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ABSTRACT

The dispersed carbonaceous matter (kerogen), illite, and magnetic response of the Tindelpina Shale Member in the lower part of the thick, extensive Tapley Hill Formation provide three complementary methods for zoning the low-grade regional metamorphic character of Umberatana Group (Adelaide System) sediments as they crop out between Adelaide, Olary, and Marree in the Adelaide Geosyncline. The methods are based on the following parameters: kerogen structure (as determined by X-ray diffraction) and composition (percentage carbon, hydrogen to carbon atomic ratio, $\delta^{13}C_{PDB}$); illite crystallinity; and amplitude and type of aeromagnetic anomalies.

Kerogen is the most definitive indicator of metamorphic change in the Tindelpina Shale. It has been used to delineate a western subgraphitic zone (85-91%C, $H/C > 0.10$) which is separated from an eastern graphitic zone (91-98%C, $H/C < 0.10$) by a north-trending line through Adelaide, Mintaro, Orroroo, and Baratta. A similar two-fold zonation appears to exist in the Mouth Painter - Copley - Marree area. Metamorphic adjustment stable carbon isotopic composition of the kerogen is also evident. Kerogen rank correlates well with illite crystallinity. Illites in the western zone have Weaver indices of less than six. Crystallinity increases to the east where 2M illite becomes the dominant illite polymorph. The eastern graphitic zone largely coincides in location and extent with a zone of linear aeromagnetic anomalies of amplitude exceeding 100 gammas. In the lower Tapley Hill Formation the anomaly is attributed to remanent magnetism, probably associated with metamorphic growth of magnetite.

All three indicators suggest an increase in metamorphic grade from west to east across the geosyncline, in agreement with published observations based on conventional petrographic analysis of pelitic (and to a lesser extent, carbonate) rocks. Illite and chlorite, characteristic of the anchizone of burial diagenesis, are the major sheet silicates in the shales studied, although incipient metamorphic alteration of chlorite to biotite has

occurred in some specimens from the graphitic zone. The subgraphitic and graphitic facies of the Tindelpina Shale correspond with the chlorite and biotite (and higher) zones, respectively, of low-pressure intermediate-type metamorphism previously established for the Mount Lofty and Flinders Ranges.

Greater depth of burial of the lower Tapley Hill Formation in the eastern half of the geosyncline would account for the metamorphic trend observed in its organic matter and clay mineral content. Differential burial does not, however, adequately explain the magnetics, nor the absence of biotite-grade rocks in the central Flinders Ranges. Other magnetically anomalous beds are found throughout the Adelaide System and in overlying Cambrian strata. For the magnetism in these different stratigraphic intervals to be of metamorphic derivation, a regional thermal event, perhaps related to the Cambro-Ordovician Delamerian Orogeny, must be postulated.

INTRODUCTION

In the Adelaide Geosyncline (Fig. 1), the Umberatana Group of the late Precambrian Adelaide System is notable for its record of two major glacial episodes (Thomson, 1969). Part of the interglacial succession is the Tapley Hill Formation (Coats in Thomson et al., 1964), 3.5 km of thinly and evenly laminated dark grey siltstone which immediately overlies the lower tillite. The basal Tindelpina Shale Member of the formation is of special interest for several reasons. These include:

1. Its persistence throughout the geosyncline (Fig. 2) which makes it a useful lithostratigraphic marker (Thomson, 1969).
2. Its uniform lithofacies; the member is a finely laminated black carbonaceous pyritic shale, with various minor thin sandstone, grit, and carbonate interbeds, less than 100 m in total thickness (Coats, in Thomson et al., 1964).
3. The nature and origin of the carbonaceous matter, particularly in view of its Precambrian age and its association with tillite.
4. The magnetic properties of this interval in the stratigraphic column; strong linear magnetic anomalies are associated with the unit, implying a high magnetic iron content (Tipper and Finney, 1966; Tucker, 1972).
5. Its association with localized secondary copper mineralization (e.g. Summers, 1953; McKay, 1968); otherwise abnormal enrichment in ore metals is not a feature of this particular black shale (Sumartojo, 1974).

Studies of various aspects of this remarkable formation were commenced independently by the authors, as follows: mineralogy and geochemistry (J.S.), magnetic properties (D.H.T.), organic geochemistry (D.M.M.), and sedimentology (V.G.). This paper reports those of our results to date which bear directly on the regional variation in metamorphic grade of the lower Tapley Hill Formation and other late Precambrian (and Lower Palaeozoic) sediments within the Adelaide Geosyncline. Complete accounts of the individual studies will be published elsewhere.

GEOLOGICAL SETTING

The Adelaide Geosyncline of South Australia is an elongate arcuate belt of folded by generally little altered late Precambrian (Adelaidean) and Cambrian sediments extending from Kangaroo Island in the south, northwards through the Mount Lofty and Flinders Ranges to the Barrier Range in the northeast and the Peake-Denison Ranges in the northwest, over a distance of some 1100 km (Fig. 1). It represents a gently subsiding intracratonic mobile zone (or ?aulacogen; Scheibner, 1972) in which up to 24 km (in total stratigraphic section) of sediments of predominantly shallow-water marine or lagoonal facies accumulated between about 1400 and 550 m.y. ago (Thomson, 1969). Thin and flat-lying or slightly folded early Adelaidean sediments extend westwards on to Carpentarian (1800-1400 m.y.) crystalline basement of the Gawler Platform in the area known as the Stuart Shelf (Fig. 1). The basement cover rocks thicken rapidly to the east across the Torrens Hinge Zone and into the fold belt where the sedimentary pile attains its maximum thickness (Thomson, 1970). The exposed sediments of the geosyncline are bounded on the southeast by Cambrian metasediments in the Kanmantoo Trough, and on the east by Cainozoic cover of the Murray Basin, older Precambrian crystalline rocks of the Willyama Block, and Mesozoic deposits in the Lake Frome Embayment of the Great Artesian Basin. Two other groups of basement inliers, the Mount Painter and Denison Blocks, and the subsurface Muloorinna Ridge which runs between them, together define the northern margin of the geosyncline. Although named and described as a miogeosyncline by Sprigg (1952), this important site of prolonged Precambrian sedimentation is not a typical geosyncline (Geol.Soc.Australia, 1971 - Tectonic Map of Australia and New Guinea, 1:5 000 000, Sydney).

The Precambrian sedimentary sequence of the Adelaide Geosyncline has been subdivided into four parts, each of which is thought to represent a major cycle of sedimentation: (in ascending order) the Callanna Beds, Burra Group, Umberatana Group, and Wilpena Group (Thomson et al., 1964). Tillites and their associated sediments in the Yudnamutana and Yerelina Sub-Groups mark the bottom and top, respectively, of the Umberatana Group (Fig. 3). If the lower (Sturtian) and upper (Marinoan) tillites are correlated with dated tillites elsewhere in Australia (Dunn et al., 1971) then this would place an age range of 740-670 m.y. on the deposition of the Umberatana Group, which occurred over almost the entire geosyncline as presently known (Thomson, 1969; Preiss, 1973). The palaeogeography of the basin during this time and the regional stratigraphy of the Umberatana Group were recently studied in great detail by Preiss (1973) as part of a palaeoecological investigation of the diverse and prolific stromatolites contained therein.

Overlying and almost coextensive with the lower glacials is the Tapley Hill Formation. Throughout the geosyncline the base of this formation is usually delineated by a black shale, the Tindelpina Shale Member. The shale horizon commonly forms areas of poor outcrop and low relief (Plate 1), in contrast to the prominent outcrops of the underlying tillite. Hence field recognition of the shale relied heavily on the presence of the tillite. The contact between the Tindelpina Shale and the upper Tapley Hill Formation is not always recognizable, especially at extensively weathered outcrops. In many cases the boundary is transitional. Indeed, Preiss (1973) considered that the persistence of the Tindelpina Shale Member may have been overstated (e.g. by Thomson, 1969) because in some places the Tapley Hill Formation is essentially siltstone throughout. Our observations tend to confirm this opinion. Nevertheless, the name 'Tindelpina Shale Member' for the basal part of the Tapley Hill Formation is convenient and will be retained in this paper.

According to Preiss (1973), the lower Tapley Hill Formation represents a transgressive basinal marine facies comprising organic-rich muds and silts, in part dolomitic; its deposition was very slow and took place under euxinic conditions in moderately deep water. Interbedded dolomite was probably laid down in shallower water near the basin margin early in the transgression. This transgression may have been a result of a eustatic rise in sea level following the decline of the first glaciation.

PETROGRAPHY AND MINERALOGY OF TINDELPINA SHALE

Hand specimens of the Tindelpina Shale have the appearance of a dark grey to black, finely laminated silty shale. When weathered the rock shows a colourful alternation of red and greenish bands (0.5-3 mm thick), which correspond with the bedding plane lamination. Thin veins of calcite occasionally transect the bedding.

Under magnification the rock in thin section (Plate 2A) is seen to consist mainly of quartz (60-80%), muscovite (illite) and chlorite (10-30%), and organic matter (0.5-2%). The lamination is due to variations in the proportions of these constituents. Darker laminae contain more organic matter and clay minerals than the lighter laminae. Pyrite (up to 5%) may occur within the darker bands. In many cases, this sulphide has altered to iron oxides. Individual bands do not show any discernable grading. Angular and subangular grains (up to 0.04 mm) of detrital quartz are evenly distributed throughout the rock. Grains of calcite, dolomite, and feldspar are found in some specimens. Accessory tourmaline, zircon, and rutile have also been recognized. Detrital muscovite and biotite (less frequently present) are characterized by their random orientation. Cleavage, when developed, is defined by orientation of the phyllosilicates at an angle to the bedding plane lamination (Plate 2B).

The mineralogy of the Tindelpina Shale is simple and uniform. X-ray diffractograms of both bulk samples and the $<2\mu m$ size fraction confirm that the main minerals present are chlorite, illite (muscovite), and quartz, together with minor feldspar and calcite. Other constitutents recognized under the microscope do not appear on the diffractograms because of their low concentration. The organic carbon content of the samples studied ranges from 0.18% to 1.11% and averages 0.51% (McKirdy, unpublished results).

REGIONAL METAMORPHISM IN THE ADELAIDE GEOSYNCLINE

The Precambrian and Lower Palaeozoic rocks of the Mount Lofty Ranges and Kangaroo Island in the southern region of the Adelaide Geosyncline have been divided into four metamorphic zones by Offler and Fleming (1968). This zonation is based on the maximum areal distribution of specific index minerals (viz. chlorite, biotite, andalusite-staurolite, and sillimanite) in pelitic rocks. It reveals a general increase in metamorphism from chlorite grade along the western front of the ranges eastwards into areas of biotite grade and higher.

It is of interest that Offler and Fleming (1968: inset fig. 6) extrapolated their biotite zone northwards to the Willyama Block and also showed a narrow belt of metasediments up to amphibolite grade around the Mount Painter Block (cf. Coats and Blissett, 1971). Subsequent field and petrographic analysis of rocks from the Flinders Ranges, notably by Bell (1969), Binks (1971) and Preiss (1971), has confirmed the general pattern of regional metamorphism suggested by Offler and Fleming (op. cit.) for the geosyncline as a whole.

Most published studies of metamorphic phenomena in the Adelaide Geosyncline have depended mainly on evidence obtained with the petrographic microscope. Such an approach is not without its limitations. Pelitic sediments in which early metamorphic index minerals and fabric (e.g. slaty cleavage) most readily develop are often very fine grained. Differences in bulk rock mineralogical and chemical composition may mean that certain critical minerals do not form. The diagenetic and metamorphic recrystallization noted in certain carbonates (Binks, 1971; Preiss, 1972, 1973) is difficult to quantify. Our joint investigation of the organic content, clay mineralogy, and magnetic properties of the Tindelpina Shale suggests three new quantitative techniques for detecting the onset of lower greenschist facies regional metamorphism across the Adelaide Geosyncline.

METHODS OF PRESENT STUDY

Kerogen structure and composition

It is becoming increasingly apparent that kerogen, the insoluble comminuted carbonaceous matter commonly dispersed in fine-grained sedimentary rocks, responds to diagenesis and metamorphism in much the same way as coal (McKirdy, in press), and that like coal it is much more sensitive to the changes in temperature which are responsible (along with increased pressure) for the modification of clay mineralogy and appearance of zeolite facies mineral assemblages characteristic of burial metamorphism (Kisch, 1969). The maturation of kerogen is reflected in: progressive changes in its elemental (C,H,N,O,S) composition (Forsman and Hunt, 1958; Forsman, 1963; McIver, 1967; Long et al., 1968; McKirdy, 1971); loss of alkyl chains and heteroatomic functional groups, and increased aromatic condensation in the kerogen structure as revealed by infrared absorption spectroscopy (Long et al., 1968; McKirdy, 1971); increased ordering or crystallinity of the incipient graphite lattice as shown by X-ray and electron diffraction analysis (French, 1964; Landis, 1971; McKirdy, 1971; Diessel and Offler, 1973); and increased carbonization evident from differential thermal analysis and reflectance measurements (Diessel and Offler, op. cit.). In addition, recent data obtained by Baker and Claypool (1970) and McKirdy and Powell (in prep.) suggest that the stable carbon isotope composition of kerogen also changes during incipient metamorphism. In the present study, elemental, X-ray diffraction, and stable carbon isotope analysis were employed to characterize the kerogens isolated from a suite of 24 samples of Tindelpina Shale collected from the localities shown in Figure 2.

<u>Isolation</u>. Powdered shale (-200 mesh, B.S.S.) was first treated with dilute HCl to ensure removal of any carbonates. Repeated digestion of the carbonate-free shale in a 1:5 mixture of concentrated HCl (32%) and HF (40%) dissolved the bulk of the silicate fraction of the rock. After decanting the spent acid the insoluble residue was washed repeatedly in 5N HCl, by centrifugation and decantation, until the washings no longer assumed a yellow-green colour. The residue was then similarly washed in distilled water until neutral to pH paper. Pyrite was removed with sodium borohydride according to the method of McIver (1967). The borohydride treatment was found to release fresh pyrite grains which had apparently been trapped within a matrix of particulate kerogen. A rough separation (involving some small loss of kerogen) was achieved by stirring the mixture in distilled water and carefully decanting the kerogen in suspension. The suspension was then centrifuged and the residue air-dried at 60°C. Examination of the dry crude kerogen concentrate under the microscope revealed the presence of small grains of acid-resistant heavy minerals (e.g. rutile, tourmaline) often coated with organic

matter. A further separation was attempted by dispersing the concentrate in chloroform in a glass centrifuge tube, immersing the tube in an ultrasonic bath, and stirring the contents intermittently for 5 min. The tube was then briefly centrifuged (at 1500 rev/min) and the kerogen in suspension decanted. Sonication of the residue was repeated until no further kerogen remained in suspension upon centrifuging. Final prolonged centrifugation and air-drying gave the kerogen concentrate (flakes of black coal-like material) which was gently ground to a powder in an agate mortar before storing in a vacuum desiccator over humidity-indicating silica gel.

X-ray diffraction analysis. Kerogen powder (2-3 mg) was spread evenly as a slurry in ethanol on a 16-mm glass disc and the solvent allowed to evaporate. The mount was carefully placed in the rotary sample holder of a Philips Recording Diffractometer where (not spun) it was analysed under the following instrumental conditions: Cu K α radiation, Ni filter; 40 kV/ 24 mA ; 1° beam slits; goniometer scan rate 1° 2θ/min, 2θ range 10-60°; chart speed 10 mm/min; EHT on flow counter 1680 V; time constant 4; nominal attenuation 4×10^2. The profile of the major kerogen reflection on the resulting diffractogram was described in terms of its d spacing at maximum intensity (d_{002} at I max) and ratio of height to width at half height (h/w), following Landis (1971).

Elemental analysis. The kerogens were analysed for carbon, hydrogen, and ash by the CSIRO Microanalytical Service, Melbourne. Using this information, the percentage carbon on a dry ash-free basis (% C d.a.f.) and hydrogen to carbon atomic ratio (H/C) were calculated for each sample.

Carbon isotope analysis. Seven of the kerogen samples were submitted to Geochron Laboratories Inc. of Cambridge, Massachusetts, for stable carbon isotope analysis. Results are given as $\delta^{13}C$ values, relative to the PDB standard, where

$$\delta^{13}C \text{ per mil} = \left[\frac{^{13}C/^{12}C \text{ sample}}{^{13}C/^{12}C \text{ standard}} - 1 \right] .1000$$

The $\delta^{13}C_{PDB}$ measurements quoted have a precision of $\pm$ 0.05 per mil.

Illite crystallinity

The transition from diagenesis to metamorphism is difficult to recognize petrographically. Weaver (1960, 1961) was the first to discover a correlation between the 'sharpness' of the basal (001) X-ray diffraction peak of the clay mineral illite and the degree of metamorphism of its host rock in very weakly metamorphosed shales from the Ouachita Mountains, Texas. The X-ray diffraction analysis was performed on oriented mounts of the < 2μm size fraction, Weaver defined 10Å (1μm) peak 'sharpness' as the ratio of peak height at 10Å to that at 10.5Å (herein referred to as the Weaver index). An increase in peak sharpness reflects progressive ordering of the illite layer lattice and growth in crystallite size; in other words, improved crystallinity. Employing an alternative method of quantifying the sharpness of the 10Å peak (viz. width in mm at half peak height determined under strictly controlled instrumental conditions, termed the Kubler index), French investigators (e.g. Kubler, 1967; 1968; Dunoyer de Segonzac et al., 1968) have since confirmed that illite crystallinity is a reliable and sensitive measure of degree of burial diagenesis and low-grade metamorphism.

During the passage from late diagenesis into metamorphism, named the anchizone[1] by Dunoyer de Segonzac (1970), illite crystallinity becomes independent of rock type and so may be used to define the limits of the transition zone (viz. Weaver index 2-12 : Kubler, 1968, fig. 3). Maxwell and Hower (1967) observed that under the conditions of increased temperature and pressure

1. Derived from the term anchimetamorphism (anchi = close to)

consequent upon deep burial of argillites from the Precambrian Belt series of Montana and Idaho, a transformation of the 1Md polymorph of illite to the 2M polymorph occurred. The 2M form of illite is now recognized as being characteristic of the anchizone of burial diagenesis (Dunoyer de Segonzac, 1970).

Recent developments in the study of illite crystallinity include its determination from oriented rock slabs (Weber, 1972) and its measurement by infrared spectroscopy (Flehmig, 1973).

Isolation. The $< 2\mu m$ size fraction was isolated from a powdered sample (4 g) of each shale by the standard settling technique. Oriented mounts on ground glass slides were prepared for X-ray diffraction study. To permit determination of the proportion of 2M polymorph in the illites, separate oriented mounts were made from the $< 2\mu m$ fraction of powdered shale which had been first treated with 6N HCl overnight on a steam bath to eliminate chlorite (and biotite).

X-ray diffraction analysis. X-ray diffractiograms of the $< 2\mu m$ size fractions were run under instrumental conditions similar to those employed in kerogen analysis, except that narrower (½°) beam slits were fitted. The effects of instrumental drift were taken into account by use of an external muscovite standard. The Weaver index was measured directly from the 10Å illite peak on each diffractogram, whereas the corresponding Kubler indices were computed from Ferrero's conversion curve (Kubler, 1968, fig. 3). The relative amount of 2M polymorph present in the illites was estimated from the ratio of the 2.80Å and 2.58Å peak intensities on the chlorite-free diffractograms, according to the method of Maxwell and Hower (1967). The intensity ratio of the 5Å and 10Å peaks was also measured to obtain information on the chemical composition of the octahedral layer, as described by Esquevin (1969).

Magnetic response

The magnetic response of rocks may be due to induced or remanent magnetization, or both. Remanent magnetism in sedimentary rocks can arise by various means. For example, it can be acquired mechanically during deposition, in which case it is termed detrital remanent magnetism (Nagata, 1962); or as a result of deep burial beneath a thick sedimentary pile: the 'moderate temperature viscous remanent magnetization' of Irving and Opdyke (1965). Insofar as the latter is a thermal mechanism it is conceivable that the widespread occurrence of remanent magnetism in the sediments of a basin may be due to their regional metamorphism.

In a Bureau of Mineral Resources (BMR) aeromagnetic survey of the Orroroo 1:250 000 Sheet area in the Adelaide Geosyncline, Tipper and Finney (1965) found that over much of the region the magnetic expression of the deep (pre-Adelaidean) basement was masked by near-surface rocks. This masking phenomenon was observed to increase towards the southeast and was considered to be due to either magnetic disturbance from metamorphic rocks or a regional increase in sedimentary iron. According to Binks (1971), field data support regional metamorphism as the cause of the masking effect. Tipper and Finney (1965) subdivided the Orroroo Sheet area into six zones of specific magnetic character, one of which was associated with the Tindelpina Shale.

A more extensive and detailed investigation by Tucker (1972) has shown that over much of the area in which Adelaide System sediments crop out in the Adelaide Geosyncline, contour maps of total magnetic intensity show prominent linear anomalies due to near-surface sources. These anomalies usually have amplitudes of 100-500 gammas and often can be traced for 50 km or more, running parallel to the sedimentary layering. The sources of the linear anomalies are magnetic beds up to several hundred metres thick, which are conformable with the sedimentary layering and are separated from one another by beds that are essentially non-magnetic. The magnetic beds are present at various stratigraphic levels throughout the Adelaide System (and Cambrian) sequence. For example, in the Orroroo 1:250 000 Sheet area, 14 magnetic beds were detected in the Wilpena, Umberatana, and Burra Groups (Fig. 3).

One of the most consistently detected magnetic beds of the geosyncline is the one closely associated with the Tindelpina Shale Member. This bed has been informally named the lower Tapley Hill magnetic bed by Tucker (1972). Interpretation of vertical-field ground magnetometer anomalies indicates that the magnetic bed extends from the middle of the Tindelpina Shale Member upwards over a total thickness of 250 m (Fig. 4).

Amplitude and polarity of anomalies. Aeromagnetic surveys of the Orroroo and adjacent Sheet areas by the BMR and others were flown at an altitude of 150 m on east-west lines about 1500 m apart, employing a total-field fluxgate magnetometer. From the recorded data, contour maps of total magnetic intensity, mostly at a contour spacing of 10 gammas, have been produced for the entire area by the South Australian Department of Mines. The amplitude (which may be above or below local background, i.e. positive or negative) of linear near-surface-source magnetic anomalies over the lower Tapley Hill magnetic bed was measured from the contour maps. By this method the smallest detectable anomalies were found to be about 10 gammas in amplitude. For the Orroroo area, however, amplitudes were estimated directly from the original flight charts, and in this case the smallest anomalies recognized have an amplitude of about 3 gammas. A picture was thus obtained of the variation in amplitude and polarity of anomalies associated with the lower Tapley Hill magnetic bed across the entire Adelaide Geosyncline.

<u>Resolution of components of remanent magnetism.</u> Details of remanent magnetization of rocks, viz. its direction, intensity, and mechanism of acquisition, are generally obtained by the study of rock samples in the laboratory (Nagata, 1962; Irving, 1964). In special cases, directional components of the intensity can be derived from analysis of the magnetic anomalies as they exist over the rocks in situ (Sutton and Mumme, 1957; Hall, 1959; Hood, 1963). Usually the magnetic susceptibility and geometry of the source need to be known in order to break down anomalies into the relative components of induced and remanent magnetism. In the Adelaide Geosyncline, the interpretation of anomalies over the lower Tapley Hill magnetic bed was simplified because: induced magnetization (susceptibility) appeared to be negligible in comparison with remanent magnetization (Tucker, 1972); the remanence was consistent over large areas; and anomalies could be traced over outcrop around anticlinal structures. Vertical-field ground magnetometer profiles were run across two adjacent noses of a plunging anticlinal structure 70 km northeast Orroroo. The anomalies were sufficiently well defined to allow meaningful plotting of anomaly amplitude and sign versus strike of outcrop. In the particular case where a strong component of remanent magnetization acquired before folding is preserved close to the plane of bedding, such a plot can be used to give the original azimuth of the remanence.

It should be emphasized that this technique does not have a wide application, mainly because of the necessity of having well defined anomalies over an anticlinal structure sufficiently small so that changes in magnetic response are unlikely to be due to subtle facies variations along strike which affect magnetic mineral content.

TABLE 1. Analytical data.

Sample No.	KEROGEN Structure			KEROGEN Composition			ILLITE Structure				MAGNETICS Zone
	$\frac{h}{w}$	d_{002} Å	Degree of disorder	$\frac{H}{C}$	C d.a.f. %	$\delta^{13}C$ PDB	Weaver index	Kubler index	2M %	$\frac{I002}{I001}$	(see Fig.11).
13	n.d.	n.d.	n.d.	0.17	n.d.	n.d.	3.8	5.6	100	0.47	1
19	2.1	3.41	d_{1A}	0.25	87.1	-24.2	2.3	7.6	<25	0.24	n.m.
9	2.9	3.50 3.39	d_2 d_{1A}	0.11	90.7	-18.8	5.2	4.9	50	0.21	n.m.
16	1.6	3.40	d_{1A}	0.15	91.2	-22.9	4.4	5.2	<25	0.25	n.m.
15	2.1	3.52 3.40	d_2 d_{1A}	0.15	90.9	n.d.	5.0	4.9	37	0.28	n.m.
17	2.0	3.45 3.37	d_2 d_{1A}	0.18	90.8	-23.4	3.3	6.1	37	0.29	n.m.
5	2.6	3.47 3.37	d_2 d_{1A}	0.19	85.5	n.d.	5.9	4.7	28	0.30	n.m.
18	3.0	3.39	d_{1A}	0.19	89.8	n.d.	4.0	5.4	<25	0.31	n.m.
8	1.1	3.48 3.38	d_2 d_{1A}	0.23	89.1	n.d.	4.8	5.0	25	0.31	n.m.
21	n.d.	n.d.	n.d.	0.11	n.d.	n.d.	4.6	5.1	100	0.15	n.m.
22	2.5	3.41	d_{1A}	0.19	89.3	n.d.	3.4	6.0	35	0.27	n.m.
12	3.5	3.49 3.38	d_2 d_{1A}	0.13	90.9	-23.8	5.0	4.9	94	0.29	n.m.
14	6.7	3.39	d_{1A}	0.11	94.7	n.d.	9.9	4.2	100	0.33	2
6	12.2	3.38	d_{1A}	0.09	96.4	n.d.	6.9	4.4	<25	0.31	2
10	21.6	3.36	d_1	0.06	96.8	-14.7	9.3	4.2	100	0.45	1
2	26.2	3.36	d_1	0.07	96.7	n.d.	7.7	4.4	66	0.29	3
20	11.6	3.38	d_{1A}	0.09	95.2	-17.5	8.6	4.3	100	0.30	1
3	18.9	3.40	d_{1A}	0.05	95.3	n.d.	13.4	3.9	<25	0.30	1
4	36.6	3.37	d_{1A}	0.01	97.6	n.d.	7.8	4.4	92	0.41	1
7	17.8	3.38	d_{1A}	0.06	98.3	n.d.	4.5	5.1	86	0.13	2
11	40.2	3.38	d_{1A}	0.05	98.1	n.d.	12.6	3.9	100	0.18	1
1	26.8	3.38	d_{1A}	0.04	97.5	n.d.	7.8	4.4	100	0.18	3
23	n.d.	n.d.	n.d.	0.09	94.7	n.d.	7.2	4.4	100	0.26	1
24	n.d.	n.d.	n.d.	0.02	n.d.	n.d.	4.7	5.1	100	0.16	1

n.d. = not determined n.m. = anomaly amplitude less than 20 gammas

RESULTS

Kerogen

X-ray diffraction, elemental, and isotopic data for the kerogen concentrates are presented in Table 1.

Inspection of the diffractograms immediately showed that structurally the kerogens fall into two distinct groups (Fig. 5), herein informally referred to as 'subgraphitic' and 'graphitic'. Subgraphitic kerogens are characterized by a broad diffuse reflection at 2θ of about 26° (d_{002} at I max = 3.50 - 3.37Å; h/w = 1.1 - 3.5), with a much weaker reflection near 44°. In most cases the main peak appeared to be a composite one (cf. Landis, 1971) comprising a mixture of Landis's d_2 and d_{1A} forms of disordered graphite (Table 1). The diffraction trace of such a mixture is shown in Figure 5. Kerogens of the graphitic type gave a more intense symmetrical basal reflection at slightly higher 2θ (d_{002} = 3.40 - 3.36Å; h/w = 6.7 - 40.2), and several other reflections (viz. 100, 101 and 004) are also clearly developed (Fig. 5). These kerogens are analogous to the graphites d_{1A} and d_1 of Landis (1971). Their lattice possesses a higher degree of order than does that of the subgraphitic kerogens. Obviously the graphitic kerogens are more highly metamorphosed equivalents of the subgraphitic material.

The kerogens in Table 1 can be divided into the same two groups on the basis of their elemental chemical composition. Subgraphitic kerogens have a carbon content of 85-91% d.a.f. and a H/C ratio of > 0.10, which corresponds to a coal rank in the medium volatile bituminous to semi-anthracite range. The graphitic kerogens, on the other hand, contain 91-98% C d.a.f., with an H/C value of < 0.10 and are thus analogous to anthracite or meta-anthracite (Teichmuller and Teichmuller, 1968). A plot of H/C ratio against percentage C d.a.f. (Fig. 6) shows that together the two kerogen populations delineate an elongate compositional field which is mostly reasonably interpreted as a metamorphic trend, viz. increase of percentage C d.a.f. and decrease of H/C ratio with advancing metamorphism.

A further regular variation in kerogen composition is revealed by plotting H/C ratio against $\delta^{13}C_{PDB}$ (Fig. 7). A marked increase in $\delta^{13}C_{PDB}$ occurs with decreasing H/C value and strongly suggests a metamorphic modification of the carbon isotopic composition of Tindelpina kerogen similar to that reported by Baker and Claypool (1970) and McKirdy and Powell (1974). From the limited isotopic data available it appears that the subgraphitic kerogens have $\delta^{13}C_{PDB}$ values in the range -24 to -19 per mil, whereas the two graphitic values are both greater than -18 per mil.

Except in samples from early Precambrian sedimentary rocks (Oehler et al., 1972), Precambrian kerogens generally have $\delta^{13}C_{PDB}$ values in the range -35 to -25 per mil, similar to those of photosynthetically-produced organic matter preserved in younger sediments. The isotopic composition of the least altered Tindelpina kerogen is thus consistent with its probable derivation from a photosynthetic biota. Saturated hydrocarbons (including the isoprenoids, pristane, and phytane) with a molecular weight distribution typical of organic matter derived from aquatic photosynthetic micro-organisms have also been isolated from sample 22 of the Tindelpina Shale (McKirdy, unpublished results). Algal sheath fragments up to 150μm in length have recently been discovered in a macerate of a core sample of Tindelpina Shale from Copley (locality 8, Fig. 2) by Dr M.R. Walter of BMR. In 1962, B.V. Timofeev reported finding a sporomorph acritarch and plant tissue debris in slates of the Tapley Hill Fromation from its type locality south of Adelaide (Glaessner, 1963, p. 231).

Both structural and compositional parameters indicate that the kerogens analysed may be classified into two major groups of distinctly different metamorphic facies. From Figure 8 it is evident that the subgraphitic kerogens come from the western side of the Adelaide Geosyncline whereas the graphitic kerogens are confined to the eastern side.

Illite

The Weaver and Kubler indices of each illite, together with its estimated content of 2M polymorph and (002)/(001) intensity ratio, are given in Table 1.

Firstly, it can be seen (Fig. 9) that a good correlation exists between illite crystallinity (Weaver index) and kerogen rank (H/C ratio) in the rocks sampled. Those shales from which subgraphitic kerogens were isolated contain illites of relatively low crystallinity (Weaver index <6; Kubler index > 4.5) whereas those which yielded graphitic kerogens accommodate (with two apparent exceptions) illites of high crystallinity (Weaver index > 6; Kubler index < 4.5). The Weaver indices of illite samples 7 and 24 appear to be anomalously low. However, this may simply be a function of a difference in thickness of the $< 2\mu m$ fraction sedimented on the glass slide mount. Weber (1972) found that the thicker the mount, the higher was the resultant Kubler index (and hence the lower the Weaver index) for the same clay sample. No particular attempt was made in this study to ensure that all 24 oriented clay mounts were of the same thickness before their analysis by X-ray diffraction.

The relation between the crystallinity and 2M polymorph content of the illites is somewhat erratic. In general, however, the illites from the subgraphitic shales contain less than 50% 2M polymorph, in contrast to those from the graphitic shales (65-100% 2M). The exceptions to the above generalization (viz. samples 3, 6, 12, 13, 21) are possibly explicable in terms of regional variation in bulk composition of the shale (and by inference, illite).

Further evidence for variation in the chemistry of the Tindelpina illites is contained in Figure 10, a plot of Kubler index against intensity ratio of the 5Å and 10Å (cf. Esquevin, 1969). Apart from demonstrating that the illites fall within the anchimetamorphic zone, this figure also reveals a significant spread in the composition of their octahedral layer, from ferromagnesian ($I_{002}/I_{001} = 0.1 - 0.3$) to aluminous ($I_{002}/I_{001}$ 0.3). Aluminous illites attain a high crystallinity more readily than ferromagnesian illites (Esquevin, 1969; Dunoyer de Segonzac, 1970).

Hence, insofar as the chemistry of the illites permits, their structure (crystallinity, percentage 2M polymorph) corroborates the twofold metamorphic zonation of the geosyncline into a western low-grade region and higher-grade areas to the east.

Magnetics

The type and regional distribution of magnetic anomalies attributable to the lower Tapley Hill magnetic bed are shown in Figure 11. The particular magnetic zone in which each kerogen/illite sample locality falls is listed in Table 1.

In some areas the magnetic bed is difficult to detect, or indeed has not been detected, either with aeromagnetic or ground magnetic methods. Broadly, the magnetic response is higher in the eastern part of the geosyncline where the amplitude of the aeromagnetic anomalies is 50-100 gammas (or more). On the western side of the basin and in the central Flinders Ranges, the magnetic response of the lower Tapley Hill Formation is low, the anomalies generally being less than 20 gammas. The position of the discontinuity (or transition) between areas of low magnetic response in the west and high magnetic response in the east, largely corresponds to that for other magnetic beds (Fig. 3) within the geosyncline irrespective of their stratigraphic position.

Whereas the difference in response can be attributed to a difference in magnetic iron content of the interval, from the magnetometer data it is not possible to determine whether or not this is also related to a difference in the total iron content of the sediments.

An independent study by Brotherton (1967) of the mineralogy of one horizon in the Wilpena Group south of Adelaide, where it passes from an area of high metamorphic grade to one of low grade within a distance of about 20 km, revealed a marked decrease in the quantity of magnetite while the total iron oxide content remained fairly constant at 5-8%. Brotherton ascribed the presence of magnetite to its metamorphic generation from hematite. Aeromagnetic anomalies over the bed studied had amplitudes of up to 200 gammas in the region of high metamorphic grade, and of 20 gammas or less in the lower grade area (Tucker, 1972).

As in many of the other magnetic beds in the Adelaide Geosyncline, the magnetic minerals in the lower Tapley Hill magnetic bed are usually weathered away for up to 200 m below ground level. Largely for this reason, efforts to identify the mineral causing the magnetic response have proved unsuccessful. However, rounded grains and flakes of magnetite, totalling about 0.2%, were found in a one-metre interval of percussion-drill cuttings from the Tindelpina Shale Member near Copley (locality 8). Admittedly this concentration is rather low, but then the sample comes from an area lacking a significant magnetic response. Pyrrhotite has been noticed in minor amount in the lower Tapley Hill Formation, particularly in areas of localized structural disturbance. However, its concentration is thought to be too low, and its occurrence too spasmodic, to satisfactorily explain the extensive linear anomalies associated with the unit. It is considered likely, therefore, that magnetite is the magnetic mineral concentrated in the lower Tapley Hill Formation, and that it is of metamorphic origin.

A special feature of the lower Tapley Hill magnetic bed is the predominantly remanent character of its magnetization. The symmetrical shape of the vertical field magnetic anomalies over the bed indicate that the magnetization lies close to the plane of bedding (cf. Gay, 1963, p. 170). Furthermore, the sign of the anomalies changes from place to place, being positive on one limb of an anticline and negative on the other. Detailed interpretation (Tucker, 1972) of the component of this remanent magnetization in vertical-field ground magnetic anomalies over two anticlinal structures in the test locality 70km east-northeast of Peterborough demonstrated that the remanent magnetization was probably acquired in at least two stages. Before the bed was folded it acquired a remanent magnetic component close to the plane of sedimentary layering in a direction $135 \pm 30^{\circ}$. After folding, a second component was imposed, again close to the bedding plane but in a direction normal to the trace of outcrop.

Precisely when the interpreted prefolding remanent component was acquired is not known. The main folding of Adelaidean sediments in the geosyncline occurred during the Early Ordovician as part of the Delamerian Orogeny (Thomson, 1969, 1970). Hence, the first remanent component must have been acquired in Early Ordovician time or before. If its derived horizontal direction ($135 \pm 30^{\circ}$) and inclination (0°) preserve information on the attitude of the Earth's magnetic field at the time of magnetization, then at least its orientation is broadly consistent with the palaeolatitudinal position of Australia in the Cambro-Ordovician as shown by Embleton (1973).

Because of the unorthodox (in situ) method of analysis of the remanent magnetization of the lower Tapley Hill magnetic bed it is not possible to be sure how the magnetization originated. Nevertheless, a thermal mechanism involving viscous remanent magnetization appears more likely than a detrital one because the prefolding remanent component associated with the lower Tapley Hill magnetic bed is also evident in other beds within the Umbertana (and possibly Wilpena) Group. In other words, a similar effect is observed over a total stratigraphic thickness of at least 2 km. It seems probable, then, that the prefolding remanent component was produced by heating of the sedimentary pile either before or in the early stages of the Delamerian Orogeny.

Hence interpretation of the magnetic data has led to the following conclusions. The linear magnetic anomalies over rocks of the Adelaide System are caused by magnetic beds conformable with the sedimentary layering. The magnetic mineral concentrated in these beds and causing the anomalies is magnetite, apparently of metamorphic origin. At least part of the presently observed magnetism of the lower Tapley Hill magnetic bed seems to have been acquired by heating before the bed was folded. The regional change from areas with anomalies of amplitude 100 gammas and above, to areas of 20 gammas or less, probably therefore corresponds to a decrease in metamorphic grade.

SYNTHESIS

Detailed investigation of the kerogen, illite, and magnetization of the Tindelpina Shale Member of the Tapley Hill Formation has revealed a regional variation in the intensity of its low-grade metamorphic alteration. The structure, and elemental and isotopic composition of the kerogen; the crystallinity and structure of the illite; and the amplitude and nature of the magnetization, all display evidence of metamorphic control and are consistent in indicating an increase in metamorphic grade from west to east across the Adelaide Geosyncline. On the basis of the parameters considered, two zones can be distinguished: a region of incipient to weak metamorphism along the western margin of the geosyncline, and higher-grade areas farther to the east; the dividing lines trend north through Adelaide, Mintaro, and Orroroo to Baratta, and northwest through Mount Serle into the Willouran Range (Fig. 11).

The eastward increase in metamorphic grade of the Tindelpina Shale is most clearly defined by structural and compositional changes in the kerogen. The division (or transition) between the two metamorphic zones corresponds to a carbon content of 91% d.a.f., an H/C ratio of 0.10, and an h/w measurement of about 5.0 for the kerogen (002) reflection. In terms of illite crystallinity the equivalent Weaver index is 6, whereas for total field magnetic anomalies it is the western limit of aeromagnetic anomalies exceeding 100 gammas in amplitude.

The above lines coincides closely with the boundary between the chlorite and biotite zones of greenschist facies metamorphism established by Offler and Fleming (1968) for the southern part of the geosyncline on the basis of the first appearance of biotite in phyllites, metagreywackes and calc-schists. In this regard the claim of Maxwell and Hower (1967) that the transformation of the disordered 1Md polymorph of illite to the ordered 2M polymorph reaches completion within the biotite isograd is of interest. This study has shown that 2M illite is certainly the dominant polymorph in the eastern graphitic facies of the Tindelpina Shale. Furthermore, in specimens from this zone examined in thin section, incipient metamorphic alteration of chlorite to greenish biotite has commenced. Where slaty cleavage is developed (cf. Plate 2B), the biotite is aligned parallel to it. Biotite is also sometimes present in Tindelpina Shale from the western subgraphitic zone, but in this case it is larger in grainsize, shows little or no preferred orientation, and appears to be detrital. It is perhaps also worth noting that a careful search of various thin sections of graphitic Tindelpina Shale failed to reveal clusters of minute grains of metamorphic monazite (Overstreet, 1967) in close association with the organic matter, as reported by Huebschman (1973) from a lithologically similar unit, likewise metamorphosed to biotite grade, in the Precambrian Belt-Purcell Supergroup. Sumartojo (1974) found phosphate levels close to average for a black shale and ascribed them to submicroscopic apatite.

Recent work by Diessel and Offler (1973) on the reflectance of both 'coalified' and 'graphitized' phytoclasts in unspecified metamorphic rocks from the Mount Lofty Ranges, demonstrated a marked difference in mean maximum reflection ($\bar{R}_o$ max) of the two varieties of carbonaceous matter. Although both types were present in the chlorite zone, only the graphitized phytoclasts persisted into the biotite zone (and beyond). Reflectance measurements (by courtesy of Drs C.F.K. Diessel and R. Offler) on five samples of Tindelpina Shale, four of subgraphitic facies and one of graphitic facies, showed that the former had values ($\bar{R}_o$ max = 5.51 - 6.05) characteristic of coalified phytoclasts of the chlorite zone whereas the latter gave a value ($\bar{R}_o$ max = 10.7) typical of graphitized material from the biotite zone. These additional data constitute further evidence for the correspondence of the subgraphitic and graphitic facies of the Tindelpina Shale with the chlorite and biotite zones, respectively, of regional metamorphism within the Adelaide Geosyncline.

The observed pattern of variation in metamorphic grade of the late Precambrian to Lower Palaeozoic sedimentary rocks within the Adelaide Geosyncline has been variously attributed to either greater depth of burial of sediments in the eastern half of the geosyncline or a thermal event related to the Cambro-Ordovician Delamerian Orogeny. The writers consider both to have contributed to the metamorphism of the lower Tapley Hill Formation.

In the eastern Mount Lofty Ranges, outcropping Proterozoic and Lower Cambrian metasediments (the latter including the Kanmantoo Group) are thought by Daily (1969) to have been originally metamorphosed by deep burial under a cover of Middle and possibly Upper Cambrian sediments, up to 10 km thick (Milnes, 1973) and subsequently eroded during or prior to Permian glaciation. A similar situation may have existed further north in the eastern Flinders Ranges, where Ordovician sediments may also have contributed to the sedimentary pile. It is here too that the Umberatana Group attains its maximum thickness (Preiss, 1973).

According to Coats (in Coats and Blissett, 1971, p. 117), the extensive metamorphic halo developed in sediments around the Mount Painter Block could have resulted from the blanketing effect of upper levels of the vast sedimentary pile on units lower in the sequence, so allowing their 'uniform heating' by isolated younger granitic intrusions associated with Early Palaeozoic igneous activity. Alternatively, the metasediments may simply represent a contact metamorphic aureole directly related to the younger granites (dated at 431 m.y. by Compston et al., 1966). Both explanations presuppose adjacent igneous centres as the heat source. Such was not the case along the southern flank of the geosyncline, however, where the Encounter Bay Granite was emplaced during Middle and Late Cambrian time, well before the culmination of the metamorphism of the surrounding sediments in the Kanmantoo Trough (Milnes, 1973; Daily and Milnes, 1973). Metamorphic conditions prevailed until about 470 m.y. ago.

The occurrence throughout the geosyncline of rocks with apparent Early Ordovician (ca 465 m.y.) isotopic ages (Compston et al., 1966) dates the waning of regional metamorphism associated with the Delamerian Orogeny. Offler and Fleming (1968; see also Fleming and Offler, 1968) found evidence for pretectonic metamorphic crystallization of andalusite and staurolite porphyroblasts in the Angaston-Kapunda area. This indicates that high-grade metamorphism had commenced before the first phase of penetrative movement within the rocks. Offler and Fleming (1968, p. 262) concluded that 'folding was not the cause of metamorphism. Rather, the metamorphism was more likely to have been initiated in response to an unusually high heat flow from the mantle'. The foregoing conclusion fully accords with the data presented in this paper, even to the extent of explaining the observed prefolding component of remanent magnetism in the lower Tapley Hill magnetic bed.

Scattered along the metamorphic arc are isolated outcrops of various granitic rocks, the crystallization ages of which appear to become progressively younger to the north (see Compston et al., 1966; and Milnes, 1973). This suggests that the geothermal high postulated by Offler and Fleming (1968) may have migrated or fluctuated in intensity during the course of the metamorphism (cf. Sutton, 1965). Tucker (1972) invoked a migratory or time-varying habit for the centre(s) of heating that gave rise to the magnetically anomalous zones of the lower Tapley Hill Formation and other beds in order to explain their differing characteristics. Areas where the prefolding component of remanent magnetism is low (e.g. magnetic zones 2 and 3, Fig. 11) may have been heated longer after folding than areas where it is best preserved (e.g. magnetic zone 1). Alternatively, weak prefolding remanent magnetism may mean that heating before folding was also weak.

Thus, differential burial (deeper in the eastern half of the geosyncline) would account for the metamorphic trend observed in the kerogen and clay mineral content of the lower Tapley Hill Formation. It is questionable, however, whether it would adequately explain the development of remanent magnetism in beds throughout the Adelaide System, particularly those higher in the sequence and in overlying Cambrian strata (cf. Tucker, 1972). Nor is it easy to account for the lack of biotite-grade metamorphism and magnetically anomalous beds in the sedimentary rocks of the central Flinders Ranges, as well as the absence of magnetic anomalies over the lower Tapley Hill Formation southeast of Adelaide (Fig. 11), if one assumes a simple depth-of-burial mechanism. There is no reason to suppose that the sedimentary cover in these regions was not as thick as, or thicker than, that in other parts of the geosyncline (cf. Parkin, 1969, figs 27 and 42; Wopfner, 1970).

In demonstrating a correlation between the structure and composition of kerogen and other low-grade metamorphic phenomena, this study has established the validity and usefulness of kerogen as an index of organic maturation. The novel synthesis of organic geochemical, mineralogic, and aeromagnetic data is of potential application elsewhere, particularly in view of the common occurrence of carbonaceous shales in similar Precambrian (and younger) low-grade metamorphic terrains.

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FIGURE CAPTIONS

Fig. 1. Location map of Adelaide Geosyncline

Fig. 2. Tindelpina Shale outcrop and sample localities

Fig. 3. Major magnetic beds in Adelaide Geosyncline

Fig. 4. Stratigraphic position of the lower Tapley Hill magnetic bed

Fig. 5. Kerogen X-ray diffractograms
- (a) subgraphitic
- (b) subgraphitic; mixture of d_2 and d_{1A} forms
- (c) graphitic

Fig. 6. Variation of H/C ratio with % C d.a.f. in kerogens

Fig. 7. Variation of $\delta^{13}C_{PDB}$ with H/C ratio in selected kerogens

Fig. 8. Localities of subgraphitic and graphitic kerogens

Fig. 9. Variation of illite crystallinity (Weaver index) with kerogen rank (H/C)

Fig. 10. Variation of Kubler index with illite (002)/(001) intensity ratio

Fig. 11. Type and regional distribution of total field magnetic anomalies associated with lower Tapley Hill magnetic bed. Idealized profiles indicate the relationship of amplitude and sign of anomalies over north- trending fold structures.

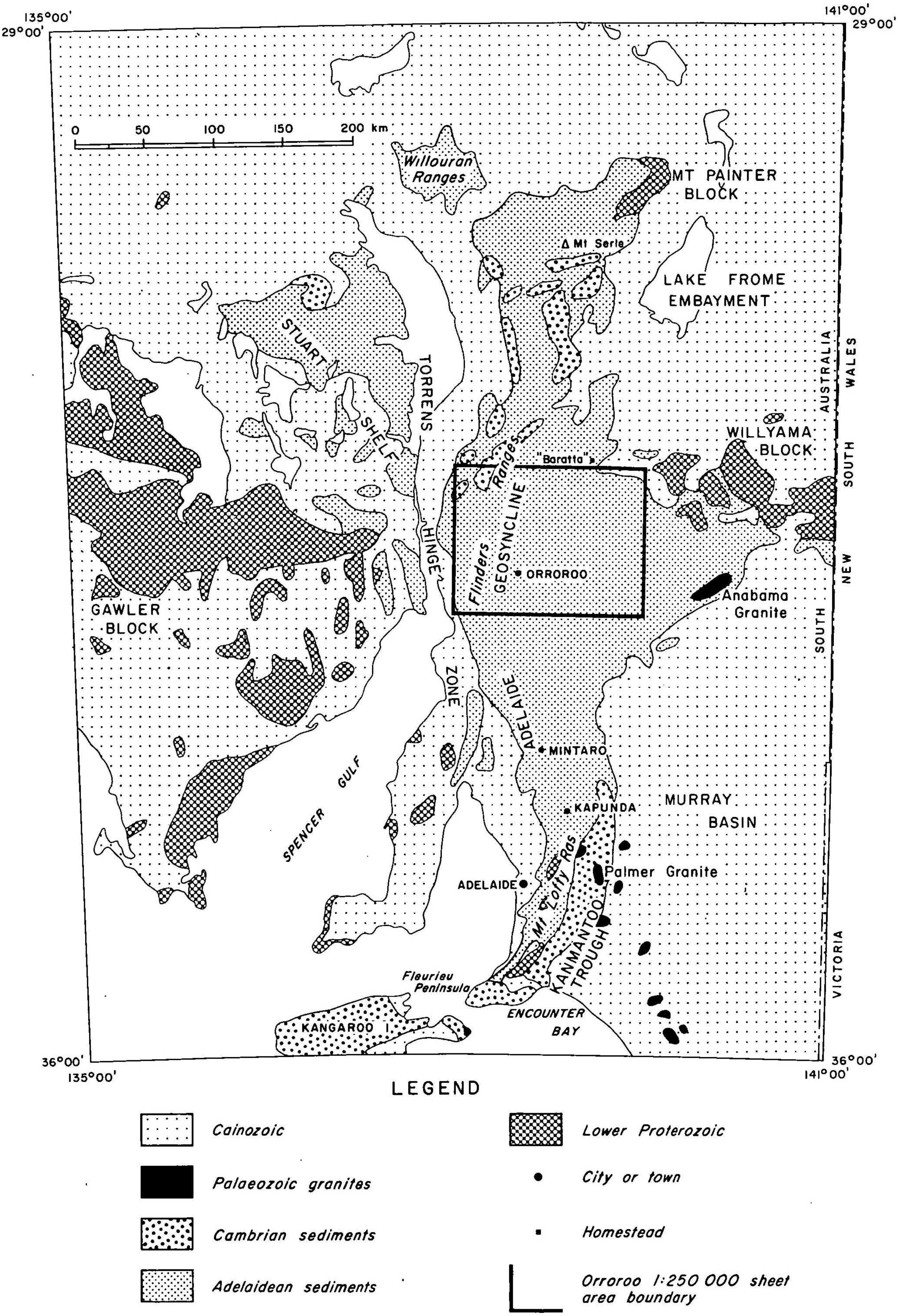
PLATE CAPTIONS

Plate 1 Lower Tapley Hill Formation outcrop at Tindelpina Hut.

Plate 2A Typical lamination in Tindelpina Shale.

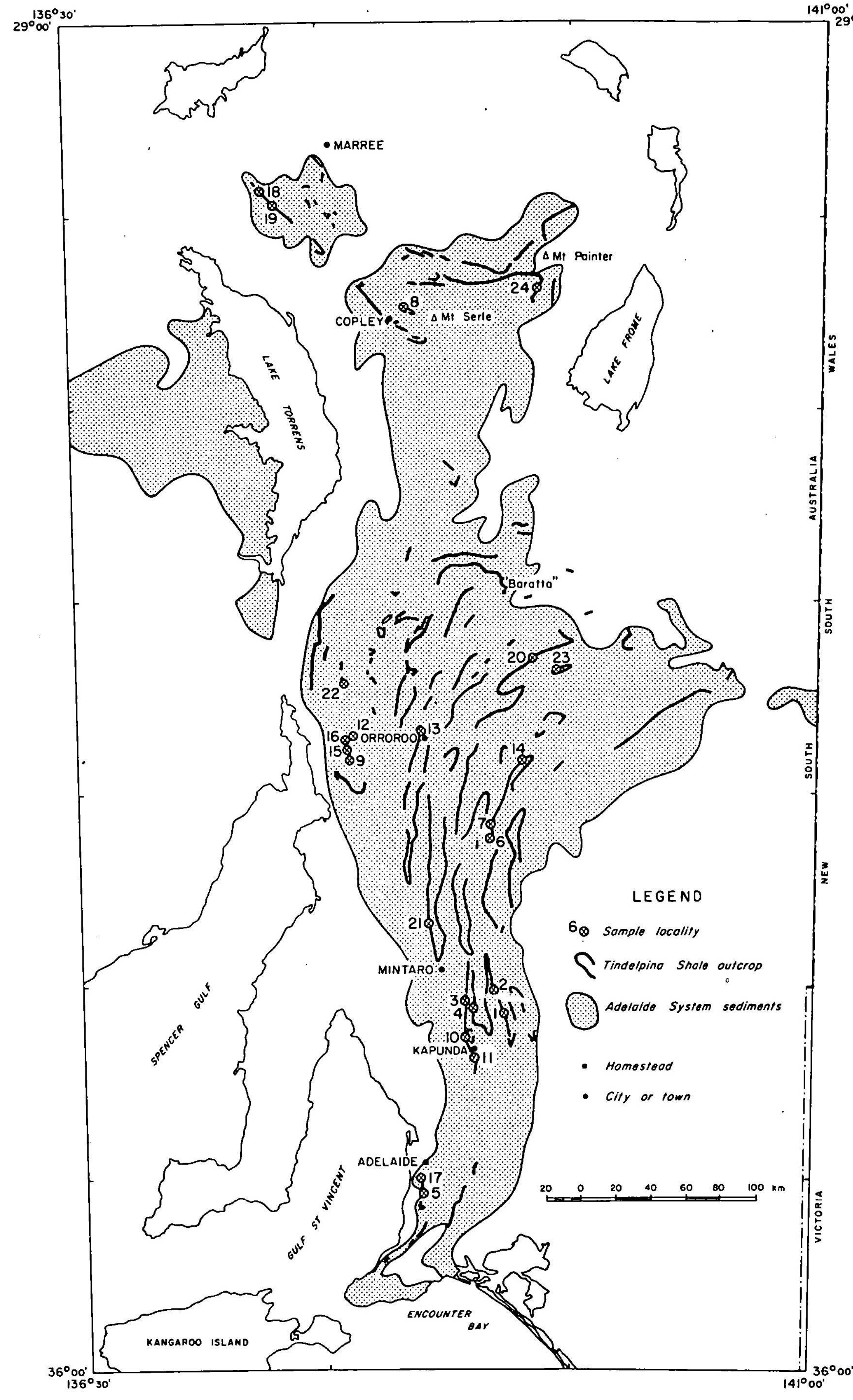
2B Cleavage development in Tindelpina Shale.

Fig. 1



135°00'
29°00'
141°00'
29°00'
0 50 100 150 200 km
Willouran Ranges
MT PAINTER BLOCK
Δ Mt Serle
LAKE FROME EMBAYMENT
STUART SHELF
TORRENS
HINGE
ZONE
Flinders Ranges
GEOSYNCLINE
ADELAIDE
"Baratta"
ORROROO
WILLYAMA BLOCK
Anabama Granite
GAWLER BLOCK
SOUTH AUSTRALIA
NEW SOUTH WALES
VICTORIA
SPENCER GULF
MINTARO
KAPUNDA
MURRAY BASIN
Palmer Granite
ADELAIDE
Mt Lofty Ras
KANMANTOO TROUGH
Fleurieu Peninsula
ENCOUNTER BAY
KANGAROO I
36°00'
135°00'
36°00'
141°00'
LEGEND
Cainozoic
Palaeozoic granites
Cambrian sediments
Adelaidean sediments
Lower Proterozoic
City or town
Homestead
Orroroo 1:250 000 sheet area boundary

Fig. 2



Record No. 1974/30

SA/BI-4A

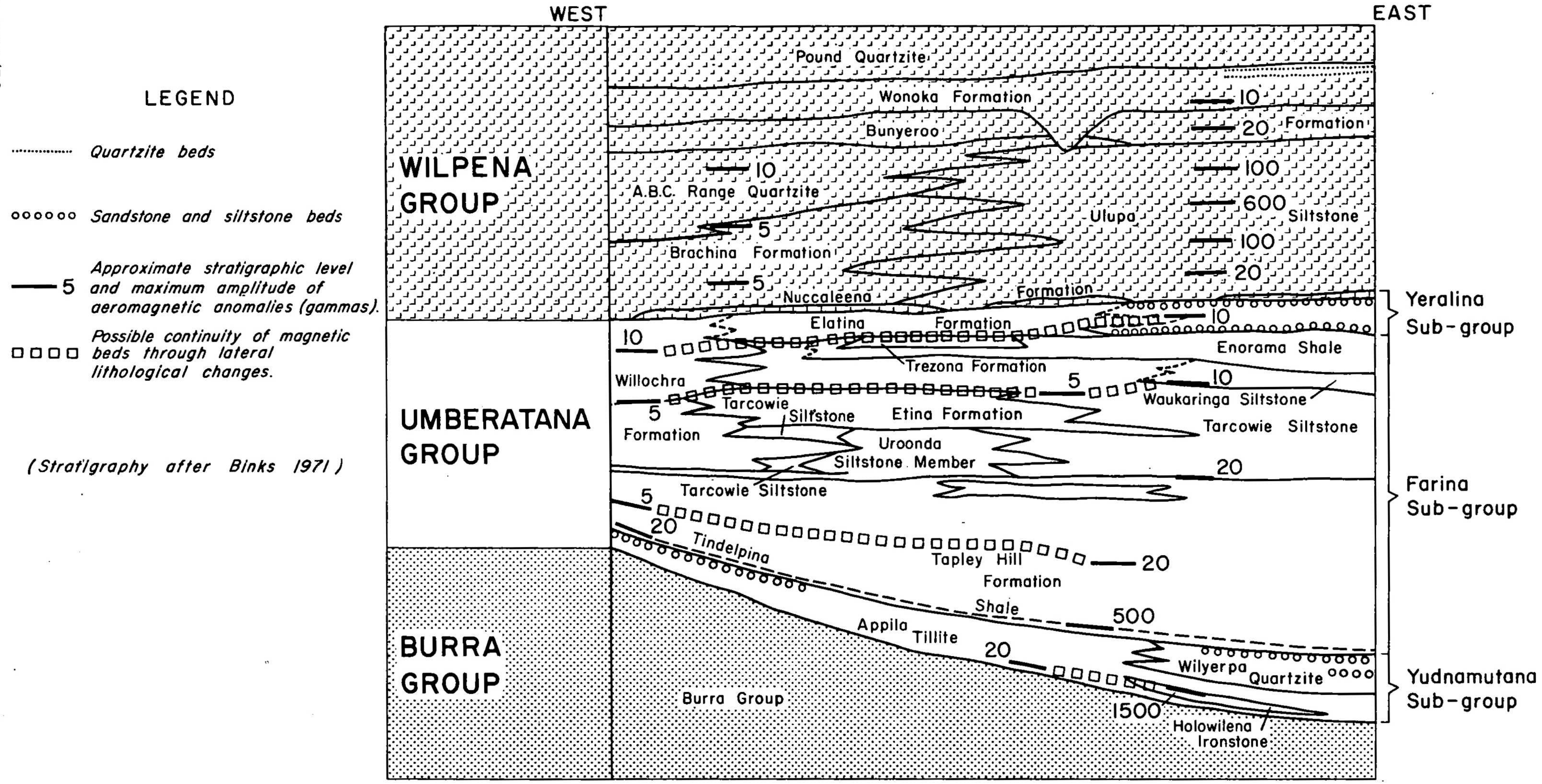

LEGEND
Quartzite beds
Sandstone and siltstone beds
Approximate stratigraphic level and maximum amplitude of aeromagnetic anomalies (gammas).
Possible continuity of magnetic beds through lateral lithological changes.
(Stratigraphy after Binks 1971)
WEST
EAST
WILPENA GROUP
UMBERATANA GROUP
BURRA GROUP
Pound Quartzite
Wonoka Formation
Bunyeroo Formation
A.B.C. Range Quartzite
Brachina Formation
Ulupa Siltstone
Nuccaleena Formation
Elatina Formation
Trezona Formation
Enorama Shale
Willochra Formation
Tarcowie Siltstone
Etina Formation
Waukaringa Siltstone
Tarcowie Siltstone
Uroonda Siltstone Member
Tarcowie Siltstone
Tindelpina Shale
Tapley Hill Formation
Appila Tillite
Wilyerpa Quartzite
Holowilena Ironstone
Burra Group
Yeralina Sub-group
Farina Sub-group
Yudnamutana Sub-group
10
20
10
100
600
100
20
5
5
10
10
5
10
5
20
5
20
20
500
20
1500

Fig. 3

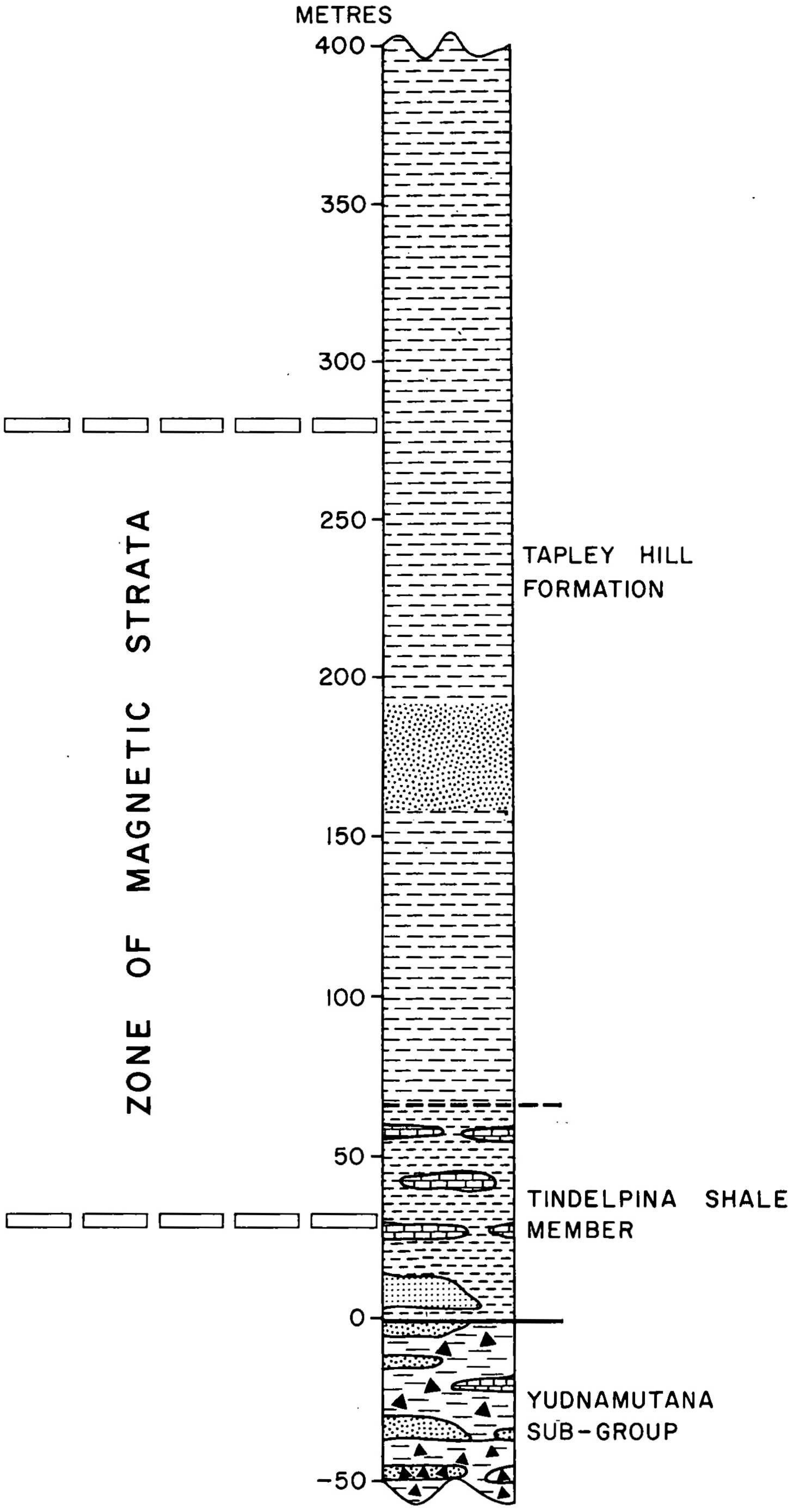

METRES
400
350
300
250
200
150
100
50
0
-50
ZONE OF MAGNETIC STRATA
TAPLEY HILL
FORMATION
TINDELPINA SHALE
MEMBER
YUDNAMUTANA
SUB-GROUP

Fig. 5

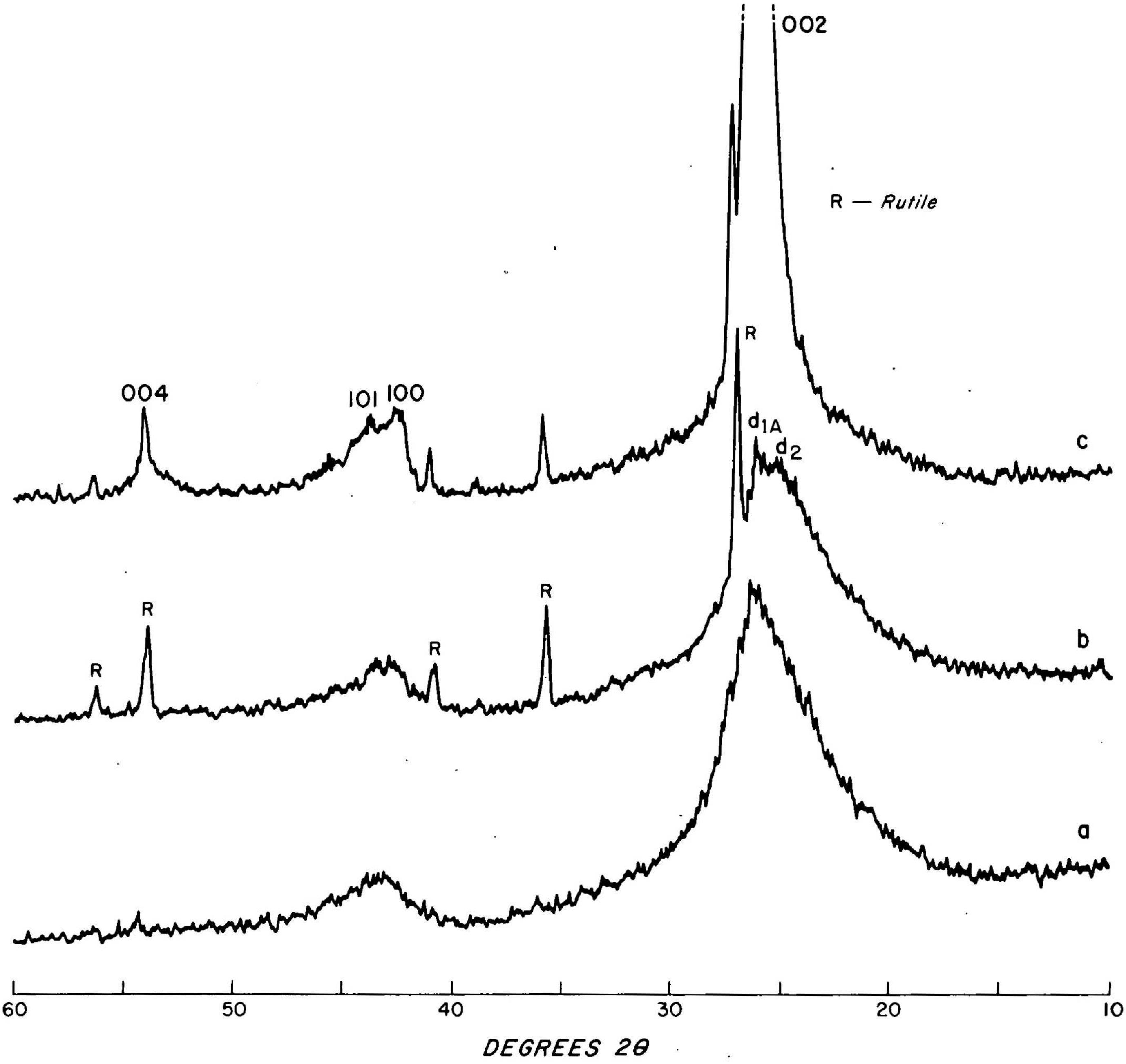
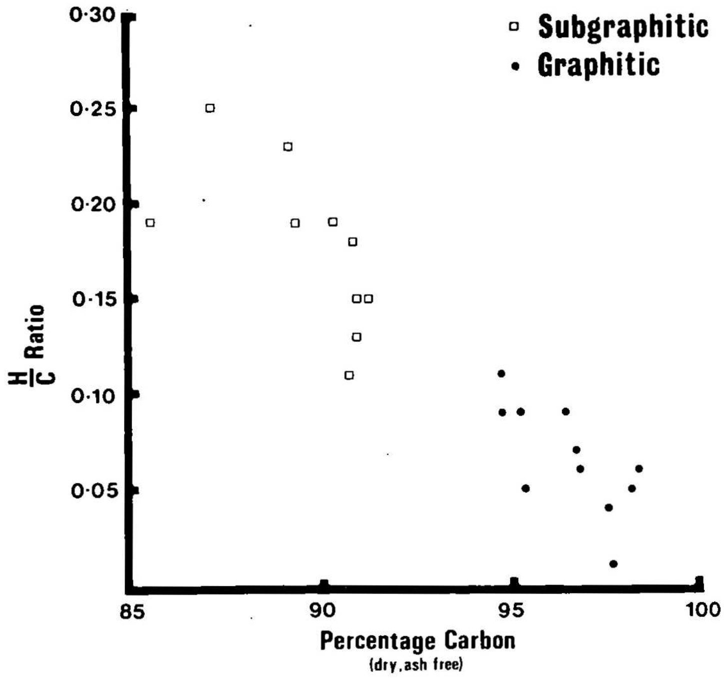
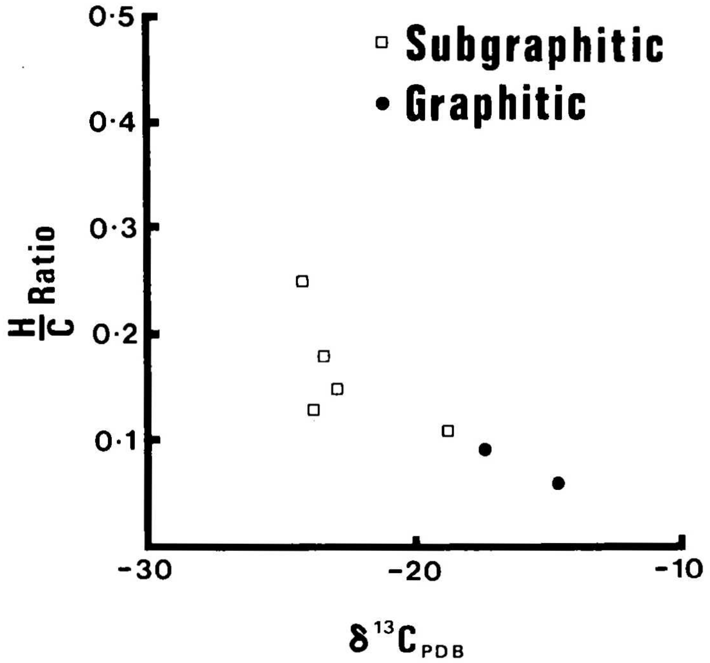

002
R — *Rutile*
R
004
101 100
d_{1A}
d_2
c
R
R
R
R
b
a
60
50
40
30
20
10
DEGREES 2θ

Fig. 6



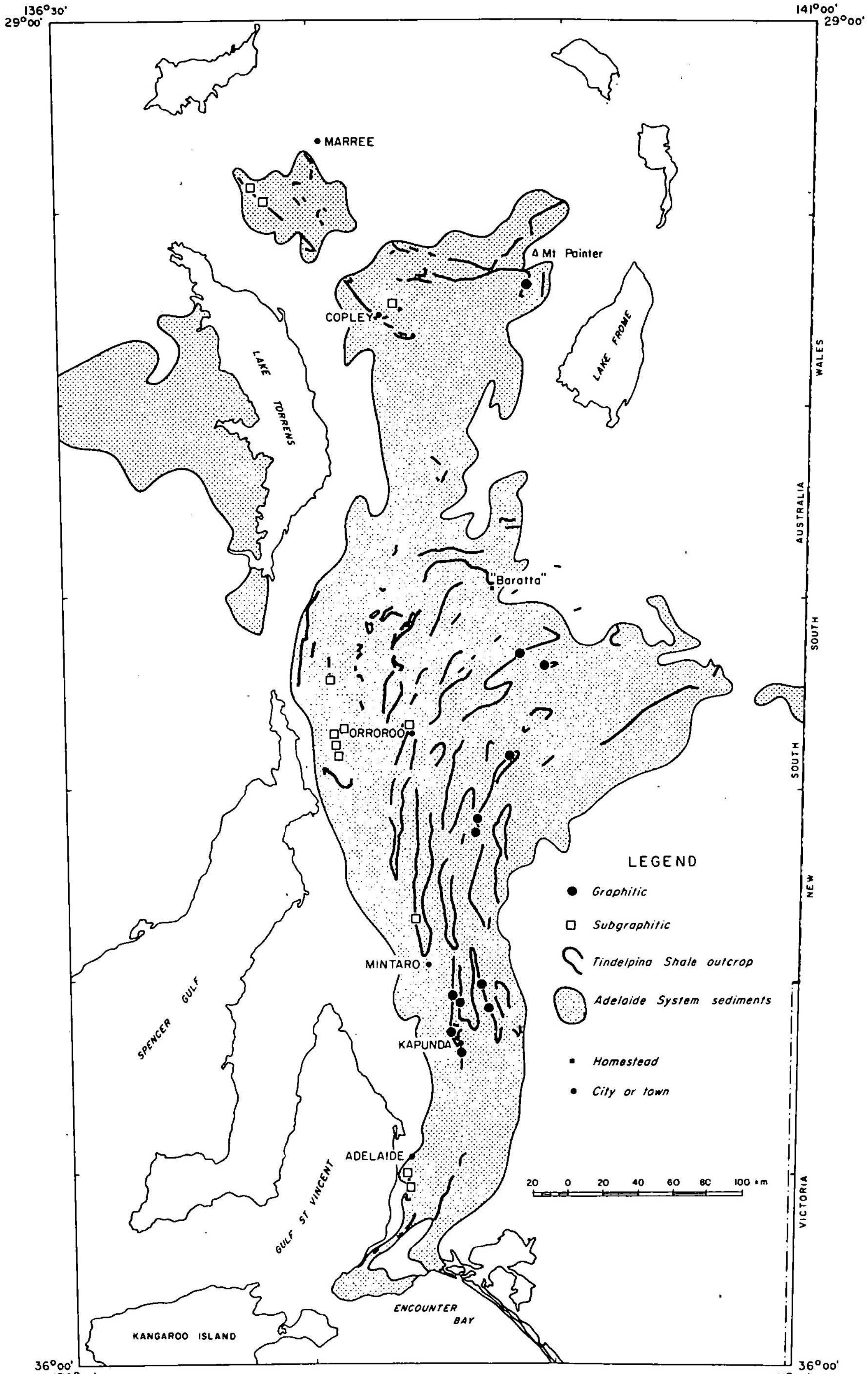
SA/BI-8A

Fig. 7



SA/BI-9A

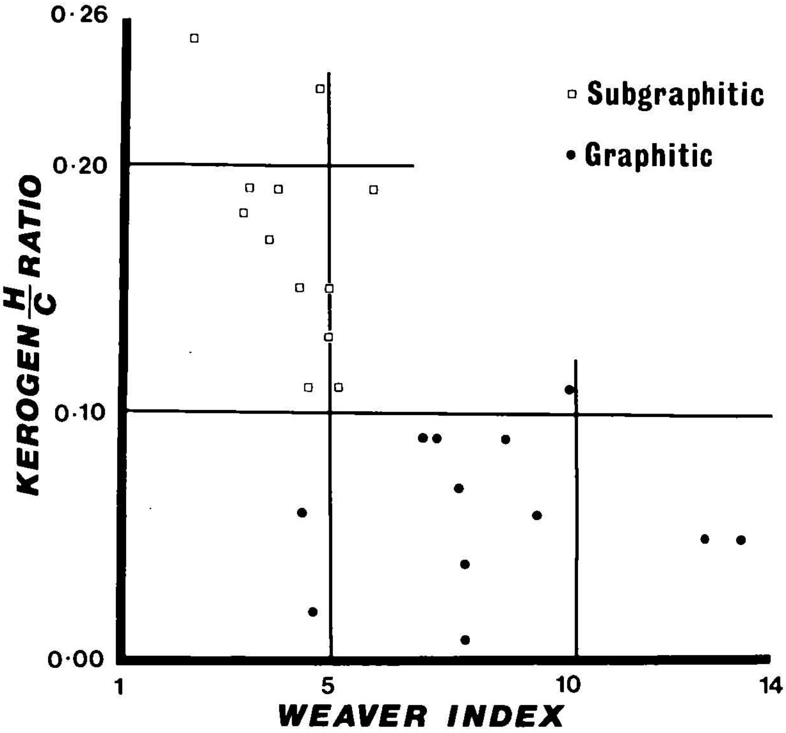
Fig. 8



Record No. 1974/30

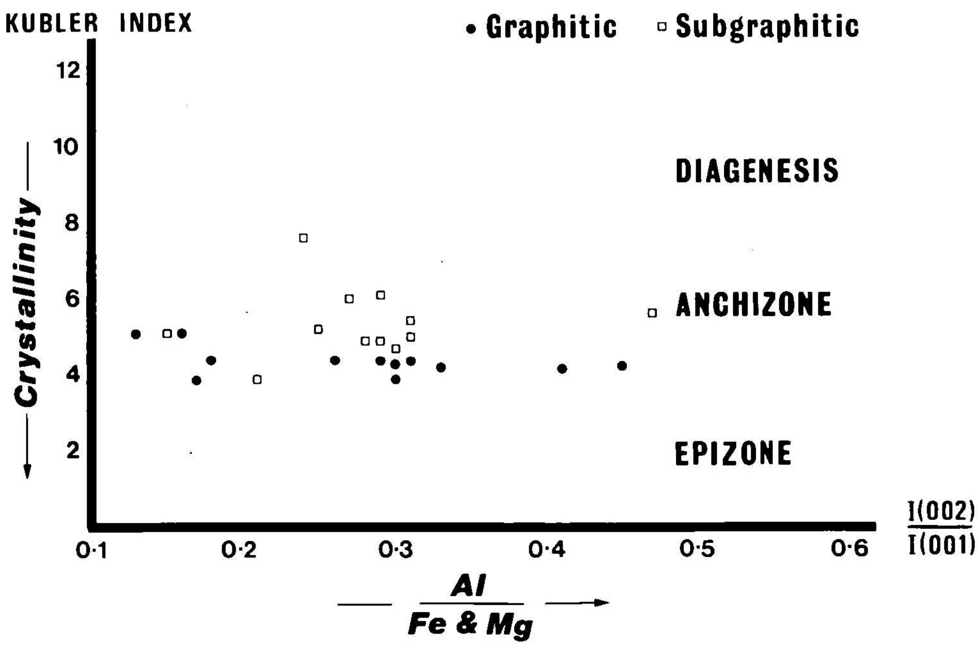
SA/BI-10A

Fig. 9



SA/BI-11A

Fig. 10



SA/BI-12A

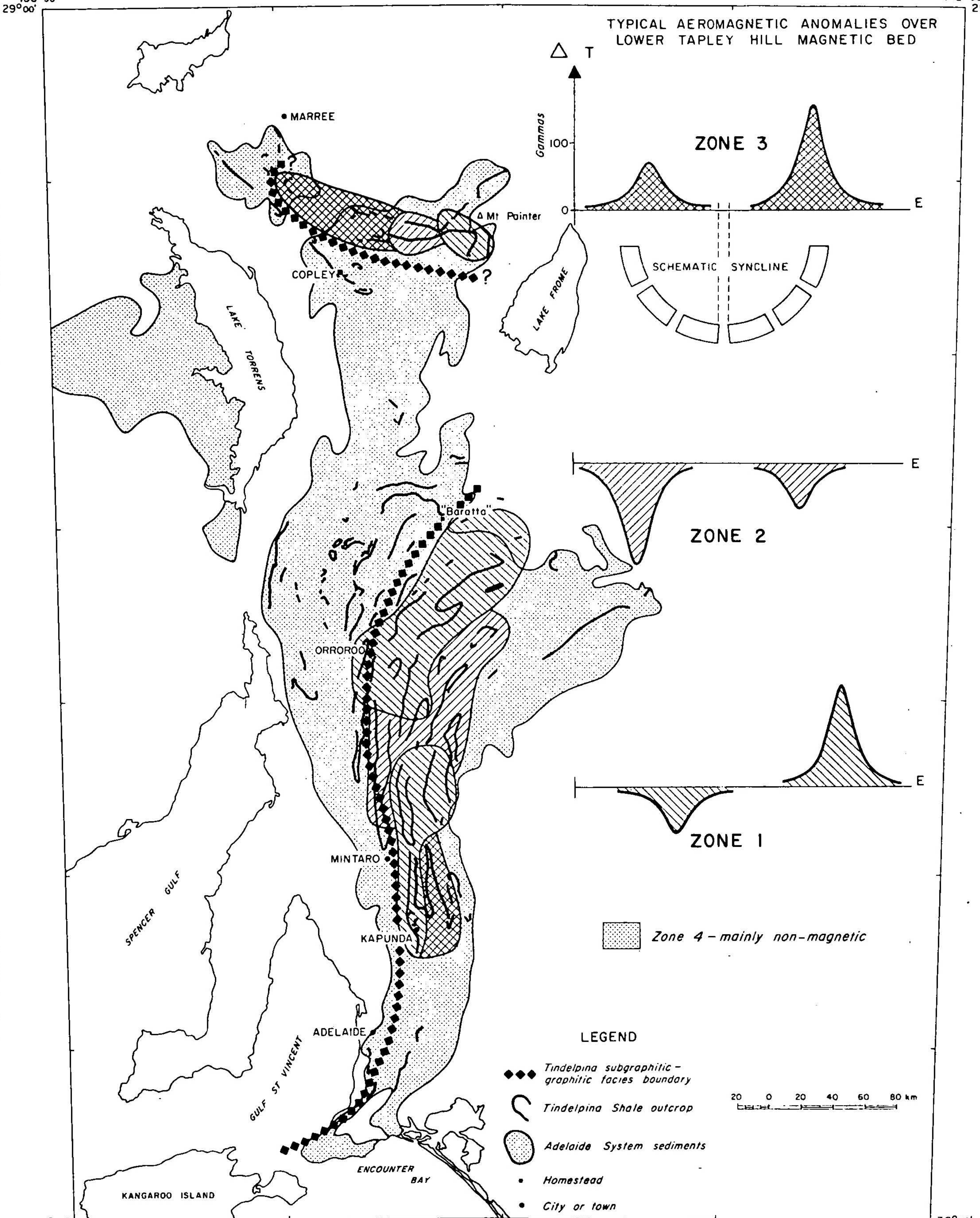

136°30'
29°00'
142° 30'
29°00'
TYPICAL AEROMAGNETIC ANOMALIES OVER LOWER TAPLEY HILL MAGNETIC BED
Δ T
Gammas
100
0
E
ZONE 3
SCHEMATIC SYNCLINE
ZONE 2
ZONE 1
Zone 4 – mainly non-magnetic
MARREE
Mt Painter
COPLEY
LAKE TORRENS
LAKE FROME
"Baratta"
ORROROO
MINTARO
KAPUNDA
ADELAIDE
SPENCER GULF
GULF ST VINCENT
ENCOUNTER BAY
KANGAROO ISLAND
LEGEND
Tindelpina subgraphitic – graphitic facies boundary
Tindelpina Shale outcrop
Adelaide System sediments
Homestead
City or town
20 0 20 40 60 80 km
36°00'
136°30'
36°00'
142°30'

PLATE I

PLATE 2A

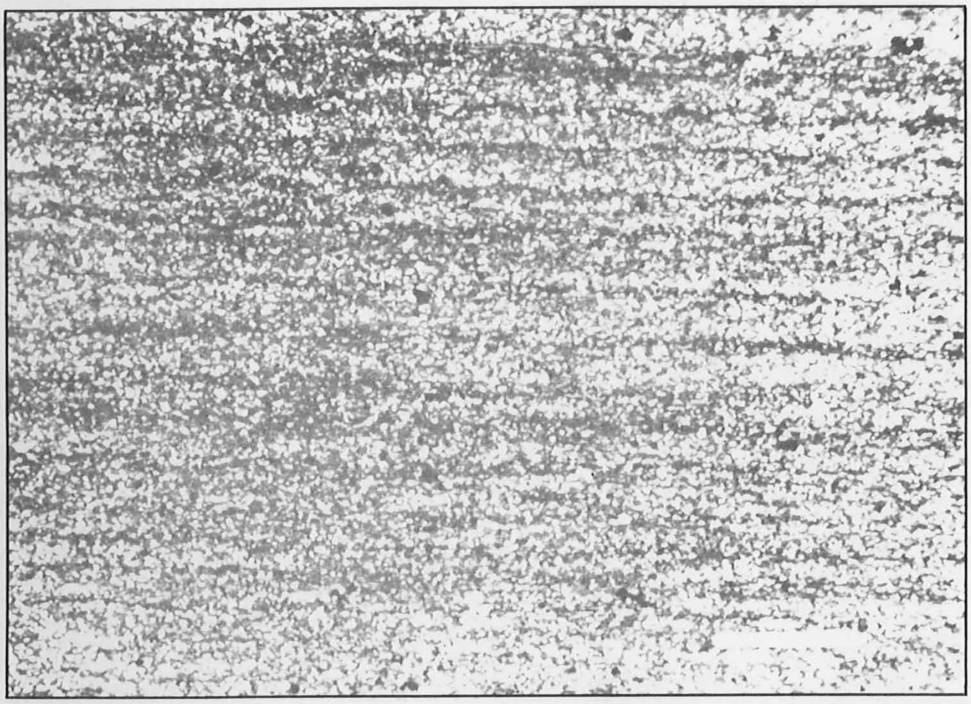


PLATE 2B