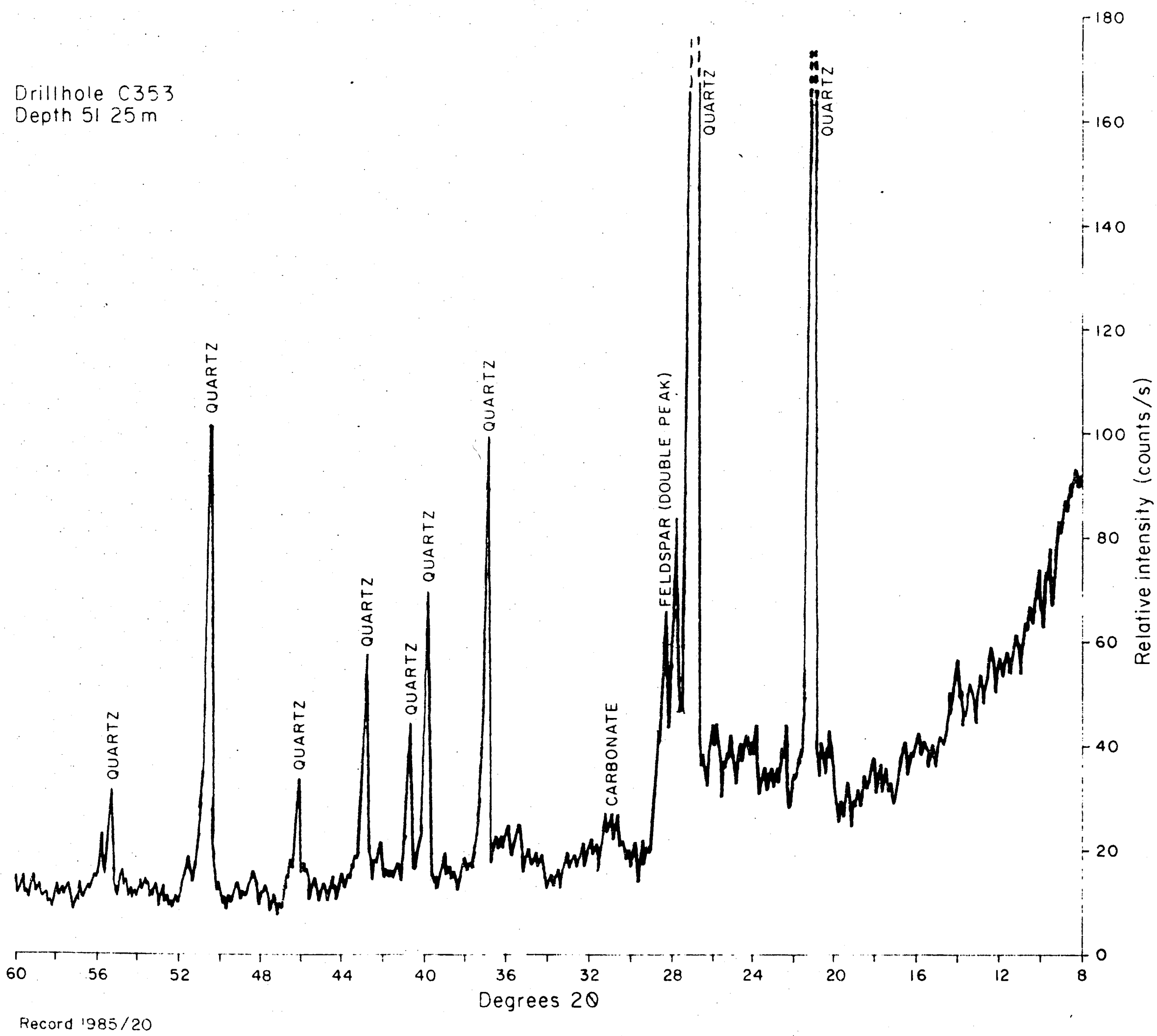

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Fig 17 X-ray diffractogram of feldspar from sand in the Ondyong Point Formation

11/155-16/71

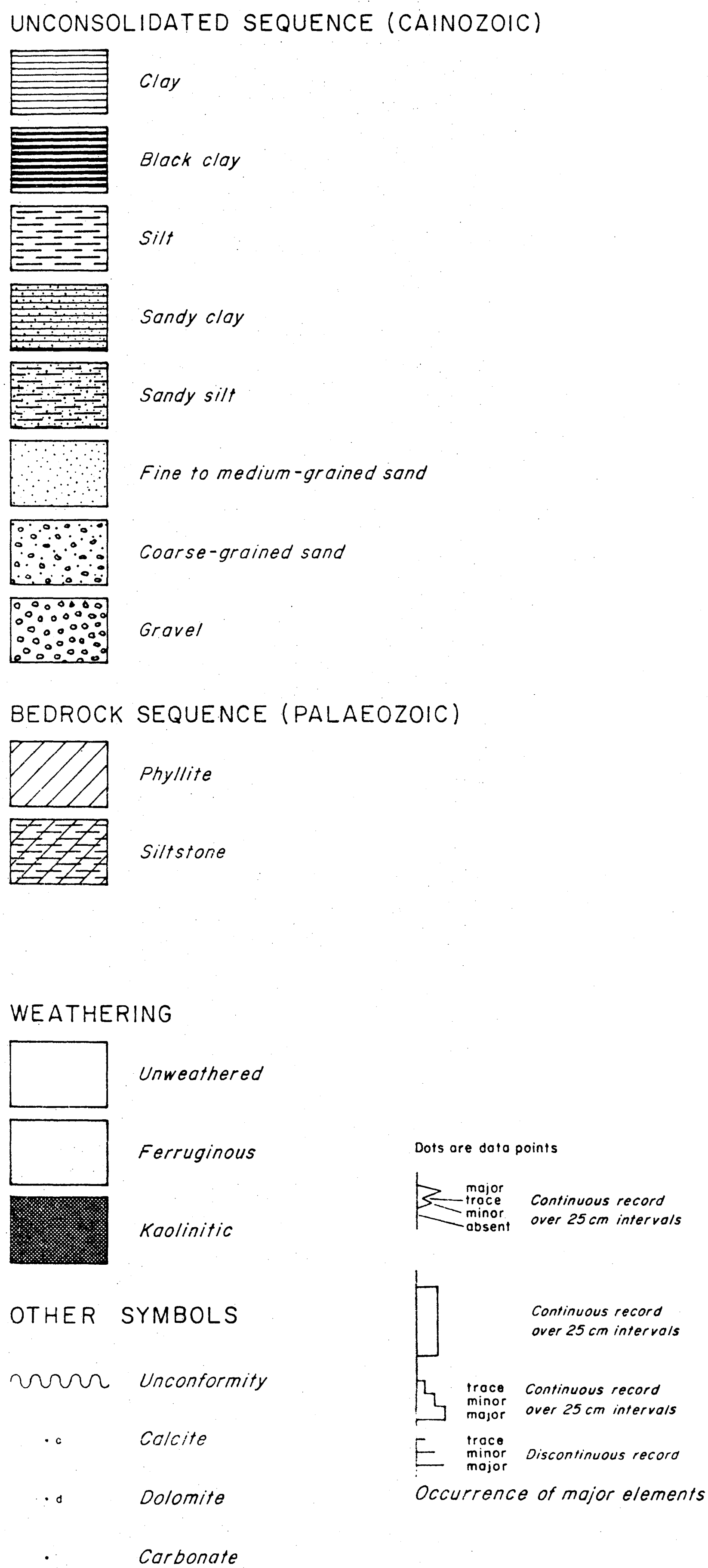

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Fig. 18 Legend for drillholes C353 and C354