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DEPARTMENT OF MINES
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PERMIAN PALEOGEOGRAPHY AND DEPOSITIONAL ENVIRONMENT OF THE ARCKARINGA BASIN, SOUTH AUSTRALIA

by

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SUPERVISING GEOLOGIST
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PERMIAN PALEOGEOGRAPHY AND DEPOSITIONAL ENVIRONMENT OF THE ARCKARINGA BASIN, SOUTH AUSTRALIA

ABSTRACT

The Arckaringa Basin, situated in northern South Australia, is an intracratonic Permian basin, composed of deep marginal grabens or half grabens and a central area of shallow basement, the latter covered by only a thin sediment blanket. The sedimentary sequence comprises, in ascending order, diamictites and cyclically graded greywacke (Unit 2), a dark coloured, shale sequence (Unit 1) and dark grey, micaceous siltstones, sandstones and coal-seams (Mt. Toondina Beds). Along the eastern margin of the Basin, coarse clastics with clayey, sandy and dolomitic matrix, containing striated, fluted and soled cobbles and pebbles, are exposed. The thickness of the sediments ranges from about 100 feet (30 m) in outcrop, 800 to 1200 feet (240 to 365 m) over the area of shallow basement to more than 5000 feet (1524 m) in the centre of some of the grabens.

The Arckaringa Basin was established by downfaulting of the graben structures in late Carboniferous - early Permian times, but short-lived movements along the same trends were already experienced in the Devonian. Upfaulting of adjacent basement blocks created uplands on which plateau glaciers formed during the early Permian. Moraines and eskers were deposited along the basin margin whence glacial debris was transported into the distal troughs by mudflows and turbidity currents. Available evidence suggests that the Permian glaciation was concluded in mid Sakmarian time and that the cyclically graded greywackes

are largely the product of postglacial turbidity currents fed by high intake rates of detrital material which was maintained by continuous movements along the marginal faults. Tectonic stability in the late Sakmarian produced a low-energy, marine environment during which the dark shales of Unit 1 were deposited. Temporary evaporitic conditions are documented locally. This and other changing environments are thought to be responsible for the restricted nature of the foraminiferal fauna. Regression of the sea in early Artinskian was brought about by renewed diastrophism and the freshwater silts, sands and coals of the Mt. Toondina Beds, deposited under a moist subtropical climate conclude the Permian depositional cycle.

INTRODUCTION

Permian glacigene sediments were first recognised in South Australia by Selwyn in 1859, but far the greatest advance in the knowledge of Permian sediments and basins has been achieved in the course of petroleum exploration within the last decade. Geophysical surveys, followed by exploration drilling have revealed five substantial Permian basins, in addition to the one already known from surface exposures in the Adelaide Region. One of them, the Cooper Basin, has attained major economic importance as a natural gas province. Up to date four gas and condensate fields have been discovered in the South Australian portion of the Cooper Basin with recoverable reserves of natural gas amounting to more than 1 trillion cubic feet (Wopfner, 1966; Martin, 1967a). The hydrocarbon potential of other Permian Basins has not been fully explored yet.

All South Australian Permian basins are either completely or almost completely covered by sediments of younger depositional phases (Wopfner, 1969). The only exposures of Permian sediments occur on some upfaulted blocks of the Troubridge Basin and along the eastern margin of the Arckaringa Basin. The Permian phase of deposition was controlled by specific tectonic events, differing from those controlling both preceding and subsequent depositional phases. Therefore, the Permian basins have to be regarded as separate entities of infra-basin status. The nomenclature at present applied to South Australian Permian basins is shown on Figure 1.

All Permian basins in South Australia are intracratonic, but the nature of the underlying "basement" varies from folded

Devonian, Ordovician and Cambrian sediments, to early Precambrian granitic rocks. The establishment of the Permian basins was strongly controlled by down-faulting along one or several of their margins, generally along northeast or northwest trending lineaments, but sedimentation also spread across less disturbed portions of adjacent platforms. Movements along some of these controlling lineaments were initiated in the late Devonian (Wopfner and Allchurch, 1967; Wopfner, 1969; e.g. Renmark and Boorthanna Troughs) but these were only of short duration. The main period of tectonic instability commenced in late Carboniferous - early Permian times and persisted, with fluctuating intensity, throughout most of the Permian. Syndepositional faulting is well documented from the Renmark Trough, the Arckaringa Basin and the Cooper Basin. In the latter, the only basin where the Permian depositional phase is known to have extended into the lower Triassic (Paten, 1969), faulting was accompanied by syngenetic structural growth throughout the deposition of the Permian and lower Triassic sediments (Wopfner, 1966; Kapel, 1966; Martin, 1967a; Wopfner, 1969).

The early Permian to late Carboniferous period of glaciation is documented beyond doubt in the area of the Troubridge Basin, south of Adelaide, where many fine examples of polished and striated glacial pavements, overlain by Permain tillites (_sensu stricto_) are well exposed and easily accessible, (Campana and Wilson, 1955; Horwitz, 1960; Ludbrook, 1967). However, strong bias towards glaciation, interpreting any coarse clastic sediment within the Lower Permian as a "glacigene", and over-generalisations have sometimes led to rather unrealistic paleogeographic concepts and the present author is by no means free of this criticism.

The present paper is an attempt to evaluate the depositional environment and the palaeogeography of the Arckaringa Basin, situated in the central part of northern South Australia (Fig. 1). This evaluation is based on new stratigraphic information and lithologic studies of four shallow, stratigraphic wells drilled by the South Australian Department of Mines in 1969, the results obtained previously in the Coontanoorina Well No. 1 (Wopfner and Allchurch, 1967; Harris and McGowran, 1967) and field investigations of Permian exposures along the eastern margin of the Arckaringa Basin. Additional new information particularly with regard to basement configuration and structural data, was derived from geophysical surveys carried out by the Petroleum Division of the South Australian Department of Mines in the past two years. These surveys included regional gravity coverage and semi-detailed reflection and refraction seismograph surveys (Milton, 1969a, b and c.)

BASIN FRAMEWORK

The Arckaringa Basin, is by definition, a late Palaeozoic basin and its basin-fill does not include the thin veneer of late Jurassic and early Cretaceous sediments of the Great Artesian Basin depositional cycle, which blanket the Permian sediments (Freytag, 1965; Wopfner and Allchurch, 1967; Wopfner, 1969).

Tectonically, the Arckaringa Basin is essentially an intracratonic basin the sediments of which rest largely on the northern extension of the Gawler Platform and its pre-Palaeozoic accretions (Fig. 1). To the north and northwest, the basin may overlap early Palaeozoic tectonic elements of the circum-Denison arc (Wopfner, 1969) but information in these regions is scarce and the relationships between Permian and pre-Permian rocks are not yet fully established. Interconnection with the Pedirka Basin to the northeast and the Denman Basin to the southwest may be possible (Fig.1).

New data obtained over the past two years have led to considerable changes in our concept of the basin's configuration, differing from that shown in earlier publications (Wopfner, 1964). Today, three distinctive basinal features are recognised within the Arckaringa Basin; the Boorthanna Trough along its eastern margin, the arcuate shaped trend of the Wallira and Phillipson Troughs along the southern margin and the shallow platform cover of the central basin area (Fig. 2).

By far the best known feature of the Arckaringa Basin is the Boorthanna Trough. Not only are Permian sediments exposed along its eastern margin (Parkin, 1956; Wopfner, 1964; Heath, 1965) and in the piercement structure at Mount Toondina (Freytag, 1965) but it has also the greatest density of seismic coverage (Moorcroft, 1964; Milton, 1969a and b) and drilling information (Ludbrook, 1961; Wopfner and Allchurch, 1967). The eastern margin of the Boorthanna Trough abuts against the Adelaidean and earlier Precambrian inliers of the Denison Block (Fig.1). This boundary is largely fault controlled and syngenetic, down-basin step-faulting is recorded along the northern-most part of this boundary (Moorcroft, 1964). The southern part of the trough shelves on to red-beds of Adelaidean or early Palaeozoic age, whilst to the west a north-northwest trending hinge zone connects the area of troughing with the area of the shallow, stable platform. This hinge zone is approximated by the line up of negative gravity anomalies along the western margin of the trough (Fig. 3). Northeast trending gravity features clearly discernible on the same map(Fig.3) are thought to present older structural features of the platform. Thus the Boorthanna Trough would best be classified as a half graben, the structural trend of which was initiated in Devonian time, but rejuvenated and fully developed in the early Permian (Wopfner and Allchurch, 1967). The maximum thickness of Permian sediments in the Boorthanna Trough,indicated by seismic surveys is in excess of 4000 feet.

The central area of the Arckaringa Basin is characterised by a gently undulating floor of shallow, crystalline basement (Milton, 1969c). The basement floor slopes northward, where it merges with a narrow, west-southwest trending lobe extending off the northern portion of the Boorthanna Trough (Fig. 2). The undulations of the basement floor are of very low amplitude, too low to show up in the generalised contour map, Figure 2. They are thought to be caused by structural trends within the basement and are well displayed on the gravity map, Figure 3. The same map shows three pronounced positive gravity anomalies (Mabel Creek, Coober Pedy and Mount Woods anomalies) forming the southern margin of the central basin area. Seismic refraction work, shallow drilling (Brady No.1) and the exposed crystalline rocks at Mount Woods identify these gravity features as "bald-headed" basement highs, across which Permian sediments are either absent or very thin (Fig.2).

The third feature of the Arckaringa Basin, situated to the south of the "bald-headed" basement highs is indicated by the north-convex trend of negative gravity anomalies (Fig.3). The west to southwest trending narrow feature has been termed the Wallira Trough while the southeast trending "low" is referred to as the Phillipson Trough. On a previous map of the basin (Wopfner, 1964) the latter feature was referred to as the Lake Phillipson Trough and, in the absence of geophysical data, its trend was shown to extend northwards towards and beyond Coober Pedy. This basin-shape has subsequently been adopted by Canaple and Smith (1965), and Ludbrook (1969). From the data presented here (Figs. 2 and 3) it will be apparent that the Phillipson trend swings to the northwest where it connects with the Wallira trend. Seismic reflection and refraction surveys have shown that the Phillipson Trough is a complex structure, consisting of two lobes with a maximum accumulation of Permian sediments in excess of 4000 feet (1219 m) (Milton, 1969c). Almost 3000 feet (914 m) of Lower Permian sediments were drilled in Lake Phillipson Bore (Ludbrook, 1961) situated on the north-eastern slope of the trough. The southern limit of the trough has as yet not been determined.

The Wallira Trough is, at least in its north-eastern part, a narrow graben, controlled by syngenetic faults. The greatest displacement occurred along the northern margin, as indicated by the steep gravity-gradient (Fig. 3) and confirmed by seismic reflection and refraction surveys (Figs. 2 and 8). Rejuvenation of this fault in post-Mesozoic time has resulted in a clear surface trace in the form of a low fault scarp. Maximum sediment fill is about 5000 feet (1524 m). The south-western extension of the trough, indicated by the Bouguer gravity map has not yet been investigated. The southern slope of the Wallira Trough is, at least in parts, also fault controlled and shallows rapidly southward (Figs. 2 and 8). Exposures of igneous rocks of the Gawler Platform mark the southern boundary of the basin in this region.

The western and north-western margins of the Arckaringa Basin are still largely unknown. It is fairly certain that Permian sediments overlap, at least in some parts, the Cambro-Devonian sediments of the eastern Officer Basin but exact boundaries have not been established.

STRATIGRAPHY

The Permian sequence of the Arckaringa Basin contains three litho-stratigraphic units consisting, in ascending order, of basal coarse-clastic sediments, a dark shale unit in the middle and an interbedded sequence of siltstones, coal and fine grained sandstones at the top.

Freytag (1965) defined the top unit as the Mount Toondina Beds, designating the exposures at Mount Toondina as the type locality (Fig. 2). Wopfner and Allchurch (1967), in describing the subsurface sections in the Cootanoorina Well No. 1 adopted the name Mount Toondina Beds but in the absence of formally defined names for the two lower units, informal terms were used. The Shale unit below the Mt. Toondina Beds was referred to as "Unit 1" and the basal coarse clastics were called "Unit 2". The Cootanoorina Well was the first well drilled with adequate geological control and the electric and radioactivity logs obtained from that well, allowed separation of the three rock units by characteristic log responses; in particular, a clear lower boundary for the Mount Toondina Beds could be established by a marked change in formation resistivity.

Using the old Lake Phillipson bore, drilled almost 70 years ago, as the "standard subsurface section", Ludbrook (1967) named two lower units Lake Phillipson Beds and Stuart Range Beds. Unfortunately the name "Lake Phillipson Beds" has been found to be invalid, as the term Phillipson Beds, used for a rock unit in the Canning Basin (Casey and Wells, 1961) has priority. In order to comply with the Australian Code of Stratigraphic Nomenclature the basal Permian unit of the Arckaringa Basin will have to be redefined (Ludbrook, 1969).

The correlation presented here is based on electric and radioactive log characteristics (Fig. 4) and is consistent with palynological and micropalaeontological data (Harris and McGowran, 1967 and pers. comm. Harris, 1969; McGowran, 1969). Since wire line log correlations cannot be extended to the Lake Phillipson bore, since there is doubt about the lower boundary of the Mt. Toondina Beds in the section of this bore (Harris and McGowran, 1967), and since a new name is needed for the lowest unit, the author prefers to apply for the purpose of this paper, the partly informal terminology used for the Permian section in the Cootanoorina No.1 Well (Wopfner and Allchurch, 1967) and in subsequent stratigraphic wells drilled in the Arckaringa Basin (Demaison, 1969). Furthermore, since accurate velocity data over the whole Permian section were obtained in the Cootanoorina No.1 well, the same rock units can now be identified also by seismic methods, providing the sediments are thick enough to yield good seismic results (Milton, 1969a and 1969b).

Description of rock-units

UNIT 2: Exposures of this basal unit occur intermittently along the western margin of the Peake and Denison Ranges (Parkin, 1955; Wopfner, 1964; Heath, 1965). Although the Permian age of these sediments has not been established by palaeontological evidence, their lithology and boundary relationships combined with geophysical data, can leave very little doubt that they belong to the basal Permian succession.

The basal beds consist generally of ill-sorted, coarse clastics, the size of the components ranging from pebble size to boulders up to 10 feet (3 m) in diameter, with an average size of about 6 inches (15 cm). Cobbles and boulders are generally sub-rounded; striated, fluted and "soled" pebbles are abundant, (Figs. 5, 6 and 10). Matrix composition ranges from clayey sandstone in the north to ill-sorted, loosely consolidated sandstone further south (Fig. 5), and to calcareous or dolomitic sandstone in the southern-most exposure (Fig.10).

At Mount Dutton, where one of the best sections is exposed, the basal coarse clastics grade upwards into thinly bedded, sandy shale with rare pebbles, generally less than 5 cm in diameter. The clay fraction in this shaly unit is dominantly illite (Heath, 1965).

In subsurface, two distinctive facies developments are discernable within the stratigraphic interval of Unit 2. One facies is characterised by the dominance of diamictites whereas the other facies consists of cyclically graded sequences of coarse and fine clastics. The inter-relationship between these two facies has not been fully established yet. In places they certainly intertongue laterally but there is also good evidence that the graded sequence overlaps the diamictite facies on structural highs and along some of the basin margins.

The diamictite facies is known from the Lake Phillipson Bore (Ludbrook's - 1961 - boulder clays), from the Boorthanna Trough and a very thin sequence was also encountered in Wallira No. 2, on the northern slope of the Wallira Trough. The diamictites consist of a groundmass of calcareous claystone with up to 15% of randomly interspersed fine to medium grained quartz. These quartz grains are very well rounded, of very high sphericity and their surfaces are invariably frosted. Scattered through this matrix are, with varying density, granule to cobble size clasts of granite, quartzite, and other exotic rocks. Irregular or lenticular sand bodies are also present. In Wallira No. 2 where 21 cm. of diamictite resting directly on crystalline basement, were recovered in a drill core (Fig. 7), the sediment consists of a dark greenish grey unsorted groundmass of fine to medium grained clayey arenite with angular to sub-rounded clasts up to 2 cm. in diameter. Its composition is about 30% quartz, 25% rock fragments, 5% feldspar and 40% matrix. The latter consists of illite, montmorillonite, kaolin, carbonate (dolomite and siderite) and sub-microscopic quartz (?rock flour). The illite/kaolin ratio is 1.3.

In the deeper parts of the troughs where apparently the greatest thickness of diamictites was deposited, thick intervals of green splintery shale are intercalated between the diamictites and a thick band of chocolate-brown shale sometimes occurs near the base. The shales (both green and brown) are very clean or slightly micromicaceous clay shale and are generally thinly fissile.

The cyclically graded facies of Unit 2 consist of interbeds of coarse, ill-sorted greywacke type clastics and arkoses ranging from conglomerate to silt size or silty shale. Individual clasts up to 2 feet (60 cm) apparent diameter have been recovered in drill cores. Graded bedding has been observed in cores from the Cootanoorina No. 1, Karkaro No. 1 and Wallira No. 2 wells (Fig. 7). Slump structures are a common feature, particularly within the finer grained sediments. The shape of the pebble to cobble-size components is generally subrounded, but angular and well rounded components are also present. Elongated pebbles have their longer axis orientated parallel with bedding. The cobbles and boulders contained within this facies of Unit 2 commonly reflect the composition of the nearest basement high. Thus within the outcrop area and in Cootanoorina No. 1 they consist largely of Adelaidean sediments and pre-Adelaidean crystalline rocks of Denison Block provenance; in Wallira No.1 the coarse clastics comprise porphyritic rhyolites and other igneous rocks of northern Eyre Peninsula, whereas in Karkaro No. 1 the dominant rock types are granitoid rocks similar to the underlying basement. In the last named well, an almost unconsolidated coarse arkose which is best described as granite wash, was encountered a few feet above the basement contact. In Wallira No. 2, where the thickest sequence of this facies has been encountered so far, the basal 300 feet contain an abundance of red volcanic rock fragments, indicating a southerly source, whereas the dominance of metamorphic rocks higher up suggest a more local provenance, possibly the Coober Pedy Basement High.

The differences in matrix are considered to be of considerable genetic significance and are therefore dealt with in some detail. In Cootanoorina No.1 the dominant matrix is micritic or less commonly sparry carbonate, usually dolomite or a dolomite-calcite mixture. In Karkaro No.1 the matrix consists generally of fine grained sandstone with some kaolin, but in the better sorted arkoses, matrix is almost absent, resulting in a semi-friable, highly porous sediment. In Wallira Nos. 1 and 2 the most common matrix consists of fine-grained, illsorted, pyritic sandstone with small amounts of clay. The clay fraction consists of kaolin (both crystallised and disordered type), montmorillonite and trace amounts of illite, with illite/kaolin ratios ranging from 0.04 to 0.01. The upper part of core 7 in Wallira No.2 (1094 to 1095 feet; Fig. 7) contains no clay at all and the sediment is cemented by crystalline gypsum and dolomite. The gypsum poikilitically encloses the clasts of the framework in such a manner that there is often no contact between adjacent grains.

The thickness of Unit 2 varies from about 100 feet (30 m) of the outcrop section at Mt. Dutton (Heath, 1965), 440 feet (145 m) in Wallira No. 2 and more than 1000 feet (300 m) in the deep centres of the troughs. The unit is absent in Mount Furner No.1 (Fig.4).

Plant spores and pollen recovered from this unit in Cootanoorina No.1 date it as Lower Permian (Harris and McGowran, 1967) but basal sediments in the deeper parts of the troughs may possibly extend into the late Carboniferous. A lowermost Sakmarian age was suggested by Ludbrook (1961) for the basal diamictite facies in the Lake Phillipson bore.

UNIT 1: This, the middle unit of the Permian sequence of the Arckaringa Basin, consists substantially of dark grey to dark greenish-grey shale, and pale to mid-grey silty to sandy shale. The lower parts of this unit are plastic when wet and contain thin interbeds or lenses of fine grained, calcareous, pebbly sandstone. The dominant clay mineral is kaolin with some montmorillonite and illite. Varying amounts of carbonate are also present. Thin interbeds or lenses of fine grained, calcareous sandstone with occasional granules or pebbles occur at irregular intervals.

The middle part of Unit 1 in Cootanoorina No. 1 is composed of a mid-grey, micaceous siltstone, with about 110 feet (33 m) of anhydritic siltstone near its base (between 2080 and 2190 feet, 633.9 m and 667.5 m). The top part is a grey, micaceous shale with lenticles or laminae of siltstone or very fine grained sand. Kaolin is again the dominant clay mineral with some montmorillonite and illite. The clastic grains of the silt-sand laminae are composed of quartz, feldspar, lithics and mica. Accessory minerals are, in order of abundance, tourmaline, chlorite, garnet, biotite, mica and zircon.

Similar features are displayed in the limited exposure of this unit near Mount Dutton. Heath (1965) describes this unit as greenish to bluish-grey laminated shales, consisting of approximately equal amounts of kaolin and illite, with irregular blebs and lenses of fine quartz sand.

Unit 1 generally contains foraminifera and some rare micro-fossils have been described by Ludbrook (1967) from intervals of the Stuart Range Beds, apparently equivalent to Unit 1. The foraminiferal fauna encountered in the sediments of Unit 1 consist entirely of arenaceous species. Even when specimen numbers are high, the assemblage disappears suddenly at the top of the unit in the Karkaro and Wallira sections(McGowran, 1969, pers. comm.), and within the unit in Cootanoorina (Harris and McGowran). In the latter well, the disappearance of foraminifera, but not microplankton above 2200 feet (670.5 m) coincides with the onset of deposition of anhydritic and gypsiferous siltstones (Wopfner and Allchurch, 1967). The age of Unit 1 is Sakmarian.

The thickness of Unit 1 varies between 855 feet (260.6 m) in Cootanoorina No. 1 and 88 feet (27 m) in Mount Furner No. 1 (see Fig. 4).

MOUNT TOONDINA BEDS: This unit was first described from Mount Toondina in the northern Boorthanna Trough, where these sediments are exposed in a circular, piercement type structure (Freytag, 1965). In the type-section, about 250 feet (76 m) of grey siltstone, carbonaceous shale, fine-grained sandstones and several coal seams are exposed. Many of the siltstones are laminated or thinly interbedded with carbonaceous shale and exhibit low angle asymptotic or festoon type current-bedding. Plant fossils, contained in a shaley siltstone at about the middle of the type section, comprise _Glossopteria indica_ Schimper, _Sphenophyllum_ sp. _Cordaites australis_ (McCoy) _Gangamopteris_ sp. _Schizoneura_ sp. and equistalean stem impressions (Freytag, 1965).

The Mount Toondina Beds encountered in the various stratigraphic wells exhibit the same basic lithological charateristics as described from the type section. In Cootanoorina No. 1 an upper unit, consisting of pale to dark grey micaceous (biotitic), feldspathic siltstones, interbedded with carbonaceous shale and seams of black coal may be distinguished from a lower unit, comprising mainly pale grey, calcareous siltstones with thin interbeds of fine-grained calcareous and feldspathic sandstones. The two units are separated by about 50 feet of fine-grained, lithic greywacke, composed of angular to subangular grains of quartz (30%), lithics (25%), feldspar (15%), micas (10%) and clay matrix (20%).

To the west of the Boorthanna Trough, the lower portion of the Mount Toondina Beds shows a marked increase in sand/shale ratio together with a slight overall coarsening of grain size (see section between Cootanoorina No. 1 to Karkaro No. 1; Fig. 4). A particularly thick sequence of fine to medium grained, friable, feldspathic sand was encountered in Mount Furner No. 1 below a normal "upper" sequence of Mount Toondina Beds (Demaison, 1969).

The base of the Mount Toondina Beds can be identified reliably on electric and radioactive logs. This is strikingly demonstrated by the resistivity curves in Cootanoorina No. 1, where this boundary is marked by an increase in resistivity of 12 ohm m^2/m (Wopfner and Allchurch, 1967).

The Mount Toondina Beds generally contain a varied micro-flora with an abundance of megaspores (Harris, 1969). Palynological evidence indicates an Artinskian age (Harris and McGowran, 1967), and they are thus equivalent with the lower and middle member of the gas-bearing Gidgealpa Formation of the Cooper Basin (Wopfner, 1966; Martin, 1967b; Paten, 1969).

The greatest thickness of Mount Toondina Beds (1279 feet, 390 m) was encountered in Mount Furner No.1 . This compares with 1080 feet (329 m) in Cootanoorina No. 1, 710 feet (216 m) in Karkaro No. 1 and 235 feet (72 m) in Wallira No.1. The Mount Toondina Beds are absent in Wallira No. 2 (Fig. 4).

The Permian sediments of the Arckaringa Basin are overlain, either disconformably or with slight angular unconformity by the Upper Jurassic to Lower Cretaceous sediment-sequence of the Great Artesian Basin.

DISCUSSION

Status of environmental interpretation

Important progress in the understanding of Permian deposition in South Australia, until then summarily regarded as glacial and fluvioglacial sediments, was made by Ludbrook's discovery of foraminifera in Lower Permian sediments of the Troubridge Basin, the Arckaringa Basin and the Renmark Trough (Ludbrook, 1956, 1961, 1967) and the establishment of Lower Permian age for parts of the pre-Mesozoic sequences of the Arckaringa and the Pedirka Basins by palynology (Balme, 1957). A number of palaeogeographic models have been proposed since, to account for:

(1) The trough-shape of a number of Permian basins;

(2) The mode of entry to the sea;

(3) The presence of marine fossils in coarse clastic sediments of glacial origin;

(4) Presence of cyclically graded bedding and micritic carbonates in sediments of presumed glacial origin ; and

(5) The "restricted" foraminifera fauna of Lower Permian sediments; particularly Unit 1.

Ludbrook (1961, 1967, 1969) proposed over-deepening by ice followed by marine incursion in fiords with marine glacial deposition and thought that low water temperatures or low salinities were responsible for the restricted faunas.

The present author (Wopfner, 1964) suggested a similar concept for the Arckaringa Basin but argued for a more mature landscape than that suggested by Ludbrook (op cit), and inferred that isostatic sea-level changes may have been responsible for the entry of the sea. Neither of these models are now considered satisfactory. In applying features of the Quaternary glaciation to Permian succession, the great difference in the time spans involved is too easily overlooked; deposition of the Permian sequence in the Arckaringa Basin required at least 20 million years compared with the 1 to 1.5 million year span of the Quaternary glaciation.

Based on seismic results and new information obtained from the Cootanoorina No. 1 well, Wopfner and Allchurch (1967) emphasised the tectonic control of Permian troughs and proposed transport of glacial debris by density currents into the deeper part of the trough to account for the graded bedding and the micritic carbonates in Unit 2.

A quiet water, marine environment with physical restriction up-section was envisaged by the same authors for the sediments of Unit 1. Similarly, Harris and McGowran (1967) suggested that the

Arckaringa Basin at the time of deposition of Unit 1 "formed a gulf which became for a time normal marine in a sense, but not open marine".

It will be evident from the descriptive part of this paper that the Permian sediments of the Arckaringa Basin resulted from a variety of events leading to complex and diverse environmental conditions. In order to derive a model which, hopefully, will account for all the known data, a number of aspects will have to be considered in the following discussion.

Permian fiords or grabens ?

The answer to this question has to be derived from evidence on pre- and early Permian morphology and tectonisms.

Modern fiords are drowned, glacial valleys formed exclusively along coasts of high relief (Fairbridge, 1969) - in other words in a juvenile topographic setting. They are open to the sea and commonly associated with them are submarine canyons down the adjacent continental slope (Holtedahl, 1950; Bruun et al., 1955; Brodie, 1964; Anderson, 1968). Despite the steep-walled surroundings and the apparently high erosional gradients, sediments deposited in fiords, and for that matter in lakes of glacial valleys, are surprisingly fine grained, mainly in the medium grained sand to silt range (Pantin, 1964; Weynschenk, 1949). Deposition of coarse clastics is generally restricted to the mouths of streams issuing into fiords, where local deltas may develop (Brodie, 1964). The more distal parts may occasionally receive psephytic material from local gravity slides (Heim, 1921) or from catastrophic rock falls which may dump large masses of blocks and boulders. In Norwegian fiords, where flood-waves initiated by such rock falls have caused severe damage to human habitation for many centuries (Bugge, 1937; Jørstad, 1956) up to 1.5 million cubic metres of rock have been dumped by one single fall (Kaldhol and Kolderup, 1936, p.12).

It can not be denied that certain sedimentological features of Unit 2 of the Arckaringa Basin could be explained by post-glacial deposition in a fiord - environment. However, a comparison between the cross - sections of fiords and the section across Wallira Trough, by far the narrowest of all Permian troughs in South Australia (Fig.8), demonstrates the fundamental difference in profile. The glaciated valleys clearly show the juvenile topography in which they evolved whereas the Wallira Trough is easily identified as a graben-structure, formed by syngenetic faulting of a mature landscape. The same argument applies equally or even more so to other Permian troughs in South Australia, all of which are fault-controlled.

Good evidence for the mature nature of the pre-Permian landscape was obtained in the Karkaro well No. 1, where the bottom hole cores encountered, what would appear at first sight, large granite boulders beneath the Permian sediments. The boulders, the surfaces of which were rough with individual protruding quartz grains, were separated by layers of laminated greywacke-siltstone, 5 to 15 cm thick and with good geopetal textures (scour and fill). All "boulders" were composed of slightly schistose biotite granite of identical composition. As there was nearly 100 per cent core recovery from this interval it could be established that the "boulders" were in fact in situ fragmented parts of the basement (Fig. 9). Any doubt of this interpretation is dispelled by the sudden increase of the geothermal gradient observed at the top of the basement blocks (Fig.9). The reconstruction of the core record from the bottom of Karkaro No. 1 (Fig. 9) shows a basement morphology suggestive of tors or exhumed core stones (core boulders) not unlike the present day topography developed on granitic terrains in Australia, as for instance in the Everard Ranges (about 90 miles NW of Karkaro) or the Devils Marbles in the Northern Territory (Olliver, 1965). The open joints between the basement blocks were obviously filled by water-deposited sediments, and as these sediments are very similar to the finer fractions of the overlying Permian sediments, it is probable that they were laid down at the onset of Permian deposition in that area.

Views on the origin of tors and core-stones vary greatly and current hypotheses were summarised by Cunningham (1969). They range from exhumation of a differentially rotted regolith, formed under a tropical climate (Linton, 1955) to scarp retreat under tundra conditions (Fitzpatrick, 1958). Regardless of the differing mode of origins proposed for the development of tors and core stones, it is evident from study of the literature that these landforms are incompatible with the violent erosion of a juvenile landscape and it would appear that they are unable to survive the rasping and plucking forces of glaciers.

The gently undulating pre-Permian basement floor (Fig. 2) also indicates a mature, or even old pre-Permian topography which would have been modified by block faulting just prior to and during Permian deposition.

The picture which emerges is one of an upfaulted plateau with adjoining grabens or half-grabens. The uplifted portions of this landscape became the foci of glacierisation.

Depositional environment

The various lithologies which comprise the basal Permian sediments of Unit 2 require equally varied and complex environments in time and space.

No doubt, the coarse clastics with striated and fluted cobbles and boulders exposed along the eastern margin of the Arckaringa Basin represent true glacial deposits. The abundance of striated cobbles, but also participation of fine grained matrix material (including illite) is greatest in the north, both features becoming less abundant towards the south of the outcrop area. Fine grained matrix material first changes to a sandy matrix (see Fig. 5) and finally to a sandy, micritic matrix. The latter deposits are clearly water laid sediments. This indicates an increasing distance of the present outcrops from the buoyancy line (the line along which the bottom of the ice-flow loses contact with the ground) from north to south. Thus the sediments at Mt. Dutton are interpreted as morainic or near-morainic deposits, the more sandy sediments further south (Fig. 5) may represent eskers, whereas the southernmost exposures are most likely downslope deposits possibly within the calving zone, which could account for the abundance and large size of erratics embedded in calcareous and dolomitic, lithic sandstones (Fig. 10).

Some of the diamictites probably also represent primary morainic deposits. The basal diamictite in Wallira No. 2 for instance (Fig. 7) exhibits lithological features identical to the tillites which rest on the glaciated pavements of the Troubridge Basin. The illite/kaolin ratio of 1.3 of the clay fraction of this rock also supports a primary glacial origin.

The diamictites of the deep troughs are lithologically very similar to tillitic deposits, but the inter-calations of clean, fissile green and chocolate coloured shale-beds are not easy to reconcile with primary morainic deposits. It is suggested therefore that these sequences represent redeposited glacial debris which was transported down the basin slope by mudflows, similar in mechanism to that envisaged for olistostromes (Floreau, 1959; Gorler and Reutter, 1968). The clean and fissile nature of the interbedded shales, deposited during periods of quiescence is in keeping with a sediment laid down in the distal parts of the troughs.

The conglomeratic and cyclically graded greywacke-facies of Unit 2 resulted largely from the transport of detrital material by turbidity currents. Intertongueing of the two facies may have been due to bi-lateral intake, the turbidite facies having originated on the slopes adjacent to active faults and the diamictites on the more stable slopes.

Transport of glacial debris from the basin margin into distal parts of the Boorthanna Trough by turbidity currents has been suggested previously by Wopfner and Allchurch (1967) and a similar model was put forward by Frakes and Crowell (1967) to account for the facies of (?) Permian diamictites of the Falkland Island.

However, whereas Wopfner and Allchurch (1967) suggested that most of the turbidite facies of Unit 2 was derived from primary glacial debris, new evidence from the stratigraphic drilling indicates that the overlapping, stratigraphically higher parts of this facies may be the product of a terminal to post glacial phase. This interpretation is based on the nature of the matrix-clays and the presence of gypsiferous and pyritic cement.

Hamilton and Krinsley (1967, p. 787) state that the finer than 0.06 mm fraction of unaltered tillite from the Bultfontein Mine in South Africa "contains about 50 per cent quartz, 20 per cent sodic plagioclase, 5 per cent muscovite and no detectable clay." In other tillites analysed by the same authors they found up to 7 per cent illite, but no "recognisable non-illitic clay." They also stress the point that in unweathered Pleistocene material from Fennoscandia, illite is the only clay present in drift derived from crystalline rocks.

Except for the basal diamictites in Wallira No.2, none of the Unit 2 sediments of the central Arckaringa Basin, the provenance of which was undoubtedly the crystalline basement of the platform, show comparable features. The amounts of fine clastics (less than 0.10 mm grain size) contained within the coarse clastics are very small, indicating winnowing of the fines; there is no rock flour. The dominant clay minerals are kaolin and montmorillonite neither of which is indicative of boreal weathering conditions. The cyclically graded bedding again shows deposition out of turbidity currents.

Another significant feature is the gypsiferous matrix of the conglomerate encountered in Wallira No. 2 between 1060 and 1095 feet (323.0 and 333.9 m) (Fig. 7). The loosely packed, open framework of the sediment indicates a primary nature of the gypsum rather that a subsequent filling of the pores during diagenesis. The formation of gypsiferous sediments does of course not necessarily require an arid, evaporitic environment. Gypsiferous sediments are forming for instance in Milford Sound in New Zealand (Pantin, 1964), in an area with an annual precipitation in excess of 250 inches (6250 mm) and in water with an oxygen saturation between 80 and 90 per cent near the water-sediment interface (Garner, 1964). Kaplan (1964) explains these anomalous conditions of oxidising water above a reducing environment within the sediment by continued renewal of the water and rapid biological decomposition of the organic matter in the sediment. Continuous burial by influx of detrital material preserves these conditions. The gypsiferous, pyritic sediments from the margin of the Wallira Trough fulfil most of these criteria, and similar conditions could have persisted in some of the Lower Permian graben structures, particularly during deepening by renewed tectonism. The coarse, ill sorted but winnowed nature of this sediment together with the presence of exotica of southern provenance, may be explained by reworking of glacial material by currents under conditions similar to those described by Holtedahl (1950) and Anderson (1968) from the continental slope of Norway.

The dominance of material of local origin within the kaolinitic greywacke which overlays the gypsiferous conglomerate suggests a source of active, high-gradient erosion rather than reworking of glacial material alone. Furthermore, the matrix-kaolin also requires a source of subaerially formed weathering products. As syngenetic faulting during deposition of these greywackes is indicated by seismic evidence (Milton, 1969c), a tectonic origin may be deduced. The detrital material was eroded off rising fault blocks and transported via scarp-foot fans and deltas into the adjacent, subsiding troughs, whence it was redistributed by turbidity currents. Of course, tills and other glacial debris, deposited previously about the basement highs would have been eroded also.

A very similar tectonic setting, but further removed from the high is envisaged for the sediments of Unit 2, encountered in the Karkaro well No. 1. The better sorted deposits such as the granite wash near the base of that section indicate however a more fluviatile aspect.

From the evidence presented above one may state with considerable confidence that the upper, overlapping sections of Unit 2 originated in a post-glacial environment.

The dark grey shale-silt sequence of Unit 1 resulted from a quiet water marine environment with largely fine clastic sediment intake. This interval represents a period of tectonic quiescence, which contrasts with the preceding phase of block faulting and epeirogenetic adjustments. Minor episodes of tectonic instability are indicated by the occasional interspersions of thin sand and granule conglomerate beds. The sea was already present in the Boorthanna Trough during the deposition of Unit 2 and the same applies at least to the upper parts of Unit2 in the Phillipson Trough (Ludbrook, 1961), and probably also in the Wallira Trough. In the Mt. Furner Well, Unit 1 is clearly transgressive over basement and a transgressive relationship may also be expected in the area south of Karkaro No. 1.

The well rounded and frosted quartz grains of the intercalated sandblebs and lenses indicate a low rate of clastic intake and deposition under generally stable, marginal marine conditions; the clastic material remained exposed on the water sediment interface for long periods before final burial occurred. The dominance of kaolin again suggests a source of subaerial weathering products. Minor and short lived episodes of tectonic unrest are reflected by the occasional interspersion of thin beds of fine sand to granule conglomerate.

The presence of anhydrite in the middle part of Unit 1 in the Cootanoorina section (in contrast to gypsum) indicates the temporary development of evaporitic conditions, brought about by physical restriction of a part of the Boorthanna Trough. Formation of anhydrite by diagenesis as described by Shearman (1966) from the Trucial Coast is not considered likely in this case.

Evaporitic conditions are difficult to reconcile with the cold water environment suggested by Ludbrook (1969; 1967) to explain the restricted foraminiferal fauna of equivalents of Unit 1. McGowran (in Harris and McGowran, 1967) demonstrated that the sudden disappearance of foraminifera in Cootanoorina No. 1 coincides with the onset of evaporitic conditions. From the high specimen number and low diversity also found in the more recently drilled stratigraphic wells, McGowran (1969) concluded that Unit 1 was deposited in a marginal marine environment in which slight geophysical changes causing changes in salinity, oxygen saturation, pH, etc. would have a profound influence on the local development of the restricted marine fauna. Such an environment is also supported by sedimentological aspects. In Cootanoorina No. 1 for instance, stagnant bottom waters, approaching euxinic conditions (in terms of Sloss, 1953 definition) are indicated by the abundance of pyrite in the dark grey, organic shale which overlays the anhydrite horizon (Wopfner and Allchurch, 1967). This is only one example of one specific environment, which developed locally within the basin. That the fine clastic nature of the sediments was caused essentially by primary intake of fine clastic rather than by lateral sorting is indicated by the overall uniformity of this unit. Composition and particle size changes very little and only slight coarsening is observed towards the basin margins.

There is general agreement that the Mt. Toondina Beds originated in a freshwater environment, and in a warm and humid climate (Harris, 1969).

On present evidence it is not possible to state whether the change from the marine environment (Unit 1) to the freshwater environment of the Mt. Toondina Beds was caused by depositional regression or tectonic events. Available data show an increase in thickness from south to north (Fig. 4) and this tends to favour an overall tectonic control, although locally depositional regression may have been important. The basin floor was apparently tilted to the north by gradual but continuous subsidence of the northern portion of the basin. Rate of sediment intake was sufficiently high for deposition to keep pace with the negative movements and rate of burial was comparatively fast as feldspars and micas, but particularly biotite were deposited without significant alteration.

The lower units of the Mt. Toondina beds are largely fluviatile, flood-plain and lake deposits. The increase of the sand/shale ratio from east to west and the coarsening of the sediments in the same direction shows closer proximity to source areas in that direction. The mineral composition in Karkaro and Mt. Furner suggests a major source in the Everard-Musgrave Block, but some material may have been derived also from the Mabel Creek "basement high". The thick sand-section in the middle of the Mt. Toondina Beds in Mt. Furner No. 1 was interpreted by Demaison (1969) as a deltaic channel fill (finger sand).

Deposition of the upper, coal bearing unit of the Mt. Toondina Beds occurred in shallow lakes and on the alluvial plains and marginal to these environments fresh water coal swamps of considerable magnitude developed.

It is not possible to give an exact time limit at which the Arckaringa Basin ceased to exist.

Deposition of the Mt. Toondina Beds within the northern parts of the Arckaringa Basin extended close to the beginning of the Upper Permian, but was probably terminated earlier in the southern Basin area. Further palynological studies may possibly be able to decide this question.

The termination of the Arckaringa Basin as a sediment receptacle was probably brought about by uplift and final stabilisation of the Permian diastrophism. The area remained essentially stable during the Mesozoic and experienced only minor rejuvenation of tectonism (Mt. Toondina piercement, Wallira fault) in post-Mesozoic times.

CONCLUSIONS

Deposition within the Arckaringa Basin was controlled by syngenetic faulting and Permian climatic conditions, which ranged from boreal at the beginning to moist, subtropical towards the end, and the sedimentary sequence reflects the interplay between those controlling factors.

The Permian depositional phase was introduced by strong diastrophism, leading to the development of graben and half-graben structures of considerable magnitude. The initiation of at least some of these structural trends (e.g.Boorthanna Trough) dated however back to Devonian times, and Permian movements resulted from rejuvenation of already existing zones of weakness within the earth's crust. This is not only a feature of the Arckaringa Basin, but also of other South Australian Permian basins. The Permo-Devonian period of diastrophism may possibly have been the first indication of impending breakaway of the Australian continent from a southern land mass, the final removal of which is well documented in the late Jurassic and Cretaceous history of southern Australia (Wopfner, 1969).

As the commencement of the Permian glaciation appears to be almost simultaneous with the onset of diastrophism, the formation of at least some of the Permian glaciers may have been dependent on the formation of uplands by Permo-Carboniferous fault movements. The strong affinities of the erratic components of local sources within the eastern and southern Arckaringa Basin would seemingly support such an interpretation. Horwitz (1960, p. 241) who studied some moraines of the Troubridge Basin in detail, also observed that the erratic boulders and cobbles of that region were derived from local sources. Campana and Wilson (1955) envisaged mountain type glaciers for the area of the Troubridge Basin rather than a solid sheet and Glaessner (1959) stated that he could "see no reason why these areas (of Permian glaciation) should not have been individually glaciated highlands, rather than parts of a circumpolar solid ice cap".

Within the Arckaringa Basin both northward and westward flows of ice are indicated by the composition of the erratics, suggesting local foci of glaciation rather than a continental ice sheet. As all available evidence indicates a subdued pre-Permian topography, it is suggested that the Permian glaciers originated on upfaulted highlands such as the Denison Block and the Gawler Block which were formed by Permo-Carboniferous diastrophism. The glaciers which developed on these fault-blocks would have been plateau-type glaciers, best described as ice cap glaciers in terms of the classification proposed by Hobbs (1935). Glacial debris was dumped along the basin margins and thence transported by mudflows and turbidity currents into the distal parts of the troughs. Present evidence suggests that, within the region of the Arckaringa Basin, the Permian glaciation came to an end by about mid-Sakmarian time. If this is correct the duration of the glaciation period would have been about 7 million years.

Some of the central basin areas such as the Karkaro - Mt. Furner region, were neither covered by ice nor did they become inundated until post-glacial times.

Eustatic changes of sea level may have had some influence on post-glacial deposition, but by far the major control on post-glacial sedimentation was exercised by continued diastrophism, which maintained a high gradient between the source areas and base level. The coarse detrital material, together with kaolin, the latter produced by subaerial weathering, were deposited in river deltas and scarp foot fans whilst transport into the deeper parts of the troughs was largely achieved by turbidity currents.

Gradually diminishing intensity of tectonism led to the low energy - marginal marine environment in the later part of the Sakmarian, during which the dark shales of Unit 1 were laid down.

Mild renewal of epeirogenetic movements near the beginning of the Artinskian expelled the sea not only from the Arckaringa Basin, but also from other Permian Basins, e.g. the Cooper Basin. The moist, subtropical climate promoted prolific plant growth and the formation of coal swamps, whereas elsewhere, thick sand bodies were deposited in some of the river channels. Throughout the remaining duration of the Permian depositional phase, fluviatile, lacustrine and paludal conditions prevailed up to its termination.

In presenting the above model for the Arckaringa Basin, the author, although not claiming finality, hopes to have demonstrated that diastrophism was a major factor controlling Permian deposition whereas climatic control provided the "overprinted" modulation. The conclusions reached from this study however are not only valid for the Arckaringa Basin but may be applied equally well to other Permian basins in South Australia.

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Text to Figures

Fig. 1 Permian Basins in South Australia and distribution of pre-Permian rocks.

Fig. 2 Structure contour map and approximate margins of Arckaringa Basin. Structure contours of base of Permian compiled from drilling and seismic control.

Fig. 3 Bouguer gravity map of Arckaringa Basin. Main basement features are identified by roman numerals: I - Denison Block; II - III and IV - Mabel Creek, Coober Pedy and Mt.Woods Basement High; V - northern slope of Gawler Platform. (Map compiled from state gravity map 1:1000000 of Petroleum Division, Geol. Surv. S.Aust.).

Fig. 4 Radio activity log correlation of recent stratigraphic wells in the Arckaringa Basin. The Section has been compiled with reference to the top of the Permian (Mt.Toondina Beds). (Section compiled by Demaison and Townsend, Petroleum Division, Geol. Surv. S.Aust.).

Fig. 5 Exposure of conglomerate with ill sorted sandy matrix (unit 2) containing striated and "soled" cobbles and pebbles, exposed on eastern margin of Arckaringa Basin. Exposure near Warrina, 25 miles (40 km) SSE of Mt.Dutton.

Fig. 6 Striated pebbles from exposure pictured in Fig. 5 and from Mt.Dutton.

Fig. 7 Examples of varying lithologies of Unit 2 from the Arckaringa Basin. (1) Sandy, illitic diamictite resting on porphyritic microgranite (dark coloured) in Wallira No.2 (Core 7, 1095.6 to 1096.5 feet; 333.9 to 334.2 m). Note irregular contact between diamictite and crystalline basement. (2) Graded bedding in Cootanoorina No.1 (Core 7, 2863.8 to 2864.8 feet; 872.9 to 873.2 m). The sediment is cemented by micritic carbonate. (3) Ill-sorted conglomerate, cemented by crystalline, gypsiferous matrix, from Wallira No.2 (Core 7, 1094.0 to 1094.8 feet; 333.4 to 333.6 m). (4) Cyclically graded bedding in kaolinitic pyritic greywacke from Wallira No. 2 (Core 6, 829.2 to 830.9 feet; 252.7 to 253.3 m). Darker colours of fine grained layers are due to invasion by drilling mud. Scales in centimetres and inches.

Fig. 8 Comparison between the graben structure of the Permian Wallira Trough and the glacial topography of fiords and glaciated valley lake. Formation boundaries in Wallira Trough are based on seismic reflection data. (Cross-section of Wallira Trough after Milton, 1969).

Fig. 9 Reconstruction of bottom hole section in the Karkaro Well No. 1 showing formation of "core stones" (core boulders) in the granitic basement. Temperature log on right demonstrates marked in crease in geothermal gradient at the top of the boulderised granite surface.

Fig.10 Erratic block, composed of Sturtian (Precambrian) tillite and measuring 3.5 x 9.5 feet (1 x 2.9 m), weathered out from medium grained, calcareous-dolomitic sandstone (foreground) with lenticular pebble-conglomerates. Pebbles and cobbles, some with striations, are scattered over the surface. Outcrop of Unit 2 sediments, 10 miles (16 km) north of Anna Creek bore. Scale on hammer in inches.

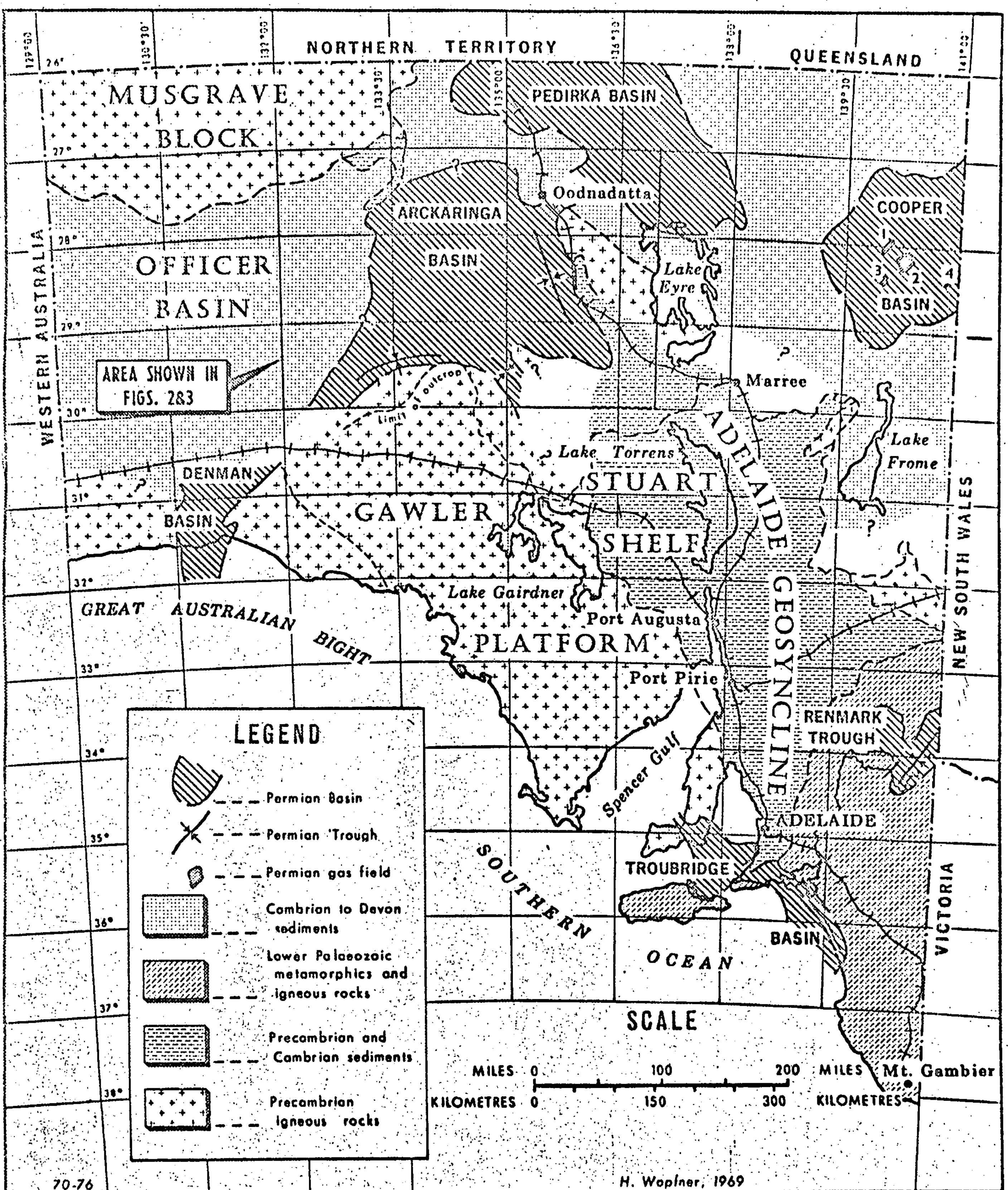


Fig. 1 Permian Basins in South Australia and distribution of pre-Permian rocks.

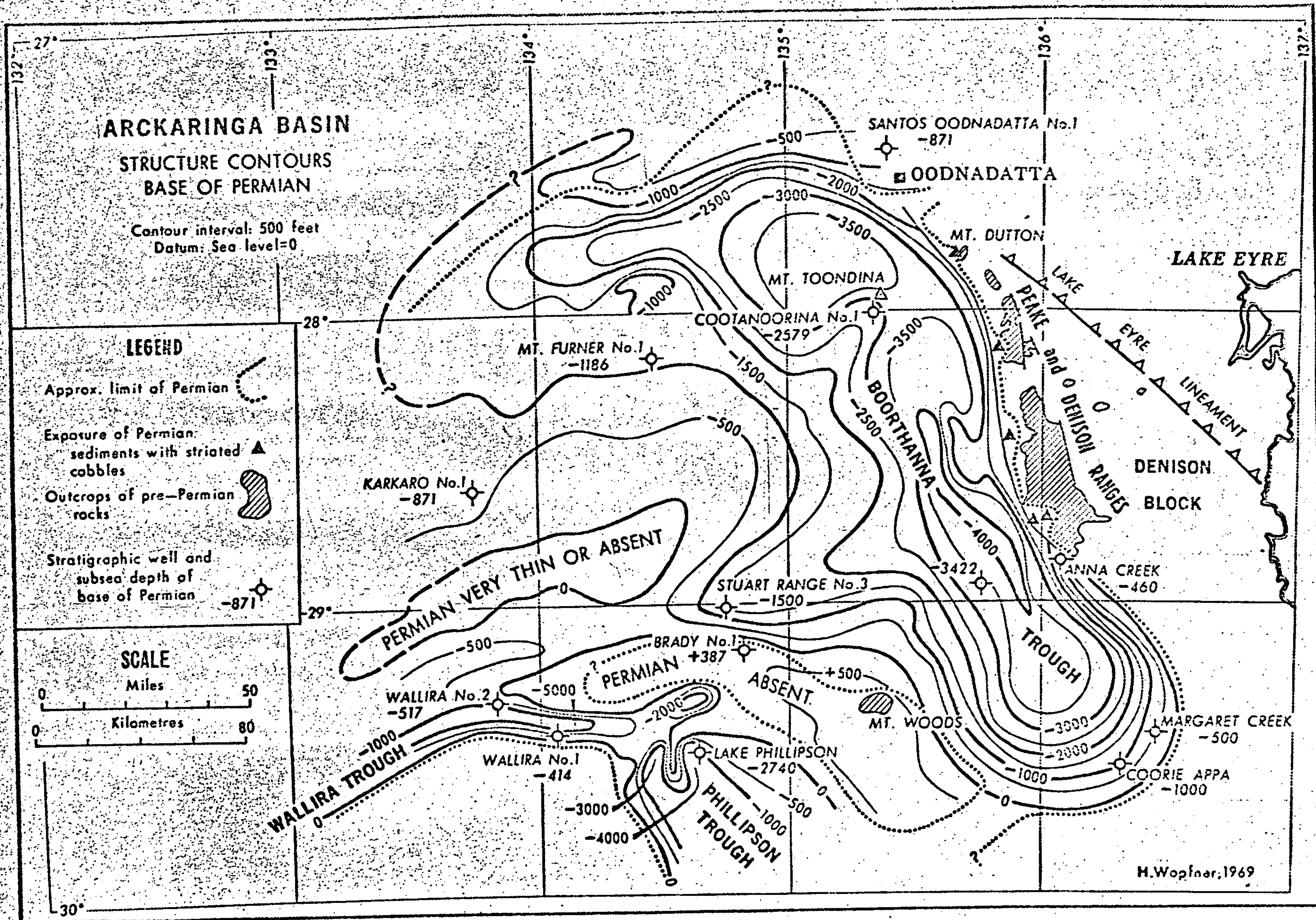


Fig. 2 Structure contour map and approximate margins of Arckaringa Basin. Structure contours of base of Permian compiled from drilling and seismic control.

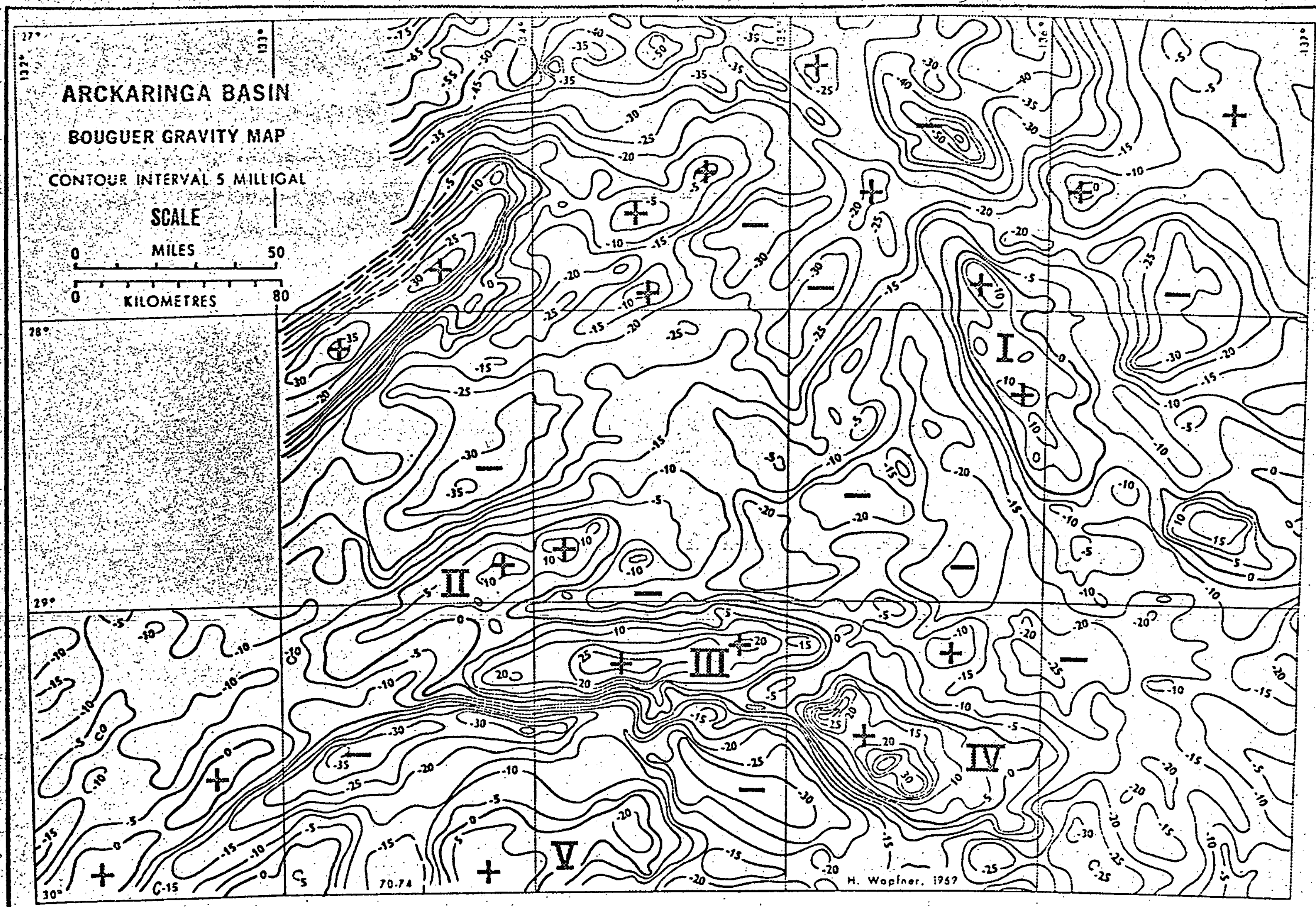


Fig. 3 Bouguer gravity map of Arckaringa Basin. Main basement features are identified by roman numerals: I - Denison Block: II -III and IV - Mabel Creek, Coober Pedy and Mt. Woods Basement High; V northern slope of Gawler Platform. (Map compiled from state gravity map 1:1000000 of Petroleum Division, Geol. Surv.S.Aust.)

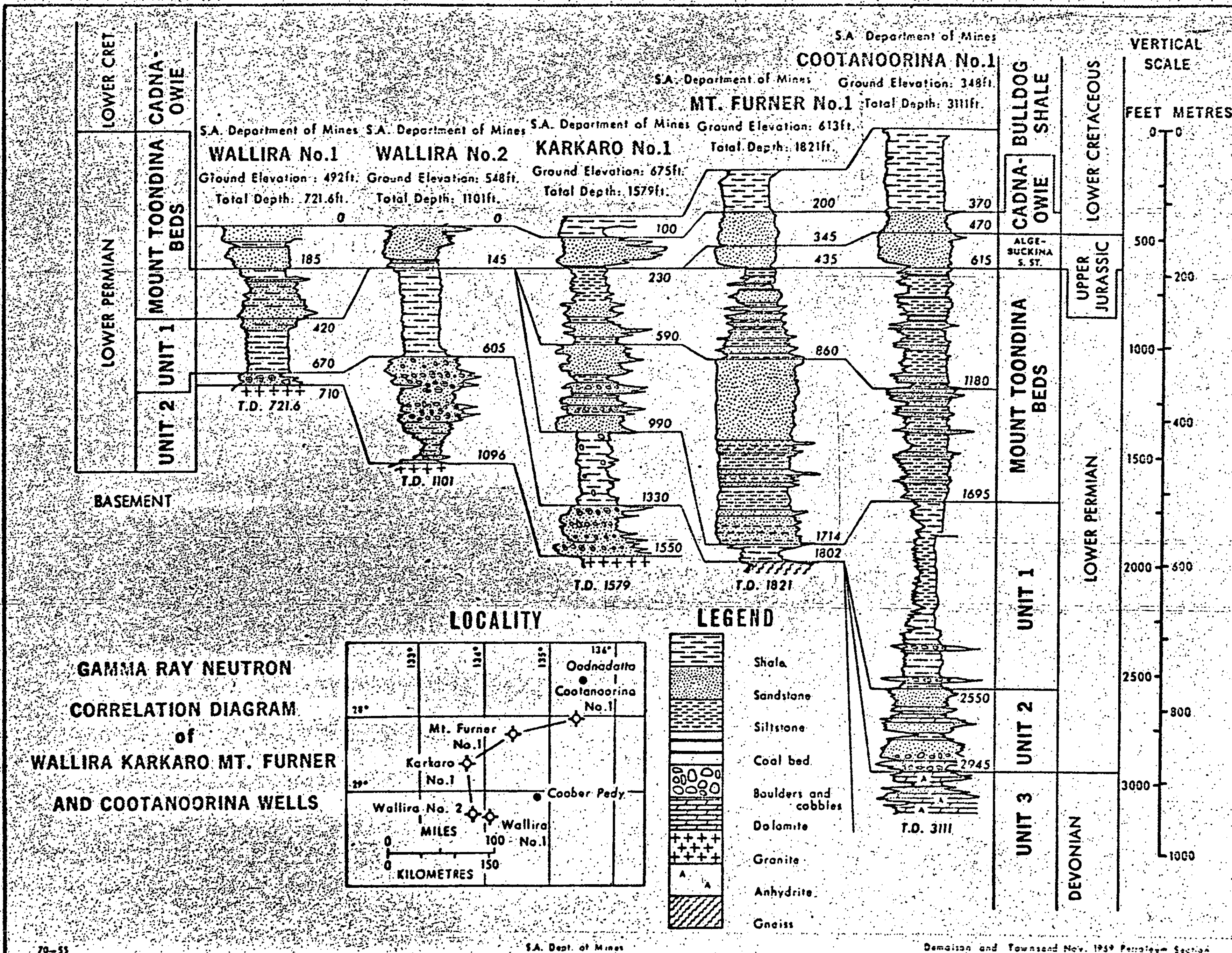
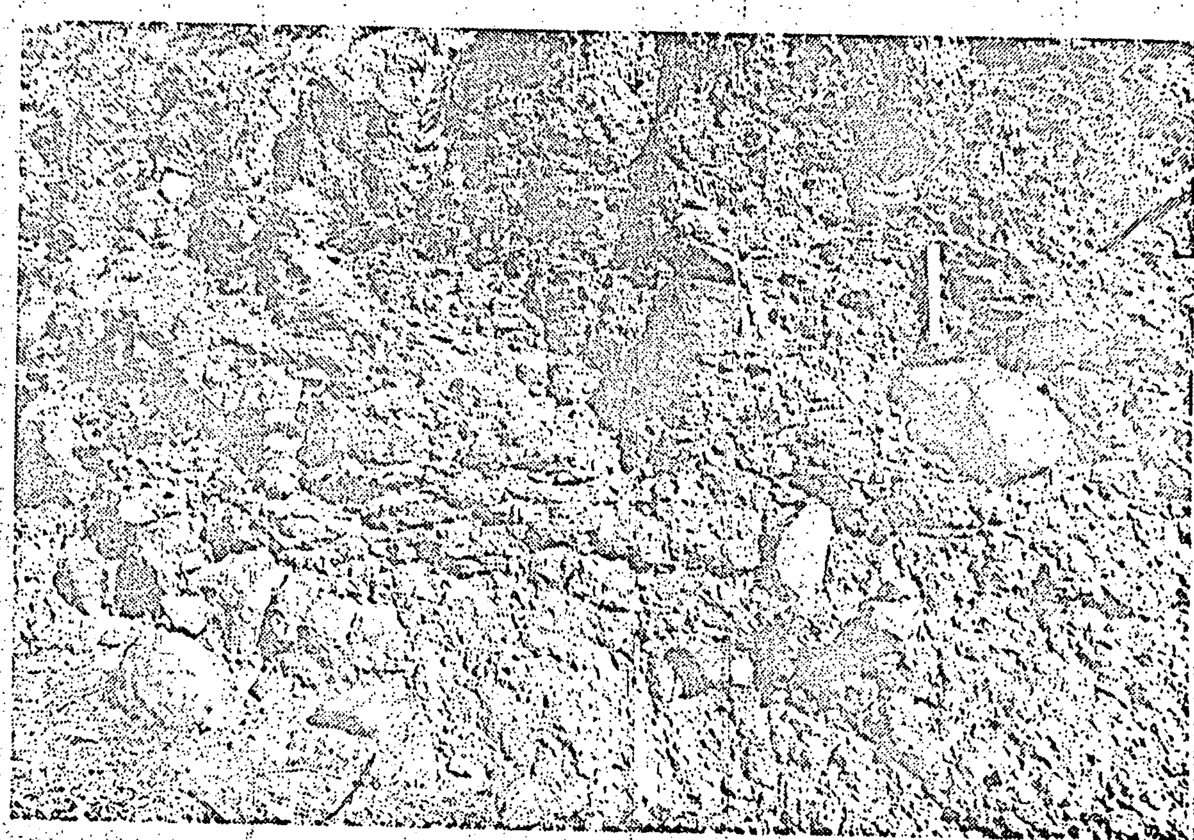


Fig. 4 Radio activity log correlation of recent stratigraphic wells in the Arckaringa Basin. The Section has been compiled with reference to the top of the Permian (Mt. Toondina Beds). (Section compiled by Demaison and Townsend, Petroleum Division, Geol. Surv. S.Aust.).



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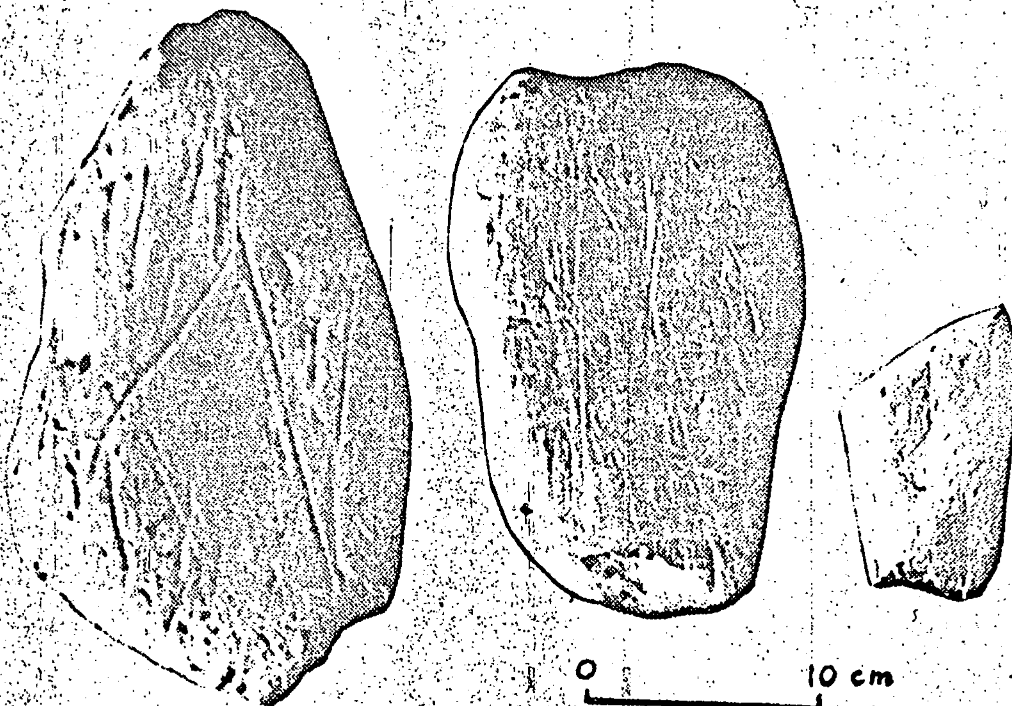

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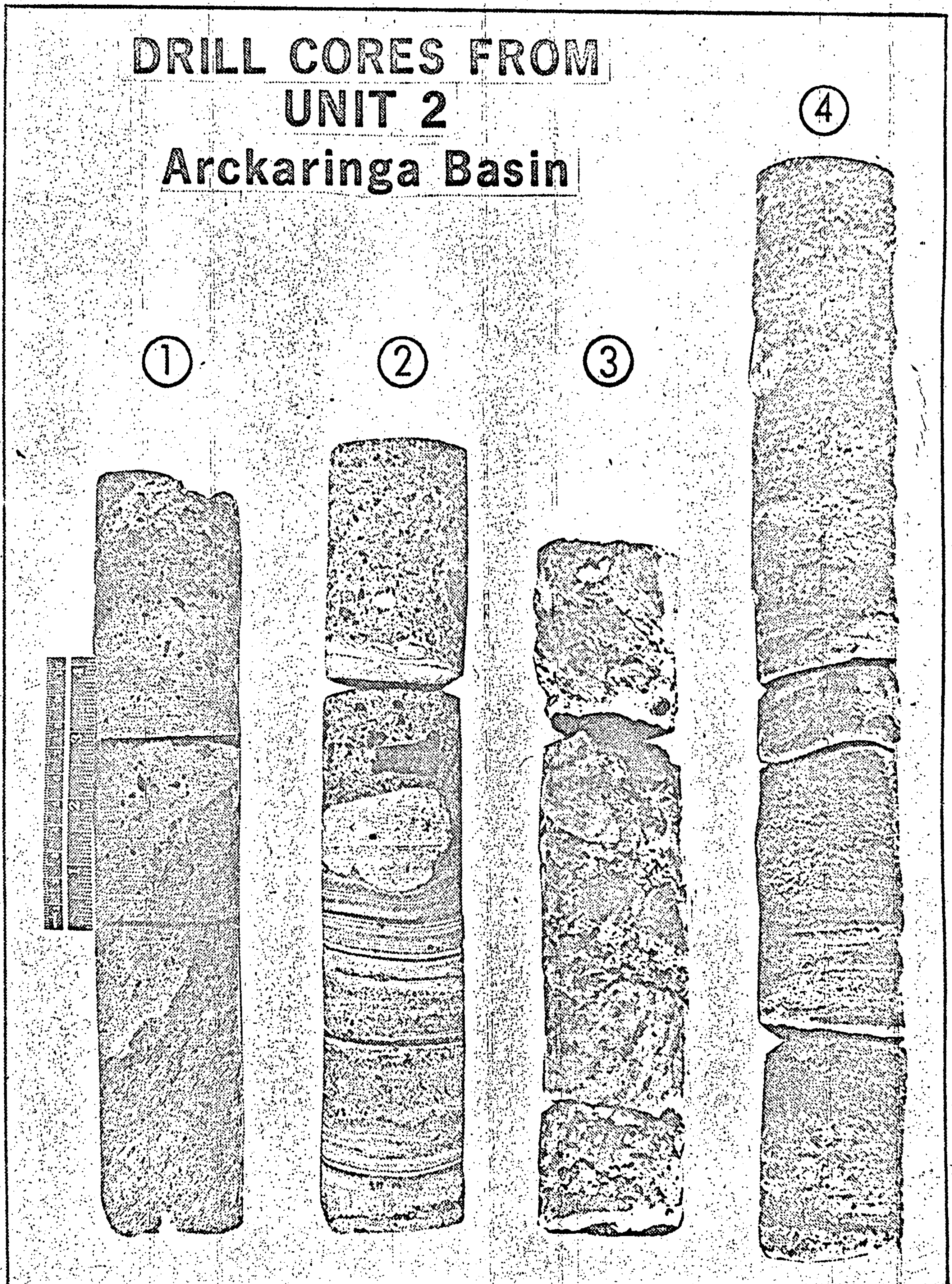
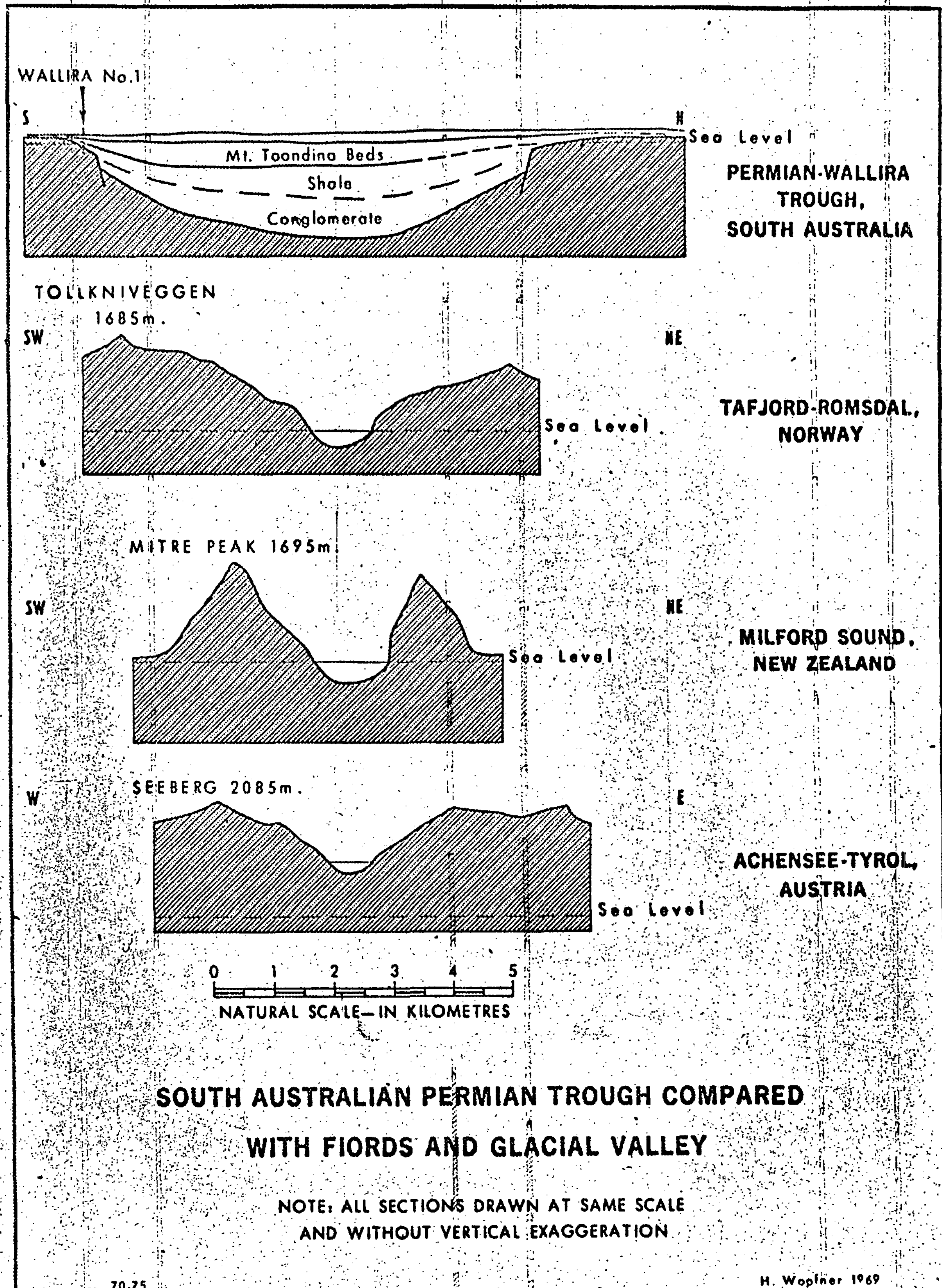


Fig. 7



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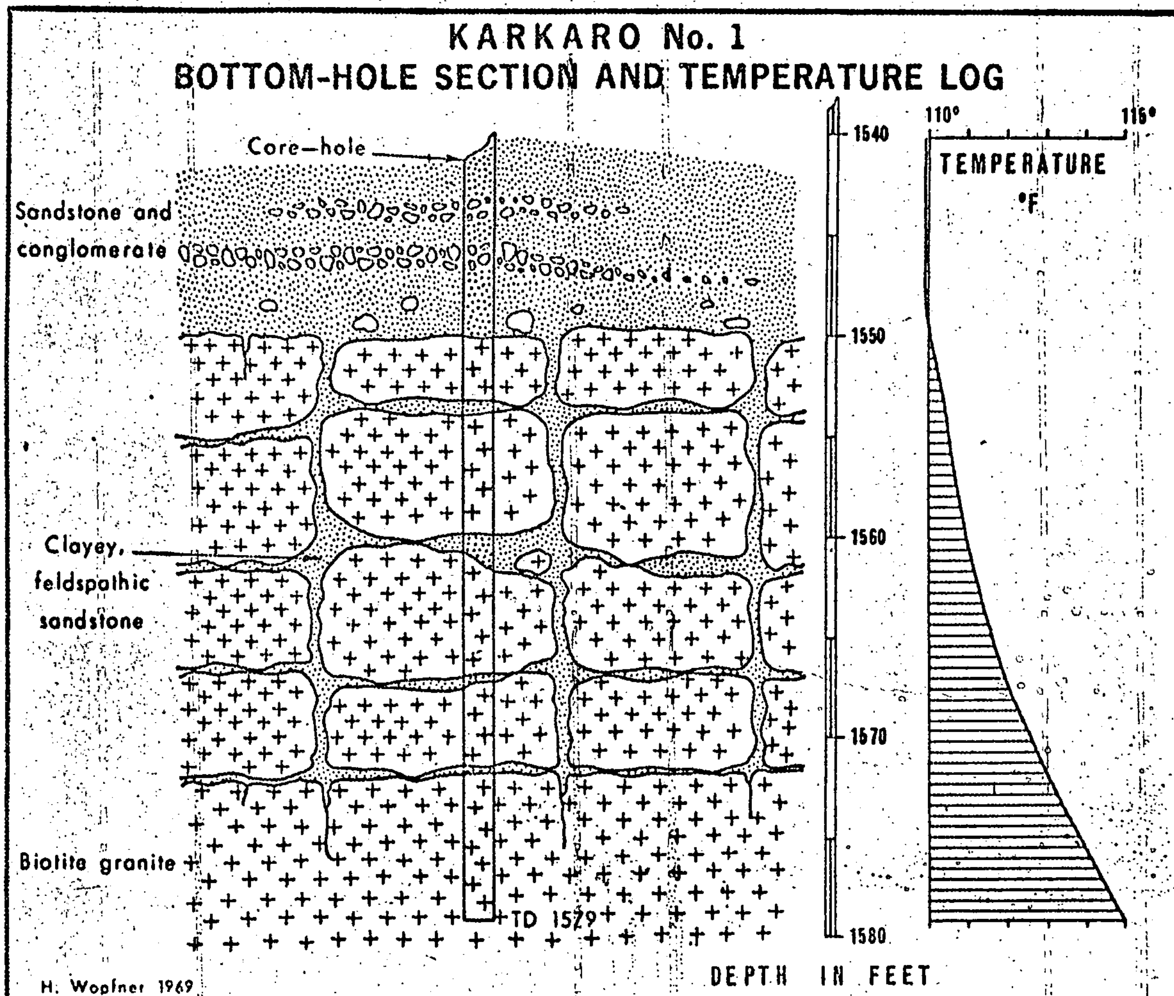

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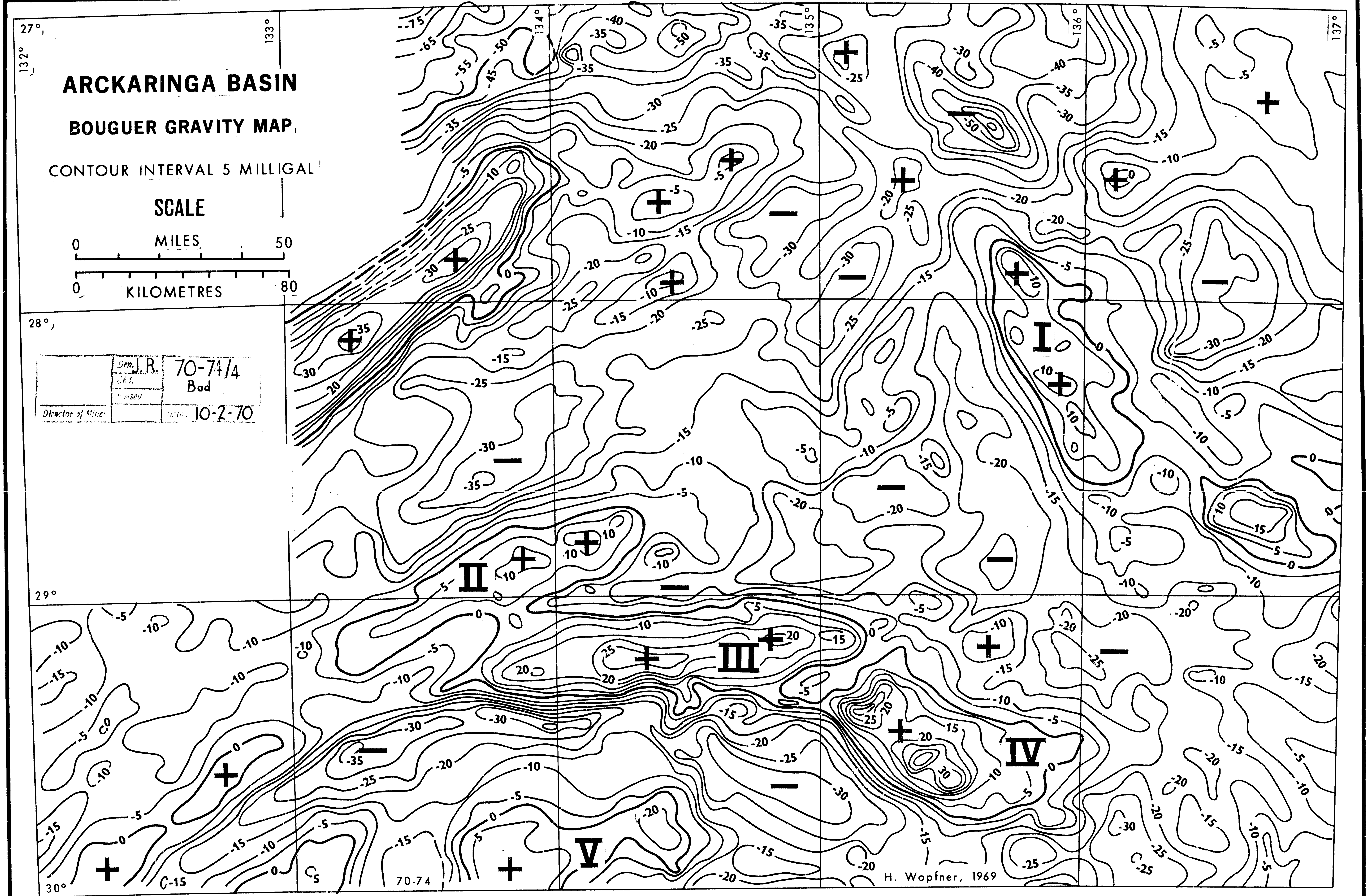
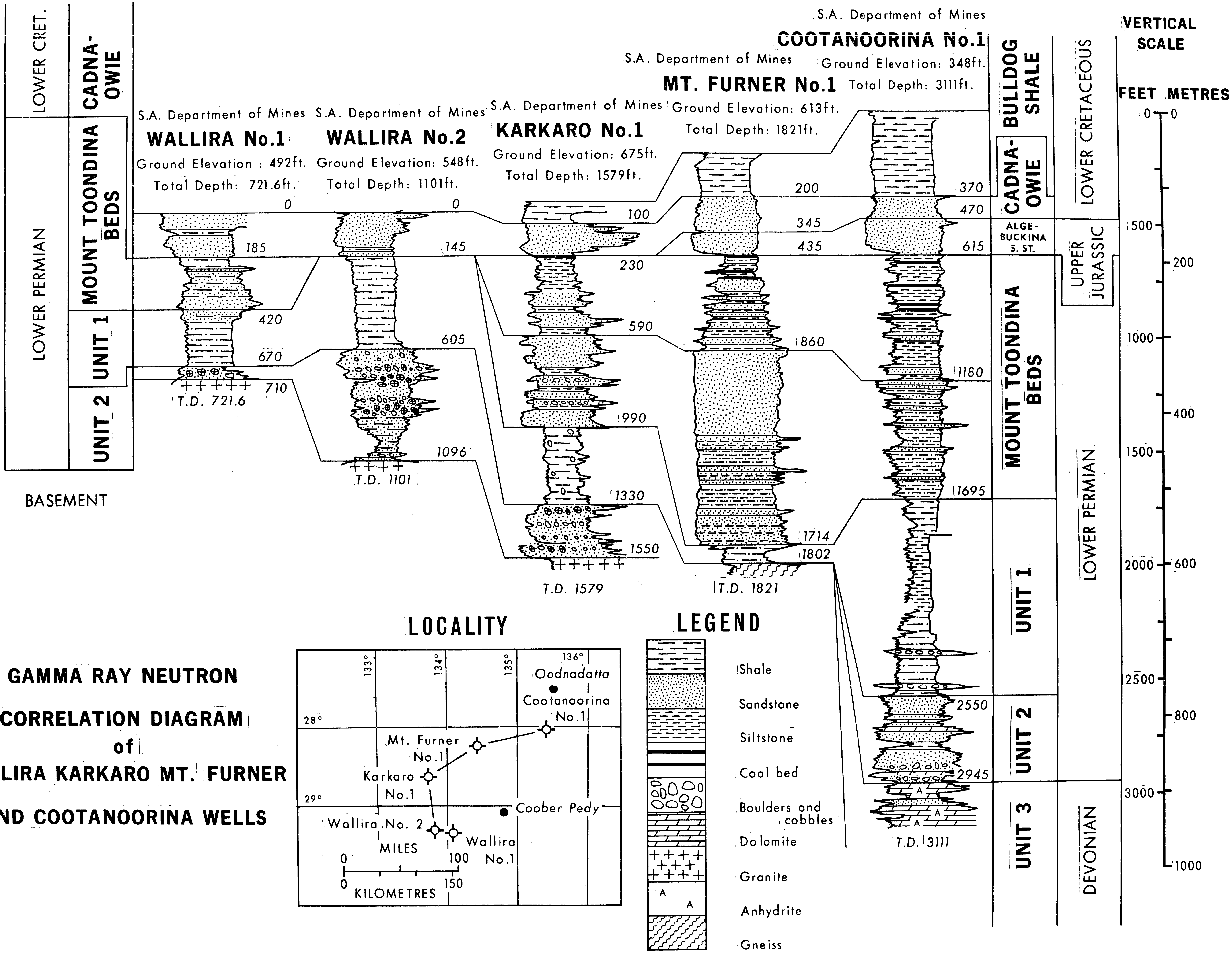

ARCKARINGA BASIN
BOUGUER GRAVITY MAP
CONTOUR INTERVAL 5 MILLIGAL
SCALE
0 MILES 50
0 KILOMETRES 80
Drn. J.R. 70-74/4
Ckd.
Passed
Bad
Director of Mines
Date: 10-2-70
27°
28°
29°
30°
132°
133°
134°
135°
136°
137°
I
II
III
IV
V
70-74
H. Wopfner, 1969

GAMMA RAY NEUTRON CORRELATION DIAGRAM of WALLIRA KARKARO MT. FURNER AND COOTANOORINA WELLS



S.A. Dept. of Mines

Demaison and Townsend Nov. 1969 Petroleum Section