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PALAEOENVIRONMENTAL
INTERPRETATION OF THE
LATE PROTEROZOIC SKILLOGALEE
DOLOMITE IN THE WILLOURAN
RANGES, SOUTH AUSTRALIA

GEOLOGICAL SURVEY

by

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REGIONAL GEOLOGY

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Palaeoenvironmental interpretation the Late Proterozoic Skillogalee Dolomite in the Willouran Ranges, South Australia

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ABSTRACT

The Skillogalee Dolomite is a thick (up to 4000 m), predominantly peritidal carbonate sequence (dolomite, magnesite) of the Late Proterozoic Adelaide Geosyncline, representing a major marine inundation of an evolving, intracratonic rift basin. In the Willouran Ranges, rapid deposition occurred in a complex of sub-parallel, differentially subsiding, extensional sub-basins. Sedimentation kept pace with subsidence to maintain a subdued topography within the basin. Repetitive shoaling and exposure resulted in a change from subtidal stromatolite biostromes and cryptalgal laminites through intertidal oncolites, intraclastic dolomites and dolomitic grainstones, to extratidal intraformational magnesite and continental arenaceous deposits. Syn- and post-depositional piercement diapirism of underlying strata occurred preferentially along bounding faults.

Strontium isotope values of cryptalgal dolomites and magnesites (0.7090-0.7119) are similar to those for other Precambrian carbonates of accepted marine origin. Cryptalgal dolomites have oxygen isotopic values of between -5 and -10 per mil versus PDB, also compatible with a marine origin. Some samples indicate evaporative enrichment, consistent with the sedimentological evidence that indicates intermittent exposure and desiccation. Intraformational magnesite-mud-pellet conglomerates are enriched in ^{18}O and ^{13}C relative to coeval dolomites. The lateral and vertical uniformity of carbonate mineralogy, fabric detail and preserved sedimentary structures indicate a primary sedimentary or penecontemporaneous origin of dolomite and magnesite.

INTRODUCTION

Intracratonic and marginal cratonic, rift-related sequences of Late Proterozoic age occur through much of central Australia (Preiss & Forbes 1981). In the Adelaide Geosyncline (Fig. 1), up to 15 km of mainly shallow water, Late Proterozoic sediments were deposited on rifted Early and Middle Proterozoic basement. The preserved strata record an evolutionary sequence spanning some 600 m.y., from pre-rift mafic dyke intrusion and basaltic volcanism (Parker 1983), to discontinuous syn-rift intracratonic graben sedimentation (Rowlands et al 1980), and subsequent epeirogenic shelf and continental margin sedimentation (Von der Borch 1980; Rutland et al 1981; Preiss 1983). The extension and subsidence mechanism that initiated the rifting is still unclear, but is believed by Von der Borch (1980) to be fundamentally similar to the pre-oceanic rifting process that formed many contemporary passive continental margins.

Dichotomy of opinion exists for the finer details of the palaeogeography and tectono-sedimentary evolution of the Adelaide Geosyncline, and in particular for the Burra Group and Skillogalee Dolomite (Fig. 2). Very thick deposits, of between 7 000 and 10 000 m, are known from the Willouran Ranges and the Peake and Denison Ranges (Ambrose et al 1981; Belperio 1986). The Group is constrained by radiometric ages of 802 ± 10 and 750 ± 53 Ma for older volcanics and younger shales respectively (Fanning et al 1986). The Skillogalee Dolomite is a prominent, repetitive siliciclastic - stromatolitic dolomite - intraclastic magnesite succession within the Burra Group. Forbes (1960,1961), Preiss (1973) and Preiss and Forbes (1981) considered the stromatolites and dolomite to be essentially of shallow marine origin, with magnesite forming in marginal alkaline lagoons, and ascribed the cyclicity to repeated marine transgressions and regressions. Conversely, Murrell (1977), Von der Borch (1980) and Uppill (1980, 1983) considered the sequence to be dominantly or entirely non-marine, essentially cyclic playa lake and perennial lacustrine deposits. Von der Borch (1980) equated the deposits with an early rift setting not unlike the present East African Rift Valley. He considered continental break-up and the development of fully marine conditions did not occur until about the Precambrian - Cambrian boundary time.

Rutland et al (1981) envisaged the Adelaide Geosyncline as representing only the western part of a multiple-rifted arch system that extended several hundred kilometres to the east. Facies gradients within the Burra Group were thus considered to reflect an evolving continental shelf with a continental margin well to the east. The "break-up" unconformity separating rift and post-rift sediments was placed by Preiss (1983) at the top of the Burra Group sequence, some 200 m.y. prior to that selected by Von der Borch (1980).

The purpose of this study is to examine in detail the stratigraphy and sedimentology of the Skillogalee Dolomite and its lateral variation within the Willouran Ranges. Specific data on facies development and palaeogeographic setting for this region, particularly a marine or non-marine interpretation for the Skillogalee Dolomite, are pertinent to the overall tectono-stratigraphic interpretation of the Adelaide Geosyncline. In addition to geological field mapping, twelve detailed stratigraphic sections of Burra Group strata were measured at select localities across the ranges. Features recorded on these transects included lithology and mineralogy of sediment and intraclasts, biogenic and sedimentary structures, palaeocurrent directions, desiccation critera, and nature of bed contacts. Samples from representative lithofacies were collected for petrographic examination, x-ray diffractometry, carbonate and organic carbon analysis, geochemistry, isotopic measurement and hydrocarbon source-rock analysis. Details of methodology and results are given in Belperio (1987 a, b, c, d).

REGIONAL SETTING

The Willouran and Peake and Denison Ranges are inliers of folded and fractured Proterozoic (predominantly Adelaidean) sedimentary rocks, that delineate a northwesterly extension of the former Adelaide Geosyncline (Fig. 1). An associated gravity low, and sub-parallel gravity highs flanking both sides of the Willouran Ranges, define the former narrow depositional trough that was continuous through to the Peake and Dension Ranges. Within this zone, deposition of Burra Group sediments occurred in a discontinuous series of half grabens (Murrell 1977). The Burra Group represents a major tectono-sedimentary cycle of siliciclastic and carbonate deposition bounded above, and possibly below, by major hiatuses (Fig. 2).

A three-fold subdivision of the Burra Group (Emeroo Subgroup, Skillogalee Dolomite, Myrtle Springs Formation) has been applied in the Willouran Ranges (Forbes 1984). The basal Emeroo Subgroup is an arenaceous sequence of thick sandstones, quartzites, siltstones and shales. The base is taken as the first major sand body above the evaporative carbonates and clastics of the more deformed Callana Group sediments (Forbes & Preiss 1987). A phyllitic mudstone marker bed (the Camel Flat Shale of Murrell, 1977), is taken as the base of the carbonate-dominated Skillogalee Dolomite. Together with the Tilterana Sandstone (Fig. 2), these comprise a "basal siliciclastic facies" to the Skillogalee Dolomite. The main phase of sedimentation for the Skillogalee Dolomite is characterised by a repetitive sequence of dolomites, magnesites and arenaceous beds. The overlying Myrtle Springs Formation is recognised by the return to dominance of carbonate-poor sandstones and siltstones.

LITHOLOGIES

The Skillogalee Dolomite is characterised by repetitive (but not cyclic) lithologies of intraformational carbonates, (dolomite and magnesite), cryptalgal laminated carbonates and argillaceous siltstones and sandstones. Diagenetic chert replacement is common but geographically and stratigraphically variable, being most abundant in the cores of stromatolites. Also present, but more rare, are oncolites, algal bioherms, halite and shortite moulds, siliciclastic conglomerates and sedimentary chert beds. Desiccation features such as mudcracks, tepees and disrupted carbonate crusts are abundant, as are wavy, flaser and trough crossbedding.

Field classification of sediments is corroborated by mineralogical analysis using X-ray diffractometry (Fig. 3) and chemical analysis (Belperio 1987a). Dolomitic grainstones, cryptalgal dolomites and stromatolites have a variable composition depending upon the degree of incorporation of silicate grains (predominantly quartz and feldspar). Pelletal magnesites also have a variable matrix of finer grained clastic dolomite and silicates.

Finely laminated micritic dolomites (dolosiltite and dololutite) with crenulated to stratiform organic laminae (cryptalgal dolomites) are fossil algal laminites analagous to modern peritidal algal sediments (Scholle et al 1983). Stromatolite biostromes, up to 2 m thick, represent greater development of algal growth structures. Algal layers are now represented by very fine dolomite crystals, partly obscured by organic staining and carbonised organic matter (micrinite). Sub-parallel bands of detrital quartz, dolomite, feldspar and mica separate the organic layers. The columnar stromatolite Baicalia burra is virtually ubiquitous (Preiss 1973). "Reef-like" stacking of biostromes occurs in marginal areas that presumably underwent slower subsidence, although discrete bioherm structures are rare.

Thin interbedded quartzose siltstones and sandstones consist of detrital quartz, feldspar and mica with a variable content of detrital dolomite grains and pellets. Sorting varies from good to poor and small scale ripples and trough crossbedding are common. Mudcracks and euhedral cubic cavities after evaporite minerals are abundant and most beds are in sharp contact with overlying and underlying carbonates.

Magnesite-mud-pellet conglomerates are abundant, particularly on the western side of the study area. Individual magnesite beds are up to 1 m thick, with composite torrent-bedded sequences up to 3.5 m thick, and grade up to 98% pure magnesite (Belperio 1987a). They consist of a framework of aphanatic magnesite mudstone clasts (typically 2-20 mm) in a poorly sorted sandy matrix of variable dolomite - magnesite - quartz composition (Fig. 4). Intermixing of dolomite and magnesite clasts is common. Talc and authigenic feldspar are also common constituents. Magnesite clasts show variable shape and rounding, and little internal structure. Rarely, a disrupted, micritic, laminated magnesite crust is preserved at the base of some intraformational beds. Torrent bedding, graded bedding and inverse - graded bedding are all common, as are basal mudcracks, tepees, shrinkage cracks, plastic injection features and rip-up structures.

Chert occurs as primary nodules, nodular conglomerates and lenses within the sedimentary sequence, but more commonly as a replacement silicification in the cores of stromatolites. Chert nodules are complexly intertwined with a dolomite and magnesite matrix.

In addition to the predominant lithofacies described above, shallow channelised and scour and fill structures are also common. They contain variable quantities of stromatolitic debris and oncolites in a quartzose to oolitic sandy maxtrix.

STRATIGRAPHY AND REPETITIVE SEQUENCE DEVELOPMENT

Twelve sections measured through the Burra Group at selected localities across the ranges (Fig. 5) are described in detail by Belperio (1987b). Summaries of the overall thickness of strata are shown in Figure 6. The Burra Group has a maximum thickness (of exposed strata) of between 7 000 and 8 000 metres in the central Willouran Ranges (Fig. 6A). Correlation along and across the ranges reveal non-uniformity of accumulation and marked facies changes. The arenaceous Emeroo Subgroup has a maximum thickness of 4 000 metres in the east, whereas the carbonate-dominated Skillogalee Dolomite is thickest (3921 m) in the central region (Figs 6B,C). The younger Myrtle Springs Formation is thickest (4436 m) to the northwest of the study area (Fig. 6D). Dramatic thickness changes with apparent onlap of Burra Group strata onto older, tectonically disrupted regions are clearly visible (Fig. 5).

Examples of repetitive strata development over vertical scales of 15 and 50 metres are shown in Figures 7 and 8. Desiccation features such as tepees, carbonate crusts (dolomite and/or magnesite) and mudcracks occur most commonly at the base of magnesite conglomerate beds, and are also associated with siliciclastic grainstones. Stromatolite biostromes and cryptalgal laminated micritic dolomite commonly grade up into intraformational cryptalgal dolomites, oncolites and dolomitic grainstones. Sandstone beds and magnesite conglomerates generally display sharp basal and upper contacts. Their thickness and repetition appears to be random. Apart from channel deposits, most beds are laterally extensive, and even decimetre thick beds may be traced along strike for many kilometes. Magnesite-mud-pellet conglomerate beds, however, display mesoscale interfingering and lensing (Fig. 7).

Chronological constraints imply a net sedimentation rate for the Burra Group as a whole of at least 0.05 to 0.15 mm per year, a figure that is in the upper range of recorded sedimentation rates of platform carbonates (Sadler 1981) but is well within the range for extensional rift-valley basins.

The measured stratigraphic sections allow for intra-basinal comparison of lithofacies. These have been combined to recreate a west to east palinspastic section using the top of the Skillogalee Dolomite as an approximately isochronous surface (Fig. 9). Some of the general observations that can be deduced from this have been noted by previous workers in this area (Murrell 1977; Uppill 1980; Utah Development Company 1983). Sedimentation occurred in a series of discrete, axial basins (numbered sub-basin 1-4 on Fig. 9). Individual lithologies and sedimentary structures are essentialy similar in each sub-basin, but there are major differences in the predominant lithologies. Thus in the east, siliciclastic deposition dominated, whilst the two central basins are dominated by much greater accumulation of carbonates (stromatolites, cryptalgal dolomites, dolomitic grainstones). Magnesite is best developed in two western sub-basins (Fig. 6F, Fig. 9). A "lower siliciclastic sequence" was recognised throughout the Willouran Ranges but is thickest towards the east (Fig. 6E, Fig. 9). An upper zone of siliciclastic dominance is evident in the two eastern sub-basins.

The axial sub-basins are clearly reflected in the present outcrop distribution of the Burra Group, separated by northwest-trending zones of tectonically-disturbed megabreccia and diapiric strata (Fig. 5). Murrell (1977) and Utah Development Company (1983) considered these tectonic complexes to have been basement palaeo-highs onto which the Burra Group sea transgressed. However, detailed mapping has not revealed interdigitating marginal coarse clastics which would be expected to have shed off any elevated basement blocks. In addition, some 4 or 5 km of onlap of peritidal deposits is required using a simple transgressive model. A more plausible explanation is that these structurally complex corridors represent the former bounding faults to rapidly subsiding and sedimenting extensional sub-basins. The faults became preferential sites for syn- and post-depositional diapiric piercement, modified by later (Cambro-Ordovician) orogenesis.

PALAEOENVIRONMENT EVIDENCE

Evidence of palaeoenvironment at the outcrop scale is provided by observation of lithology, mineralogy and sedimentary structures, and by additional chemical and isotopic analyses. Of particular interest is the need to distinguish marine depositional environments from evaporative lacustrine and playa environments. The relevant analytical results are summarised in Table 1, and details of methodology and results are given in Belperio (1987a). Isotopic analyses were undertaken on selected whole-rock specimens, and measurements are given in per mil deviations from PBD standards.

Interpretation from outcrop observations

Lithologies, mineralogies and sedimentary structures indicate peritidal deposition with repeated, intermittent exposure for the entire Skillogalee Dolomite succession. Finely laminated micritic dolomites with crenulate to stratiform organic laminae (cryptalgal dolomites) are analogous to modern peritidal algal laminites. Because of their extensive development, and lack of desiccation features, they are here interpreted as shallow subtidal in origin. Equivalent intertidal deposits are also present and are recognized by the varying degree of disruption and resedimentation as intraformational dolomite breccias, the presence of oncolites, and associated tepees, mudcracks and euhedral evaporite moulds. Stromatolite biostromes represent greater development of algal growth structures and, because of their extensive stratiform development, are also interpreted as largely of shallow subtidal origin. Intertidal stromatolites are also clearly recognisable from the degree of reworking, more common chert replacement, and associated dolomite grainstones and intertidal channel deposits.

Sedimentary magnesite beds are also intimately associated with desiccation features such as basal disrupted carbonate crusts, tepees and mudcracks. Together with torrent, graded and inverse-graded bedding features, these imply repetitive subaerial exposure and erosion of semiconsolidated magnesium carbonate mud. Preferential intermixing with dolomite rather than siliciclastics further implies a marginal marine setting. By direct analogy with the modern Coorong (Forbes 1961; Von der Borch and Lock 1979), precipitation probably occurred in marginal ephemeral lakes that underwent seasonal evaporation. Magnesium may have been provided by sporadic marine flooding, by marine aerosols or by magnesium-rich groundwaters. Erosion of unconsolidated magnesite mud and dolomicritic algal mats may have resulted from repetitive shoreline migration across very low gradient, depositional flats.

Inorganic precipitation of gelatinous silica also occurs within the carbonate muds of ephemeral Coorong lagoons where it is intimately associated with both dolomite and magnesite (Peterson & Von der Borch 1965, Von der Borch and Jones 1976). Chert is also abundant in lacustrine deposits of rift valley environments as an alteration product of volcaniclastic material. However, widespread penecontemporaneous volcanism is not recognised for Skillogalee Dolomite time.

Sandstone beds show characteristics of subaerial sheet-flood deposition. These include thin, flaggy, poorly sorted beds, sharp contacts, and abundant mudcracks and remnant evaporites. If a marine setting is accepted for the carbonates, then sandstone beds represent intermittent sheet-flood deposition across playa-like, marginal marine flats.

Textural and petrographic evidence, in particular the intermixing of dolomite and magnesite intraclasts of a variety of grain sizes, and the preservation of fine algal structures, indicate that both dolomite and magnesite were formed penecontemporaneously with deposition rather than by late-stage diagenesis of precursor carbonate minerals. Modern environments of penecontemporaneous dolomite formation are poor models for explaining the great thickness and lateral uniformity of ancient dolostones such as the Skillogalee Dolomite. Tucker (1982) also considers modern environments of dolomite formation to be poor analogues for interpreting Precambrian dolomites and has suggested primary precipitation may have been the norm at that time due to a seawater of different composition to that of the present.

The combination of lithologies, mineralogies and sedimentary structures evident at the outcrop scale are thus consistent with a shallow marine to peritidal setting for the Skillogalee Dolomite, with primary or penecontemporaneous formation of dolomite on an extensive carbonate platform. Repeated, small-scale transgressions and regressions concomittant with shoaling and subsidence resulted in complex repetitive vertical sequences of peritidal marine and marginal playa-like deposits, with vertical facies changes on the scale of decimetres to metres. Shoaling generated a sequence change from subtidal, laminated, cryptalgal dolomites and stromatolites through trough-crossbedded dolomitic grainstones, to intraformational, intertidal dolomites, supratidal to ephemeral magnesites, and arenaceous sheet-flood deposits. This ideal cycle is, however, frequently disrupted by other variables. Uppill (1980) recognized a similar preferred cycle of shoaling, exposure and disruption within magnesite-dominated facies.

The thick terrigenous sequence below the Skillogalee Dolomite (the Emeroo Subgroup) was examined only briefly in this study. Interbedded flaggy sandstones, feldspathic quartzites, laminated siltstones and shales with abundant ripple marks, clay intraclasts, mudcracks, lenticular bedding and moulds after shortite and halite are consistent with deposition in alluvial and perennial and playa lacustrine environments.

Palaeosalinity

Desiccation features such as mudcracks, tepees and disrupted carbonate crusts are abundant throughout the Skillogalee Dolomite, but without supporting evidence, provide no direct evidence of palaeosalinity. Halite and shortite moulds were recorded but are relatively rare in the dolomitic facies. Von der Borch and Lock (1979) attributed the lack of evaporites in the Burra Group dolomites to a more humid climate or a better developed through-flushing hydrological system compared with underlying sabkha-style dolomites of the Callana Group. Pyrite is common within the Skillogalee Dolomite, particularly in arenaceous beds. Authigenic pyrite forms under anoxic or euxinic conditions from bacterial sulphate reduction within bottom sediments. Organic carbon and sulphur relationships have been used to distinguish oxic marine, euxinic marine and non-marine freshwater depositional environments (Berner & Raiswell 1984; Leventhal 1987). Of 22 samples analysed (Table 1), five have a discriminatory content of organic carbon and pyritic sulphur (Berner & Raiswell 1984) and plot in the range established for modern marine oxic and euxinic sediments (Fig. 10). No samples plot definitively within the range for modern freshwater lacustrine sediments. However, the C/S palaeosalinometric method does not differentiate between saline lacustrine and marine environments.

Organic Composition

Thirtyfive samples from various sediment facies of the Skillogalee Dolomite were analysed for total organic carbon (Table 1 and Belperio 1987a). Cryptalgal dolomite and stromatolite samples record the highest residual organic content, of up to 1.38% T.O.C. Intraclastic magnesite samples consistently record organic contents of <0.1% by weight.

The Skillogalee Dolomite, and the coeval or slightly older Bitter Springs Formation of the Amadeus basin, contain a diverse preserved microbiota of cyanobacteria, algae and fungi (Barghoorn & Schopf 1965; Schopf 1968). Because of metamorphism (lower greenschist facies), the Type 1 kerogens have undergone extensive dehydrogenation and are heavily altered (McKirdy & Watson 1986). The kerogen extracted from stromatolites and algal dolomites shows enrichment of the heavier ^{13}C isotope (delta ^{13}C - 8 to - 20 per mil PDB) relative to the established range for biogenic carbon preserved in Phanerozoic and Proterozoic sedimentary rocks (Fig. 11). Enrichment of ^{13}C in Precambrian carbonaceous matter has been attributed to fundamentally different environmental conditions such as lower oceanic pH or temperatures (Degens 1969) and to post-depositional metamorphism (McKirdy et al 1975; McKirdy & Powell 1974). The probable carbon isotopic shift due to metamorphism of the Burra Group is estimated by Hayes et al (1983) at about 4 per mil. Even allowing for such a correction, most samples remain anomalously heavy and correspond with the established range (-8 to -21 per mil PDB) for extant cyanobacterial mat communities (Schidlowski et al 1983).

In recent sediments, organic matter has a similar isotopic composition to the organisms living in the environment of deposition. Sediments with organic material from freshwater lacustrine environments usually have a lower ^{13}C content, with isotopic ratios generally in the range -20 to -30 per mil PDB. Marine organic carbon is isotopically heavier, with a mean of -20 per mil (Degens, 1969). Therefore, with due allowance for isotopic fractionation during diagenesis, the simplest conclusion to be drawn from the organic isotopic compositions is that the preserved kerogens from the Skillogalee Dolomite reflect the dominance of a photosynthetic cyanobacterial community in a marine or marginal marine environment.

Carbonate Isotopes

Numerous studies of Phanerozoic dolomites have resulted in clear evidence that dolomite largely forms by replacement of a precursor carbonate (Land 1984). Dolomite is rare in Holocene unrestricted marine sediments, and, in coastal evaporative deposits (sabkhas), is enriched in ^{18}O as a result of evaporation of seawater (Fig. 12). Similarly, Holocene dolomite formation from evaporative concentration of continental to meteoric-seawater mixing zone environments such as the ephemeral Coorong lakes and lagoons also result in enrichment of ^{18}O relative to normal marine carbonates. Many ancient platform dolomites, whilst displaying a general secular constancy of carbon isotopic composition, are however, significantly depleted in ^{18}O with respect to Holocence dolomites (Land 1980) and Holocene limestones (Fig. 12). This anomaly is further accentuated in late Precambrian dolomites (Schidlowski et al 1975; Veizer & Hoefs 1976).

The Skillogalee Dolomite is no exception (Table 1 and Fig. 12). Analyses reported here confirm the general range of previous analyses obtained on samples from the Skillogalee Dolomite by Schidlowski et al (1975) and Veizer and Hoefs (1976), and provide additional, new data. One sample of terrigenous mudstone (with 3% dolomite) is enriched in ^{18}O. All but two of the cryptalgal dolomite and magnesite samples are depleted in ^{18}O by some 10 to 12 per mil relative to Holocene examples. Two samples of cryptalgal dolomite, however, are clearly enriched in ^{18}O relative to other samples and plot within the fields for lacustrine or evaporitic mixing-zone dolomites. Magnesite samples are all distinctly enriched in C^{13} relative to coeval dolomites, but only marginally enriched in ^{18}O. This may indicate simple evaporative enrichment rather than meteoric mixing. The isotopically light cryptalgal dolomites and stromatolites are significantly different to Quaternary lacustrine stromatolites as exemplified by those from the Magadi - Natron basin (Hillaire - Marcel & Casanova 1987). They are however, notably similar in isotopic signature to marine biosparites of the younger Brighton Limestone (Schidlowski et al 1975).

Unaltered, penecontemporaneous carbonates should have isotopic signatures that reflect the composition of the host waters from which they were formed (Veizer & Hoefs 1976). The average delta ^{18}O value of -7.6 for the six isotopically-light cryptalgal dolomites and stromatolites may approximate the value of basin or oceanic water at that time.

Strontium Isotopes

The isotopic ratio $^{87}Sr/^{86}Sr$ shows no detectable variation in present-day ocean and coastal water, but shows a slow, systematic variation over geological time. In the absence of secondary alteration, Sr contained in biogenic carbonates records the isotopic composition of the coeval waters in which they formed. Previous studies by Veizer and Compston (1974, 1976), Burke et al (1982) and Veizer et al (1983) have established a secular trend for the Phanerozoic and Late Proterozoic (Fig. 13). These studies included dolomite samples from the Skillogalee Dolomite and the younger Brighton Limestone and Wonoka Formation of the Adelaide Geosyncline, and the Bitter Springs Formation of the Amadeus Basin in central Australia. Eight additional analyses were undertaken as part of this study (Table 1). $^{87}Sr/^{86}Sr$ ratios (normalised to $^{88}Sr/^{86}Sr = 8.3752$) were measured on 0.1 N HCL-soluble fractions of these samples in order to eliminate the influence of radiogenically enriched strontium in any non-carbonate detritus that may be present.

The "preferred" value of seawater $^{87}Sr/^{86}Sr$ composition for Skillogalee time is 0.7091 (Veizer et al 1983). It is also considered unlikely that the continental river flux of Sr in the Late Proterozoic was either less or very much more radiogenic than present-day counterparts (0.711). Three cryptalgal dolomite and two magnesite samples plot within the range for the Skillogalee Dolomite previously established by Veizer and Compston (1976). The range was considered to result from a varying degree of secondary alteration. Three samples were considerably more radiogenic (Fig. 13); all were terrigenous mudstones from the basal Camel Flat Shale (Fig. 2 and 9). The higher values may be indicative of non-marine deposition, or may have resulted from post-depositional alteration and isotopic equilibration of Sr between carbonate and non-carbonate components.

PALAEOGEOGRAPHY AND SYN-DEPOSITIONAL TECTONICS

The Burra Group generally, and Skillogalee Dolomite in particular, have been interpreted by several investigators as dominantly or entirely of non-marine origin. Murrell (1977) and Uppill (1980) inferred deposition in a large, shallow inland sea with a chemistry somewhat removed from ocean water. Von der Borch (1980) suggested the cycles within the Skillogalee Dolomite represented a repetitive playa-lacustrine sequence similar to that of the Laney Shale Member of the Green River Formation. Others, such as Forbes (1960, 1961), Preiss (1983) and Preiss _et al_ (1981), considered the cryptalgal dolomites as essentially penecontemporaneous shallow marine carbonates, with magnesite deposition in marginal alkaline lagoons.

Lacustrine basins, particularly those in a rift valley setting, are characterised by high deposition and subsidence rates, variable carbonate and clastic sedimentation, and by preservation of organic matter, features already noted in the Skillogalee Dolomite. In such settings however, lacustrine dolomites and stromatolites are also intimately associated and interdigitate with alluvial fanglomerates and aeolian and fluvial quartzose sandstones (eg. White & Youngs 1980, Elmore 1983, Smoot 1983). In more arid settings, they are associated with bedded evaporites and saline sediments. Lacustrine environments also produce characteristic "bath-tub ring" patterns of stromatolite growth as a result of fluctuating water levels (e.g. Hillaire-Marcel & Casanova 1987). The extensive and regular formation of stromatolite biostromes, the lack of interdigitating coarse continental deposits, and the absence of evaporitic strata argue against a playa or lacustrine origin for the carbonates. Sedimentary structures are consistent with a shallow marine to peritidal setting for the Skillogalee Dolomite, with repetitive shoaling, exposure and desiccation.

With due regard to possible post-depositional changes, the isotopic compositions of carbonates and residual organics provide supportive evidence of sedimentation in a marine environment. In particular, the coincidence of $^{87}Sr/^{86}Sr$ ratios of cryptalgal dolomites and magnesites with those for Precambrian limestones generally accepted as marine in origin, such as the Brighton Limestone (Preiss & Kinsman 1978) and Wonoka Formation (Haines 1986), indicates a similar marine association. Mudstone samples which are more radiogenic indicate continental sedimentation, or may indicate post-depositional exchange of Sr between silicate and carbonate phases (Veizer & Compston 1974, 1976). Oxygen isotopic composition of dolomites, magnesites and cherts similarly display a general equivalence with values previously obtained from "accepted" marine limestones. Two anomalous samples indicate evaporative enrichment and concur with the sedimentological evidence that indicates periodic exposure and desiccation, though unaccompanied by sulphate or halide precipitation. C/S ratios provide further, though limited, support for a marine origin for the cryptalgal carbonates.

The Burra Group and Skillogalee Dolomite in the Peake and Denison Ranges to the northwest (Fig. 1) display a similar mega-scale stratigraphy and cyclicity to that in the Willouran Ranges. However algal laminations and stromatolites are much less developed and intraclastic magnesites are thinner and finer grained. Also, the Skillogalee Dolomite is dominated by stacked, decimetre-thick, planar bedded grainstones of mixed quartz-dolomite composition. This is consistent with the existence of a through-going shallow seaway extending northwestwards from the Willouran Ranges, with cryptalgal dolomite and magnesite production centred about a southeastern entrance about the present Willouran Ranges. The terrigenous lower Burra Group sequence in the Peake and Denison Ranges is similarly consistent with an alluvial and perennial to ephemeral lacustrine origin.

The marked variations in the total thickness (2000-8000 m) of the Burra Group and its facies across the Willouran Ranges (Fig. 9) are interpreted as resulting from differential syndepositonal subsidence between at least four northwest-trending sub-basins. Sedimentation of predominantly continental clastics of the Emeroo Subgroup was greatest (4000 m+) in the eastern ranges. For the Skillogalee Dolomite, the locus of sedimentation shifted to the central ranges (3900 m) with predominantly shallow marine carbonates deposited. Maximum sedimentation shifted again, this time to the northwest (4400 m) in the return to dominantly terrigenous deposition of the Myrtle Springs Formation. Shallow water conditions and intermittent exposure prevailed throughout these major depositional cycles. For the Skillogalee Dolomite, variation in facies development across the basin implies a dominant source of terrigenous sediment from the northeast, a major central zone of in-situ algal carbonate production, and shallow, paralic flats conducive to magnesite precipitation to the southwest.

Within the sub-basins, the Burra Group strata thin dramatically when traced marginwards, in some cases from 4000 or 5000 m to zero over lateral distances of less than one kilometre. Although some of this is due to later (Cambro-Ordovician) deformation and thrusting (Sprigg, 1950), much of the thinning is due to syn-depositional, fault-controlled subsidence of the narrow, axial, extensional sub-basins.

Despite high rates of subsidence, sedimentation essentially kept pace throughout Burra Group time. As a consequence, little positive or negative relief was generated between sub-basins and individual beds show little lithological change when traced marginwards. Differential subsidence occurred along intra-basinal faults that are preserved today as structural corridors of tectonically disturbed megabreccia and shale-and dolomite-hosted diapiric breccia of older strata (Fig. 5). Syn- and post-depositional diapirism of partially evaporitic Callanna Group carbonates has often been invoked to explain the presence of such piercement megabreccias through much of the Adelaide Geosyncline (e.g. Webb 1961; Coats 1965; Dalgarno & Johnson 1968; Lemon 1985; Preiss 1985). Sedimentation in modern extensional basins is often intimately associated with diapirism. In the northern Red Sea for example, many elongate diapirs ascend along bounding faults between numerous narrow, axially-trending, depositional sub-basins, under overburden as little as 1 km thick (Mart & Ross 1987). With accumulation of 8 000 to 10 000 metres of sediment in Burra Group time in sub-basins of the order of 10 km width, gravitational instability and concomittant diapirism are to be expected given even minimal density inversion or conversion.

CONCLUSIONS

The earliest Adelaidean (Callanna Group) in the Willouran Ranges records syn-rift, intracratonic graben sedimentation that includes volcanics, carbonates, clastics and evaporitic sequences deposited in sabkha and playa environments (Rowlands et al 1980; Preiss & Forbes 1981). The Burra Group represents a continuation of this intracontinental extensional tectonic regime, but with a major change to marine conditions particularly for the Skillogalee Dolomite. The depositional trough extending from the Willouran Ranges to the Peake and Denison Ranges and beyond, was a persistently subsiding basin with subdued topography masking a complex of differentially subsiding sub-basins. Syn- and post-Burra Group diapirism occurred along bounding faults between sub-basins.

Interaction between sea level fluctuations, shoaling and subsidence produced a complex repetitive sequence of algal dolomites, intraclastic dolomites, dolomitic grainstones, intraclastic magnesites and arenaceous beds. Cryptalgal dolomites and stromatolite biostromes were formed in shallow marine and intertidal waters, whilst magnesite muds were deposited in marginal flats and lagoons.

Desiccation, intraformational brecciation and sheet flooding occurred as a result of shoaling, shoreline migration and exposure. Dolomite was probably precipitated directly from seawater or formed penecontemporaneously with sedimentation, possibly as a result of cyanobacterial photosynthesis. Early diagenetic silicification of stromatolites and cryptalgal dolomites, and precipitation of magnesite muds, occurred preferentially on very shallow, intermittently exposed, marginal mud flats and lagoons. This spatial association is somewhat analogous to the modern association of dolomite deposition marginal to aragonite/magnesian calcite marine sedimentation as exemplified by the Coorong lagoon and ephemeral lakes, though the tectonic setting is more akin to that of the northern Red Sea rift.

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TABLE CAPTION

Table 1 Skillogalee Dolomite; results of analyses for carbon, carbonate and sulphur, and isotopes of organic carbon and carbonates. For details of location and methodology, see Belperio (1987a).

Table 1

SAMPLE NO. (6438-)	LITHOLOGY	ORGANIC CARBON	ACID EVOLVED CO_2 (%)	TOTAL SULPHUR S(%)	SULPHIDE SULPHUR S(%)	Organic Carbon delta ^{13}C (per mil PDB)	Carbonate delta ^{13}C (per mil PDB)	Carbonate delta ^{18}O (per mil PDB)	Carbonate $^{87}Sr/^{86}Sr$
RS276	Mudstone	0.10	0.05	<0.005	<0.005	–	–	–	0.74057 ± 0.00014
RS280A	Stromatolite	0.16	23.7	0.005	0.005	–	–	–	–
RS282	Mudstone	0.13	0.28	<0.005	<0.005	−19.85	–	–	–
RS284B	Stromatolite	0.83	38.1	0.010	0.010	−8.46	+2.36	−7.8	0.71194 ± 0.00014
RS289B	Stromatolite	0.13	14.2	0.005	0.005	−10.07	+2.52	−6.6	–
RS298A	Cryptalgal dolomite	0.27	34.3	0.025	<0.005	−16.63	+2.26	−5.4	0.70932 ± 0.00009
RS298A	Cryptalgal dolomite	–	–	–	–	–	–	–	0.70927 ± 0.00007
RS299	Pelletal Magnesite	0.08	32.0	0.005	0.005	–	+7.27	−5.5	–
RS301A	Mudstone	0.04	0.57	0.015	<0.005	–	–	–	–
RS328	Chert	0.02	0.48	0.055	0.030	–	+1.38	−2.8	–
RS329E	Pelletal Magnesite	0.03	42.2	0.005	<0.005	–	+5.55	−2.9	0.71009 ± 0.00012
RS332	Cryptalgal dolomite	0.69	38.0	0.020	<0.005	−9.03	+2.61	+2.2	–
RS333	Siltstone	0.15	0.44	0.46	0.020	−15.15	–	–	–
RS334	Mudstone	0.02	1.65	0.015	0.005	–	+0.02	+1.3	0.71377 ± 0.00009
RS334	Mudstone	–	–	–	–	–	–	–	0.71392 ± 0.00009
RS380	Pelletal Magnesite	0.03	40.8	0.010	0.010	–	+3.40	−4.2	–
RS381	Pelletal chert	0.19	7.35	0.020	0.020	−23.81	+3.08	−7.5	–
RS382	Pelletal magnesite	<0.02	41.9	0.005	<0.005	–	+5.51	−2.9	0.70903 ± 0.00008
RS383	Pelletal magnesite	0.03	46.4	0.010	0.005	–	+5.89	−1.0	–
RS423	Cryptalgal dolomite	0.10	7.45	0.39	0.38	–	+3.38	−9.5	–
RS424	Cryptalgal dolomite	0.82	28.0	0.23	0.17	−15.98	+2.68	−6.8	–
RS425	Cryptalgal dolomite	1.38	2.10	1.49	1.48	–	+0.39	−9.4	–
RS426	Cryptalgal dolomite	0.59	9.65	0.72	0.66	−20.22	+2.16	+2.7	–
RS427	Cryptalgal dolomite	0.28	8.45	8.35	8.30	−20.08	–	–	–

FIGURE CAPTIONS

Fig. 1 Location of the Willouran Ranges and distribution of thicker Burra Group sediments in central South Australia. Structural elements of the Adelaide Geosyncline modified after Flint & Parker (1982).

Fig. 2 Schematic Burra Group lithostratigraphy and age constraints for the Willouran Ranges.

Fig. 3 Mineralogy of 35 Skillogalee Dolomite samples from Belperio (1987a). Ternary plot of normalised XRD peak heights.

Fig. 4 Outcropping, 30 cm thick magnesite conglomerate bed consisting of coarse grained, micritic magnesite pellets in a matrix of finer magnesite, dolomite and silicate grains (SADME negative 36147). Sharply overlies finely laminated cryptalgal dolomite. Overlain by a sedimentary chert bed consisting of peloids of chalcedonic silica, detrital quartz and feldspar and minor micritic magnesite and dolomite clasts in a light grey, siliceous, sandy matrix. Chert is sample 6438 RS 381 in Table 1. For stratigraphic position, see Fig. 8.

Fig. 5 Simplified geological plan and east-west cross-section of the Willouran Ranges showing locations of detailed stratigraphic transects.

Fig. 6 Geographic variation within the Willouran Ranges, in the estimated thickness of the Burra Group (A) and measured thickness of the Emeroo Subgroup (B), Skillogalee Dolomite (C) and Myrtle Springs Formation (D). Also shown are the measured thicknesses of the lower siliciclastic facies (E) and magnesite dominated facies (F) of the Skillogalee Dolomite. Measurements are related to sections and geology as shown on Fig. 5.

Fig. 7 Outcrop plan of vertically dipping Skillogalee Dolomite strata over a strike length of 600m. Location approximately midway along Section 9, central Willouran Ranges.

Fig. 8 Example of repetitive sequence development. Detailed stratigraphic section for part of the Skillogalee Dolomite, Screechowl Creek (Section 8). Samples refer to analyses in Table 1.

Fig. 9 Palinspastic reconstruction of east-west section across the Willouran Ranges showing variation in thickness and dominant facies of the Skillogalee Dolomite. Constructed from detailed stratigraphic sections shown on Fig. 5. Separating depositional sub-basins are complex structural corridors of disrupted older strata, tectonic breccia and diapiric megabreccia that mark former intra-basinal faults. Vertical exaggeration 5x.

Fig. 10 Plot of organic carbon versus pyritic sulphur for 22 samples from the Skillogalee Dolomite. Modern environment fields from Berner & Raiswell (1984).

Fig. 11 Plot of organic carbon isotope values versus organic carbon content for 10 Skillogalee Dolomite samples. General range of isotopic values for biogenic carbon preserved in Phanerozoic and Proterozoic strata after Degens (1969) and Oehler et al (1972). Range for extant marine and freshwater cyanobacterial mat communities after Schidlowski et al (1983).

Fig. 12 Plot of delta ^{13}C versus delta ^{18}O (versus PDB) for 16 Skillogalee Dolomite samples. Included are data from Schidlowski et al (1975) and Veizer & Hoefs (1976) for the Skillogalee and for the younger, marine Brighton Limestone. Data ranges are indicated for: (1) Precambrian platform carbonates after Schidlowski et al (1975) and Veizer & Hoefs (1976); (2) extant shallow marine bioclasts after Milliman (1974); (3) lacustrine stromatolites from the Magadi-Natron basin after Hillaire-Marcel & Casanova (1987); (4) the regressive

Coorong lagoon showing trend from aragonitic to dolomitic sediments after Botz & von der Borch (1984); (5) Coorong ephemeral lake magnesites after Botz & Von der Borch (1984).

Fig. 13 Strontium isotope data for eight Skillogalee Dolomite samples (age ca.775 ± 25 Ma) compared with the secular trend of seawater composition established after Burke et al (1982), Veizer et al (1983) and Veizer & Compston (1974). Also shown are data ranges and accepted values of previous analyses by Veizer et al (1983) and Veizer & Compston (1976) for the Skillogalee Dolomite, the marine Brighton Limestone (ca.700 ± 50 Ma) and marine Wonoka Formation (ca. 650 ± 50 Ma) of the Adelaide Geosyncline, and the Bitter Springs Formation (ca.800 ± 50 Ma) of the Amadeus Basin.

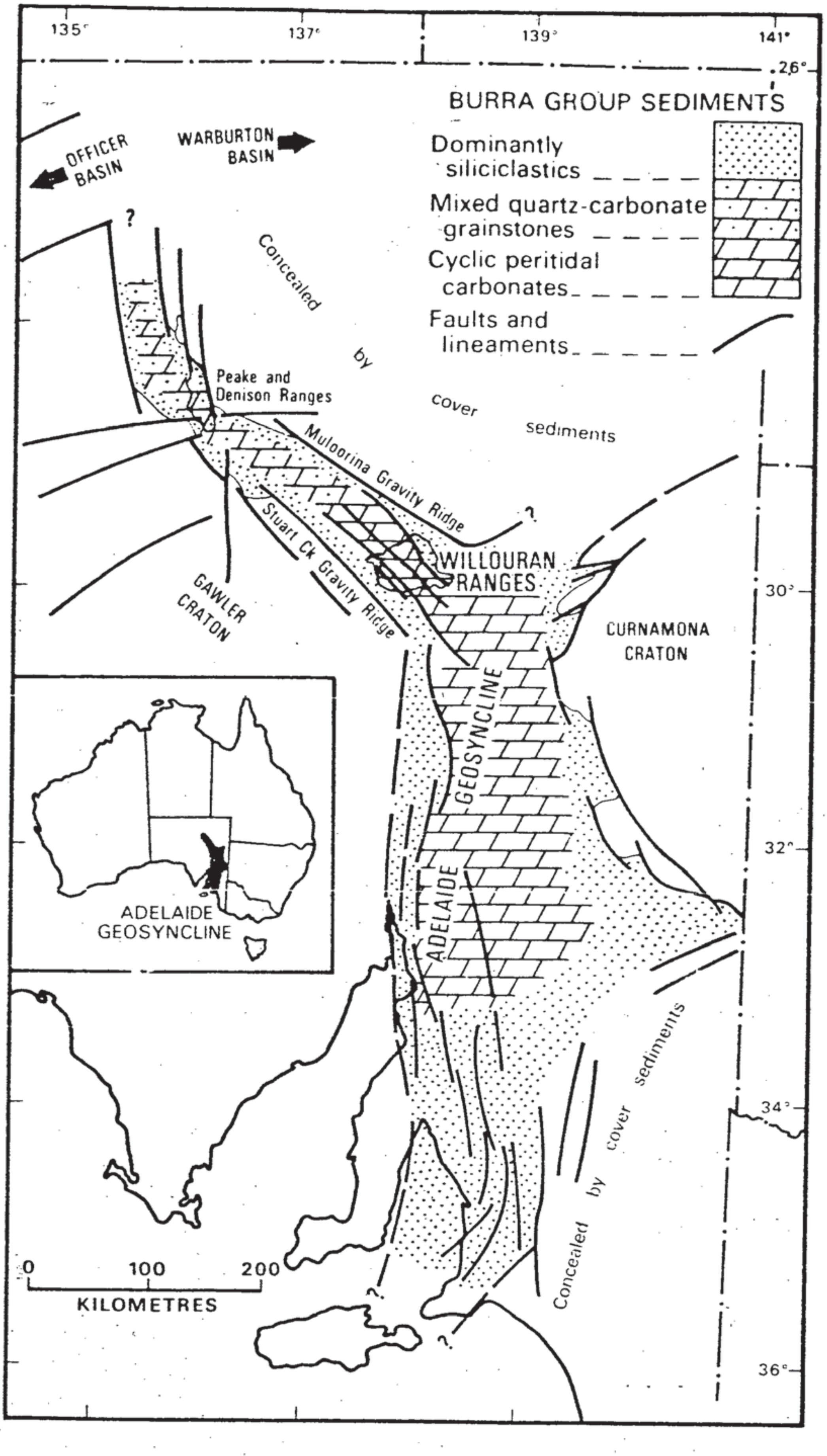


Fig. 1

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O.	DATE 29·1·88
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE As shown	
DISTRIBUTION OF BURRA GROUP AND LOCATION	DATE Jan. '1988	PLAN NUMBER	
	CHECKED	S 19764	

4457

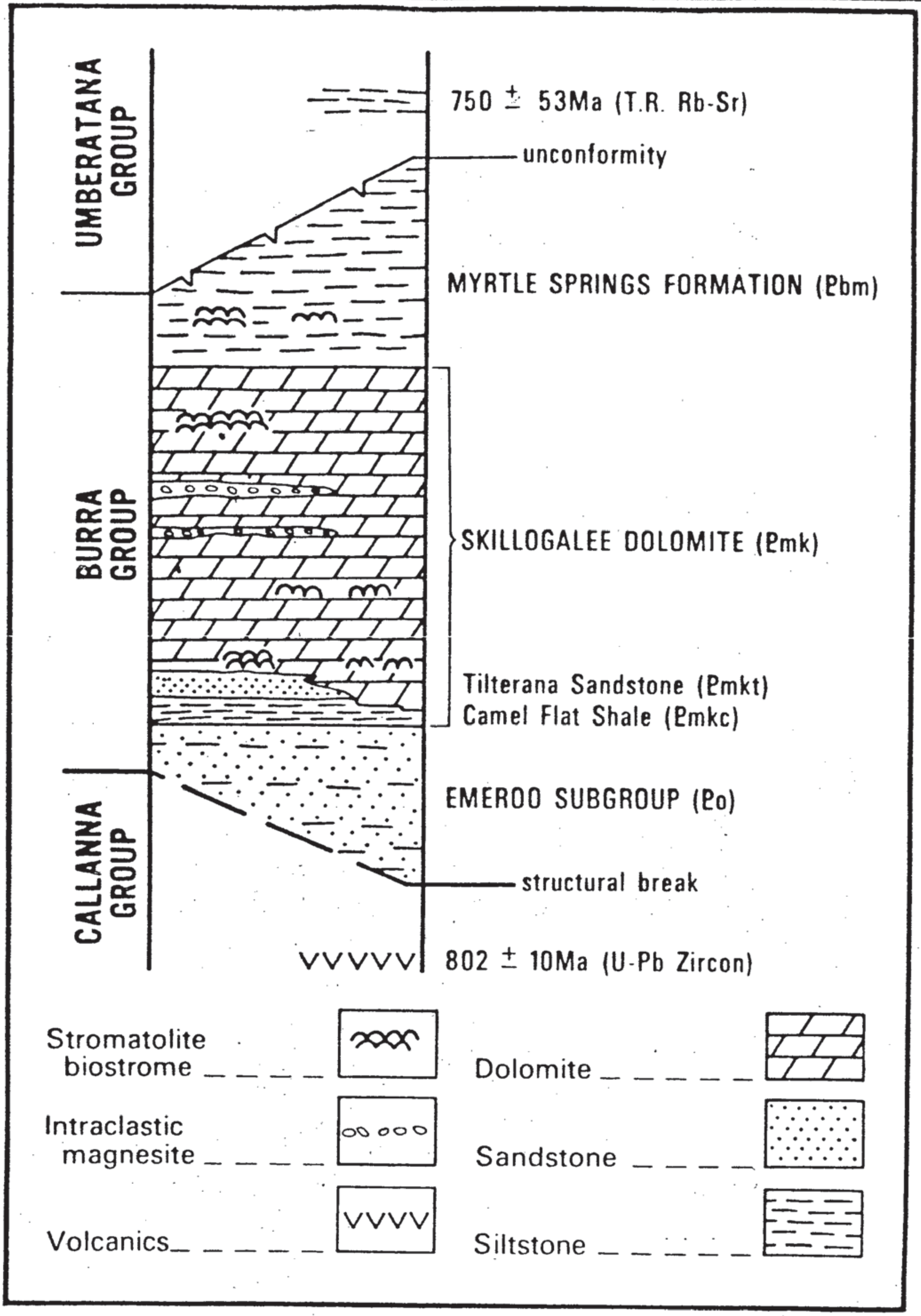


Fig. 2

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES

SCHEMATIC BURRA GROUP LITHOSTRATIGRAPHY AND AGE CONSTRAINTS

COMPILED: T. Belperio	C.D.O.	DATE: 25 · 1 · 88
DRAWN: E.A.	SCALE	
DATE: Jan. 1988	PLAN NUMBER: S 19765	
CHECKED		

4457

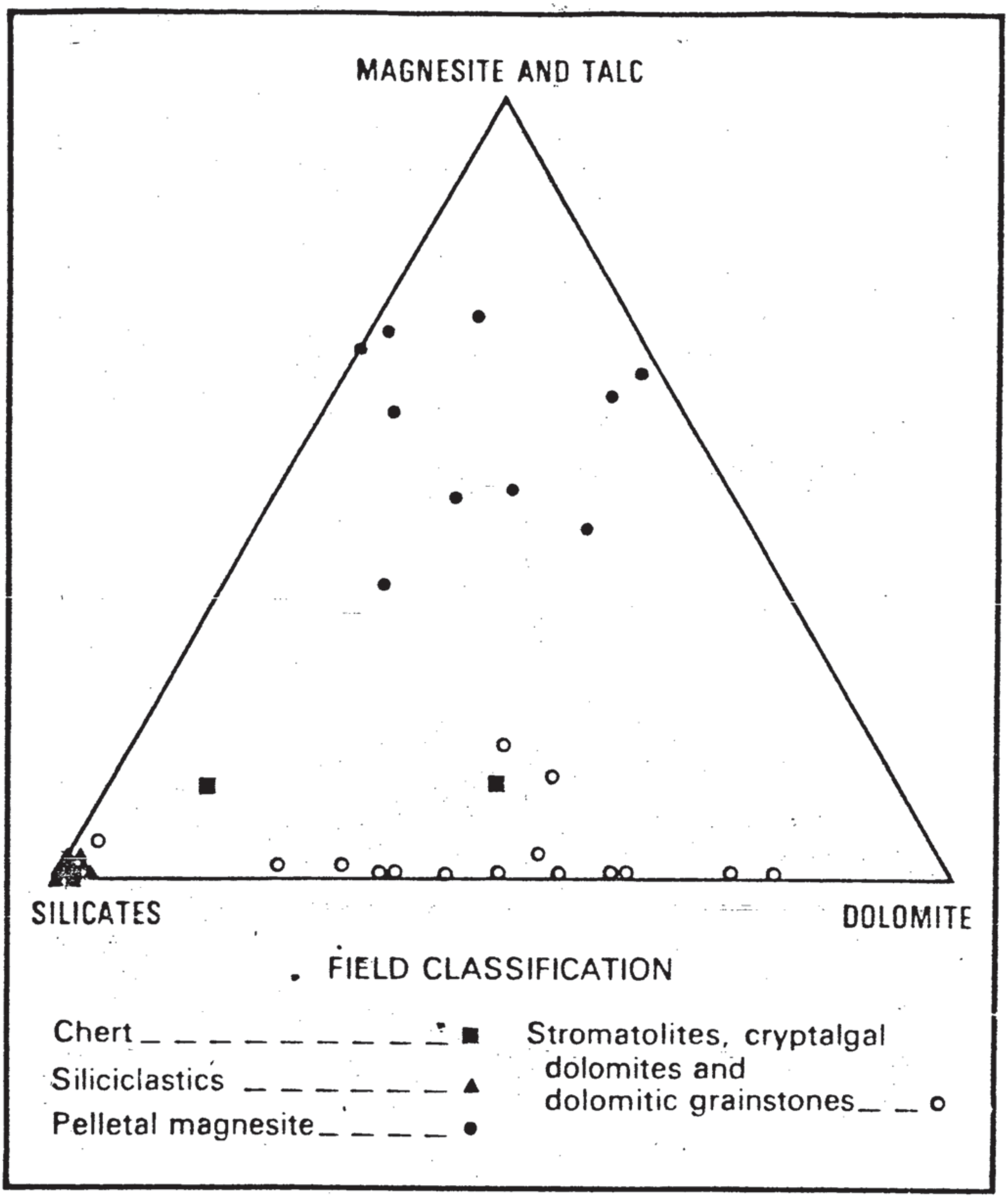
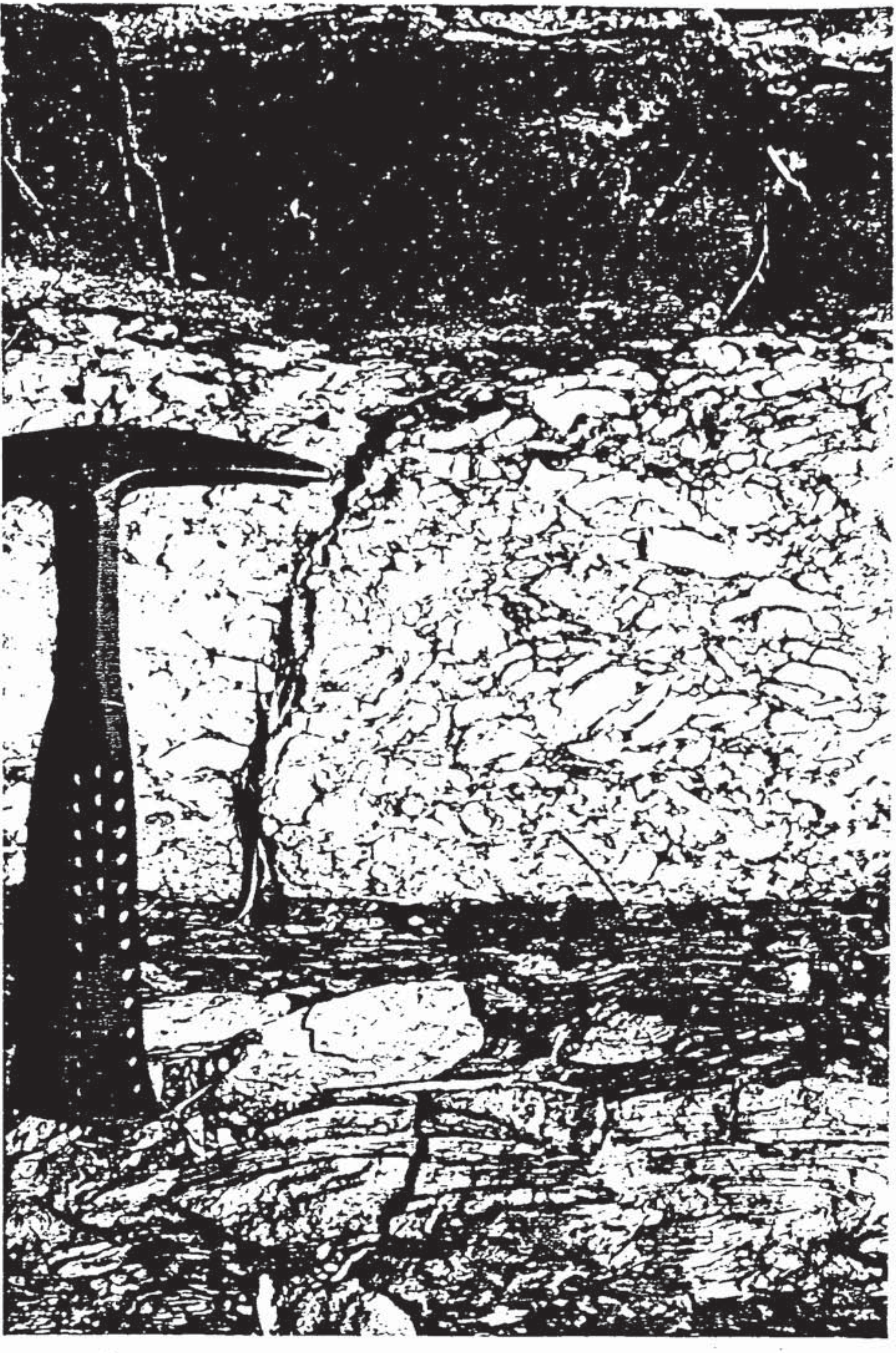


Fig. 3

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O	29 · 1 · 88 DATE
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE	
MINERALOGY OF SAMPLES	DATE Jan. 1988	PLAN NUMBER	
TERNARY PLOT OF NORMALISED XRD PEAK HEIGHTS	CHECKED	S 19766	

4457



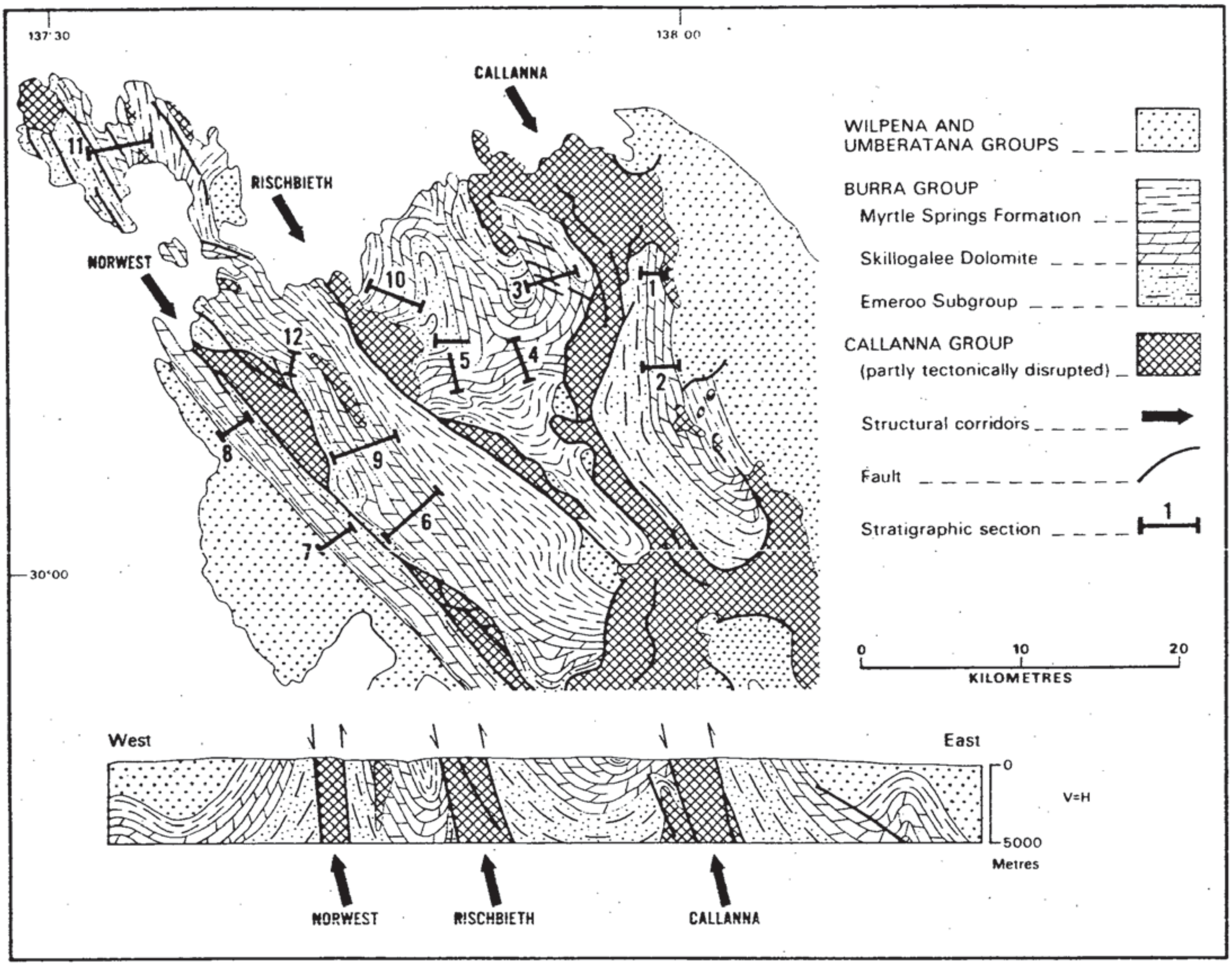
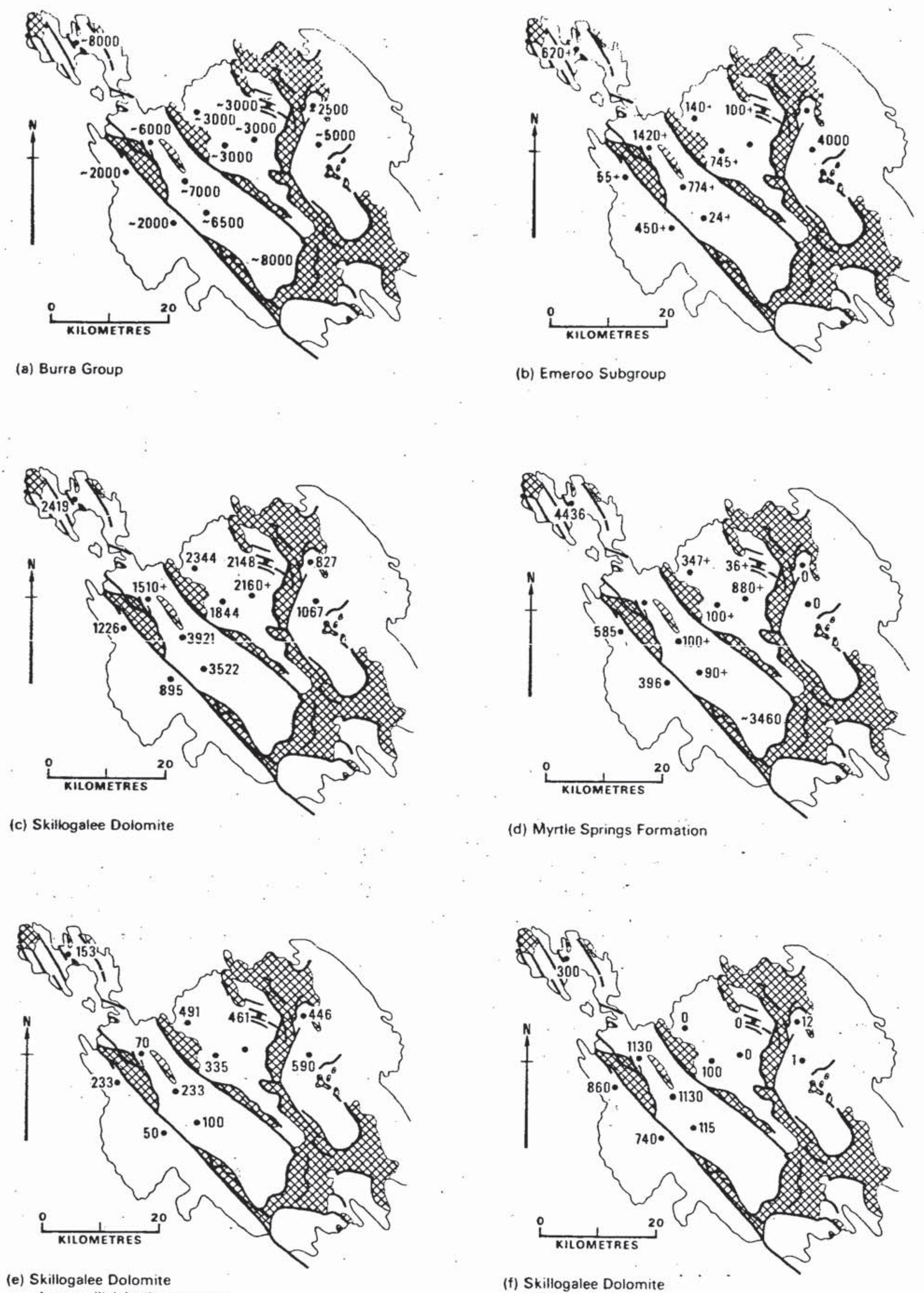


Fig. 5

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O. 29 · 1 · 88 DATE
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE As shown
SIMPLIFIED GEOLOGICAL PLAN AND EAST-WEST CROSS SECTION	DATE Jan. 1988 / CHECKED	PLAN NUMBER S 19767

4457



Thickness in metres — — • 100 For geology see Fig.5

Fig. 6

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES

THICKNESS VARIATION OF TOTAL BURRA GROUP

COMPILED T. Belperio	C.D.O. 29.1.88 DATE
DRAWN E.A.	SCALE As shown
DATE Jan. 1988	PLAN NUMBER
CHECKED	S 19768

4457

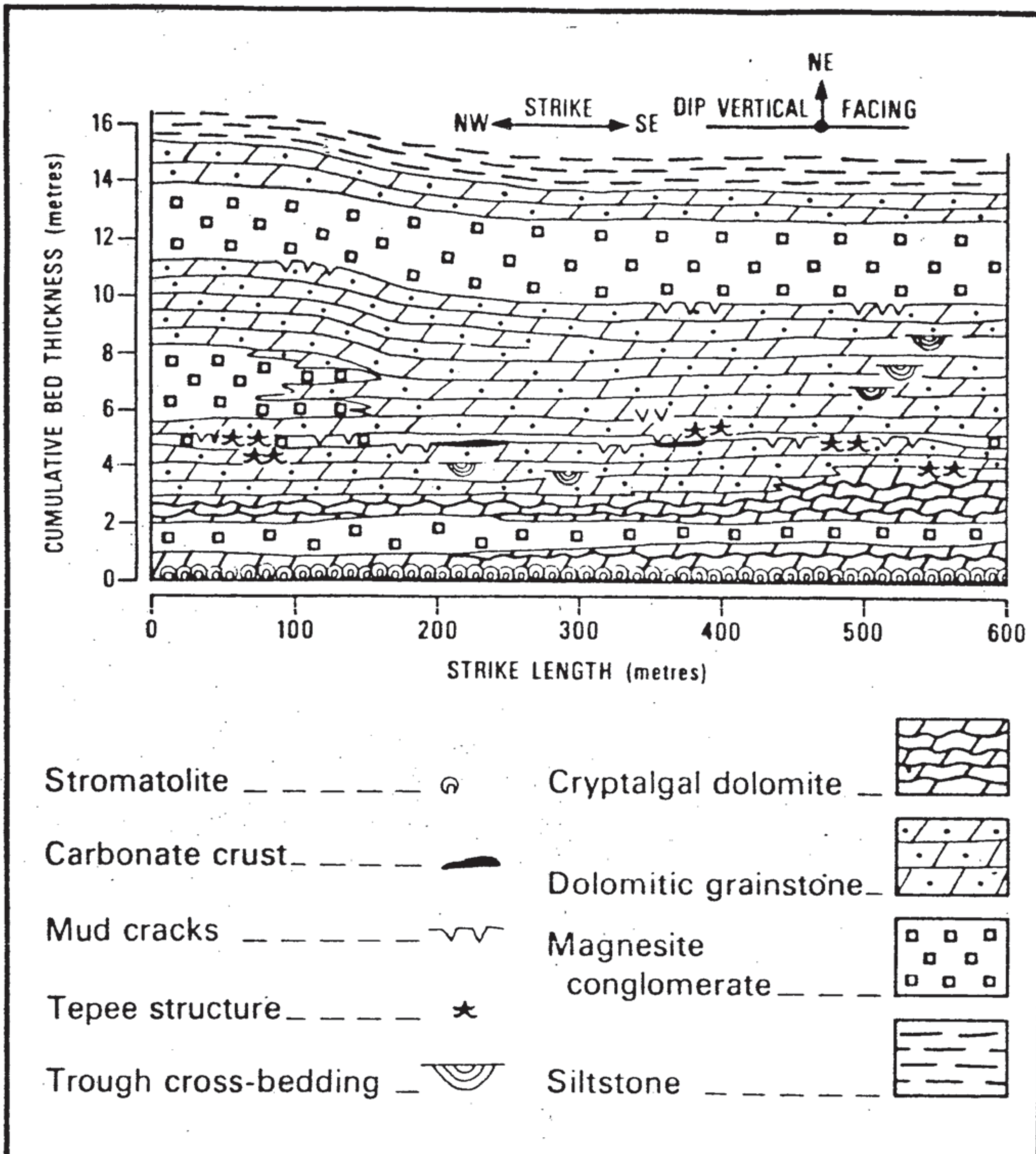


Fig. 7

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O. DATE 29·1·88
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE
OUTCROP MIDWAY ALONG SECTION 9	DATE Jan. 1988	PLAN NUMBER
	CHECKED	S 19769

4457

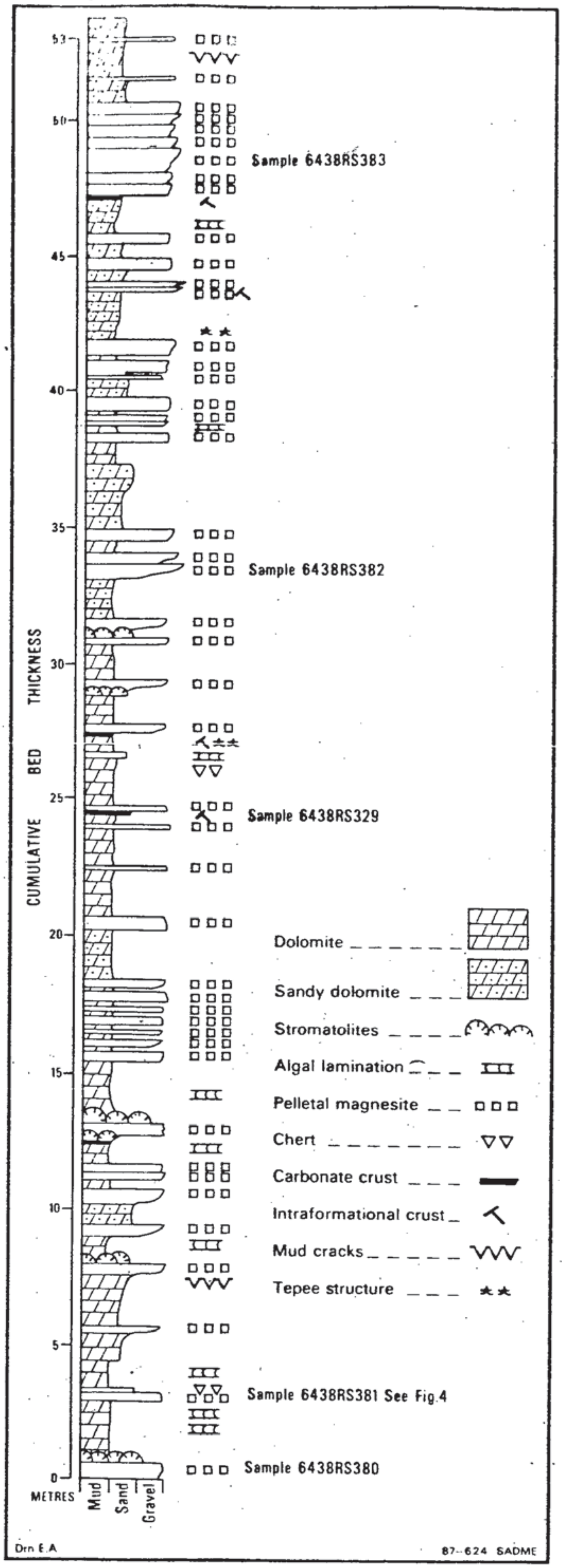


Fig. 8

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	COMPILED *T. Belperio*	C.D.O. 20 · 1 · 88 DATE
SCREECHOWL CREEK	DRAWN *E.A.*	SCALE
DETAILED STRATIGRAPHIC SECTION	DATE *Jan.'1988*	PLAN NUMBER
	CHECKED	**S 19770**

4457

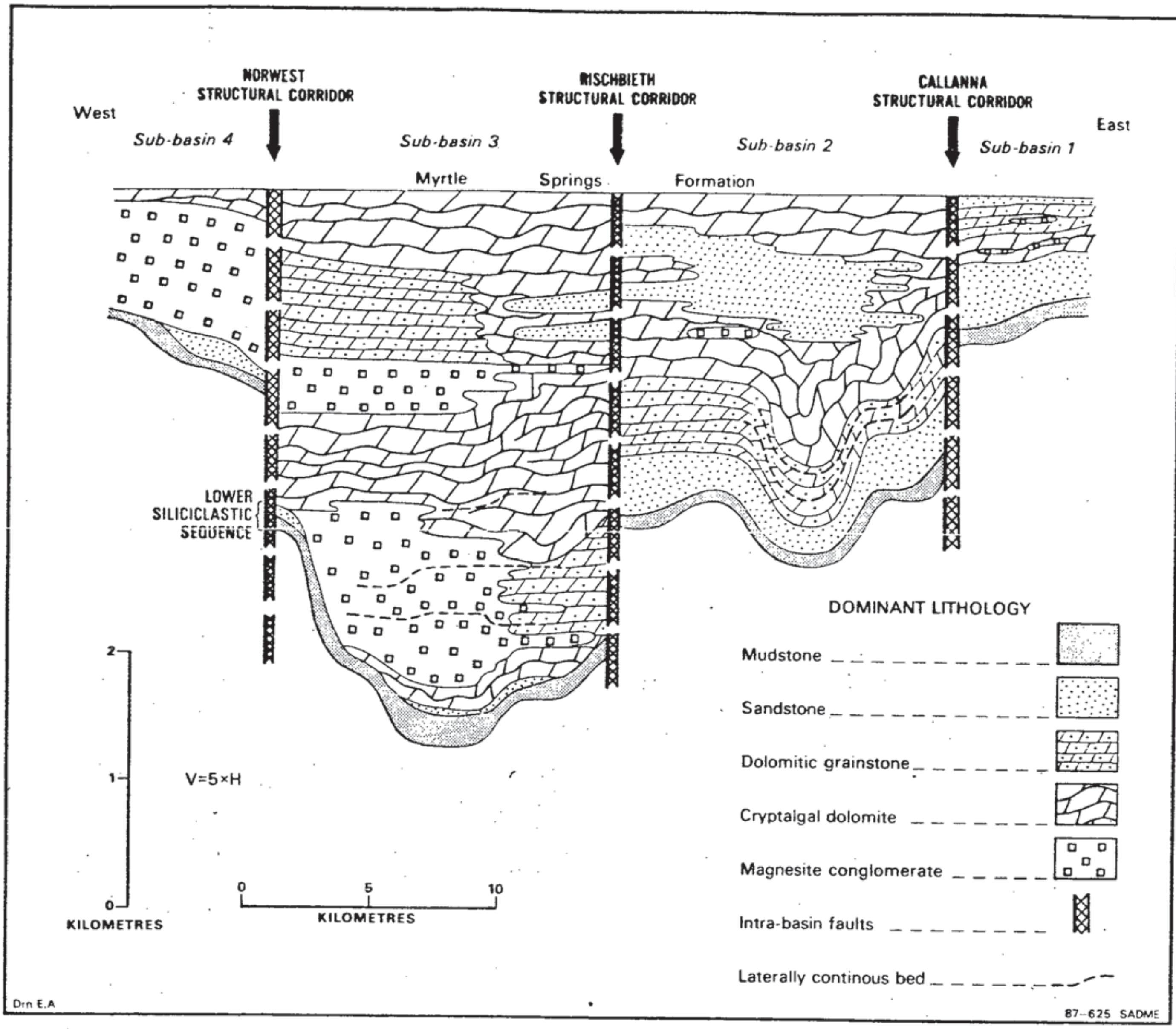


Fig. 9

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O. DATE 29·1·88
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE As shown
DEPOSITIONAL BASIN	DATE Jan. 1988	PLAN NUMBER
PALINSPASTIC EAST – WEST CROSS SECTION	CHECKED	S 19771

4457

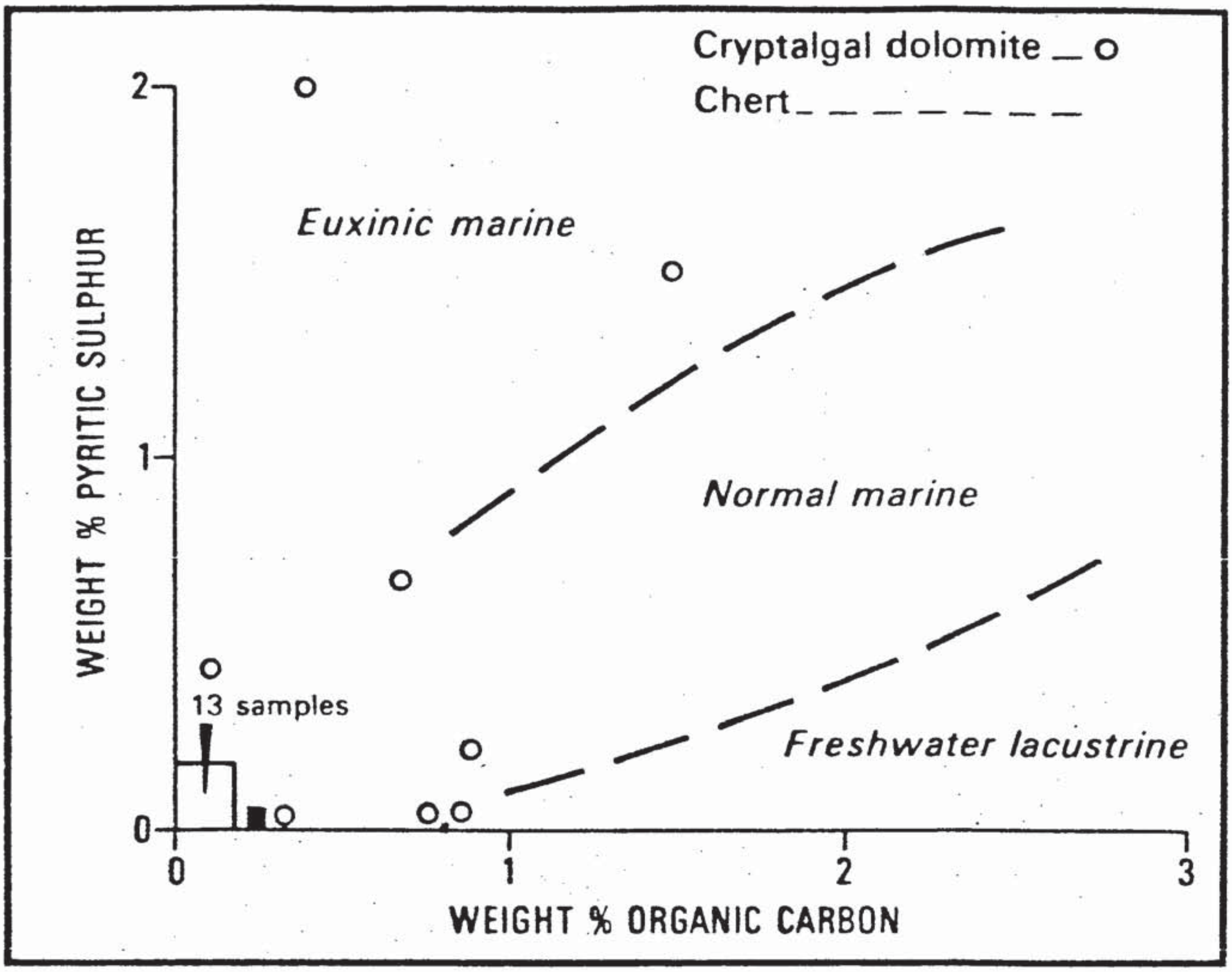


Fig. 10

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O. 29·1·88 DATE
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE
PLOT OF ORGANIC CARBON VERSUS PYRITIC SULPHUR	DATE Jan. 1988	PLAN NUMBER
	CHECKED	S 19772

4457

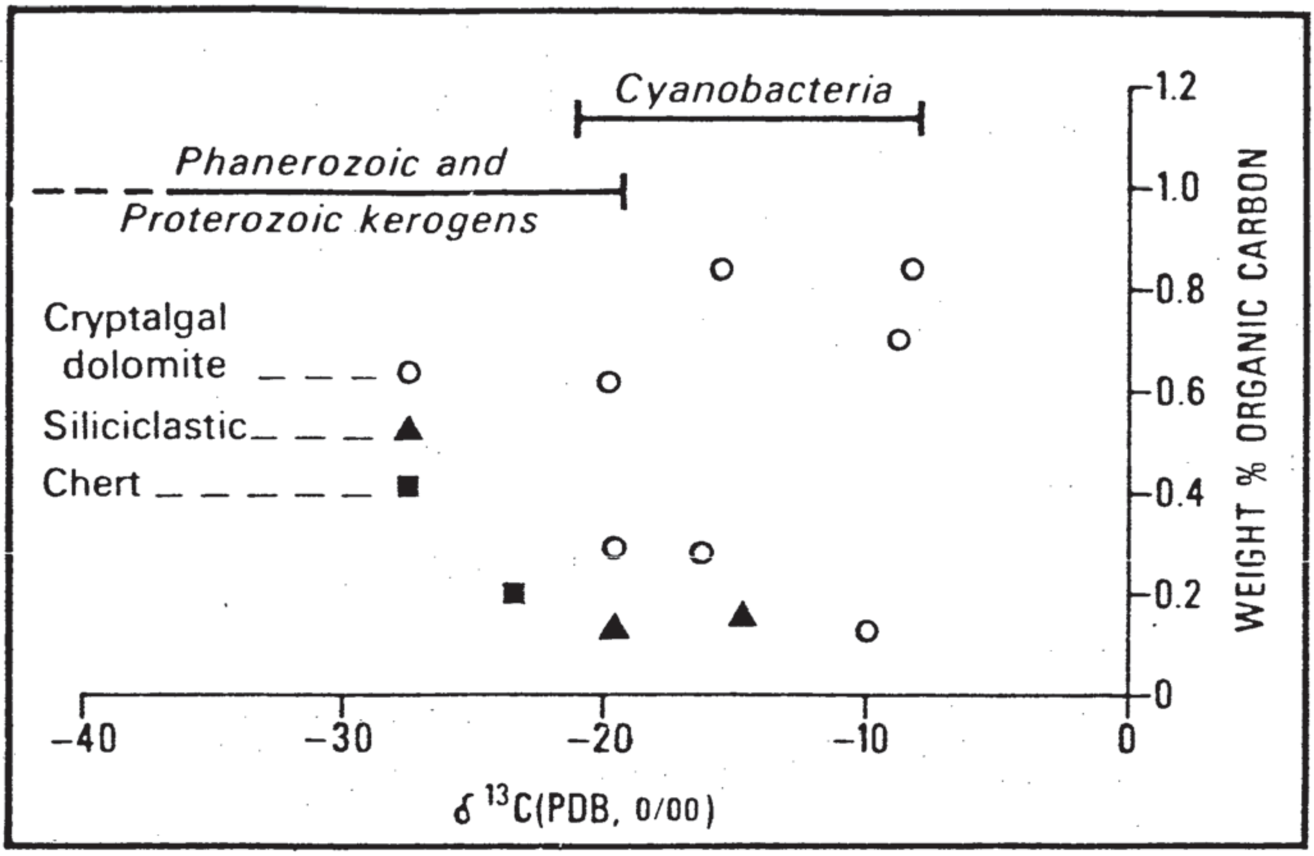


Fig. 11

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O. 29·1·88 DATE
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES	DRAWN E.A.	SCALE
PLOT OF ORGANIC CARBON ISOTOPIC COMPOSITION VERSUS ORGANIC CARBON CONTENT	DATE Jan.'1988	PLAN NUMBER S19773
	CHECKED	

4457

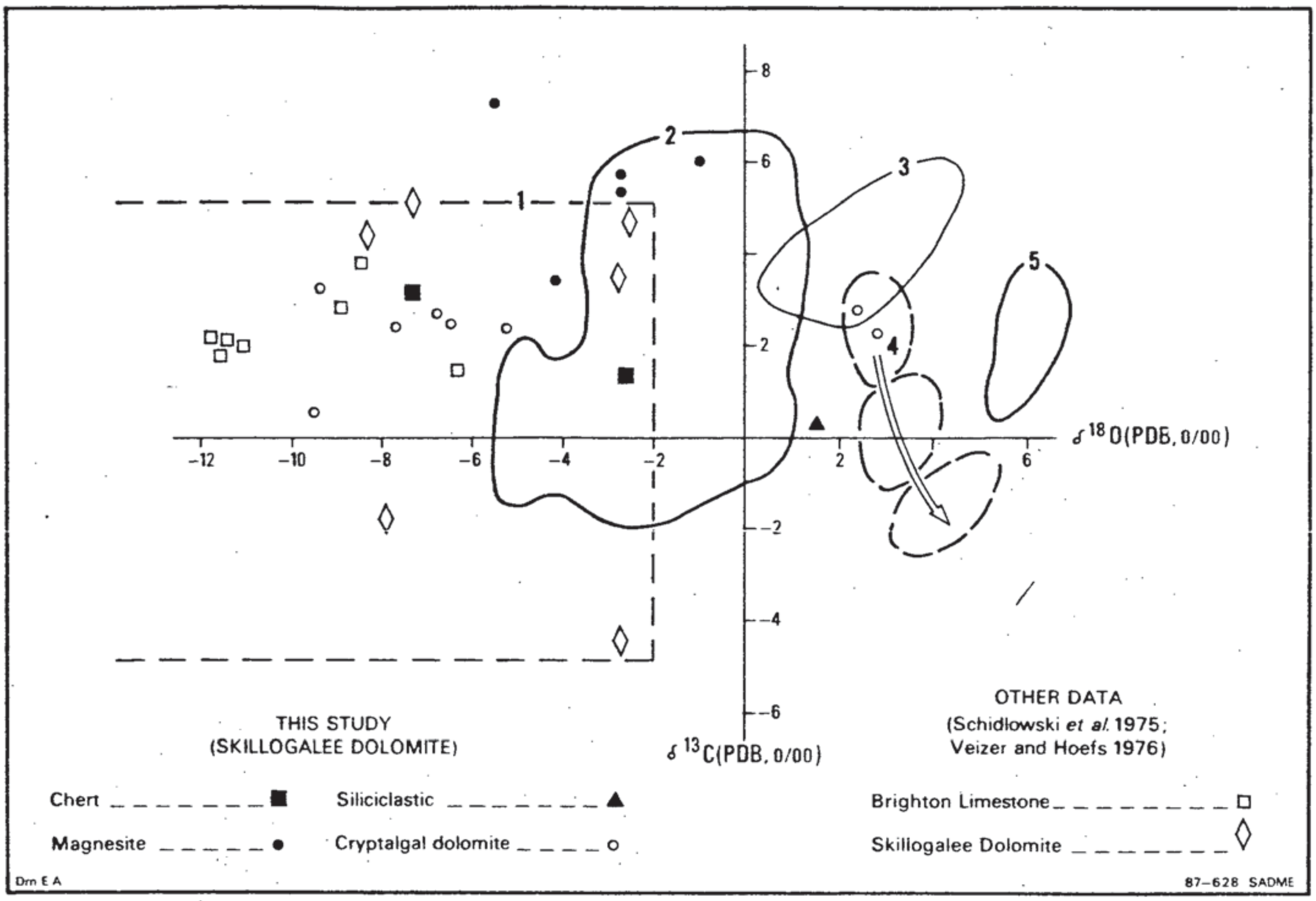


Fig. 12

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES

CARBON AND OXYGEN ISOTOPE VALUES FOR CARBONATE COMPONENT

COMPILED T. Belperio	C.D.O. DATE 29 · 1 · 88
DRAWN E.A.	SCALE
DATE Jan. 1988	PLAN NUMBER
CHECKED	S 19774

4457

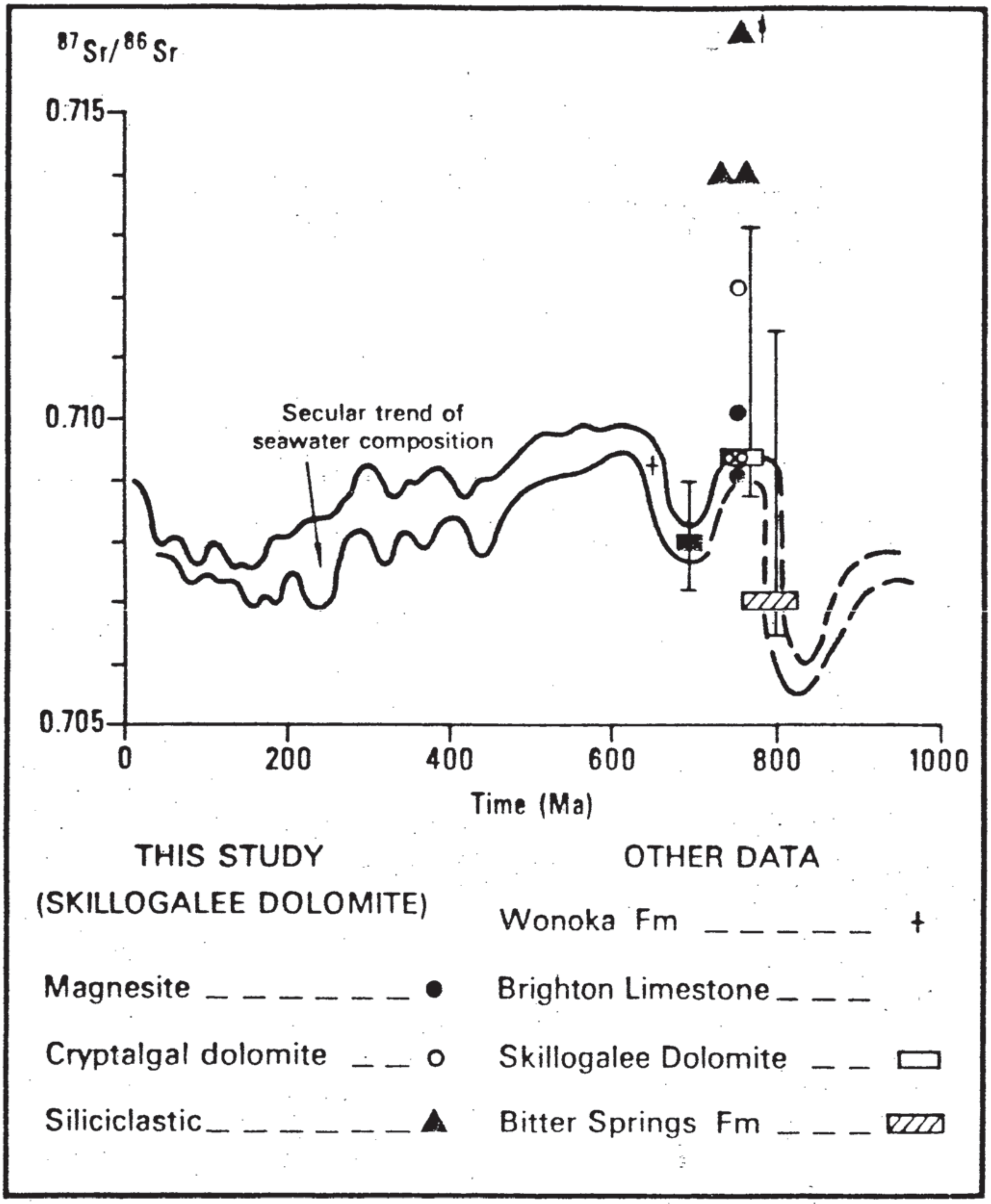


Fig. 13

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED T. Belperio	C.D.O. 29. 1. 88 DATE
SKILLOGALEE DOLOMITE IN THE WILLOURAN RANGES.	DRAWN E.A.	SCALE
STRONTIUM ISOTOPE DATA COMPARED WITH THE SECULAR TREND OF SEAWATER COMPOSITION	DATE Jan.'1988	PLAN NUMBER S 19775
	CHECKED	

4457