PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Observations of the Lineament--Ore Relation

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Observations of the lineament–ore relation

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Geological and geophysical features of the Australian continental crust follow systematic distribution patterns characterized by major linear discontinuities, or lineaments. These lineaments form the floor plan of the regional tectonic framework, and appear to represent fundamental crustal thresholds and corridors of disturbance along which maximum crustal energies have been channelled. The effects are variously expressed as lineament-associated intensifications of intrusion, deposition, dislocation, deformation, metamorphism and mineralization.

In Australia, over two decades of systematic study led to the recognition that major Australian ore deposits are related to major lineaments. This was a retrospective observation that established the relation for known deposits. The subsequent prospective use of the relation in mineral exploration is exemplified in the discovery of the giant lineament-related Olympic Dam Cu–U–Au deposit at Roxby Downs, South Australia.

Major Australian examples of the lineament–ore relation are described in comparison with apparently similar relations in North America, and these are briefly considered in regional and global contexts.

1. Introduction

As its title will indicate, this paper is not intended to be a general review of the relation between ore deposits and lineaments, nor of the extensive works of the many authors currently operating in that worldwide field of enquiry, as recorded, for instance, in the valuable volumes published by the Basement Tectonics Committee in the U.S.A. Instead it is restricted largely to the Australian scene with which I am more familiar, and is directed to particular characteristics of a selection of Australian lineament-related ore deposits considered at a variety of interdependent scales, and showing a common structural signature. In that sense it is a personal report, based on observations made and recorded during my active involvement in Australian mineral exploration over the last forty years. It includes only brief references to comparable lineament-related ore deposits in North America, and to the significance of their regional structural features in a global context.

Throughout the study of Australian crustal lineaments, I have been greatly indebted to the pioneering work of Sherbon Hills on Australian morphotectonics, beginning in the 1940s with his splendid three-dimensional topographic model of Australia and his recognition of the fundamental continental lineaments that it revealed. He demonstrated an overall Australian pattern of intersecting lineaments representing 'zones of yielding' in the basement, along which high-energy metallogenic processes took place. He referred to the occurrence of ore at intersections of linear structures with a favourable lithology, and concluded that the location of Australian mining districts on megalineaments indicated a tectonic basis for the formation of Australian ore deposits (Hills 1953; 1961). At about the same time, lineament–ore relations in South Australia were also observed and described by Dickenson & Sprigg (1953). In more recent years, especially since the availability of Landsat imagery, there has been a resurgence of interest in Australian lineaments, directed principally at aspects of general geology. Among those who carried Australian lineament tectonics into the field of metallogenesis, a representative coverage may be obtained from the more available literature in the works of Scheibner (1974), Heidecker (1974), Thomson (1965), Lacy (1974, 1980), O'Driscoll (1965, 1983 *a*, *b*), and from the collateral references which they provide.

It will be seen that the lineaments discussed here are recognized as pattern discontinuities that can be observed coursing through displays of geological, geophysical and topographic data of various kinds and at a variety of scales. In studying aeromagnetic contour maps, Tucker (1983) has referred to a magnetic pattern discontinuity as a 'pattern break', a simple, realistic and self-explanatory term that may be equally applied to any assembly or compilation of relevant information.

In attempting to develop a philosophy of the lineament–ore relation, I have tried, wherever practicable, to avoid presenting pictures of drafted lineament patterns without also presenting to the viewer a corresponding display of the basic data in which the lineaments are visible. This allows the viewer not only to see things for himself, but also to realize the subtleties and variations in the basic data that are glossed over by the artificial simplicity of the drafted interpretation. I recommend the wisdom of the adage 'one picture is worth a thousand words', and I am convinced that its message is never more true than in the treatment of lineaments.

This paper therefore carries a much higher than average ratio of illustrations to text. Most of the illustrations with their captions are largely self-explanatory, and I have kept the text to a minimum consistent with the requirements of clarity. The recognition of lineaments, especially of the significant ones, requires an informed training in awareness and perception. During uncounted discussions over the years, the exclamation that repeatedly echoes in my recollection is 'Yes, now that it is pointed out, I can see it quite easily!'. But that is only the beginning, and largely a matter of eyesight. Lineaments do not assume meaning until they are qualified by the observed responses of the rocks which they underlie or transect. To judge them effectively, the observer needs not only eyesight, but also insight, based on a considerable degree of field experience.

The accompanying illustrations show linear pattern breaks in a variety of guises, some as narrow linear traces through the overall pattern, others as corridors of measurable width. The megalineaments which extend through the Australian continent for hundreds of kilometres are expectedly wider than their shorter regional relatives. A discussion of the characteristics of lineaments and linear corridors is given in O'Driscoll (1981 *b*). Because lineaments appear in all sizes, it is necessary, for practical exploration purposes, to recognize the particular lineament–ore relation that is commensurate with the size of the ore-body being sought. To be effective, observations have to be made at the right scale.

Empirical studies over many years led to the conclusion that most major Australian ore deposits hosted by a particular lithology occur at or within 4 km (2.5 miles) of the position where their host lithology is crossed and disturbed by a conspicuous, relatively narrow, regional lineament exceeding 80 km (50 miles) in length. A further auspicious characteristic is the presence of a second, approximately orthogonal, lineament sharing the intersection. The ingredients of this structural signature, together with fine-tuning techniques not available for publication, were formally listed in writing (O'Driscoll 1972) and established as the paradigm for the future selection of exploration targets for gold, nickel and other base metals. The selection in 1974 of the Olympic Dam tectonic target in South Australia was a direct and unmodified application of the established structural criteria listed in the 1972 paradigm. As with most scientific studies of associative occurrences, the study of the lineament–ore relation was first a study of coincidences. In this vein it is appropriate to view some of the evidence as it has appeared on the Australian scene.

2. Australian continental gravity lineaments

Large-scale crustal lineaments traversing the Australian continent were early recognized in geomorphic data by Hills (1956, 1961) and are clearly evident in the Bouguer gravity contour map as shown by the paired indicator arrows in figure 1 (after O'Driscoll 1981 *a*). They are conspicuous and singular pattern discontinuities, or pattern breaks, and are evidently related to the major Australian ore deposits of Archaean age in Western Australia, and of Proterozoic–Palaeozoic age to the east. These are truly megalineaments of the kind recognized by Hills, and pass through or under, strata of all ages. Figure 2 shows the same data, as a tonal density slice produced by a technique of image diffusion which accentuates elements in the pattern. The presence of these major lineaments is reflected in the patterns of field geology as will be seen.

3. Western Australian geological ingredient patterns

Geological ingredient maps are particularly effective in revealing major regional lineaments. As shown in figure 3, the Western Australian granitic shield is evidently crossed by a network of intersecting lineaments which lead into it from surrounding areas. In this and other figures, geological ingredient trends are symbolized by R (rock), while gravity trends are symbolized by G, magnetic trends by M and photolineament trends by P. Where no confusion is likely, as in figure 1 and 2, the symbol has been omitted and only the numbers used. The shape of the granite shield in figure 3 is clearly influenced by NS lineaments R8 and R9, by WNW trends R1 and R3, and by NNE trends R6 and R7, apart from the Fraser Range trend that truncates its southeast corner. Lineaments R4 and R10A coincide respectively with the corresponding gravity lineaments 4 and 10A in figure 2, and their intersection is straddled by the giant Kalgoorlie–Kambalda ore fields.

In the same area the response of particular geological ingredients to particular lineament sets is demonstrated in figure 4, where the double ingredient of Archaean felsic volcanics and sediments emerges as an angular trapezoid panel, bounded on its northern and southern edges respectively by parallel WNW lineaments R1 (from figure 3) and 4 (from figure 2). Thus the Kambalda nickel field is seen to be located on a major WNW lineament that not only forms the linear southern margin of the main distribution area of Archaean felsic volcanics and sediments to the north of it, but also extends out across the continental shelf into the floor of the Indian Ocean, where it forms the linear southern margins of the Zenith Shelf (ZS) and Wallaby Platform (WP).

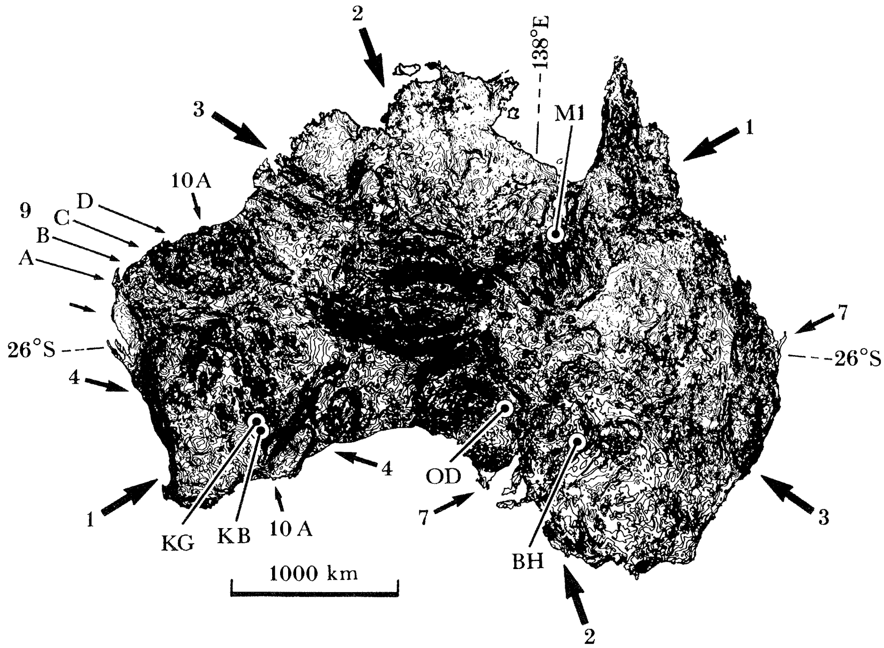

Figure 1. Bouguer gravity contours of Australia (Bureau of Mineral Resources 1971, 1975) showing numbered continental gravity lineaments related to major ore deposits at Kalgoorlie gold (KG); Kambalda nickel (KB); Mount Isa Pb–Zn–Cu (MI); Olympic Dam Cu–Au–U (OD); Broken Hill Pb–Ag–Zn (BH). Kalgoorlie and Kambalda appear to be located at a triple intersection. The lineaments are best seen by looking at a low angle along their tracks (after O'Driscoll 1981 *a*).

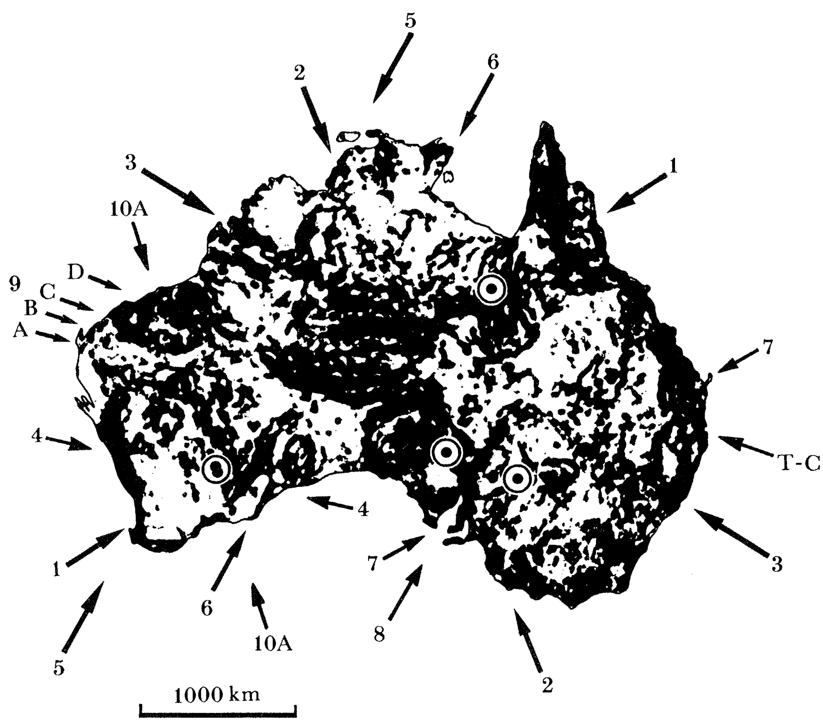

Figure 2. Image diffusion of gravity contours in figure 1 reproduced in high contrast to create a tonal density slice. This accentuates some of the linear features. Spot markers are major deposits from figure 1 (after O'Driscoll & Keenihan 1980).

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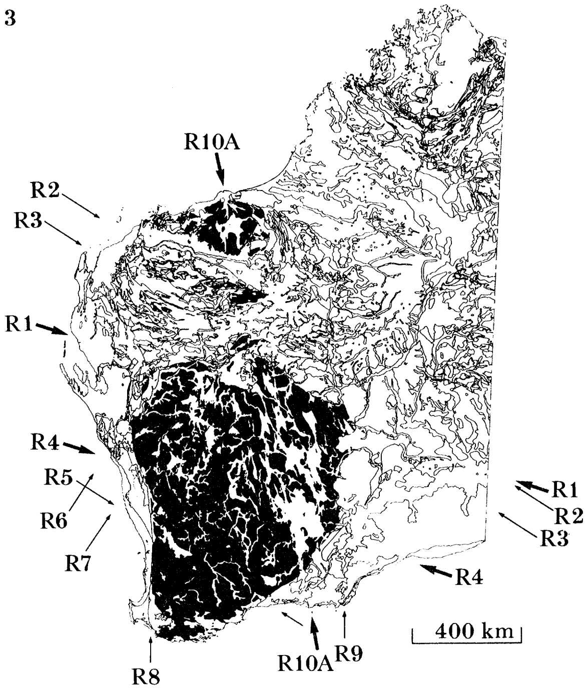

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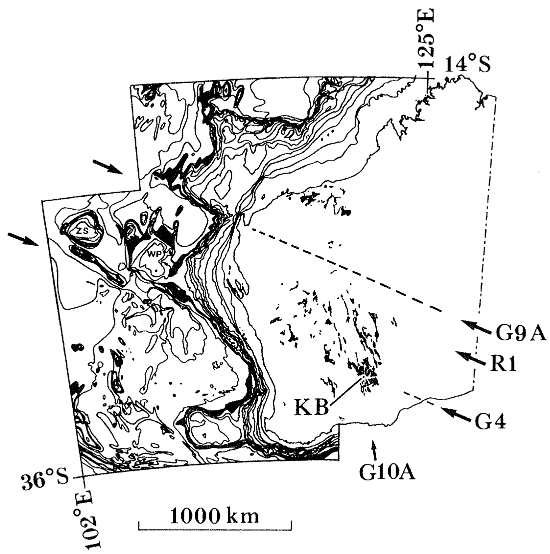

FIGURE 3. Geological ingredient map of Western Australia (Geological Survey of Western Australia 1979). Black areas are geological ingredients representing Archaean granite and granite gneiss. Boundaries of all other geological ingredients are shown as filigree linework. Regional lineaments (pattern breaks R1, R2...etc) exercise a structural control both at the margins and interior of major granite shield.

FIGURE 4. Geological ingredient map of Western Australia (cf. figure 3) with Archaean ingredients representing felsic volcanics and sediments, shown in black. The ingredient pattern reflects the major gravity lineaments seen in figure 1 which, in turn, are reflected in sea-floor contours of the adjacent Indian Ocean (from Veevers & Cotterill 1978). Kambalda nickel deposit located at KB (after O'Driscoll 1982).

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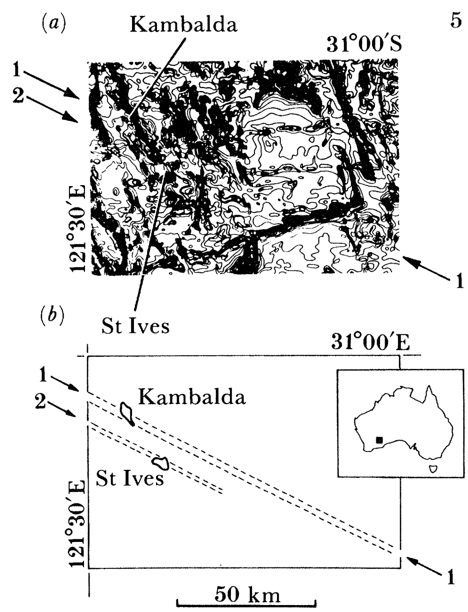

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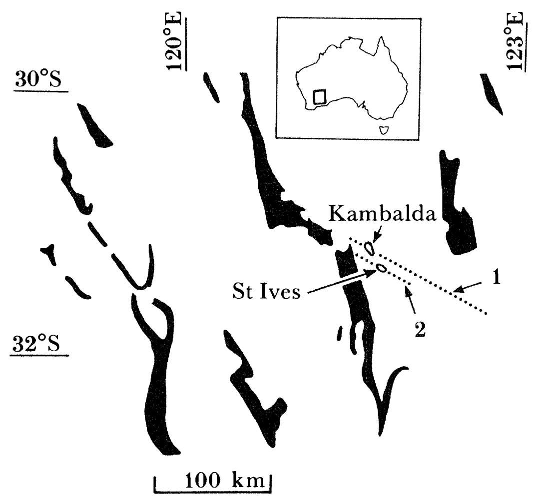

FIGURE 5. (*a*) Aeromagnetic contours of area containing major nickel deposits at Kambalda and St Ives, Western Australia, showing that the deposits are positioned on WNW aeromagnetic pattern breaks (1) and (2) respectively. (*b*) Overlay tracing of (*a*) showing tracks of WNW linear pattern breaks (corridors) in relation to the two clusters of deposits (after O'Driscoll 1981*c*).

FIGURE 6. High-grade metamorphic zones (black) in southern part of West Australian nickel belt (from Barrett *et al.* 1977). The central zone shows a classical sinistral flexure ('Tethyan twist') where it is intersected by the WNW magnetic lineaments, (1) and (2), transferred from figure 5 (after O'Driscoll 1981*c*).

Lineament-related nickel deposits in Western Australia

Major nickel sulphide deposits in the nickel belt of Western Australia are located on WNW aeromagnetic lineaments or corridors as described by O'Driscoll (1981*c*). The most important of these deposits are at Kambalda and St Ives, and the WNW lineaments related to them, numbered (1) and (2) respectively, are shown in figures 5*a*, *b*. They are excellent examples of magnetic lineaments appearing as pattern breaks crossing through the NNW stratigraphy.

Where a WNW lineament intersects a north-striking lithology, the intersection characteristically coincides with a sinistral flexure in the lithology, colloquially known as a 'Tethyan twist' (O'Driscoll 1984). The two lineaments in figures 5*a*, *b* are associated with local effects of this kind in the Kambalda–St. Ives field. Where these lineaments extend to intersect a high-grade metamorphic zone (figure 6), they display a classical sinistral flexure (O'Driscoll 1981*c*).

Figures 7*a*, *b* show how the major NNW lineament (10A) – the 'gold line' – is also a locus of major nickel deposits occurring where the line is crossed by WNW regional lineaments. These are directed to about 300°; about 10° clockwise from the major WNW gravity lineaments. This relation is the same as that between R1 and R2 in figure 3.

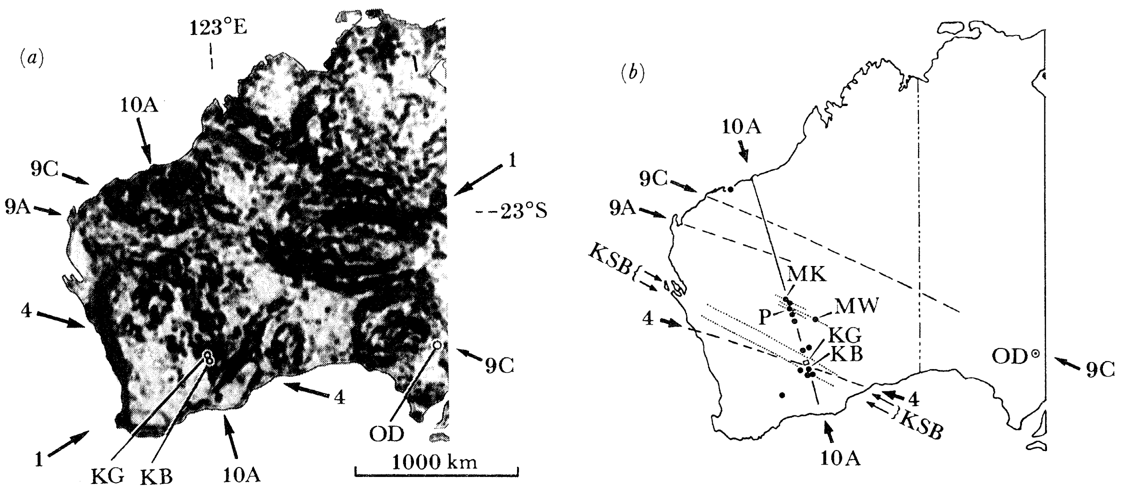

Figure 7. (*a*) Diffused image of Bouguer gravity contour pattern of western and central Australia. Lineament 10A (the 'gold line') is known to be the locus of major gold deposits including Kalgoorlie (KG). (*b*) Overlay tracing of (*a*) showing principal nickel deposits (black dots). The first four ranking deposits have preferred positions along lineament 10A where it is crossed by WNW lineaments. They are Kambalda and St Ives (KB), Perseverance (P), and Mount Keith (MK). The Kalgoorlie–Shark Bay magnetic corridor, KSB (O'Driscoll 1981*c*) coincides with the Kalgoorlie–Kambalda position, forming a multiple intersection with lineaments 1, 4 and 10A, indicating a special tectonic status for that position. Other deposits shown at Mt Windarra nickel (MW) and Olympic Dam Cu–Au–U (OD). (After O'Driscoll 1982*c*).

4. Australian gravity lineaments related to Pacific Ocean bathymetry

Pattern breaks in the sea-floor contour plan of the southwest Pacific Ocean appear as immense megalineaments. When these are related to the Australian continental gravity lineaments, shown in figure 8, the two appear to be part of the one immense systematic pattern of megalineaments extending without demur from continent to ocean over an expanse of more than 7000 km. Thus, the NNW gravity lineament 10A, which hosts Kalgoorlie and Kambalda, and its systematic partner, lineament 2, hosting Olympic Dam, are seen to be part of a family of NNW trends, with gigantic similarly spaced parallel relatives far out in the Pacific Ocean. So too, for the NNE continental lineaments 5, 6 and 8. In addition, the WNW Tethyan trend T-1 (O'Driscoll 1980) appears to set the keynote for the same system of WNW lineaments in the Australian continent.

The association of major ore deposits with major continental lineaments may be compared with a 'metallogenic road map' as described in figure 9. The major deposits shown cover the spectrum of ore types ranging through gold (Kalgoorlie; Telfer; Bendigo; Cobar; Olympic Dam), copper (Mount Isa; Wallaroo-Moonta; Olympic Dam; Kanmantoo; Cobar), lead–zinc (Broken Hill; Mount Isa), uranium (East Alligator River; Olympic Dam), manganese (Groote Eylandt) and diamonds (Argyle); all with a common heritage of a lineament association which overrides the exclusive contrasts of classifications that otherwise separate them.

The lineament association at this scale is informative in establishing the principle, but not sufficiently defined to lead straight to an ore body. The fine tuning must be done in greater detail at ore-deposit scale especially through the use of aeromagnetic and high-frequency photolineament surveys (O'Driscoll 1981 *b*).

5. Australian geological ingredient lineaments

Australian geology expressed entirely as ingredient outlines, drawn from published maps, is shown and described in figure 10. The process is equivalent to subtracting all colours from the map, allowing only the boundaries between them to remain. The effect is to reveal a variety of conspicuous pattern breaks that will otherwise lie undetected in the coloured medium. In figure 10, only a few conspicuous lineaments have been marked, but the viewer will be able to identify others by inspection. The conspicuous lineament R12, identified by Hills (1956), appears to be part of the sea-floor lineament A in figure 8, and a member of the extensive NNE system including R7A and R14. R12 is also notable for hosting, at its junction with R16, the new porphyry–copper field at Goonumbla, near Parkes, New South Wales. Lineament R2, partly visible in figure 3, is seen to be much longer than its companions, and to extend east into South Australia.

A closer view of the western part of figure 10 is given in figure 11, where the conspicuous NNE system is shown in equal relation to the widely differing ore environments of nickel, gold and tin-tantalum. The Kambalda–St Ives nickel centre, already singularly positioned at a multilineament intersection (figures 5, 7) is found to have yet another major structural contributor (R20) to its favoured position.

The systems of regional lineaments in eastern Australia are shown in greater detail in figure 12. Here the southern part of the lineament R12 is seen to be a corridor, and is posted with twin arrows. As the name implies, the NNW Bendigo–Broken Hill corridor (BN–BH) is the host corridor to major ore deposits at Bendigo (gold) and Broken Hill (Pb–Zn) (O'Driscoll 1983 *a*). Two dominant trends in this eastern area are the WNW Toowoomba–Charleville and Nelson Bay–Cobar lineaments, T–C and NB–CR (see figure 10), with numerous parallel relatives transecting the east coastline. The southern part of this area is described in figure 13. One particular message conveyed by this figure is that WNW regional lineaments already seen to be related to Precambrian ore deposits, maintain their identity as active contributors to the structural control of Palaeozoic ore deposits, and of Palaeozoic–Mesozoic hydrocarbons in Australia's greatest on-shore petroleum field, the Cooper Basin. This basin is already known

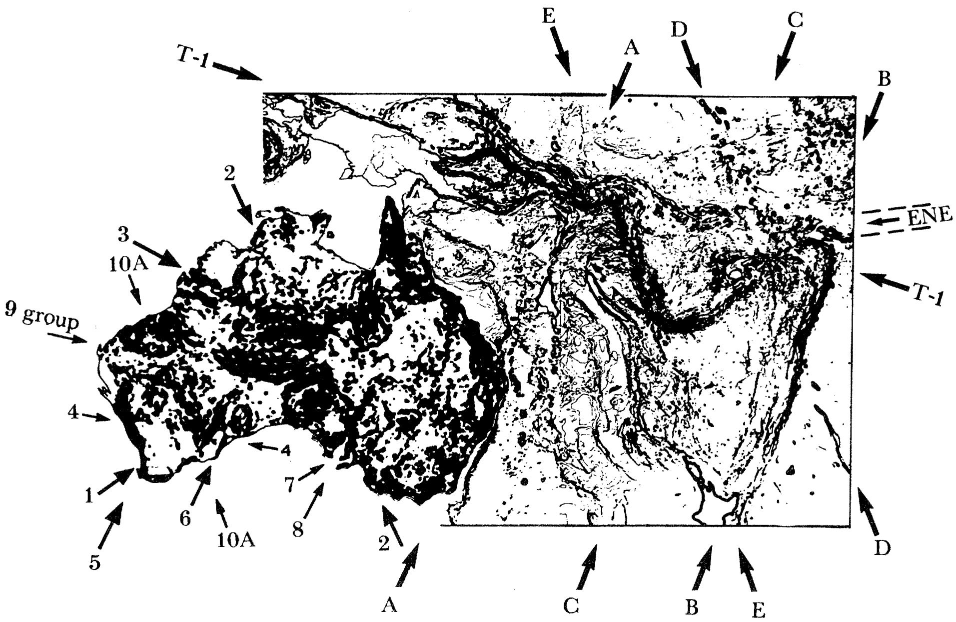

FIGURE 8. Diffused image of Australian Bouguer contour map (from figure 2) set in relation to a bathymetric contour map of the southwest Pacific area (data from Scripps Institute). Continental gravity lineaments appear to be repeated in the Pacific bathymetric pattern, particularly NNE and NNW trends, with a high degree of regularity in spacing (from O'Driscoll 1980, 1982). The giant corridor marked 'ENE' is an enigmatic feature corresponding in direction and position to a westerly extension of the Galapagos fracture zone in the eastern Pacific. It also corresponds, in direction, to the Proterozoic dyke suite in southwestern Australia, and to Tertiary basalt ingredient trends in southeastern Australia. For Lineament T-1, see figure 26.

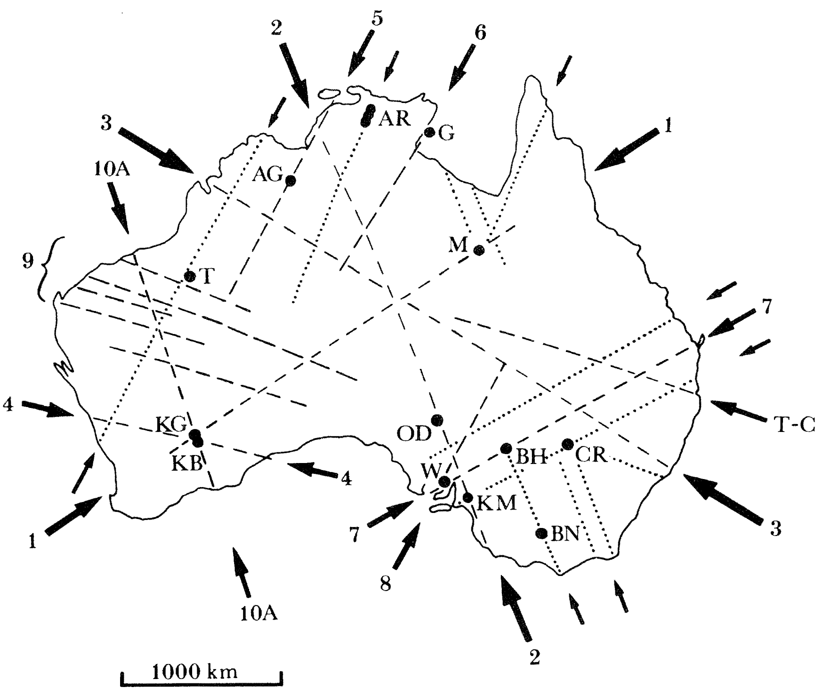

FIGURE 9. A metallogenic 'road map' of Australia showing the main structural 'highways' and the principal 'cities' of ore deposits. The numbered gravity lineaments are from figure 2. Other trends are from geological ingredient patterns (O'Driscoll 1982, 1983*b*). Ore centres are Cobar (CR), Bendigo (BN), Broken Hill (BH), Kanmantoo (KM), Wallaroo-Moonta (W), Olympic Dam (OD), Mount Isa (M), Kalgoorlie (KG), Kambalda (KB), Telfer (T), Argyle (AG), East Alligator River (AR) and Groote Eylandt (G).

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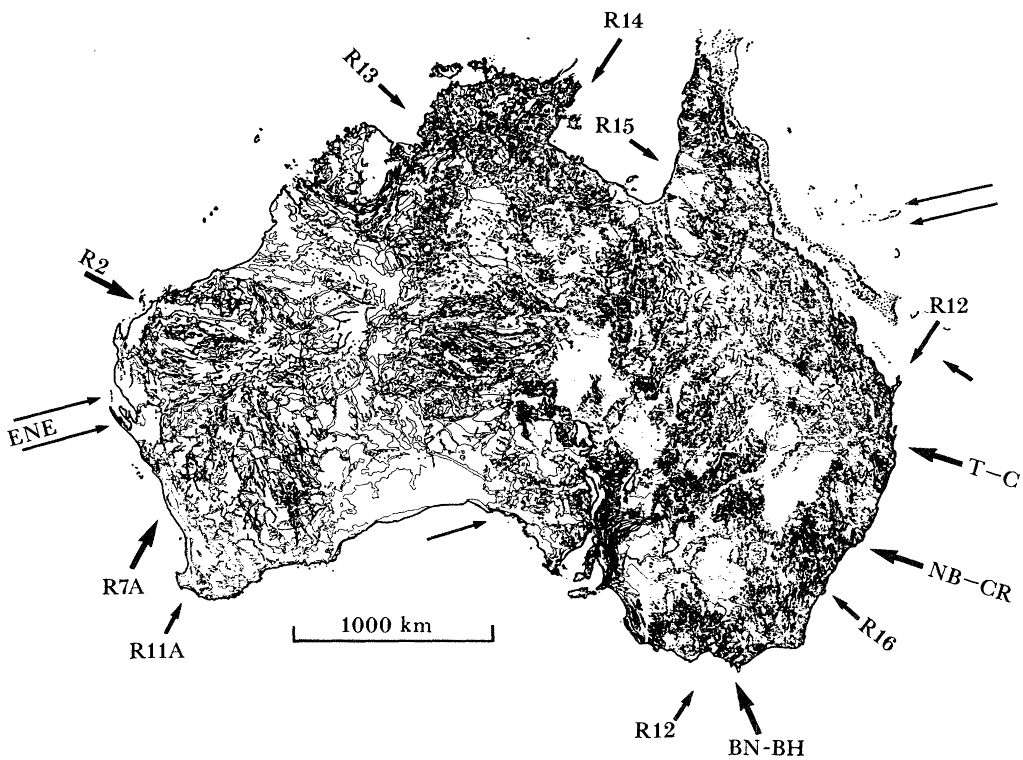

FIGURE 10. Geology of Australia represented by geological ingredient outlines traced from Government maps at scales ranging from 1:1000000 to 1:2500000.The Toowoomba–Charleville Lineament (T–C) is clearly seen (O'Driscoll & Kennihan 1980). South of it is a parallel relative, the Nelson Bay–Cobar Corridor (NB–CR), which extends to South Australia. The Bendigo–Broken Hill Corrider (BN–BH) is also visible (O'Driscoll 1983*a*, *b*).

FIGURE 11. Geological ingredient outlines of Western Australia (from figure 2) show a pervasive set of NNE lineaments that are part of the system established by gravity lineaments 5 and 6 in figure 2. Four major deposits related to them are Kambalda nickel (1), Perseverance nickel (2), Telfer gold (3) and Greenbushes Sn–Ta (4).

FIGURE 12. Geological ingredient outlines of southeastern Australia show that the T–C and NB–CR Lineaments (figure 10) have a number of parallel WNW relatives cutting across the coast and extending some hundreds of kilometres inland.

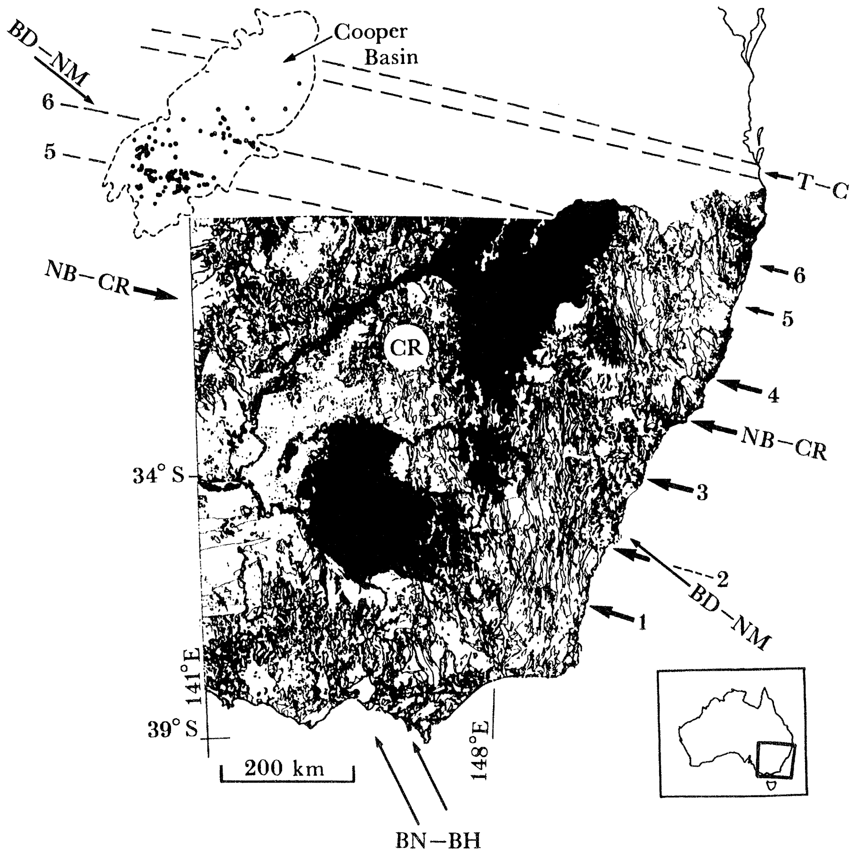

FIGURE 13. A closer view of part of figure 12, showing geological ingredient outlines of New South Wales and Victoria, with the quaternary ingredient shown in black wash. Petroleum discoveries in the Cooper Basin to the northwest are shown as black dots. The linear relatives of T–C and NB–CR lineaments are serially numbered, independently of other figures. Lineament 3 corresponds to Scheibner's Lachlan Lineament (Scheibner 1974). The Bomaderry–Nymagee Lineament (BD–NM) is a remarkably straight pattern break (R16 in figure 10) apparently the sharp northerly edge of a 30 km wide 'tram track' corridor extending through the centre of the major Cooper Basin petroleum occurrences. *En route* it contributes a 'Tethyan twist' to the Cobar (CR) host rocks, which are also located on the NB–CR Lineament. The Woodlawn Cu–Pb–Zn deposit is located on Lineament 2 (O'Driscoll 1982). Lineaments 5 and 6 can be traced through to the Cooper Basin where they exercise an obvious control over the WNW alignments of the Permian–Jurassic oil and gas deposits.

to be centred on continental gravity lineament 8 at its junction with gravity lineament 3 in figure 2 (O'Driscoll 1982).

In studying Australian patterns we see the oldest part of the continent, the Archaean shield in Western Australia, to be crossed through by linear belts and corridors of disturbance which are hosts to ore bodies of Precambrian age. These particular structural belts appear to continue westerly out of the continent into and through the younger Indian Ocean floor (figure 4). Travelling east, we find these same features to extend across the continent, maintaining their continuity, without tangible interruption, through a succession of younger rocks, and continuing to play host to younger ore bodies.

Farther still to the east, as seen in figure 8, major components of the continental pattern, already found to be on-shore hosts to ore deposits and intrusives ranging from Precambrian to Tertiary in age, continue to be repeated in megalinear splendour for several thousand kilometres across the floor of the Pacific Ocean. The 'problem' of their straightness is an imaginary problem, because this very quality, manifest on a Mercator projection, identifies them as spirals on the globe, thus sharing one of nature's most common forms of distribution observed in matter ranging from galactic to atmospheric (O'Driscoll 1980).

6. A repeated structural signature for ore occurrence

Major nickel deposits in Western Australia are located where their north-northwesterly host lithologies are crossed by a WNW regional lineament (O'Driscoll 1981*c*), often with a sinistral flexure ('Tethyan twist') visible in the host rocks at the point of intersection. This characteristic relation is repeated on broader scales as well. In the instance of the first-ranking deposits of Western Australia, at Kambalda–St Ives, the local lineament–ore signature, as shown in figure 5, is a diminutive replica of the lineament intersection seen on a broad scale in the Bouguer gravity pattern in figures 1 and 2, where the key components of the signature are the megalineaments 10A and 4. This is seen in greater detail in figures 14*a*, *b*, which show that this broadscale signature is not peculiar to Kambalda, but is found also at the Olympic Dam deposit 1400 km to the east. This type of repetition of the same structural signature at different scales suggests that it is a feature of general principle rather than a topical peculiarity.

7. The Adelaide Geosyncline

The Adelaide Geosyncline, a Proterozoic meridional trough or depression in South Australia, has been the workshop of a multitude of investigators and the subject of many descriptions. A comprehensive review of both literature and concepts may be seen in Rutland *et al.* (1981). As a field for studying lineament–ore relations, it provides good material and impressive examples. The accompanying figures with their captions are largely self-explanatory. Figure 15 illustrates the effectiveness of geological ingredient outlines for revealing geological pattern breaks, especially of the WNW system, rendered visible as linear tracks of disturbance hundreds of kilometres in length, crossing through the geologic pattern of the geosyncline, and coinciding with significant discontinuities in rock types and distribution, and, more importantly, with significant ore deposits.

The Kapunda and Burra copper deposits, now exhausted, are important historically. Kapunda was Australia's first major copper mine, beginning production in 1844. Burra followed suit a year later and for the next 30 years, the two were major supporters of the struggling economy of South Australia. It is fitting that their historical significance is matched by the fidelity of their contributions to the recognition of the lineament–ore relation.

As illustrated on a sub-continental scale in figure 15, the Kapunda and Burra deposits are both seen to be related to WNW lineaments crossing the Adelaide Geosyncline and extending for some hundreds of kilometres through the geological ingredient data in surrounding areas. For both deposits this lineament relation, together with its accompanying 'Tethyan twist' signature, can be followed from regional scale, through ore-field scale, down to deposit scale (figures 16–21), and the relation expressed at successive steps by the geological ingredients is clearly demonstrable.

The copper deposits at Mount Gunson and Olympic Dam belong to the Stuart Shelf on the western flank of the geosyncline, and are considered separately but in a similar manner. All four deposits in figure 15 also share the additional common feature of being related to the giant NNW gravity corridor, G2, shown in figures 1 and 16.

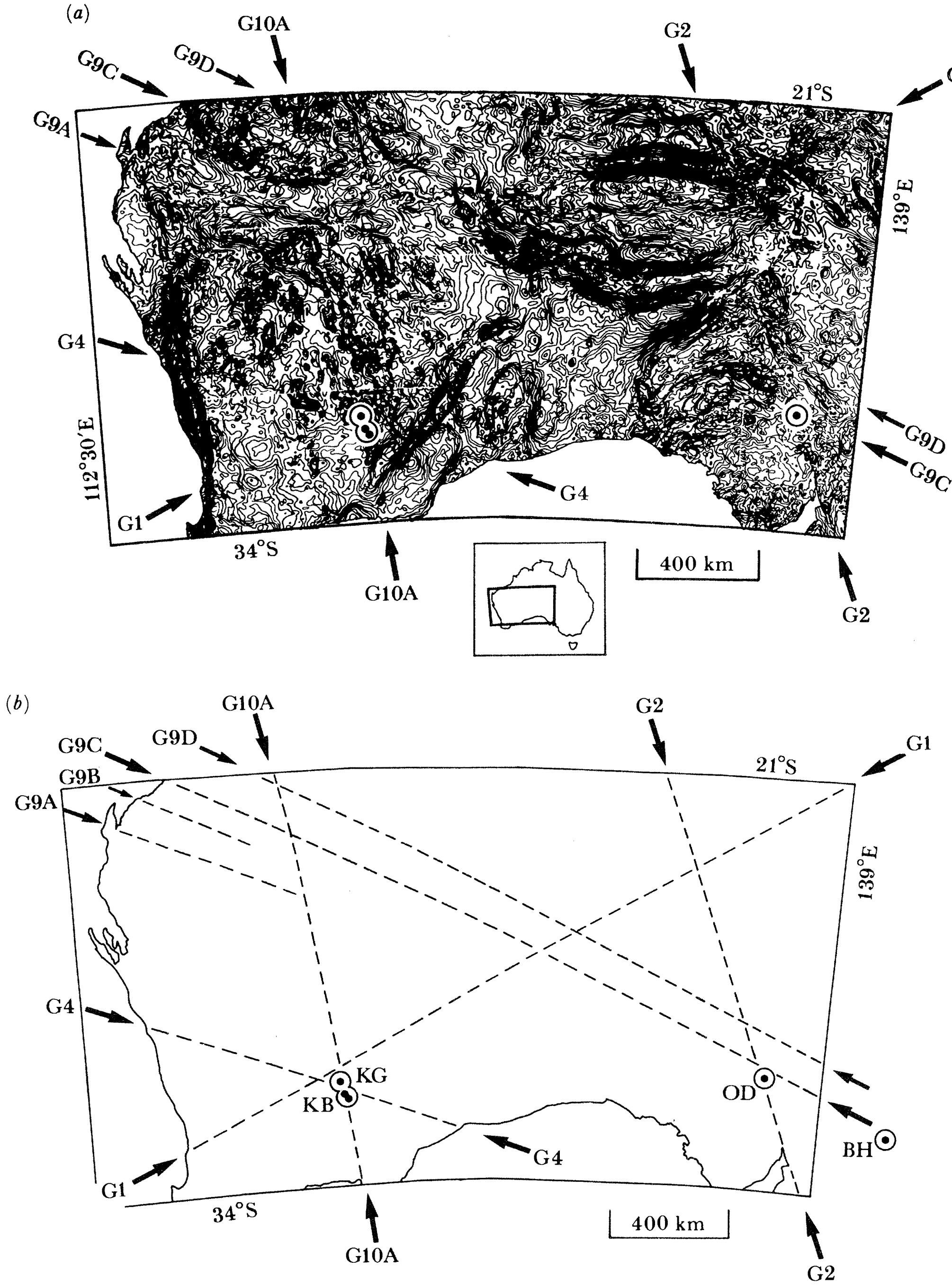

FIGURE 14. (*a*) A closer view of portion of figure 1 showing Bouguer gravity contours over southwestern and south-central Australia. The Kambalda–St Ives nickel deposits (KB in figure 14*b*) are related to a classical regional structural setting, where a NNW gravity lineament (G10A), here representing stratigraphy, is crossed by a WNW gravity lineament (G4), representing a gravity pattern break, probably reflecting a deep crustal discontinuity (cf. figure 4). At 1400 km to the east of Kambalda, the Olympic Dam Cu–Au–U deposit (OD in figure 14*b*) occupies a similar structural setting where the NNW gravity lineament, G2, is intersected by the WNW gravity lineament G9C, itself a major trend in its system. (*b*) Overlay tracing of figure 14*a*, showing the tracks of major gravity lineaments. It is probably significant that with respect to the WNW gravity lineament G9C, the Broken Hill Pb–Ag–Zn deposit (BH) occupies a structural position similar to that of Olympic Dam. For Broken Hill, the corresponding NNW component of the structural signature is clearly seen in the Bendigo–Broken Hill Corridor (BN–BH in figures 10, 12 and 13), which is an ingredient corridor more than 1000 km in length, and a host corridor to major deposits of gold, lead, silver, zinc and uranium (O'Driscoll 1983*b*). The gravity lineament G1, which extends to Mount Isa, may be seen in its entirety in figure 1.

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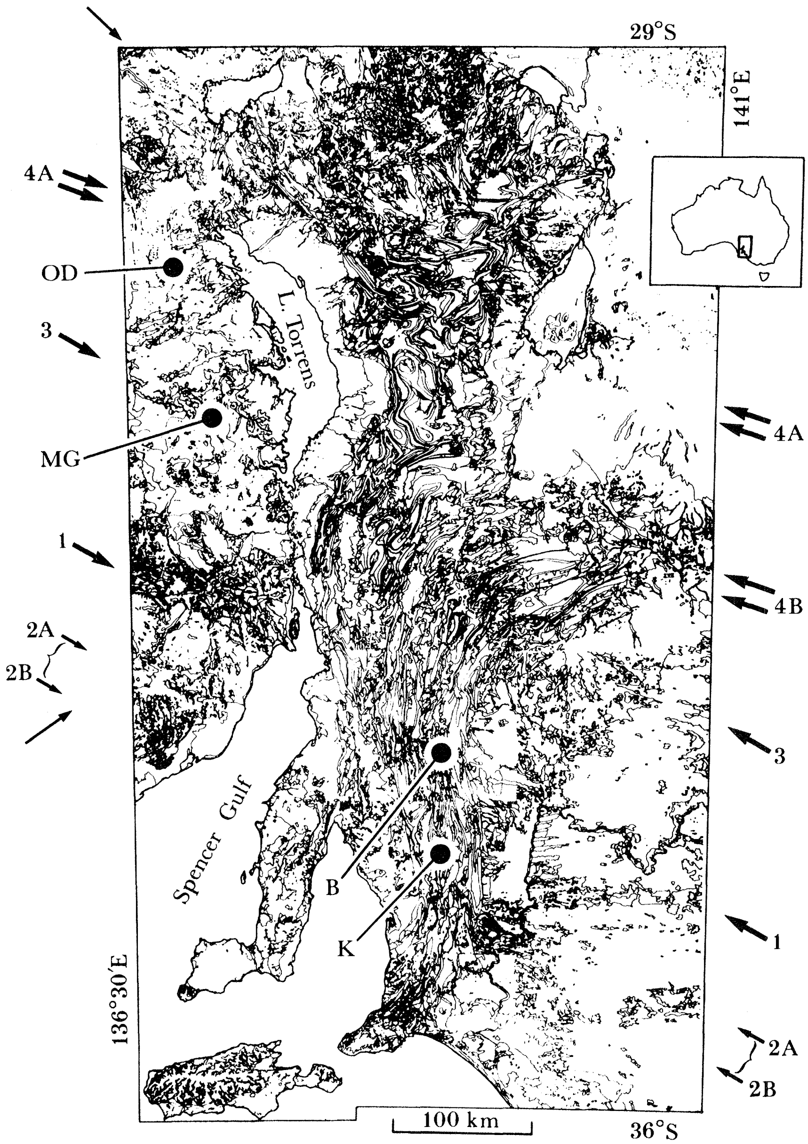

Figure 15. The geology of the Adelaide Geosyncline and surroundings, represented by geological ingredient outlines from published maps of 1:250000 scale (S Australian Department of Mines and Energy). The Geosyncline is a meridional Proterozoic trough corresponding in this figure to the central core of denser linework. Among other things, the overall pattern shows conspicuous WNW pattern breaks which cross through the Geosyncline from surrounding areas. These WNW lineaments are also found to coincide with marked changes in the distribution of minor intrusives, and of particular sedimentary facies, and with local deflections of strike ('Tethyan twists') They also coincide with significant relatively shallow ore deposits at Burra, (B) on lineament 1; at Kapunda, (K), on lineament 2A; and at Mount Gunson, (MG), on lineament 3. For the Olympic Dam deposit, (OD), buried at a thousand feet, it remained for photolineament work to reveal the definitive regional lineament (Woodall 1984, fig. 4), which proved to be parallel to, and immediately south of lineament 4A, a major continental lineament corresponding to gravity lineament G9C (figures 14*a*, *b*) and representing an immense WNW system to be related to a proposed global Tethyan system (O'Driscoll 1982, 1983*b*).

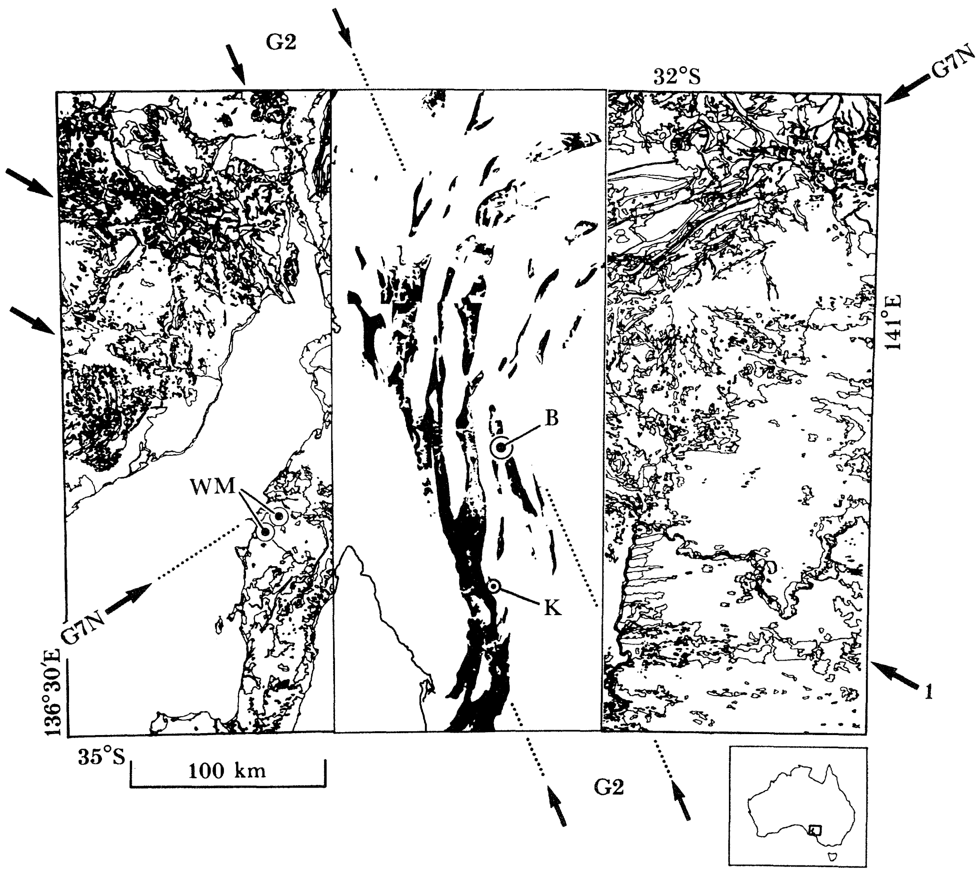

FIGURE 16. Southern part of Adelaide Geosyncline (figure 15) with central panel replaced by geological ingredient plan of Proterozoic Burra Group sediments. The Burra ore deposit (B) is located on WNW lineament 1 (cf. figure 15), the passage of which corresponds to a sinistral disjunction ('Tethyan twist') of the surface distribution of Burra Group rocks. G2 is NNW gravity corridor (see figure 1), and G7N is northern edge of ENE gravity corridor G7. These two continental lineaments exercise an obvious structural control over the Burra Group rocks. The Wallaroo–Moonta (WM) copper deposits are related to G7N in the same relative position as the Broken Hill Pb–Ag–Zn deposit (O'Driscoll 1983*b*).

8. OLYMPIC DAM DEPOSIT, SOUTH AUSTRALIA

The Olympic Dam deposit in South Australia is one of the world's largest deposits of Cu–Au–U, the discovery hole for which was drilled in June–July 1975. The geology of the deposit has since been described by Roberts & Hudson (1983). The deposit is considered here only in terms of its signal contribution to the philosophy of the lineament–ore relation, and some brief historical comment is appropriate.

As mentioned earlier, field studies in the 1960s led to the recognition of a particular lineament–ore relation initially referable to the Broken Hill deposit (O'Driscoll 1983*b*), but recognized a decade later in the nickel and gold deposits of Western Australia. In that context, in October 1972, the lineament–ore relation was formally set down as an illustrated written list of criteria, or paradigm, for the future selection of targets for nickel and other base metals (O'Driscoll 1972). Its essential basis was that the preferred location of ore deposits was where a WNW regional lineament of specified dimensions crossed through a north-trending favourable lithology, especially where it coincided with a sinistral lithologic flexure or disjunction

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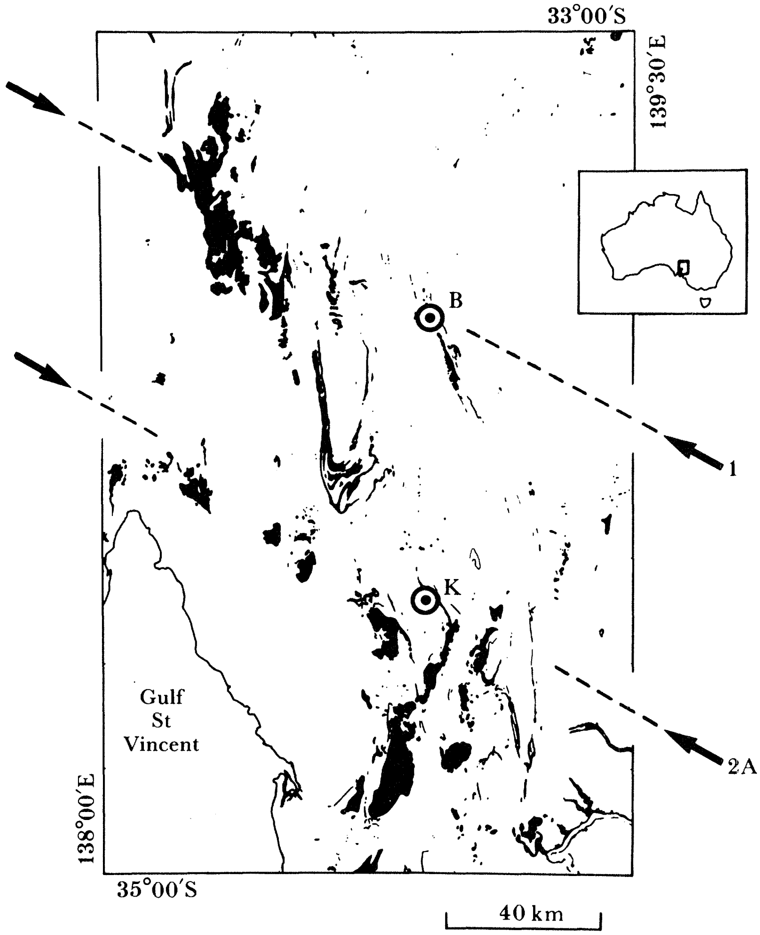

FIGURE 17. Plan of Burra region of Adelaide Geosyncline (cf. figure 15) showing, in black, the combined geological ingredients of Tertiary and Archaean rocks set in a matrix of limestones and dolomites of all ages. The combination clearly shows the essence of a left-hand 'Tethyan twist' in the WNW ingredient distribution along lineaments 1 and 2A. Burra and Kapunda copper deposits are 'B' and 'K' respectively. (Data from South Australian Department of Mines and Energy).

('Tethyan twist'), and especially if accompanied by NNE and ENE cross trends. The 'strength' of each component, in relation to adjacent patterns, was also a measure of the potential.

When in the same year (1972) a (then) major copper discovery was made at Mount Gunson, South Australia, it sounded an alert for the lineament–ore relation, because the new discovery was in a major NNW corridor (G2 in figure 1) earlier defined by O'Driscoll (1968, fig. 32). When Western Mining Corporation established its exploration base in Adelaide in February 1974, to consider a number of South Australian areas for Proterozoic sedimentary copper exploration, its Tectonic Studies Group immediately directed its South Australian photolineament work exclusively to the Torrens Sheet (Mt Gunson, figure 22) and the adjoining Andamooka Sheet (figure 23), and to no other South Australian area.

This priority was maintained because the classical lineament signature, already set down in the 1972 paradigm, was found to be repeated in the newly discovered Mount Gunson deposit, located on a singular regional WNW corridor; and the same corridor-related signature became visible in the photolineament work on the Andamooka Sheet to the north, in untested ground

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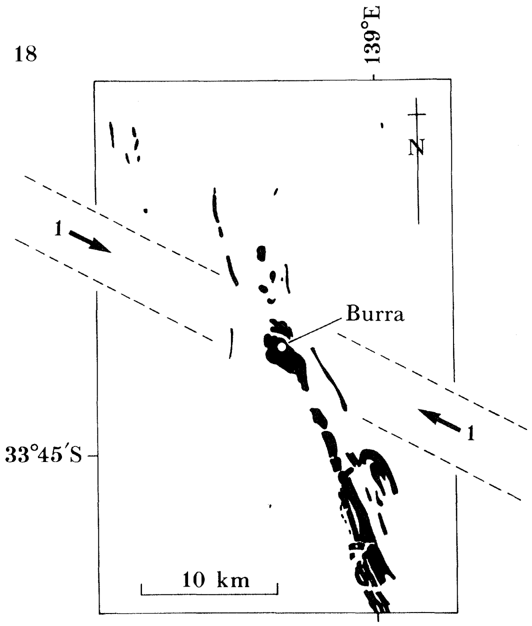

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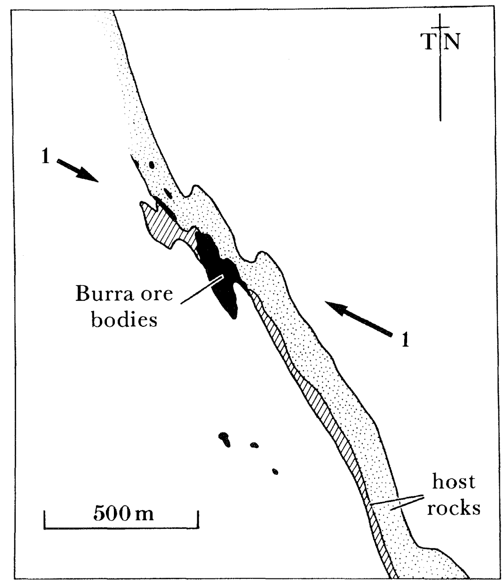

Figure 18. Enlargement of the Burra portion of figure 17, showing, in black, the details of the limestone–dolomite ingredients of the Proterozoic Burra Group rocks that host the Burra deposit. At this scale the WNW lineament 1 (transferred from figure 15) is seen to be a corridor *ca.* 5 km wide, containing the Burra deposit, and coinciding with a sinistral disjunction of the host rocks, especially along its southern edge.

Figure 19. Close-up view (from Dickinson 1942) of the Burra ore deposit (black) in host rocks of banded dolomite (dotted) and calcareous shale (striped). At this scale, the edges of the regional WNW corridor (figure 18) are outside the boundaries of the illustration. Nevertheless, the ore deposit is still positioned on a local WNW linear break, 1, which coincides with a sinistral flexure ('Tethyan twist') of the host rocks at the mine site. The axis of the ore body remains in the NNW direction of stratigraphy (figure 18), and of the giant G2 gravity corridor (figure 16).

near a locality known as Olympic Dam. Here the predictive capacity of the lineament–ore relation was to be crucially tested, and photo-lineament work on any other South Australian areas continued to be held in abeyance until an application had been lodged for an appropriate exploration licence over the Andamooka area (December 1974).

Figures 22–24, with their captions, and with additional background information available in O'Driscoll (1983*b*) and Woodall (1984) will illustrate adequately the outstanding contribution of Olympic Dam to the subject of the lineament–ore relation.

Woodall (1984) has drawn attention to the mysterious ring structure seen in the Olympic Dam photolineament pattern in figure 23. The double-circular halo, 60 km across, in the centre of the sheet, has been called 'the Andamooka ring'. Its conjunction with the WNW lineament corridor PD1, is interpreted as a ϕ-structure, comparable with that associated with the giant Bingham Canyon copper deposit in Utah (O'Driscoll 1981*b*, fig. 17). Olympic Dam is positioned where the WNW lineament, PD1, intersects the outer edge of the double ring structure. This relation is also seen at Bingham Canyon. According to recent Australian work in magnetic depth-sounding (O. Polatayko, 1983, personal communication), a strong and singular circular magnetic pattern anomaly, related to an event in the upper 50 km of the Earth's crust, corresponds neatly to the 'Andamooka ring'. This may indicate a deep-seated source of energy for the Olympic Dam mineralization, and provide reasons for its high

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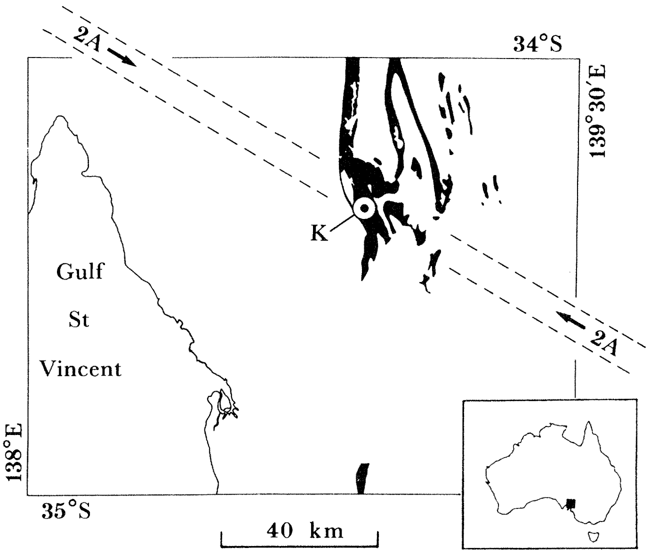

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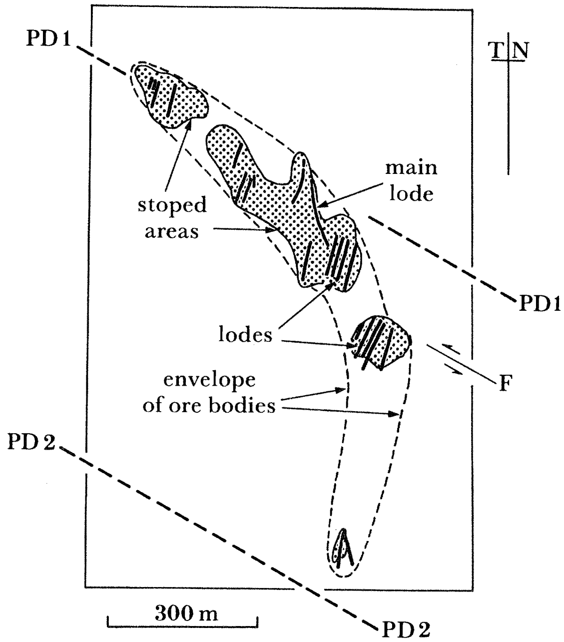

Figure 20. Geological ingredient plan of the Kapunda area, enlarged from figure 15, showing only the Proterozoic environmental rocks of the Kapunda deposit. The two ingredients, shown in black, are Tapley Hill Formation and Ulupa Siltstone. At this scale, the WNW lineament 2A, (figure 15) appears as a corridor approximately 6 km wide, containing the deposit. It clearly coincides with a marked sinistral flexure or disjunction ('Tethyan twist') in the environmental ingredient rocks.

Figure 21. A close-up view of the Kapunda ore deposit (Dickinson 1944) shows the ore envelope to be shaped like a boomerang with its northern end deflected to the west in the path of a WNW lineament (PD1) mapped in air photos. This example of a 'Tethyan twist' at ore-deposit scale is comparable with that seen in figure 19. The main lode at Kapunda is directed NNW, while its cluster of subsidiaries maintain NNE trends, almost at right angles to the WNW corridor. A second air photolineament, PD2, is found to correspond to the southern edge of corridor 2A (figure 20). A conspicuous WNW fault in the mine, with left-hand offset, is seen at 'F'.

concentrations of rare-earth minerals; and the extensive haematization, brecciation, and reworking of materials in the ore-body environment.

To summarize briefly, the Stuart Shelf Olympic Dam deposit and its kindred type, Mount Gunson, share a common but singular structural signature with other major deposits in the adjacent Adelaide Geosyncline. In so doing, they conform, in terms of the WNW lineament–ore relation, to many other major, and some minor, deposits throughout Australia, of which at least thirty examples have been cited by O'Driscoll (1981*c*, 1982, 1983*b*, 1984).

The WNW lineament–ore relation and the 'Tethyan twist' criterion have been recognized elsewhere in the world for both mineral deposits and petroleum, and a number of relevant examples have been given (O'Driscoll 1982). There is space here to illustrate only one example, in the U.S.A., jointly involving the Homestake gold deposit, South Dakota, and the Butte copper deposit, Montana, at a regional scale. This is seen in figure 25, where the geological ingredient map displays a magnificent WNW lineament extending hundreds of kilometres, through the Homestake mine in the east to the Butte deposit in the west. Segments of this trend have been described earlier (Billingsley & Locke 1941; Meyer *et al.* 1968; Hodder & Hollister 1974) but nowhere have I seen this WNW lineament displayed so effectively as with the geological ingredient treatment.

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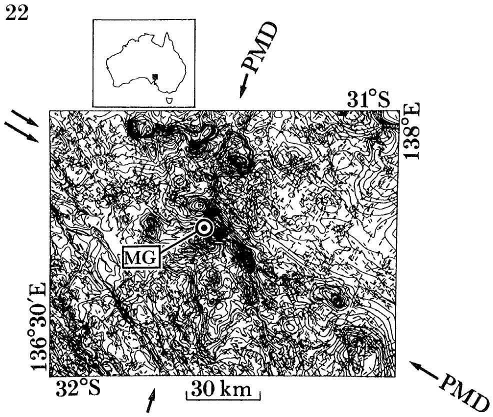

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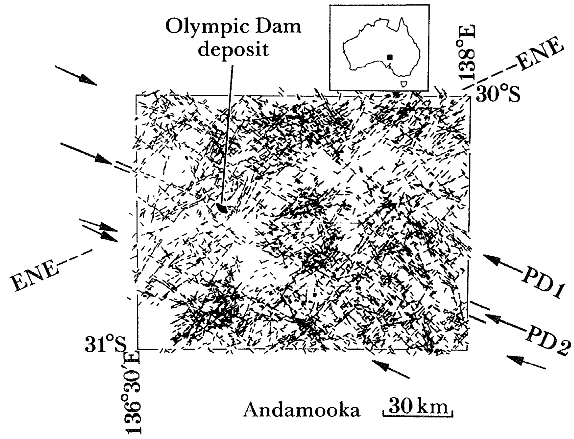

FIGURE 22. Torrens Sheet, South Australia, showing position of Mount Gunson copper deposit (MG), located at the intersection of two PMD lineaments, one a WNW corridor, and the other a NNE trend, obtained by combining air photolineaments with aeromagnetic contours, in a technique described by O'Driscoll (1981*c*). Host rocks are represented by the chain of magnetic anomalies which, entering from the south, are seen to be deflected to the west along the path of the WNW lineament (cf. figures 19 and 21) before reverting to a more northerly track along the orthogonal NNE lineament. The WNW lineament corresponds to regional lineament 3 in figure 15. Lineament 4B also passes through Mount Gunson (O'Driscoll 1982).

FIGURE 23. Andamooka sheet, South Australia, showing high-frequency photolineaments used to preselect the Olympic Dam tectonic target (after Woodall 1984). Of the four WNW photolineaments shown, PD1 achieved priority through being recognized, in aeromagnetic combination, as a corridor, similar to that related to Mount Gunson (figure 22). The Olympic Dam deposit is located on this WNW lineament, as shown, and coincides also with a sinistral flexure of the gravity anomaly (figure 24). Lineament PD2, a narrower WNW trend, corresponds to the southern edge of regional ingredient corridor, 4A, seen in figure 15 to be crossing the Adelaide geosyncline.

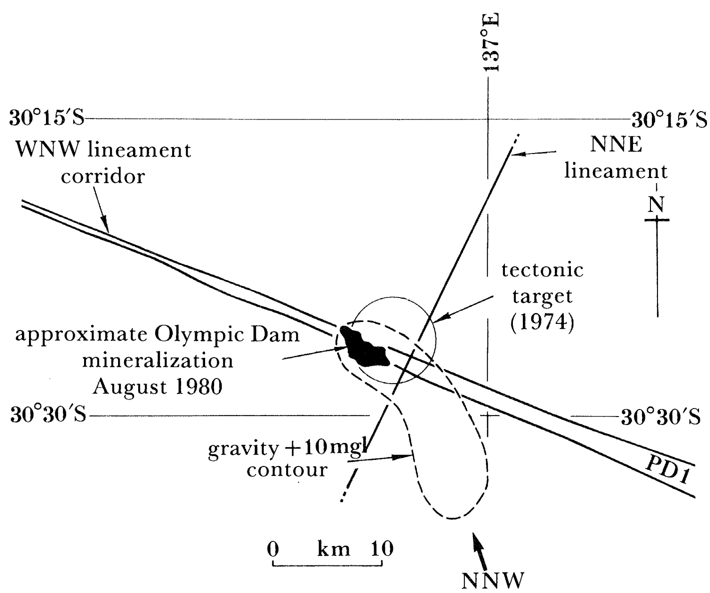

FIGURE 24. Plan of Olympic Dam deposit showing the fully outlined ore body (in black) in relation to the WNW photolineament corridor, PD1, and the NNW-trending gravity anomaly, which displays a sinistral flexure ('Tethyan twist') at its northern end, where it is crossed by the WNW corridor. The ore body, located on both the corridor and the flexure, also shows a remarkable directional response to the passage of the corridor. This was first noted by R. Woodall (personal communication 1980) and authorized for illustration in the 1981 P.E.S.A. Distinguished Lecture (O'Driscoll 1982, 1983*b*).

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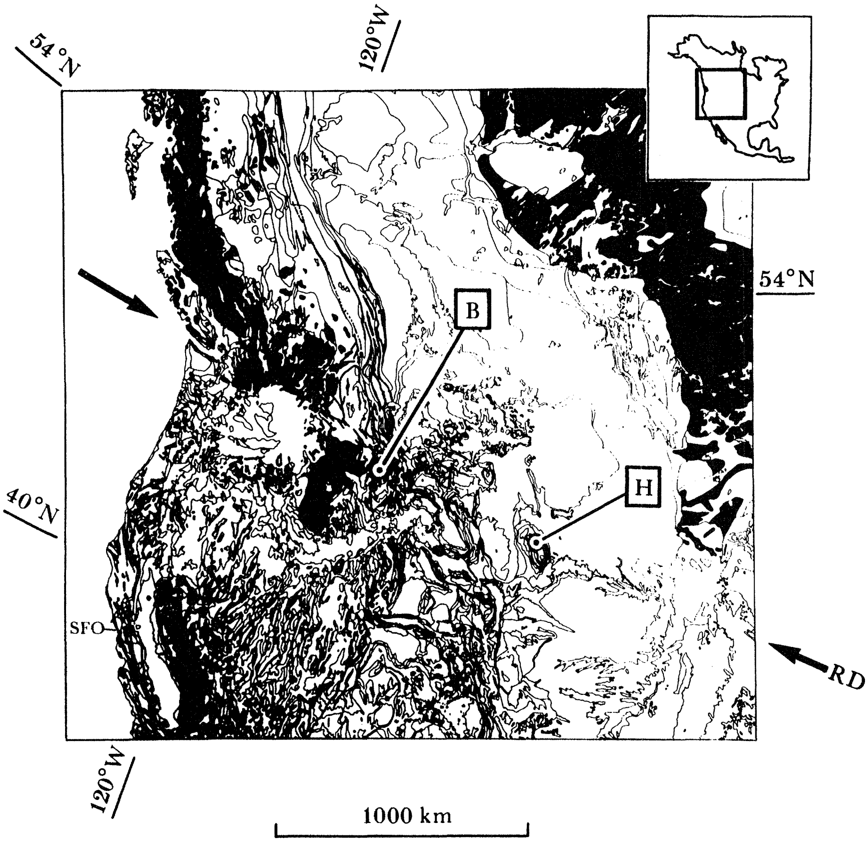

Figure 25. Homestake gold deposit (H) and Butte copper deposit (B), both of first magnitude, share the same major WNW regional lineament, RD, through northern U.S.A. as seen in a geological ingredient outline plot, including faults (from U.S. Geological Survey 1965). Black areas are intrusives from Jurassic to Precambrian in age, which show a disjunction with a sinistral sense of asymmetry where crossed by the lineament west of Butte. The 'Tethyan twist' is seen in the sinistral flexure of the northern end of the elliptical Black Hills in which Homestake is located (after O'Driscoll 1982).

9. Global lineaments

Many observers have remarked on the straightness of the continental geographic features plotted on a standard Mercator projection of the globe (Umbgrove 1974). When a Mercator map of the world continents was drawn to incorporate a mid-level 'slice' of sea-floor contours, equivalent to the deep-sea platform (O'Driscoll 1980), it was seen to accentuate two parallel WNW linear trends slanting across the map from pole to pole. The geometry of their linear traces identified them as a pair of helical spirals, 180° apart in longitude, and it was suggested that they were primordial features of a rotating globe which have survived to the present day, to be compared in form with a galactic spiral nebula.

Apart from any speculative interpretation of these two global trends, the fact remains that they were visible pattern discontinuities in a scientifically acceptable assembly of data, and that they were parallel to verifiable major WNW ore-associated lineaments and megalineaments in Australia, Africa and America (O'Driscoll 1982).

For a more direct relation to mineral occurrence, it is of interest to note that these same two trends are repeated in the world distribution pattern of polymetallic manganese nodules in deep-sea sediments seen in the Mercator map in figure 26. Their traces on a perspective view

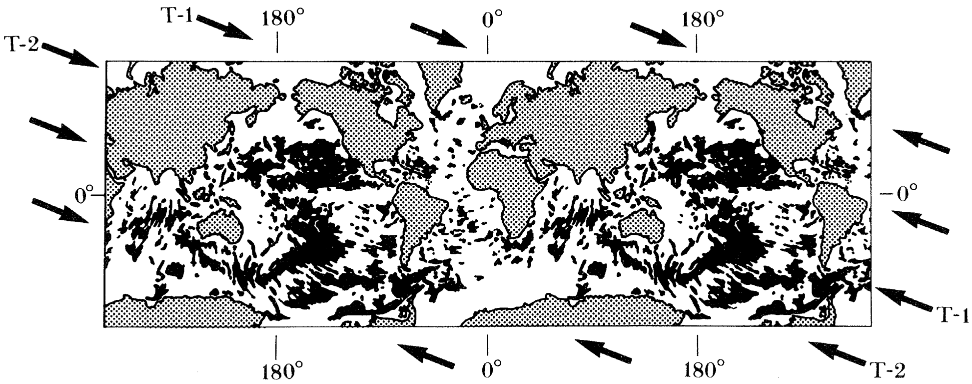

FIGURE 26. World Mercator map showing distribution of polymetallic manganese nodules in deep-sea sediments (black areas). Two long pattern discontinuities, T-1 and T-2, can be seen corresponding to the two Tethyan global lineaments described from other data by O'Driscoll (1980). (Sea-floor data from Bureau of Mineral Resources 1981).

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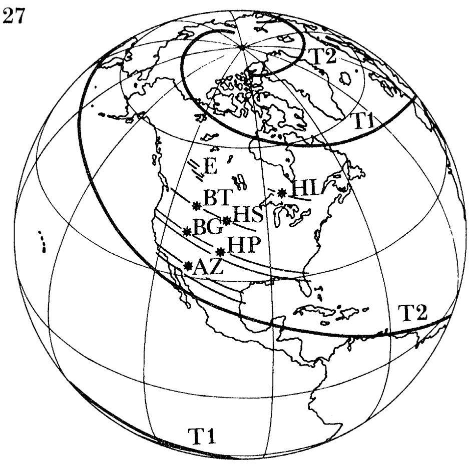

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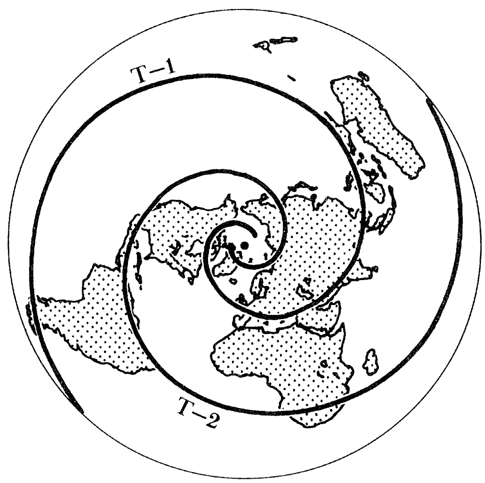

FIGURE 27. Perspective view of Tethyan global lineaments, T–1 and T–2, showing their parallelism with North American WNW megalineaments determined principally from geological ingredient maps (O'Driscoll 1980; 1982). Major mineral deposits shown are Bisbee copper (AZ), Bingham Canyon copper (BG), Butte copper (BT), Homestake gold (HS), and Hemlo gold (HL). The great Hugoton-Panhandle gas field is at HP.

FIGURE 28. When the long straight discontinuities in the world pattern in figure 26 are plotted on a polar azimuthal projection, they reveal their true character of global spirals.

of the globe are shown in figure 27, and their spiral appearance on a north polar azimuthal projection is shown in figure 28. It should be stressed that the patterns in figures 27 and 28 are not manipulative interpretations. They are the actual plots of the linear global discontinuities seen in figure 26, and correspond to those of the earlier plot of sea-floor bathymetry in conjunction with continental outlines (O'Driscoll 1980).

10. A lesson on evidence

Investigations of lineaments, which for me began in a context of mining geology, have been greatly assisted by the use of laminar kinematic models (O'Driscoll 1968), designed to study the effects of simulated movements of basement shearing upon various overlying layered materials. In this paper I have tried to emphasize that crustal tectonic patterns are essentially multilineamental, although, on the basis of field evidence, I have given a primary status to the WNW component along which are found structural attitudes comparable with the effects of a sinistral couple. What do we expect to see in the path of such a lineament or corridor? The most frequently elicited response to that question is that we should expect to find parallel WNW faults and fractures along the primary lineament track. And yet, in model work, such expected symptoms may be completely masked by an overriding display of divergent derivative features.

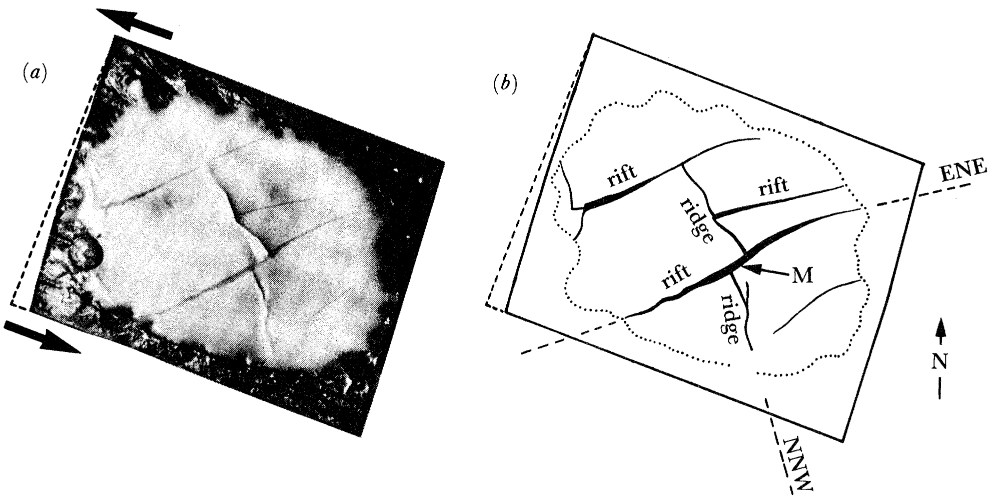

Figure 29. (*a*) Laminar kinematic model showing rifts and ridges developed in an initially underformed layer after the application of uniform sinistral WNW basement shear (after O'Driscoll 1983*b*). (*b*) Overlay tracing of main deformational features in (*a*). The apparent dislocation of the NNW ridge system by the main ENE rift is analogous to a transform fault mechanism. The two ends of the ridges abutting the rift were never together, but were developed separately in their present positions accompanied by maximum dextral shear along the rift segment 'M'. The position of 'M' is analogous to that of the Pb–Zn deposit at Broken Hill, where the model analogue rift trend is represented in the field by a strongly sheared regional ENE linear corridor belonging to trend 7 (figure 9). It is also analogous to the position of the gold deposits at Norseman, Western Australia, where the equivalent 'rift' trend is occupied by the giant Jimberlana mafic dyke.

Such a model, in figure 29, shows a layer of plastic carbohydrate of a consistency enabling it to be both pliable and brittle when deformed. Initially a flat, underformed layer, it has been mounted on a horizontal 'basement' formed by the edges of vertical laminae parallel to the long WNW edges of the model which, so oriented, is analogous to a short segment of a WNW lineament corridor. A small degree of uniform distributed sinistral shear has been applied horizontally throughout the 'basement' in the WNW direction as indicated by the arrows of the deformation couple.

The peculiarities and non-intuitive results of this model have already been described elsewhere (O'Driscoll 1983*b*). I refer to it here as an example of the kind of evidence on which we may have to rely in identifying the presence of lineaments. The deformational responses of the layered material can be recognized in terms of the conventional deformation ellipse, with the contemporaneous development of longitudinal (NNW) overthrust folding, equivalent to transverse compression, and of transverse (ENE) rifting, equivalent to longitudinal extension. Here we have material of which we know, by design, the deformational history, and in which we know the visible deformation effects to be entirely a result of the passage of a WNW linear corridor with a sinistral differential movement. However, if this foreknowledge were not available to us, and we had to rely for our conclusions on what we could 'map' in the visibly deformed area, we might unquestioningly conclude that it gave no evidence of the passage of a WNW lineament, but, on the contrary, clearly displayed lineaments in other directions at variance with it.

The lesson is clear. In particular contexts, a system of ENE rifts *is* evidence of a sinistral WNW lineament; and a NNW strike-faulted fold with transverse dextral dislocations *is* evidence of a sinistral WNW lineament; and (in other models) a clear NNE fault with sharp dextral movements *is* evidence of a sinistral WNW lineament. The ultimate diagnosis in geological field work depends not on the continued scrutiny of a localized area in greater and greater detail, but on an expanded and synoptic view which assesses the extent and continuity of a lineament corridor, and identifies the features that are repeated within it, in contrast with those that are external to it. Such a view requires an experienced judgement of field occurrences and of the relevant lineament context to which they can be related.

11. Conclusions

Major ore deposits in Australia are related to major lineaments which invariably constitute traces or belts of disturbance, dislocation or disruption in the overall crustal tectonic pattern. Their presence is not always immediately obvious, but they can be revealed by particular treatments of otherwise standard geological, geophysical and geomorphological data. They are associated with common structural ore signatures which are consistently reproduced at local and regional scales.

At first face these linear pattern breaks may be thought to post-date the ore deposits and host rocks which they disturb. However, they are probably fundamental features pre-dating their associated rocks, setting up anomalous precursory energy conditions for developing the future ore environment. As Woodall (1984) says:

> 'Major continental lineaments which represent deep crustal or mantle fractures can localize centres of deep structural plumbing, can tap heat as well as metal and can be expected to be "activity centres" over long periods of time. They thus have the potential to localize the giant deposits through preparing environments for those ore formations and localizing repetitive episodes of sourcing, migration and concentration (trapping)....It is thus not surprising if we find them, like Kalgoorlie, Mount Isa, Broken Hill and Olympic Dam, on conspicuous continental lineaments.'

If viewed in this way, lineaments may be seen as primary producers, while their rock associations are the retail outlets, each administering, according to its affinities, the type of deposit that has been made available to it, either through syngenesis or epigenesis. Conventional classifications of ore deposits based on local compositional and structural differences may then be merely descriptions of the varying retail packages rather than of the primary source. In O'Driscoll's words (O'Driscoll 1982):

> 'These aspects may tend to reverse priorities in concepts of ore environments since they imply that both the ore and its environment are dependent on an underlying tectonic control, and that tectonic factors may claim a fundamental precedence over those of environmental supply

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and distribution, i.e. over styles of ore occurrence. The environment is thus a consequence of tectonics rather than a pre-existing venue for conveying and recording subsequent tectonic effects.'

Lineaments are pre-eminently loci of anomalous geological occurrences and especially of changes in rock distribution, composition, metamorphism and alteration, and especially of *en echelon* repetitions of such effects, including ore deposits. Because they appear to have diverse multi-metallic associations, depending on the type of petrologic environment found along them, and to be equally related to deposits of various ages, they may be identified as ancient fundamental features persisting through geologic time, and episodically reactivated by oscillatory movements.

Continental lineaments, some remarkably long and persistent, appear to be systematic, crossing continental margins and plate boundaries, and to be consistent with major trends visible in global patterns (O'Driscoll 1980, 1982). Many features of the observed lineament–ore relation are not easily reconciled with what is permitted by some current theories. Nevertheless, the relation is verifiable and observable in a great many diverse and widely separated ore occurrences and environments, including the giant Olympic Dam deposit in which the successful application of the predictive value of regional lineaments was effectively demonstrated. Any theory that cannot accommodate such lineaments must itself be seriously re-examined.

I thank the Royal Society for the invitation to address this meeting, and for contributing to the cost of my attendance. I also thank Dr R. Woodall, Director of Exploration, Western Mining Corporation, for authorizing and facilitating my attendance and the presentation of hitherto unpublished information. Thanks are due also to Mr N. M. Furstner, and Mesdames K. Romeo and C. Valentine for assistance in the preparation of text and illustrations; and to Dr S. H. White and Dr J. Watterson for critically reviewing the typescript.

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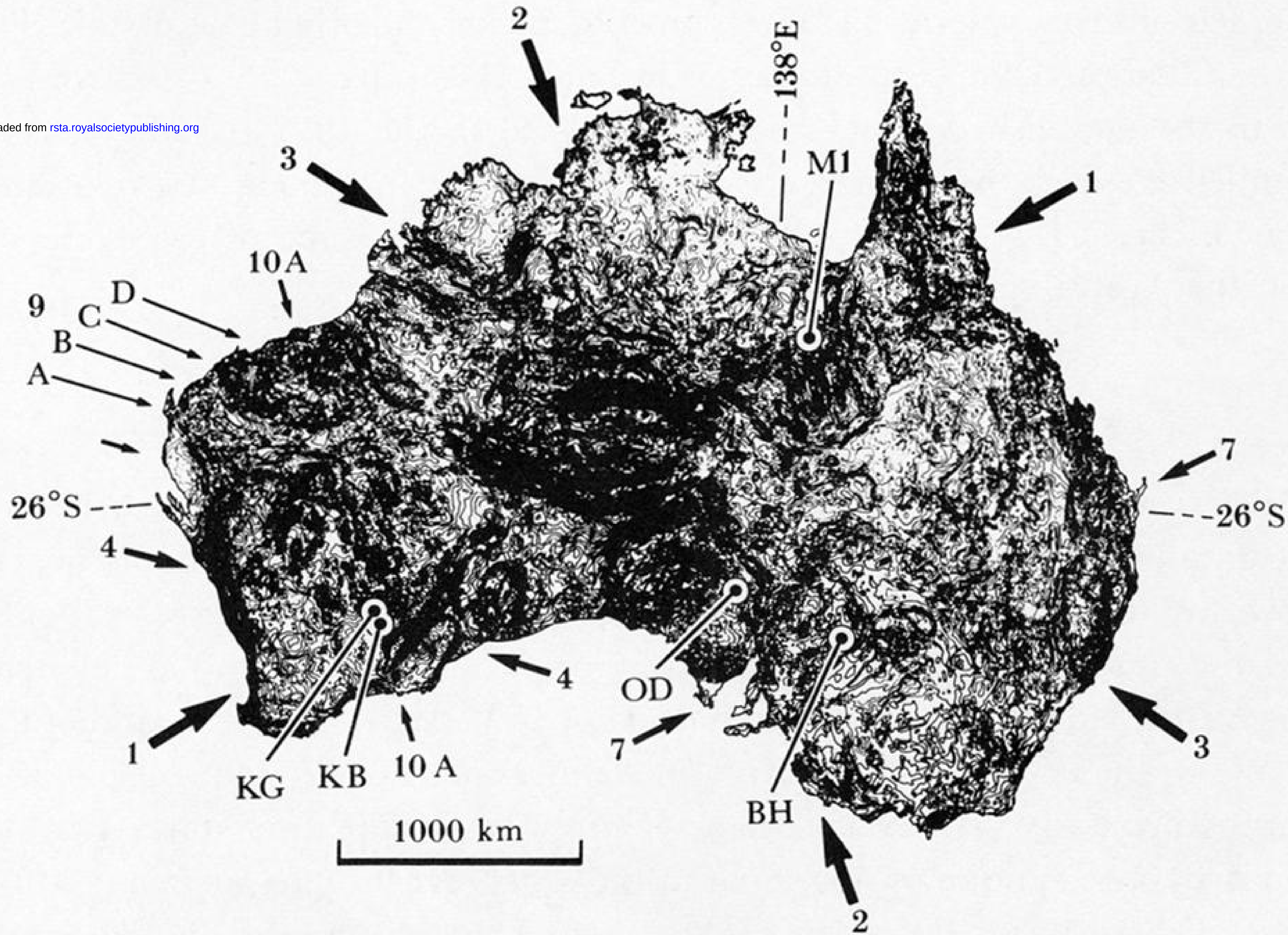

FIGURE 1. Bouguer gravity contours of Australia (Bureau of Mineral Resources 1971, 1975) showing numbered continental gravity lineaments related to major ore deposits at Kalgoorlie gold (KG); Kambalda nickel (KB); Mount Isa Pb–Zn–Cu (MI); Olympic Dam Cu–Au–U (OD); Broken Hill Pb–Ag–Zn (BH). Kalgoorlie and Kambalda appear to be located at a triple intersection. The lineaments are best seen by looking at a low angle along their tracks (after O'Driscoll 1981 *a*).

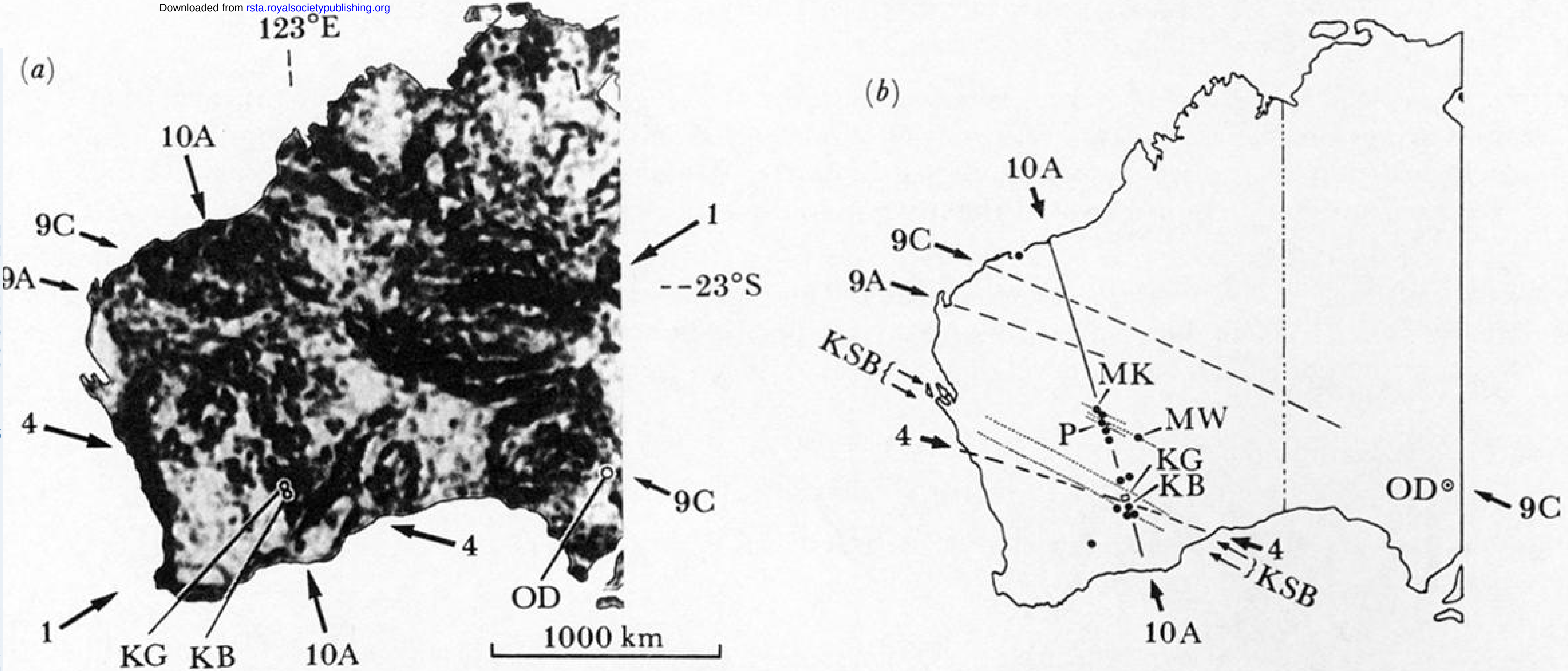

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FIGURE 7. (*a*) Diffused image of Bouguer gravity contour pattern of western and central Australia. Lineament 10A (the 'gold line') is known to be the locus of major gold deposits including Kalgoorlie (KG). (*b*) Overlay tracing of (*a*) showing principal nickel deposits (black dots). The first four ranking deposits have preferred positions along lineament 10A where it is crossed by WNW lineaments. They are Kambalda and St Ives (KB), Perseverance (P), and Mount Keith (MK). The Kalgoorlie–Shark Bay magnetic corridor, KSB (O'Driscoll 1981*c*) coincides with the Kalgoorlie–Kambalda position, forming a multiple intersection with lineaments 1, 4 and 10A, indicating a special tectonic status for that position. Other deposits shown at Mt Windarra nickel (MW) and Olympic Dam Cu–Au–U (OD). (After O'Driscoll 1982*c*).

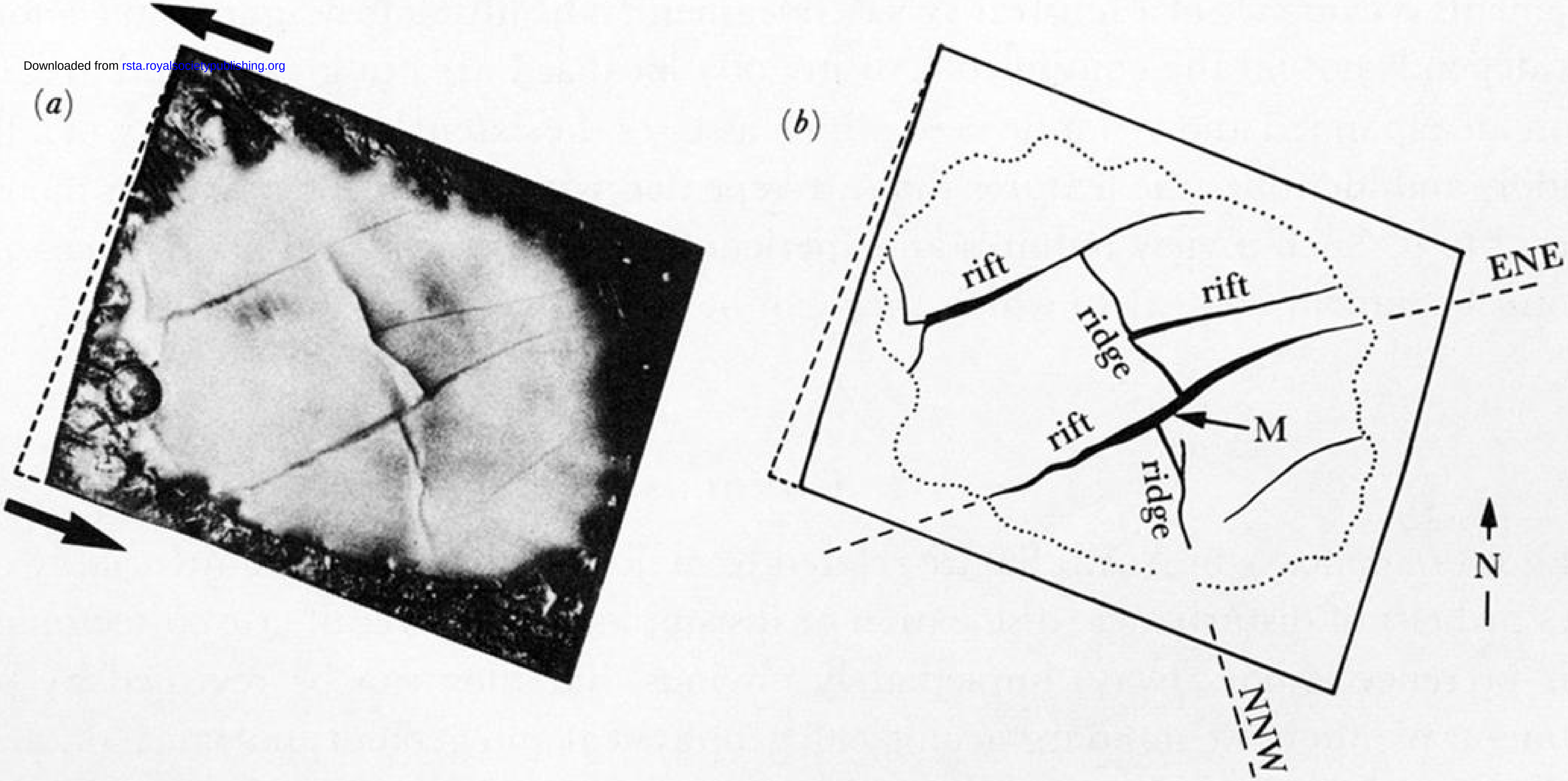

Figure 29. (*a*) Laminar kinematic model showing rifts and ridges developed in an initially underformed layer after the application of uniform sinistral WNW basement shear (after O'Driscoll 1983*b*). (*b*) Overlay tracing of main deformational features in (*a*). The apparent dislocation of the NNW ridge system by the main ENE rift is analogous to a transform fault mechanism. The two ends of the ridges abutting the rift were never together, but were developed separately in their present positions accompanied by maximum dextral shear along the rift segment 'M'. The position of 'M' is analogous to that of the Pb–Zn deposit at Broken Hill, where the model analogue rift trend is represented in the field by a strongly sheared regional ENE linear corridor belonging to trend 7 (figure 9). It is also analogous to the position of the gold deposits at Norseman, Western Australia, where the equivalent 'rift' trend is occupied by the giant Jimberlana mafic dyke.