AGSO

LINEAMENT INTERPRETATION FOR GROUNDWATER ASSESSMENT, WESTERN WATER STUDY (WILURARATJA KAPI), PAPUNYA - KINTORE REGION, NORTHERN TERRITORY

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1997

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Primary Industries and Energy: Hon. J. Anderson, M.P.
Minister for Resources and Energy: Senator the Hon. W.R. Parer
Secretary: Paul Barratt

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Neil Williams

ISSN: 1039-0073
ISBN: 0 642 25014 6

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ABSTRACT

The Western Water Study, *Wiluraratja Kapi*, area is in arid central Australia where most communities within the 60,000 km^2 region rely on groundwater as their main or only water supply. Groundwater sources vary across the study area which spans three distinct geological provinces: the Proterozoic Arunta Inlier and the Proterozoic-Palaeozoic intracratonic Amadeus and Ngalia Basins.

At least half of the study area comprises igneous and metamorphic rocks. The permeability and groundwater storage capacity of these "hard rocks" is dependent upon their interconnected networks of fractures and fissures. In the sedimentary rocks of the intracratonic basins, secondary fissuring produced by tectonically-induced fracturing is as important to groundwater yields as primary porosity and permeability characteristics. Identification of fracture zones where increased permeability is likely to enhance hydraulic conductivity is important for groundwater assessment in this region.

Interpretation of geologically-based lineaments in the study area was aimed at facilitating the designation of potential drill targets and enhancing the likelihood of successful bores. Several thousand lineaments have been interpreted from processed Landsat TM scenes. Band ratios and unmixed mineral processing were applied, along with interactive image enhancement of the processed imagery. A significant proportion of the interpreted lineaments are in Cainozoic "cover" material, their visibility attributable to minor Tertiary to Recent reactivation of basement structures transmitted through cover sediments and to the processing applied to the imagery. The lineament interpretation maps make up a dataset in the Western Water Study GIS package.

The lineament array has been synthesised into regional-scale lineament zones, some of which represent previously unmapped major crustal structures. Criteria for utilising the lineament interpretation for nominating drill targets include: long fractures; and dense, intersecting networks of fractures. The geometry of lineament zones provides information about likely causative stress directions and deformation styles of sets of zones and, accordingly, areas of increased fluid flow have been predicted. In this region, N-S striking lineament zones and conjugate NW- and NE-striking lineament intersections are favoured as being hydrogeologically important. Relationships between lineaments, lithologies, topography and local watertable depths need to be accommodated in drill target designation.

The methodology utilised for the study is transferable to other inland regions in Australia and to arid and semi-arid countries where groundwater resources need to be assessed and developed.

INTRODUCTION

The Western Water Study, *Wiluraratja Kapi*, is a two-year (1995-1997) study of water supply in Aboriginal Lands in the southwestern Northern Territory. The project is being conducted collaboratively by the Australian Geological Survey Organisation (AGSO), the Northern Territory Department of Lands, Planning and Environment (LPE), the Central Land Council (CLC) and the Aboriginal & Torres Strait Islander Commission (ATSIC). The study area covers four 1:250 000 sheets: LAKE MACKAY SF52-11, MOUNT DOREEN SF52-12, MOUNT RENNIE SF52-15 and MOUNT LIEBIG SF52-16, an area of over 60 000 km^2 (Fig. 1).

Interpretation of geological lineaments based on Landsat imagery of the study area was initiated to complement two of the overall objectives of the Western Water Study (WWS):

- develop methodologies for assessing water resources and providing adequate water supplies to people living on Aboriginal land;
- improve the long-term success of water-resource developments on Aboriginal land.

The specific objectives of the lineament interpretation were:

- interpretation of all geologically-based lineaments from processed Landsat TM data, using available image enhancement techniques, and generation of 1:250 000 scale "lineament maps" to serve as a separate dataset in the Geographical Information System (GIS) being compiled for the WWS;
- designation of potential reconnaissance drilling areas based on interpreted lineament networks that may represent fracture zones where increased permeability would increase the likelihood of successful bores.

The work was undertaken as a consultancy for AGSO between December 1995 and April 1996. The work involved a total of 300 hours of interpretation by one geologist plus approximately 150 hours by technical officers involved in digitizing the data and other technical aspects of the project.

LINEAMENT INTERPRETATION

The following definitions of "lineaments" were adopted for the WWS lineament interpretation:

Lineaments: "Correctly applied to long, often subtle linear arrangements of various topographic, tonal and geological features." (Drury,1987, p. 92).

"Alignments of regional morphological features, such as streams, escarpments and mountain ranges, and tonal features that in many areas are the surface expressions of fractures or fault zones." (Goetz & Rowan, 1984, p. 784).

Lineament interpretation and analysis has been successfully applied in recent years to hydrogeological projects in the US, Europe and Africa (e.g., Boeckh, 1992; Gustafsson, 1993; Ross & Frohlich, 1993; Pistre & others, 1995; Teeuw, 1995). In his exploration strategy for higher-yielding boreholes in the West African crystalline basement, Boeckh (1992) notes that the methodology using Landsat TM imagery and ground geophysics can be applied separately or in combination as an economical approach for use in rural and community water supply. He further suggested that the methods are transferable to fissured hard rock aquifers in other regions, particularly cratonic and platform settings in a semi-arid environment.

Several thousand lineaments have been interpreted from processed Landsat TM data for the WWS area. The assumption of the study is that the vast majority of interpreted lineaments in the area represent fractures or faults and that such tectonically induced fissuring is important to hydraulic conductivity and groundwater storage. Put simply, "all fractures are potential drains" (Pistre & others, 1995). In the areas of Proterozoic-Palaeozoic sedimentary or metasedimentary strata, a large proportion of interpreted lineaments represent primary bedding planes. Fissuring along bedding planes in response to diverse processes is as important to the hydrogeology of the region as are cross-cutting fractures/fissures.

The main output from the lineament interpretation is a digital dataset or layer: *"LINEAMENTS"*, for the four map sheets in the WWS GIS. Hard copies of GEOLOGY + LINEAMENTS and LINEAMENTS + BORE YIELDS for each sheet at 1:750 000 scale accompany this report. The rationale of the lineament sub-project, the methodology used, and criteria for designating promising localities and drill targets, are summarised in this report.

The lineament interpretation is a surficial study with ~95% of the interpretations based on Landsat TM imagery. Previously mapped faults, joints, veins and dykes were incorporated into the generated lineament maps at the outset (approximately 5% of the total number of lineaments in the dataset). As surficial maps, therefore, the lineament interpretations are aimed at supplementing other available data: geology, stratigraphic data from drill holes, seismic data, aeromagnetic data, gamma-ray spectrometric imagery and topographic data in the WWS GIS package.

In their study of Landsat interpretation of several arid Australian regions, including the Canning, Officer and Ngalia Basins, Theron & others (1984, p. 556) note that: "Desert and semi-desert regions often tend to reflect either excellent outcrop or almost total cover by aeolian or evaporite deposits, owing to the absence of the mantle of colluvial soil found in humid regions through which shallow structure is often visible. The particular problem confronting the interpreter in areas of extensive aeolian cover is therefore to develop an understanding of the way in which reactivated subsurface structure is likely to influence desert geomorphology." Those workers further noted that the disposition of evaporite deposits, drainage features, dune belts and residual surfaces are not random events, and that their careful interpretation can provide important clues to underlying structure. Thus, "the ubiquitous blankets of Cainozoic aeolian, evaporite and residual deposits which obscure bedrock outcrops over much of central arid Australia may often be turned to advantage through the medium of Landsat interpretation." The latter involves careful observation of major landform elements, including residual surfaces, present and past drainage patterns, and morphotectonic features. This advice was borne in mind for the lineament study of the

WWS area which is characterised by both excellent outcrop and typical semi-desert cover material, with sparse vegetation overall.

The WWS area is arid and most communities within the region rely on groundwater as their main or only water supply. Groundwater sources vary across the study area which spans three distinct geological provinces: the Proterozoic Arunta Inlier, and the Proterozoic-Palaeozoic intracratonic Amadeus and Ngalia Basins. Groundwater potential within large areas of the region is only now being assessed. Primary porosity and permeability of the rocks making up these provinces is extremely variable and yields are highly unpredictable, even from known aquiferous lithologies. Fissured characteristics are as important to groundwater potential as primary properties of aquifer rocks including high-yielding lithologies such as the Pacoota and Mereenie Sandstones (Amadeus Basin) and the Kerridy and Mount Eclipse Sandstones (Ngalia Basin). Groundwater yields in the crystalline granite-gneiss Arunta Inlier is even more dependent upon secondary porosity and permeability afforded by either fracturing or weathering. Additionally, much of the overall region is covered with Cainozoic sediments for which the pattern of potential aquifers and the hydrogeologic role of structures therein are unknown quantities. Importantly, fractures cross-cut bedrock and surficial lithologies that otherwise may function as aquicludes or aquitards, thereby facilitating hydraulic conductivity to local or regional aquifers.

At least half of the areal extent of the WWS area comprises igneous and metamorphic rocks. According to Freeze & Cherry (1979) unfractured metamorphic and igneous rocks have porosities that are rarely larger than 2%, and the intercrystalline voids that may make up the porosity are minute and not necessarily interconnected. This results in extremely small primary permeabilities, very low hydraulic conductivities and limited storage capacity; such crystalline rocks are, therefore, essentially impermeable. The storage capacity of unweathered "hard rocks" is restricted to the interconnected system of fractures, joints and fissures that are mainly the result of tectonic phenomena in the crust (Larsson, 1984). Pistre & others (1995) cite experimental work in deep fissured granite where apparent transmissivity is an increasing function of fracture density.

Sandstones typically have far greater primary porosities and permeabilities than igneous and metamorphic rocks. For example, Brassington (1988) cites medium-grained sandstone as having 5-30% porosity and indicative specific yields of the order of 25%, although wide ranges of sedimentary compositional and textural heterogeneities result in highly variable aquifer properties. Primary porosities and permeabilities of sediments, afforded by intergranular pore-spaces and bedding planes, are greatly enhanced by secondary fissuring produced by tectonically-induced fracturing. In the case of limestone or dolomitic sediments, such as the Bitter Springs Formation in the Amadeus Basin, secondary porosity and permeability is also enhanced by solution of carbonates. Such chemical fissuring is often extensive along fracture zones where groundwater flow is expected to be greatest.

A significant proportion of the interpreted lineaments within the study area are in Cainozoic "cover" sediments, many more than anticipated prior to commencement of the project. In their study of arid Australian regions, Theron & others (1984) note that: "A feature common to all cited case histories is the observable Cainozoic reactivation of Palaeozoic structural features". Those authors found that minor Tertiary to Recent reactivation of major basement structures transmitted through quite considerable thicknesses of Cainozoic cover (up to 250 m in the central Ngalia Basin), can be recognised at the surface through geomorphic features clearly visible on Landsat imagery. The latter observation is substantiated in the present study.

Almost all rock holes, springs and soaks in the region that contain permanent or semi-permanent surface water, correlate with intersecting networks of lineaments. The occurrence of fresh water at these localities may not in all cases be directly attributable to the cross-cutting lineaments. Water resources in the rock holes in gorges may be run-off from adjacent slopes, or ponded water from upstream drainages that accumulated after rare rainfall events, or seepage from bedrock aquifers. Such waters are protected from evaporation because of the gorge settings. However, even in these perched situations the gorges themselves follow mappable fractures/faults so that the spatial relationship between stored water and lineaments is relevant. In many instances springs probably represent discharge from perched water tables and the spatial association with interpreted lineaments suggests a role for the conjugate fractures that are seen to cross-cut the discharge points.

It should be noted that lineaments visible at 30 m resolution in the Landsat imagery are generally large geologic features that in reality represent mesoscale to microscale fractures which are not readily discernible or discrete on the ground. It is the synoptic overview afforded by the satellite imagery that enables definition of zones of aggregate fractures. This needs to be borne in mind if follow-up work involving the lineaments is considered. In the cited overseas studies, interpreted lineaments were assigned "buffer zones" when the lineament data was applied to follow-up work. For example, Gustafsson (1993) used 80 m buffer zones for interpreted lineaments in his 400 km^2 study area in Botswana when he analysed proximity of lineaments to other features. Treeuw (1995) used 90 m buffer zones for geographic analysis and classification in his 3,600 km^2 study of the Volta Basin mudstones, Ghana. Buffer zones, moreover, go some way towards accommodating non-vertical dips of fault and fracture planes that the surface lineaments represent, a consideration important to geophysical surveys and drilling of target zones that are based on the lineaments.

Possible depths of interpreted lineaments cannot be conjectured from the present two-dimensional lineament study. Deep crustal seismic data indicate that major structures in the region, such as the Redbank Thrust Zone, extend some 50 km through the crust, possibly to the mantle (Wright & others, 1991). Fractured crystalline rocks are less permeable at depth because stress variations that cause fractures are larger and, over geologic time, occur more frequently near the ground surface (Freeze & Cherry, 1979). Fractures tend to close at depth because of vertical and lateral stresses imposed by overburden loads and "locked-in" horizontal stresses of tectonic origin. However, the brittle character of rocks is maintained to depths of several kilometres. Pinneker (1980) emphasises that the saturation of fissured rocks decreases with depth. Absolute depths of fracture permeability are of limited relevance to the present study where relatively shallow and easily targeted groundwater is the overriding objective. It is, therefore, assumed that the majority of lineaments interpreted at the ground surface of the WWS area are within the depths of hydrogeological significance.

Additional to the detailed 1:250 000 lineament maps, a 1:1 000 000 synthesis map has been generated to provide a synoptic overview of the whole study area in terms of the interpreted lineament patterns. In their systematic Landsat interpretation of arid Australian environments, Theron & others (1984) adopted the strategy of firstly interpreting data at 1:250 000 scale, which they believed to be the optimum scale for regional interpretation, then combining and reducing these interpretations to 1:1 000 000 scale to produce synthesis maps. This approach was also successfully used by John Creasey (AGSO, then with CSIRO) for a lineament study of the Sydney Basin (pers. comm., 1996). The main lineament zones defined in the synthesis map of the WWS area (Fig. 11) probably represent major crustal structures that traverse the region although the nature of all of these structures cannot presently be assessed. Some of the tectonic and geometric relationships and possible hydrogeological implications of these structures are briefly addressed elsewhere in this report. The lineaments that make up the regional-scale lineament zones have been highlighted on 1:250 000 lineament maps and converted into separate ARC coverages: *"REGIONAL LINEAMENT ZONES"*. This dataset is aimed at contributing to a *"STRUCTURE"* dataset being developed for the WWS GIS and possibly to future geological mapping in the western Arunta Block and to continent-scale crustal element mapping.

In some of the recent overseas projects, cited above, geometrical or statistical procedures were utilised to analyse interpreted lineament patterns and densities in their respective study areas. This analysis was not undertaken in the present study. The lineament/hydrogeological studies reported from other countries were carried out in small, geologically homogeneous study areas (5 km^2 to <10,000 km^2) compared to the WWS area (60,000 km^2). Geometrical and/or statistical analysis may not be so readily applied to vast, lithologically and structurally complex regions. Such analysis, however, might be appropriately applied to specific areas of interest within the WWS area.

METHODOLOGY

The lineament interpretation was carried out on contiguous portions of the following Landsat TM scenes, Path/Row:103/74; 103/75; 103/76; 104/74; 104/75; 104/76. All scenes are from September or October 1994 orbits. The scenes were joined and clipped to provide coverage in the format of the four 1:250 000 sheet areas. The Landsat scenes do not fully cover the southern sheets; strips along the southern boundaries of MOUNT LIEBIG and MOUNT RENNIE therefore have not been interpreted. Two types of image processing were carried out: Band ratios by Evert Bleys and Unmixed Mineral by Phil Bierwirth (AGSO):

(a) BAND RATIOS: 5/7 = red (clay, water and green vegetation); 5/4 = green (hematite); 3/1 = blue (hematite, goethite).

(b) UNMIXED MINERAL processing using six non-thermal bands with a spectral unmixing technique (Bierwirth, 1990). This separates the data into three geological and two vegetation end-member images based on known reflectance characteristics of surface components. The three mineral unmixed images for each sheet show materials in proportions: red = clay (= carbonate = water); green = iron oxide; and blue = quartz.

Interpretation was carried out onto double clear plastic transparent film over hard copies of the processed Landsat TM imagery to which 10′ grid tick marks had been added from ERMapper's grid function. Borders and 10′ graticules were drafted onto the overlays for registration of the generated lineament maps within the GIS. Fine-point permanent pens suitable for overlay film were used for the annotation (e.g., STAEDTLER Lumocolor and ARTLINE). All tracks mapped on the 1:250 000 topographic maps for the study area and all mapped seismic lines were traced in unscannable yellow on the overlays so that these linear "cultural" features would not be interpreted as geological lineaments. All previously mapped faults shown on the 1:250 000 geology sheets were traced in red on the original overlays, the latter data being, therefore, duplicated in two GIS datasets: GEOLOGY and LINEAMENTS, respectively.

Interpretation was carried out initially on the ratioed TM images, prior to the availability of mineral unmixed images. Annotation was done in black for definite lineaments and green for more subtle lineaments. The same overlay film for each 1:250 000 sheet was subsequently transferred to hard copies of greyscale mineral unmixed images and all lineaments interpreted from the latter sets were annotated in purple. In the case of the mineral unmixed imagery, three separate images for each 1:250 000 sheet were cumulatively interpreted. The latter sets were interpreted in the following order: Fe-oxide, quartz and clay, because the greatest amount of lineament information was evident in the Fe-oxide image and the least in the clay image.

An alternative technique would have been to use the *ANNOTATE VECTOR* function in ERMapper and tag interpreted lineaments on-screen and thereby generate vector overlays for the datasets. However, by building up the interpreted lineaments on hard copies of the imagery, the on-screen enlarged, enhanced scenes were left clear rather than made progressively more cluttered with vectors, and this made perception of, and interpretation of, the spectral and geological features easier. The adopted methodolgy of using both on-screen interactive image processing functions and annotation of hard copies, proved satisfactory for the study.

Apart from tracing all previously mapped faults, joints, dykes and veins at the outset, the lineament interpretation was conducted without further reference to published geology maps, explanatory notes or literature on the geology of the area, to avoid partiality of observations of lineaments. No reference was made to information about orogenies and likely stress directions to avoid biases towards particular trends that may fit within "ideal" geometric patterns for specific deformational events. Likewise, bore locations and bore information were not taken into account at all whilst the lineament interpretation was underway.

Of ERMapper's image processing functions, the *zoom* (enlargement) and *pan* capacities were adequate to detect most of the lineaments in the imagery, with some linear contrast stretches (*transforms*) also utilised. The *sun angle* image enhancement function was experimented with, particularly east-west low angle illumination in an attempt to diminish the spectral dominance of linear sand dunes. However, it was felt that linear artefacts introduced through this filtering option were counterproductive to the interpretation.

There are inherent limitations in weighting lineaments that relate to their geological context. Lineaments that appear subtle or indistinct on the imagery may in fact be substantial structures in the near-surface and at depth, albeit with their character and magnitude obscured by a thin veneer of cover at the ground surface. The converse is also likely, i.e., less substantial lineaments may produce a stronger spectral signature than nearby major structures as a consequence of unrelated heterogeneous cover depths and compositions, and the influence of illumination factors involving the ground surface aspect, the Landsat sensor and the sun at the time of data collection. For this reason, different line weights were not assigned to the thousands of interpreted lineaments. The present study of such a vast area is a "first pass" exercise to annotate all visible lineaments, with no scope to assess the importance of all lineaments relative to each other or relative to their potential hydrogeologic significance.

The overlays proved to be too detailed for scanning so they were manually digitized by AGSO's Spatial Information Mapping Service on INTERGRAPH and subsequently converted into ARC coverages. Equal line weights were assigned to all lineaments[1]. Roads, tracks and seismic lines that had been tagged yellow on the original overlays were ignored in the digitizing phase.

RESULTS

Place names mentioned in this report are shown in Figure 2. Lineament maps at 1:750 000 scale are included as Figures 3-10 inclusive and named structures are shown in Figure 12. Contiguous portions of the northern Arunta Province and the Ngalia Basin are covered by the MOUNT DOREEN and LAKE MACKAY mapsheets, and lineament patterns therein may be expected to have some mutual geological/tectonic relationships so these maps are presented consecutively (Figs. 3,4,5,6). Similarly, the MOUNT LIEBIG and MOUNT RENNIE mapsheets cover contiguous portions of the Central and Southern Arunta Provinces and the Amadeus Basin so these maps are likewise presented consecutively (Figs. 7,8,9,10). Much information was obtained from the lineament study of the eastern sheets, MOUNT DOREEN and MOUNT LIEBIG, because of elevated topography and good rock exposure. In contrast, the lineament data for the western sheets, LAKE MACKAY and MOUNT RENNIE, is more sparse and perhaps more ambiguous in nature because of greater sand cover and/or marring by extensive fire scars. Greater detail and possibly more reliable information is, therefore, contained in the eastern sheets; these sheets are described first before their respective western counterparts.

The lineament maps are shown against a backgound of simplified geology and plots of the 1993 PAWA bore yield data. The latter are included reservedly for illustrative purposes only. For any given locality, a considerable "interpretative distance" exists between the lineament pattern and the bore yield even where there is excellent spatial correlation between good groundwater yields and major lineaments or dense, intersecting lineaments. The lineament map is a surface map whereas the bore yields represent variable sub-surface conditions and parameters that are not

[1] See also CONSIDERATION No. 2, below in this report, regarding line weighting of interpreted lineaments.

accommodated by either dataset so that no direct one-to-one relationship can be assumed. Furthermore, the 1993 bore-yield database contains some inaccurate data which are in the process of being validated and updated for the WWS. Therefore, the lineament maps plotted against bore yields (Figs. 4,6,8,10) are a means of presenting two sets of data which may be hydrogeologically related but which need to be combined with subsurface information and additional bore data for conclusive interpretations to be drawn.

The accompanying notes are not aimed at being comprehensive summaries of the whole lineament array nor exhaustive descriptions of the lineaments in terms of the geology and tectonics of each sheet area. The lineament maps themselves are the end-products of the sub-project, aimed at complementing ongoing geology and hydrogeology studies of the WWS area that are due for completion in 1997. The following notes outline lineament features that may represent geologic information that has not previously been mapped or documented and/or may be relevant to hydrogeological aspects such as infiltration, hydraulic conductivity, groundwater storage or discharge.

SF52-12 MOUNT DOREEN Figures 3 & 4

The most noteworthy lineament feature on MOUNT DOREEN is a broad, >30 km wide, WNW- to NW-striking lineament zone that diagonally traverses the whole sheet, i.e., greater than 150 km length. This lineament zone, tentatively called the Mount Wedge Fault Zone here (Fig. 12), is taken to be the surface expression of a regional-scale fault or shear system that continues beyond the map extent, and is most pronounced across the Ngalia Basin where it clearly propagates through thick Cainozoic cover. The zone continues across the Northern Arunta Complex in the northwestern corner of the sheet and the Central Arunta Complex in the southeast corner. In the latter corner the zone intersects the mapped NNW-striking Ghost Gum Fault zone plus other prominent and dense lineament networks in the Currinya Re-entrant - Central Mount Wedge area where the Stuart Bluff Range has been breached and deflected by the structures. The Mount Wedge Fault Zone represents a major structure that may be continent-wide in extent, i.e., the G3 Gravity Corridor of O'Driscoll (1986, 1990); Elliott (1996; pers. comm., 1996).

In the central-east sector of MOUNT DOREEN, north of the Currinya area of concentrated faulting, some of the interpreted northwest-striking lineaments (that are parallel with, or part of, the Mount Wedge Fault Zone) are seen to truncate a series of linear east-west orientated sand dunes. This truncation of a Quaternary dune field by inferred faulting/fracturing along a major fault zone correlates with evidence to the southeast, on the HERMANNSBURG mapsheet, where a continuation of the same northwest fault zone corresponds with deflection and kinking of a major creek, indicating recent reactivation of the zone (English, in prep.).

Conjugate to the Mount Wedge Fault Zone are numerous NNE- to N-striking lineaments that are particularly dense across the eastern half of the sheet. The conjugate pattern defines innumerable small rhomboid structures that may represent "rhombochasms" (Nilson & Sylvester, 1995) or "lozenge basins". On MOUNT DOREEN, the rhombochasms have approximate dimensions of the order of 5 x 5 km, although the structures overlap each other and have been cross-cut by E-W structures. The rhomb basins are probably still active structures that concentrate available sediment for basin in-fill; depocentres tend to migrate parallel to the most active strike-slip margins resulting in extraordinarily thick sedimentary sections in small basins (Nilson & Sylvester, 1995). The shape of such strike-slip faults in the vertical section is ideally a "flower structure" (Twiss & Moores, 1973). A double flower structure involving basement layers has in fact been interpreted from seismic data in the middle of the Ngalia Basin, at Newhaven Gas Prospect, by Deckleman & Davidson (1993). Such zones would greatly influence groundwater flow and storage in the area, the Cainozoic layers being of immediate interest.

Across the northern third of the MOUNT DOREEN sheet area, in schists and granites of the Northern Arunta Province, numerous Mesoproterozoic faults have been previously mapped and documented (Young & others, 1995) who note that these faults are commonly marked by ridge-forming quartz veins suggestive of a strike-slip, possibly transtensional regime. A great number of these gently arcuate E-W striking fault/vein networks are expressed in the Landsat TM imagery, most clearly in the haematite/goethite *unmixed mineral* image, which complement the previously mapped faults and veins of the Northern Arunta Complex.

The Central Arunta Province occupies the southern part of MOUNT DOREEN sheet. The area is largely granite-gneiss terrain. The previously mapped main structures are the E-W striking Gurner Fault Zone along the southern margin of the Ngalia Basin, and the E-SE striking Lake Bennett Fault that parallels the Siddeley Range (Shaw, 1994). The lineament study shows a major E-W fault zone to be present south of the Gurner Fault, tentatively named Black Hill Fault Zone here. The newly interpreted zone is some 20 km wide with many of the constituent lineaments having lengths of 15 - 30 km. The zone affects granite, gabbro norite, quartzite, Cainozoic sediments and playas, the latter indicating that the structures are still active. In the west this fault zone appears to be discrete from the mapped Gurner Fault Zone although both zones converge in the Currinya area in the east. This major zone correlates closely with the edge of the aeromagnetic anomaly for the Andrew Young norite pluton, west of Lake Bennett. The anomaly suggests that the pluton is steep-sided and the lineament map shows that the pluton, as expressed magnetically at depth, is bounded on all sides by major lineaments that are visible at the surface in the imagery. The spatial correlation is conspicuous although the temporal relationship between the Proterozoic pluton and the regional scale lineaments is uncertain.

High densities of fractures have been interpreted for the Vaughan Springs Quartzite, the basal unit of the Ngalia Basin. The quartzite is erosionally resistant and upstanding on rangetops. The high density of fracturing is readily apparent in outcrop. The lineaments represent pervasive brittle fractures that have been subject to considerable fissuring as a result of tectonic relaxation following compressive episodes. Fissuring may also represent insolation weathering in response to present-day diurnal temperature extremes. The fractures have evolved into rills and gullies on the range slopes. Many such lineaments are seen to continue from the quartzite through adjacent lithologies. All the above factors indicate that the fractured quartzite ridges are important recharge areas.

Mapped exposures of the high-yielding Kerridy and Mount Eclipse Sandstones in the northern Ngalia Basin are traversed by numerous lineaments, the northwesterly trend being most conspicuous. Conjugate intersections correspond well with high-yielding bores, Blue Bush and Sandstone Bores in the Wailbri Ranges being most outstanding.

Numerous lineaments traverse alluvial fans within the area. Whilst these may correspond with structures that played a role in fan formation and propagation, they are also likely to function as conduits for recharge waters from the adjoining ranges to possible aquifers within the fans themselves.

The major groundwater discharge zone across the south of MOUNT DOREEN that comprises Lake Bennett and Currinya salt lakes and the broad expanse of calcrete in-between, coincides with numerous lineaments. The above noted E-W Black Hill Fault Zone appears to be particularly important in this regard.

SF52-11 LAKE MACKAY Figures 5 & 6

Thick Cainozoic cover obscures large portions of the sheet area across which few or no lineaments are discernible. Interpreted lineaments are generally less than 10 km in length, rarely reaching 30 km, although some discontinuous lineaments with greater extrapolated lengths are represented. The obscured area southeast and east of Lake Mackay was possibly a depocentre for Late Palaeozoic deposits sediments pouring westward towards the Canning Basin off the Central Uplands following the Alice Springs Orogeny. Even if these particular deposits were subsequently relocated, this area east of Lake Mackay was a Tertiary depocentre for fluvio-lacustrine sediments transported from the mountains in the east.

The broad east-west Black Hill Fault Zone, noted above, that crosses the south of MOUNT DOREEN continues in a gentle arc onto LAKE MACKAY, defining the southern boundary of the Ngalia Basin, and possibly continues into Western Australia (to "Lasseters Shear Zone"?). The zone here is narrower and more attenuated than it is in the east.

Extensive conjugate zones of NW- and NNE-striking lineaments traverse LAKE MACKAY.

Apart from the above noted observations, the lineament patterns are relatively haphazard. This may be an illusion because continuations of the lineaments beyond the outcrops or subcrops often cannot be perceived through the thick surrounding cover, giving the effect of islands of multidirectional lineaments rather than mappable through-going features.

Numerous lineaments are visible within the Lake Mackay salt lake itself. These may be shallow features because there is little correspondence between these and deep major faults interpreted in the aeromagnetic imagery. The TMI image suggests the presence of a major "horsetail" splay fault that fans from the western edge of the LAKE MACKAY mapsheet, beneath the salt lake, eastward across half the sheet area. This fault system is prominent at depth although it is not clearly manifest in surficial lineaments. In addition, numerous large- to medium-scale E-W trending subparallel linear trends of low magnetism dominate the aeromagnetic image for much of the sheet area. These are probably E-W striking faults. These structures are obscured beneath younger cover and are not evident in the Landsat TM imagery.

Towards the northwest corner of LAKE MACKAY, immediately east of the playa itself, a large area of weathered/lateritic granite is moderately densely fractured. Fracturing and exacerbated fissuring along such zones would enhance secondary porosity and permeability of the weathered granite.

SF52-16 MOUNT LIEBIG Figures 7 & 8

East-west lineament zones dominate MOUNT LIEBIG, traversing the whole sheet. The lineament lengths range from tens of kilometres to over 100 km. These zones correspond with the major E-W orientated mountain ranges and valleys. The prevalent E-W trends represent bedding traces of the strata of the northern Amadeus Basin, the Redbank Thrust Zone and other east-west faults. In the west of the sheet area, the Redback Thrust Zone appears to swing from its east-west strike to a west-southwesterly one, the latter defined by a zone of continuous lineaments more than 5 km wide.

In the southeast corner of MOUNT LIEBIG, the E-W structural trend swings north-westerly in consonance with the Gardiner Range Anticline. These numerous NW-striking lineaments extend northwest beyond the range itself to traverse the whole mapsheet. They form pervasive cross-cutting intersections with the E-W lineaments.

A northwesterly grain across the whole MOUNT LIEBIG sheet is very nearly as prevalent as the E-W trend. Many of the individual NW lineaments are of the order of 30 km long. The northwest lineament zones traverse the Central and Southern Arunta Provinces as well as the Amadeus succession and have clearly propagated through Cainozoic cover.

A high density of lineaments with N-S or nearly-northerly azimuth trends have been interpreted across MOUNT LIEBIG, particularly within the eastern third of the sheet where exposure is excellent. Lineament lengths range from < 5 to 30 km. Lineament networks are very dense in the topographically elevated areas, with correspondingly high numbers of lineament intersections. The northerly trend is particularly dense along the northern flank of the Belt and Amunurunga Ranges and parallel ranges to the west, averaging at least one interpreted sub-parallel lineament every kilometre for a distance in excess of 120 km east-to-west. These may represent dilational structures along the Redbank Thrust Zone front, a response to extreme N-S crustal shortening along the zone. They may be particularly important conduits for recharge waters from the ranges, facilitating infiltration into the flanking alluvial fans and other potential aquifers beneath the plains to the adjacent north. Alluvial fans in this vicinity include important aquifers that supply Papunya and Mount Liebig communities.

At Atji Creek, in the Haast Bluff area, fractured weathered and fresh Arunta gneissic granite beneath shallow sediments produced reasonable yields during recent drilling (Sam Burton, PAWA, written comm. 1996). A high density of lineaments has been interpreted for the area, N-S and E-W strikes being prevalent.

The notes above for MOUNT DOREEN, pertaining to the nature of dense fracturing of the Vaughan Springs Quartzite, apply equally to the Heavitree Quartzite, the basal unit of the Amadeus Basin, which occurs on the MOUNT LIEBIG and MOUNT RENNIE sheets. The unit is probably important to recharge of areas close to the ranges, with the dense fissures facilitating infiltration of water to adjoining lithologies.

The best-yielding bore (>5 L/sec) in the Amadeus Basin half of MOUNT LIEBIG coincides with Mereenie Sandstone at the ground surface and the attenuated nose of the Gardiner Range Anticline; additionally, a 20 km long east-west lineament cross-cuts the bore location.

Putardi Spring appears to be situated at the contact between granite and overlying Arunta quartzite/schist and spatially associated northeast-striking joints.

The Cainozoic Tarrawarra Basin, in the south-central sector of MOUNT LIEBIG, immediately west of the Idirriki and Gardiner Ranges, is traversed by a strongly defined northwest-striking lineament zone. This zone is continuous with the northwesterly fold axis and parallel bedding traces of the Gardiner Range Anticline, noted above. One of the component lineaments appears to have deflected and bifurcated Deering Creek in the centre of Tarrawarra Basin. The basin is nestled between major Amadeus Basin folds and corresponding ranges that suggest good recharge potential, enhanced by series of fractures that lead from surrounding bedrock topographic highs into the basin. Based on their seismic data, various petroleum explorationists working in the Amadeus, have suggested that the Tarrawarra Basin may be highly favourable hydrogeologically (L. Rowe, pers. comm., 1994).

A large body of calcrete, covering some 75 km^2, is located west of Tarrawarra Basin, occupying a topographic low and coincident synclinal core between Glen Edith Hills and the Cleland Hills. A dense network of lineaments criss-cross the calcrete; many of the lineaments being continuous to outcrop areas. The mapped cross-section through here on the published MOUNT LIEBIG 1:250 000 geology sheet (Wells & others, 1961) shows that, beneath Quaternary cover, the syncline is exhumed down to Mereenie Sandstone. This calcrete body may, therefore, be a discharge zone in the valley floor for groundwater seeping from the underlying Mereenie Sandstone aquifer, with the discharge a function of topographic depression and possibly also facilitated by the network of intersecting lineaments.

Muranji Rockhole in the Cleland Hills, at the contact between the heavily jointed Mereenie Sandstone and the underlying Carmichael Sandstone is sited at the intersection of several lineaments. This permanent water source is regarded as particularly important given that archaeological evidence suggests that Aboriginal people were present here even during periods of greatest aridity in central Australia (Smith, 1989).

SF52-15 MOUNT RENNIE Figures 9 & 10

North-south lineaments dominate MOUNT RENNIE, particularly the eastern half of the sheet. These traverse the Arunta Complex and Amadeus Basin provinces alike.

The east-west lineaments that are so dominant on MOUNT LIEBIG to the east continue across the eastern part of MOUNT RENNIE but are not notable in the west. The continuation of the Redbank Thrust Zone in the west is ambiguous. The previously mapped portion in the Kintore Range is due west from, but not contiguous with, the main zone on MOUNT LIEBIG, and a branch of the structure may be represented by interpreted W-SW trending lineament zones.

Conjugate systems of NW- and NE-striking lineaments are well represented. Individual lineaments in these systems attain maximum lengths to 5 - 15 km.

High-yielding bores on MOUNT RENNIE include those at Kintore where the dense fracture networks enhance both recharge from the Heavitree Quartzite rangetop and the hydraulic properties of the underlying volcanic aquifer itself (Wischusen, 1994).

Both the Pacoota Sandstone and the Mereenie Sandstone of the Amadeus Basin are exposed in broad-scale synclinal folds across the southern half of the sheet area. Most lineaments corresponding with these formations represent parallel bedding traces rather than cross-cutting fractures.

Curving southward across the south-central section of MOUNT RENNIE, a chevron-shaped calcrete zone, 1 to 5 km wide, defines an inferred palaeoriver that probably once fed the Lake Neale - Lake Amadeus system in the south. The palaeoriver course curves sharply around the nose of a regional-scale Amadeus Basin syncline. To a large extent the palaeodrainage course follows folds of Mereenie Sandstone.

On MOUNT RENNIE natural discharge or perched water tables occur at Ilbilli Soak and Willie Rockhole. Ilbilli Soak is on Arunta Complex gneissic granite proximal to the Redbank Thrust and a swarm of northerly to north-northeasterly dolerite dykes. Willie Rockhole, east of Kintore, is in Arunta gneissic granite and spatially associated with NNW and WNW lineaments.

SYNTHESIS MAP

Figure 11 summarises predominant individual lineaments and zones of subparallel lineaments that may represent regional-scale structures having lengths of tens to hundreds of kilometres. These large, through-going lineaments or "regional lineaments" were progressively built up on both 1:250 000 and 1:1 000 000 scale hard copies of the lineament maps. The latter was a composite of the four sheets of the study area which afforded a synoptic overview that enhanced visibility of continuous trends traversing the whole study area.

In extrapolating regional-scale structures from the lineament array, the only criteria that can be accomodated are the *length* of a lineament or the interpretable *continuity* of a series of (sub)parallel lineaments. The actual magnitude and nature of a structure that surface lineaments may represent cannot be ascertained solely from linear traces visible on Landsat imagery. In reality, some major structures may not be visible at all because of cover material or sun angle and aspect of the particular landscape area relative to the satellite sensor. Conversely, minor surficial features may be readily discernible in the imagery and appear to be of regional extent because of the lack of cover material or parallelism with other features along a given zone. Conspicuousness does not necessarily equate with geological importance. Perceived length at the ground surface or breadth of a zone of subparallel lineaments cannot be the sole criteria with which major geological structures can be defined. The "regional lineament"or "synthesis" maps, therefore, need to be used interpretively with other datasets to designate major structural elements in the WWS area.

Notwithstanding these limitations, the overview map built up from the lineaments alone provides a clear picture of major crustal signatures that characterise the region. Most of the regional-scale lineament zones correspond to the following four general strike directions:

East-west: These are wide lineament zones (to 20 km width) made up of numerous subparallel lineaments. Some of these zones are undulose with wavelengths exceeding 100 km. Named examples include the Redbank Thrust Zone, the Gurner Fault Zone, the Black Hill Fault Zone, the Yuendumu and Waite Creek Thrusts, and lesser zones associated with Weaner Fault Zone and Coxs and Treachery Schist Zones (Fig. 12). Unnamed zones in this category are present through the Idirriki and Gardiner Ranges. The major fold structures of the region have east-west axes, parallel with the lineament zones. In the western half of the study area the east-west lineament zones swing southward to west-southwest directions; these include the Waite Creek Thrust and the main structures of the western Amadeus Basin. This regional swing from the prevalent east-west trend in the east to a west-southwest trend in the west defines a "half croissant" (as termed by Gladys Warren, pers. comm., 1996) across the 300 km width of the whole study area. The nature of the western extent of the Redbank Thrust Zone is unclear in all datasets: mapped geology, lineament interpretation, and aeromagnetic imagery. East of the Ehrenberg Range, the Redbank Thrust Zone seems to break up completely. Whilst it has been mapped further west, in the Kintore Range, there is the possibility that southward-veering splays of the Redbank Thrust Zone system may be represented by some of the mentioned W-SW striking lineament zones.

North-south: At least nine north-south striking lineament zones traverse the study area, roughly one such zone every 50 km east-west across the area. Pairs of these may represent N-S corridors rather than discrete zones. Most of the north-south structures are deflected mildly at major cross-cutting lineament zones which may invoke syn-orogeny of the respective structures.

Northwest: This lineament trend is a dominant one across the study area, although there is variation in the azimuth directions of zones in this general category. The trend comprises singular, continuous lineaments and composite zones both of which traverse the whole study area. Up to a dozen such zones are evident although some may represent very broad "corridors" (greater than 30 km wide) that cannot readily be sub-divided into discrete structures. The so-called "northwesterly" zones tend to fall into two general azimuth classses: WNW-to-NW (300° - 315° azimuth) which is dominant across MOUNT DOREEN (e.g., the so-called Mount Wedge Fault Zone), and slightly more north-northwesterly trends (315° - 330°) across the whole study area.

Northeast: Up to nine northeast-striking zones, represented by either singular lineaments or composite lineament zones, with widths less than 10 km, traverse the whole study area.

Simplistically, the dominant lineament directions correspond roughly with the cardinal directions: N-S, E-W, NW-SE, NE-SW. Importantly, these major lineament zones are seen to be continuous across the different geological provinces: the Northern Arunta, the Ngalia Basin, the Central and Southern Arunta, and the Amadeus Basin. It is probable that the prevalent lineament zones represent structures developed during, or substantially reactivated during, the latest major orogeny of the region, the Late Palaeozoic Alice Springs Orogeny and that, at the macro-scale, these dominate or overprint earlier structures. Some of the major structures probably relate to Proterozoic deformations that were subsequently reactivated during the Alice Springs Orogeny. The continuity of these structures across adjoining provinces and through younger cover material indicates that the principal stress direction that are accountable for the conspicuous structures prevailed, to some extent, through post-Palaeozoic times.

The structure and tectonics of central Australia is well-documented in the literature (e.g., Shaw & others, 1984; Bradshaw & Evans, 1988; Shaw, 1991, 1994; Collins & Shaw, 1995; Warren & Shaw, 1995). The Alice Springs Orogeny reactivated structures related to the Cambrian Petermann Orogeny and precursor tectonic events of the Late Proterozoic. The principle stress direction for the Alice Springs Orogeny was north-south which resulted in compression in this direction involving thrusting along east-west striking faults and folding along east-west fold axes. Thrusting of north block over south block was the prevalent brittle movement in the regime. East-west extension associated with north-south compression resulted in normal faulting along north-south faultlines. North-south compression and east-west extension invoke dextral (right strike-slip) shear on NW-striking brittle structures, given that the compressional relationship for the region is north block over south block. Dextral strike-slip movement is particularly evident on MOUNT DOREEN where the quartzitic Stuart Bluff Range has been drastically deflected along the most major of these northwesterly zones. NE-striking brittle structures in such a regime are expected to be subject to sinistral (left strike-slip) shear. To the east of the study area, the major northwesterly Mount Wedge Fault Zone can be interpreted to intersect the Redbank Thrust Zone at Mount Heuglin, in what must have been a major transpressive area.

This dominant northwesterly trend is parallel to Mid-Proterozoic *transfer* or *accomodation* zones of the central and eastern Amadeus Basin (Lindsay & Korsch, 1991) that functioned as depocentres for Late Proterozoic and Palaeozoic sedimentation. The northwest structure through the Ngalia Basin probably originally relates to the Proterozoic basement and the Petermann Orogeny. This broad northwest dextral zone which dominates the lineament map for MOUNT DOREEN may represent an accomodation zone and depocentre through the Ngalia Basin, similar to major parallel structures in the Amadeus Basin.

According to Nilson & Silvester (1995) geometric relations associated with north-south compression and dextral shear on major NW structures (representing a Principal Deformation Zone) invoke extension along N-S structures and a range of deformational effects along NW-striking structures. In an ideal situation with a north-south axis of principal shortening, the Principal Deformation Zone is near to due northwest (~315°); structures with azimuths of less than due northwest (e.g., ~300°) tend to be fractures; and those greater than due northwest (to ~330°) tend to be dextral synthetic Riedel shears. NE or NNE-striking structures in such a pattern would ideally be sinistral antithetic Riedel shears.

PROMISING LOCATIONS FOR GROUNDWATER

Accessible groundwater is a function of lithology, structural characteristics, geomorphology, water table depths and logistical considerations. Based on the information derived from the present study and lineament studies conducted overseas, certain criteria pertaining to fractures can be used to help designate favourable groundwater localities in the WWS area. These criteria need to be tested and combined with other datasets and qualitative information for nomination of specific drill targets.

Two parameters pertaining to fractures influence the hydraulic conductivity of a zone: *length* and *interconnectedness*. The length of a fracture system is related to the probable groundwater yield (Teeuw, 1995). Long fractures and dense networks of fractures have been found to favourably influence the three-dimensional hydrodynamic behaviour of groundwater reservoirs. Intersections of major faults/fractures in particular are prospective because they are likely to represent intensively developed parallel fissuring and channels which are either open or filled with unconsolidated material (Pinnekar, 1980). Comminution of rock at intersections is the expected result of crushing, grinding and rubbing in response to tectonic movements and preferential weathering and erosion around such loci. Contacts between adjoining lithologies may be particularly important zones because of differential shear of respective rock types: more competent lithologies may withstand imposed stresses at the expense of less competent adjacent lithologies which may be subject to collapse and intensified fracturing/fissuring (C. Elliott, pers. comm., 1996).

In the WWS, both the dilational effects on N-S structures and shearing along respective diagonal zones (NW and NE-striking) can be expected to greatly enhance hydraulic conductivity through the region. The intersections of such structures in particular and of all intersections in general are considered to be very important hydrogeologically.

ARUNTA BLOCK

Since hydraulic conductivity in crystalline basement is wholly dependent upon secondary porosity and permeability, fracture systems and weathered zones need to be targeted for groundwater exploration in the Arunta Block itself.

Dense fracture systems, in particular, long, continuous fractures and intersections or conjugate shears, should be targeted if groundwater supplies are required from the crystalline basement. North-south structures are thought to be dilational and therefore conducive to enhanced fluid flow although this theory needs to be tested.

Runoff from protruding outcrops of granites and gneisses (or via unloading structures in such landforms) may result in localised groundwater albeit in possibly younger surficial/isolated aquifers. In general, valley areas in the Arunta Block, coupled with areas of high lineament density, are favoured.

NGALIA & AMADEUS BASINS

The prime target areas are dense fracture systems, in particular, long, continuous fractures and intersections or conjugate shears involving the Mereenie and Pacoota Sandstones in the Amadeus Basin or the Kerridy and Mount Eclipse Sandstones in the Ngalia Basin. The subsurface extent of the folded Amadeus units can, to some extent, be extrapolated from the broad anticlinal and synclinal structures and seismic data. Similarly, the subsurface continuation of the Kerridy and Mount Eclipse Sanstones beneath Cainozoic cover can be extrapolated from available stratigraphic drillholes and seismic data. In areas of intersecting fractures, drilling through shallow cover material into these favoured lithologies at reasonable depths should be feasible.

North-south structures that resulted from the Alice Springs Orogeny, and which have possibly been reactivated since then, are regarded as extensional/dilational zones. Therefore, groundwater flow within N-S lineament zones is likely to be greater than within the compressional (E-W and diagonal, NW and NE) structures, depending upon secondary fissure characteristics. Intersections involving north-south lineaments and other trends are therefore favoured for groundwater concentrations.

CAINOZOIC

In the Ngalia Basin, the major northwesterly-striking dextral strike-slip zone, centred on the Mount Wedge Fault Zone, is modestly dynamic given that the setting overall is regarded as a stable craton. The edges of the numerous small rhomb basins of Cainozoic sediment are likely groundwater concentrations, particularly nearer the Currinya area. This broad zone through Cainozoic sediments across the Ngalia Basin is likely to be hydraulically connected, in terms of both lateral groundwater flow in the Cainozoic sediments themselves and probably between the Cainozoic and bedrock aquifers given that the interpreted structures extend to great depths.

Alluvial fans serve both as recharge zones and as aquifers. Fractures interpreted in and around the fans enhance hydraulic conductivity in these already porous units.

OTHER CONSIDERATIONS

1. There are numerous vehicular tracks within the study area that are not shown on the published 1:250 000 topographic maps. Some of these tracks may have been unavoidably interpreted as geological lineaments in the present study. This likelihood should be borne in mind for any follow-up work that involves the lineament interpretation.

2. In the interpretation, discrimination between definite and less-definite lineaments was subjective, based on spectral contrasts and the form of observed linear features. As the project progressed and identification became easier, the resultant

tendency was for lineaments that early on would have been deemed subtle (i.e., annotated in green on the original overlays, see Methodology Section) became more evident and would have accordingly been weighted black if they had been interpreted at a later stage. Moreover, when the mineral unmixed imagery, the *Fe-oxide unmixed* imagery in particular, was subsequently interpreted, lineaments that had been marked as subtle from the ratioed images (green annotations) immediately stood out with more definite spectral signatures. The latter lineaments were not reannotated in purple. Notwithstanding this somewhat "shifting scale" between definite and less-definite Landsat features, digitizing was done on the basis of individual colour from the composite black + green + purple interpretation overlays to produce separate subsets that, together, make up the LINEAMENT dataset.The separate subsets should be used with reservations for the above reason and because conspicuousness does not necessarily equate with geological/hydrogeological importance.

3. Fractures infilled with quartz or dolerite may restrict groundwater flow. For instance, in Teapot Creek Yard area on HERMANNSBURG, adjacent to the WWS area, a dense east-west striking doleritic dyke swarm intrudes coarse-grained granite-gneiss of the Arunta Complex. Although mildly metamorphosed, the vertical dykes are not weathered nor recessive, and, in fact, they protrude well above the differentially eroded surrounding rock. Although the synoptic view here reveals a dense system of major lineaments (along with potentially good run-off/recharge from steeply surrounding mountains), ground investigation reveals that permeability cannot be enhanced by these closed and seemingly impermeable structures. Even the contacts between the dykes and the granite do not appear to accomodate fluid flow from the surface catchment. The possibility of in-filling of interpreted structures with quartz, pegmatitie, aplite, dolerite, secondary iron oxide precipitates or occluding fault gouge needs to be borne in mind when targeting fractured areas for follow-up work.

4. The occurrence of widespread horizontal sheeting within the extensive granitic areas of the WWS area cannot be accommodated in a Landsat-based interpretation of surface lineaments. Near-horizontal fractures parallel to the ground surface are attributed to the removal of overburden load caused by erosion. In the HERMANNSBURG sheet area, unloading structures are conspicuous in granite inselbergs that protrude through a Cainozoic plain (P. English, unpublished data). Horizontal fractures at relatively shallow depths in the Arunta igneous rocks of the WWS area may be an important source of water supply yet these are not represented on the Landsat-derived lineament maps. Freeze & Cherry (1979) note that the frequency and aperture of sheet fractures decrease rapidly with depth, and that fractures of this type may be important contributors to permeability at depths up to about 100 m.

5. Many fractures owe their origin to near-surface stresses related directly or indirectly to topographic conditions (Freeze & Cherry, 1979) and in many crystalline areas, bore-yields are consequently related to topography. Freeze & Cherry cite a study conducted in North Carolina where bore yields are highest in valleys and lowest at or near the crests of hills. Yields in flat uplands and beneath slopes are between these extremes. Valleys often develop along fault zones, an observation borne out in the present study. Bore yields may consequently be influenced by two spatially related factors: greater infiltration in the valleys due to run-off from surrounding slopes, and

the tendency for greater permeability in fault zones. This assumption perhaps needs to be qualified in regions such as arid central Australia where bores are abstracting palaeowaters, and the relationship between basement faults, valleys and bore yields many not be so simple. However, given the extremely slow denudation rates in this region that has been subaerial since the Palaeozoic, and the antiquity of major structures, it is reasonable to assume that the gross topography here has altered little since the Mesozoic. The maximum age of dated groundwater in the Amadeus Basin, for instance, is about 0.6 m.y. (Jacobson & others, 1994); and the topography of the overall region has probably not changed significantly during the Quaternary, at least in terms of valley-and-ridge axes and major landforms. Paleo-recharge source zones and groundwater flow directions in bedrock aquifers are, therefore, expected to be consistent with present-day topography and subsurface configurations.

6. There is an anticipated relationship between faults, Tertiary river valley courses and potential bore yields of aquifers from these zones. Interrelatedness in these settings is compounded if major drainages follow fault zones and the drainages deposit fluvial sands along those lines; the unconsolidated fluvial sands themselves become aquifers for younger recharge events. Permeabilities of such aquifers would be further enhanced by later reactivation of the original fault zones which continue to occupy valley axes. Topography and lineaments, therefore, need to be interpreted together to pinpoint drill sites in both bedrock and Cainozoic areas. In arid regions, however, the topographically low zones are not only likely to contain concentrations of groundwater but of solutes as well.

7. Numerous, mostly NW-trending, lineaments angled diagonally to the east-west linear trend of regional sand dunes have been interpreted in dunefields at the centre of the WWS study area, i.e., encompassing the common corner of all four 1:250 000 sheets. These lineaments may be either reflections of underlying geological lineaments, such as fractures, propagated in the relatively sand-free, clayey interdunal swales or "feathered" dunes, i.e., fringes on the edges of the linear dunes formed by oblique winds after the trunk dunes were established. The resolution of the Landsat TM data does not allow identification of the nature of these lineaments. In some instances the noted lineaments are continuous with or parallel to lineaments in adjoining areas that do not support dunes, so the former option is favoured. Moreover, feathered dunes have rarely been reported from Australia. There is minor correlation between some of these lineaments in this central dunefield and parallel edging of a magnetic anomaly in the underlying basement, suggesting that these trends may be intrinsic to the geology rather than being peripheral dunal features. Unlike structures on MOUNT DOREEN that completely disrupt a series of linear dunes, as discussed above, the latter dunes remain intact with the lineaments visible only in the interdunal swales. This suggests that these inferred fractures were propagated or reactivated prior to Quaternary dune formation and affected the substrate through the area.

8. It is evident that many of the salt lakes and playa margins in the region correspond with high densities of intersecting fractures which are saturated. Here, the fractures are conduits for groundwater discharge rather than for recharge or storage. At Lake Lewis, east of the WWS area, granitic Arunta Block basement is believed to be shallow beneath the playa system, as evidenced by bounding granite inselbergs, and by seismic data. Groundwater discharge at Lake Lewis seems to be from near-surface

basement faults and fractures as well as from Cainozoic strata (the system here also receives rare surface water fed from surrounding creeks, deltas and uplands). The Lake Bennett to Currinya discharge zone in the WWS area, may similarly represent a series of springs fed under hydraulic pressure from local Cainozoic stratal and fissure groundwater and/or saturated fractured bedrock. In such a setting, aligned springs or seepages may trace the fault zone at the ground surface; this may correspond with linear enhancements of vegetation density in some environments. In the case of salt lakes of the WWS area, fault or fracture traces are rendered visible by linear concentrations of evaporites that have precipitated from discharging water as it evaporates at the playa surface preferentially along the structures.

9. Within calcrete expanses of the playa margins and in calcreted palaeochannel zones, faults and fractures are frequently delineated differently from the lineament character of the salt lakes themselves. Alignments of dolines or sink holes are visible in some of the calcrete settings, and the sizes of these must be considerable given the 30 m pixel resolution of the Landsat data. These features are particularly evident in the Fe-oxide *unmixed mineral* imagery. The dolines probably represent karstic dissolution hollows formed from percolating surface waters descending preferentially down fracture lines following occasional overflow of meteoric water during storm rainfalls. The dissolution hollows are likely to be cavernous below the ground surface, with consequent increased interconnectedness of these "chemical fissures" beneath the surface of the calcrete zones.

10. In the Cainozoic aquifers, the different sediments (gravels, sands, calcretes, clays) of respective aquifers have different infiltration rates and recharge characteristics. Cross-cutting fractures are likely to affect the respective sediments differently, further affecting the complexity of recharge, conductivity and storage capacities of adjacent aquifers. The interplay is complex both spatially and temporally, involving topography, sedimentary environment, sediment porosity and permeability, fracturing, depth of water table, recharge events, degree of mixing of modern recharge water within a given aquifer, and degree of mixing between interconnected aquifers.

11. The relationship between lineament trends and hydraulic conductivity is not straightforward. Brittle deformation causes derivative shears of several orders to form successively more deviating trends. Thus, fractures interpreted from the 30 m pixel resolution data may represent subordinate systems of associated shears that are not visible at this resolution. Even in a homogeneous rock mass, the latter are not necessarily parallel to the primary structures nor do they share the same character and magnitude. The complexity is exacerbated in heterogeneous lithologies and when ancient structures are subject to successive deformation under varying stress regimes. No assumptions concerning groundwater flow in the interpreted fractured rocks of the WWS area have been made in the present regional study.

12. Pinneker (1980) itemises inherent difficulties in establishing paths along which subsurface water moves in fissured rocks, in the designation of water-bearing zones in such aquifers and the depth of intensive fissuring in these zones. Additional to the structural features such as the orientation, length and intersection of fractures that are the focus of the present study, other parameters determine the water-bearing capacity of fractured rocks. These include: the apertures of fractures; and void ratios,

i.e., the degree of openness of the rock brought about by stress-relief expansion, and weathering along the fractures. The latter mesoscale- to-microscale parameters are beyond the scope of the present regional-scale study.

13. Larsson (1984, p.54) advises that, when drilling, the chances of intersecting fractures decrease rapidly when the fracture dip exceeds 70°: "For a given spacing of fractures, the probability of intersecting a fracture while drilling a well decreases with the increase in fracture dip magnitude, being maximum in rocks with sheet fractures and minimum in vertically fractured rock...To optimize well yield, drilling, ideally, should be at right angles to the attitude of the principal fracture system in the area of greatest fracture frequency". The dips of interpreted faults/fractures cannot be ascertained from a two-dimensional surface study, however, this consideration needs to be borne in mind for drill targets that are based on or that incorporate the lineament interpretations.

RECOMMENDATIONS

1. In future regional studies of groundwater in arid areas, a relatively low-cost lineament interpretation of Landsat TM imagery should be carried out early in the project, prior to location of expensive ground geophysical surveys and exploratory drilling programs.

2. The greyscale Fe-oxide *unmixed mineral* processed Landsat TM imagery proved to be the most beneficial to the lineament interpretation. The second most useful was the colour ratioed imagery. In future studies of comparable environments it is recommended that interpretation of similarly processed Landsat TM imagery be done in the following order: Fe-oxide *unmixed mineral*, colour ratios, Quartz *unmixed mineral*, and Clay *unmixed mineral* imagery.

3. Favoured areas need to be ground-truthed to ascertain that fracture networks are not in-filled with quartz, dolerite or other occluding secondary in-fill that would inhibit hydraulic conductivity. This information may alternatively be derived from stereoscopic examination of large-scale aerial photographs of areas of interest.

4. The lineament datasets for the WWS can be combined with plots of known high-yielding aquifers, e.g. the Mereenie and the Kerridy Sandstones, to delineate prime areas of interest.

5. The lineament datasets can be plotted with maps of alluvial fans and palaeodrainage systems to help target Cainozoic aquifers.

6. Geometrical or statistical analysis, such as Rose Diagrams, Fracture Density Indices (FDI), density contouring and kriging to make predictions of fracture densities over covered zones could be considered for specific areas or specific lithologies in the WWS area. For example, analysis of areas of the Kerridy Sandstone aquifer that are obscured by shallow cover could predict fracture orientations and densities in localities of interest. Caution would be required, however, with such analysis of covered areas where the obscured lithology may not be homogeneous or may not be flatlying. For instance, the Mereenie Sandstone is variably folded throughout the study

area so geometrical or statistical analysis of covered areas adjoining exposures of the aquifer may implicate lithologies other than the targeted one unless structural configurations are accommodated.

ACKNOWLEDGEMENTS

I thank the following AGSO people for their assistance with the project: J.E. (Libbie) Lau for organising the datasets used for the study and for helpful discussions about the area; Evert Bleys and Phil Bierwirth for excellent processing of Landsat TM data; Lynne Woodcock, Gayle Young and David Champion for technical assistance; John Creasey for advice on lineament analysis; and Ross Hill, Gayle Young, Vicki Manson and staff at the Spatial Information Mapping Service, AGSO, for digitizing the lineament maps and generation of these into ARC coverages. David Champion, Phil Bierwirth and Gladys Warren read a draft of this report and offered welcome suggestions for its improvement.

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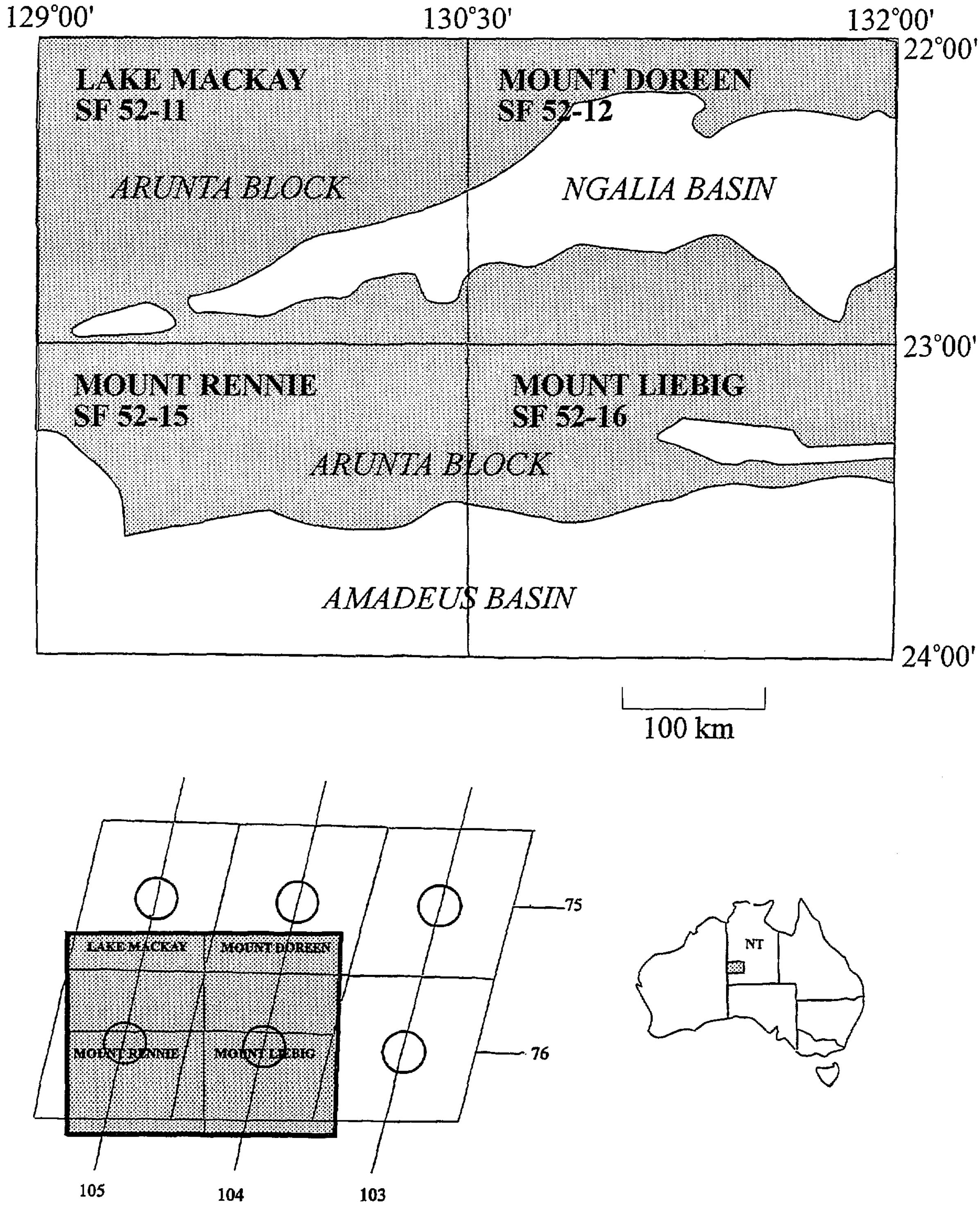

Figure 1. Western Water Study area. Location of the four 1:250 000 sheets relative to the main geological provinces; Landsat TM coverage.

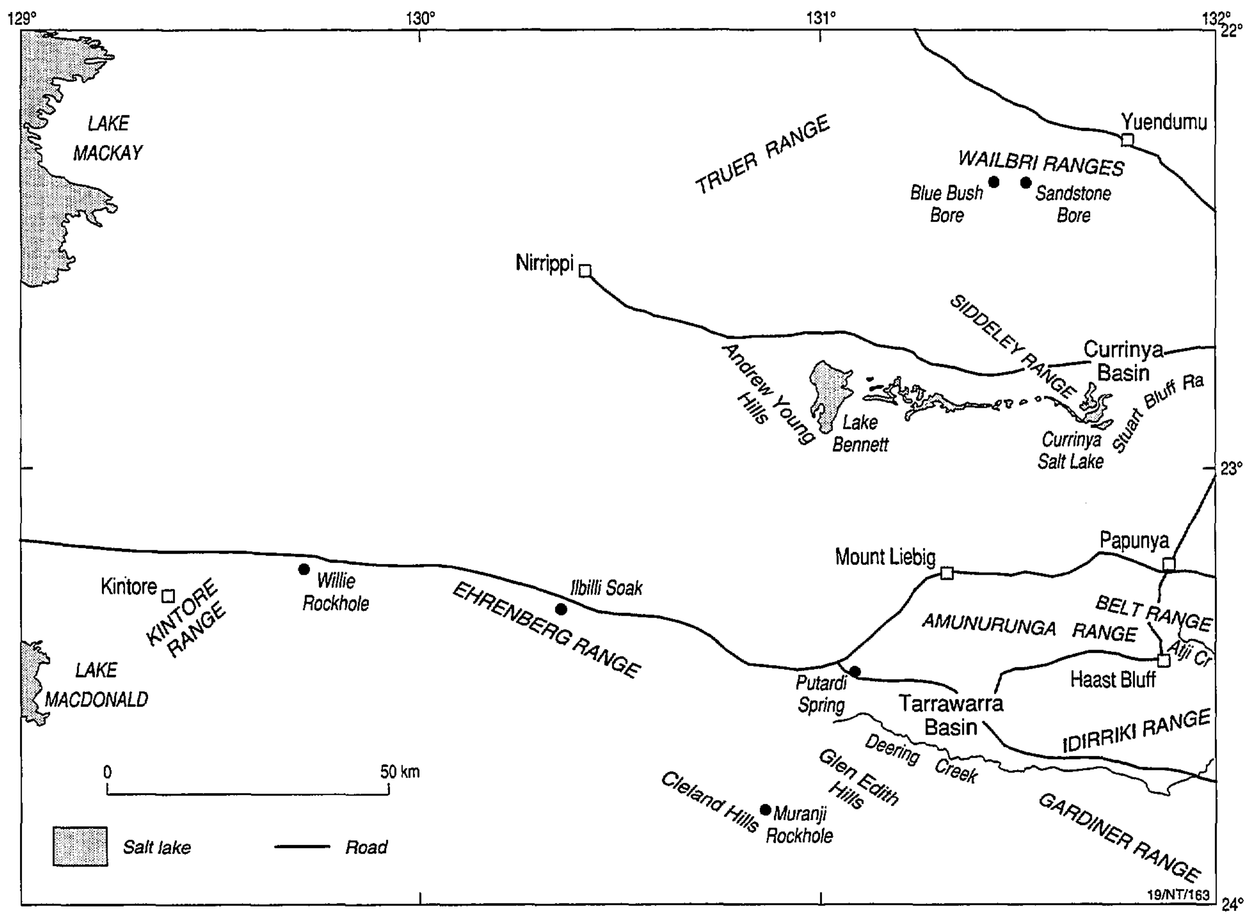

Figure 2. Place names mentioned in the text.

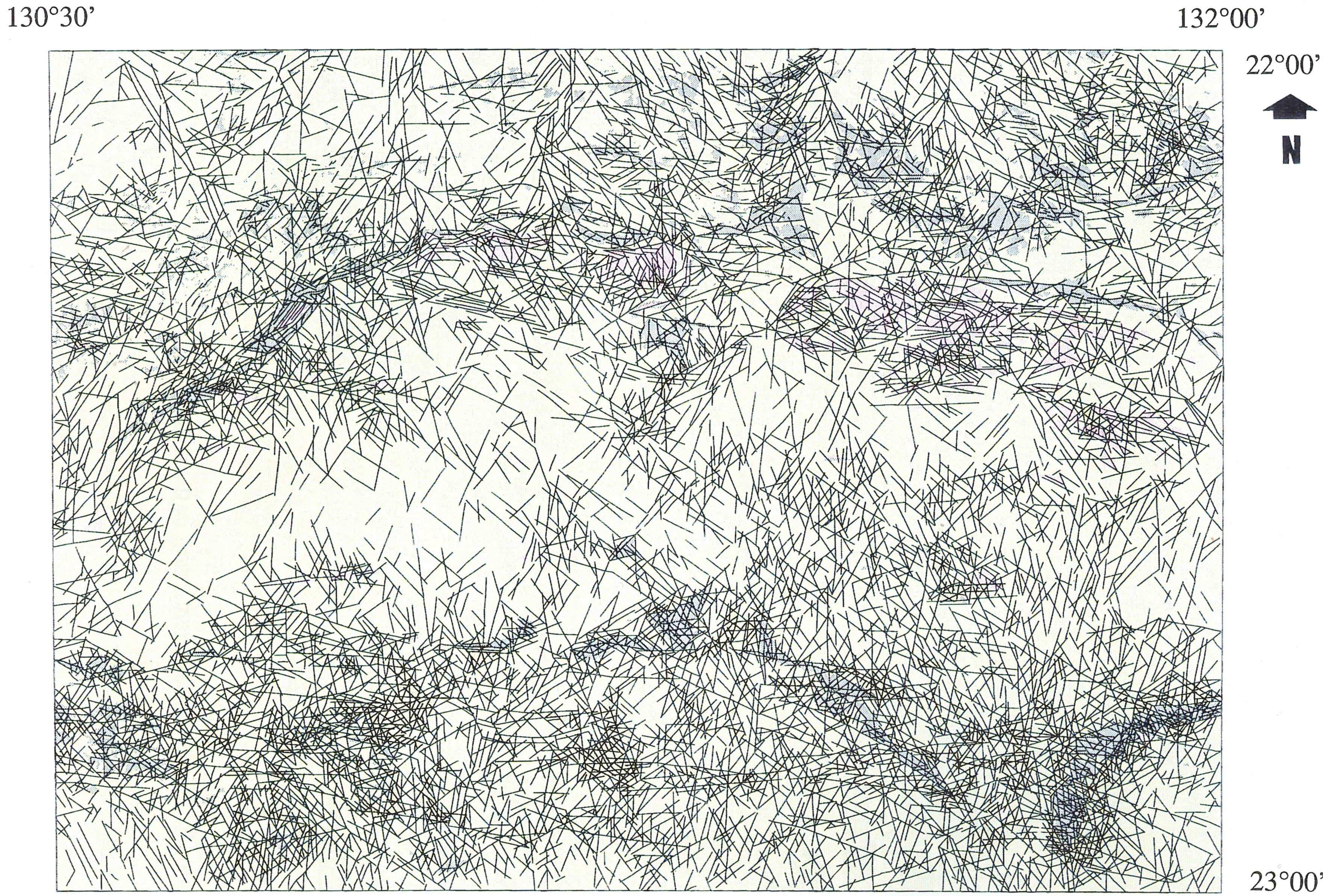

Figure 3. Lineament map for MOUNT DOREEN shown against a background of simplified geology:
Grey - Proterozoic; *Pink* = Palaeozoic; *Green* = Cainozoic.

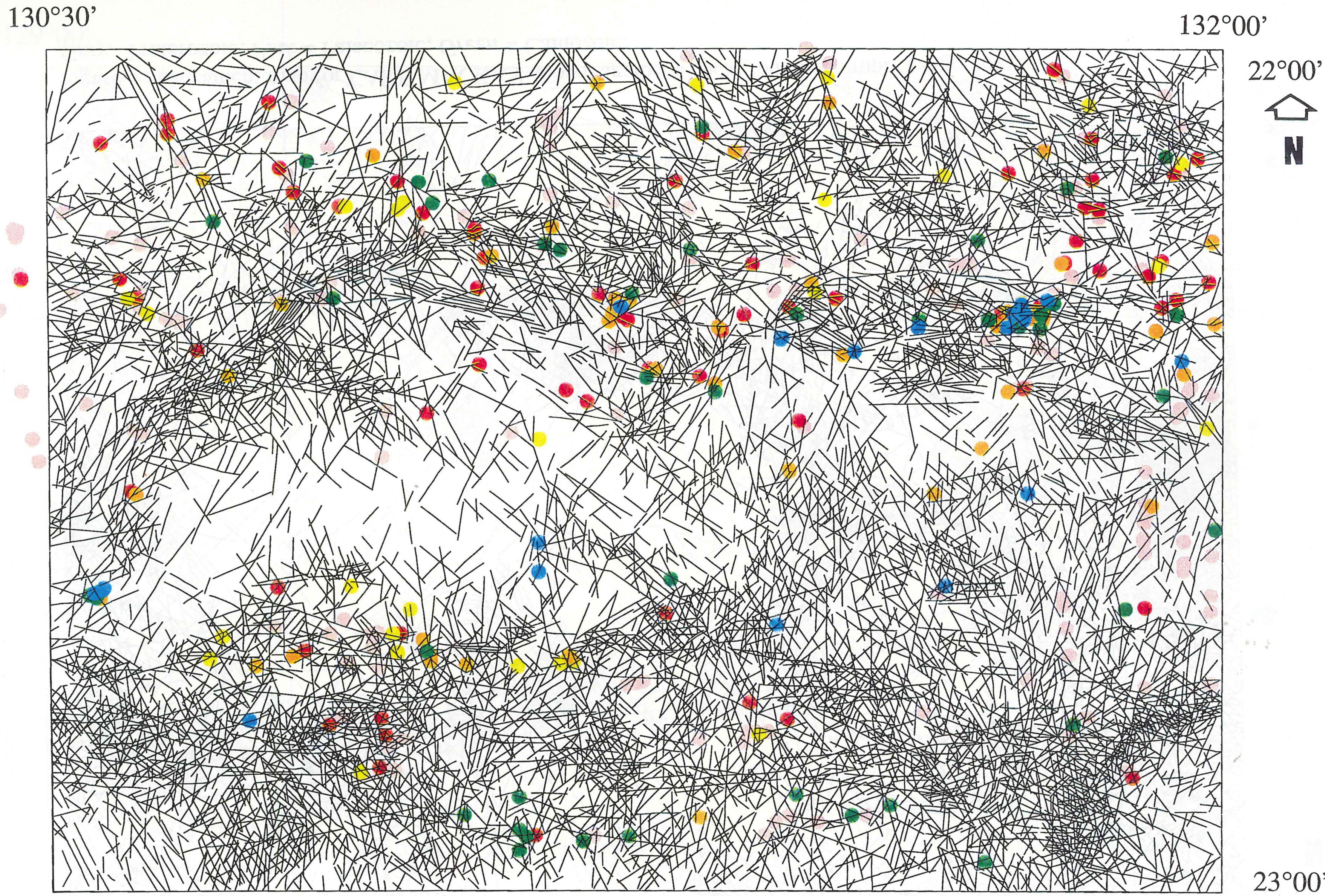

Figure 4. Lineament map for MOUNT DOREEN shown with plotted bore yield data (L/sec):
Pink = 0; *Red* = 0.1 - 0.5; *Yellow* = 0.6 - 1.0; *Orange* = 1.1 - 2.0; *Green* = 2.1 - 5.0; *Blue* = >5.0.

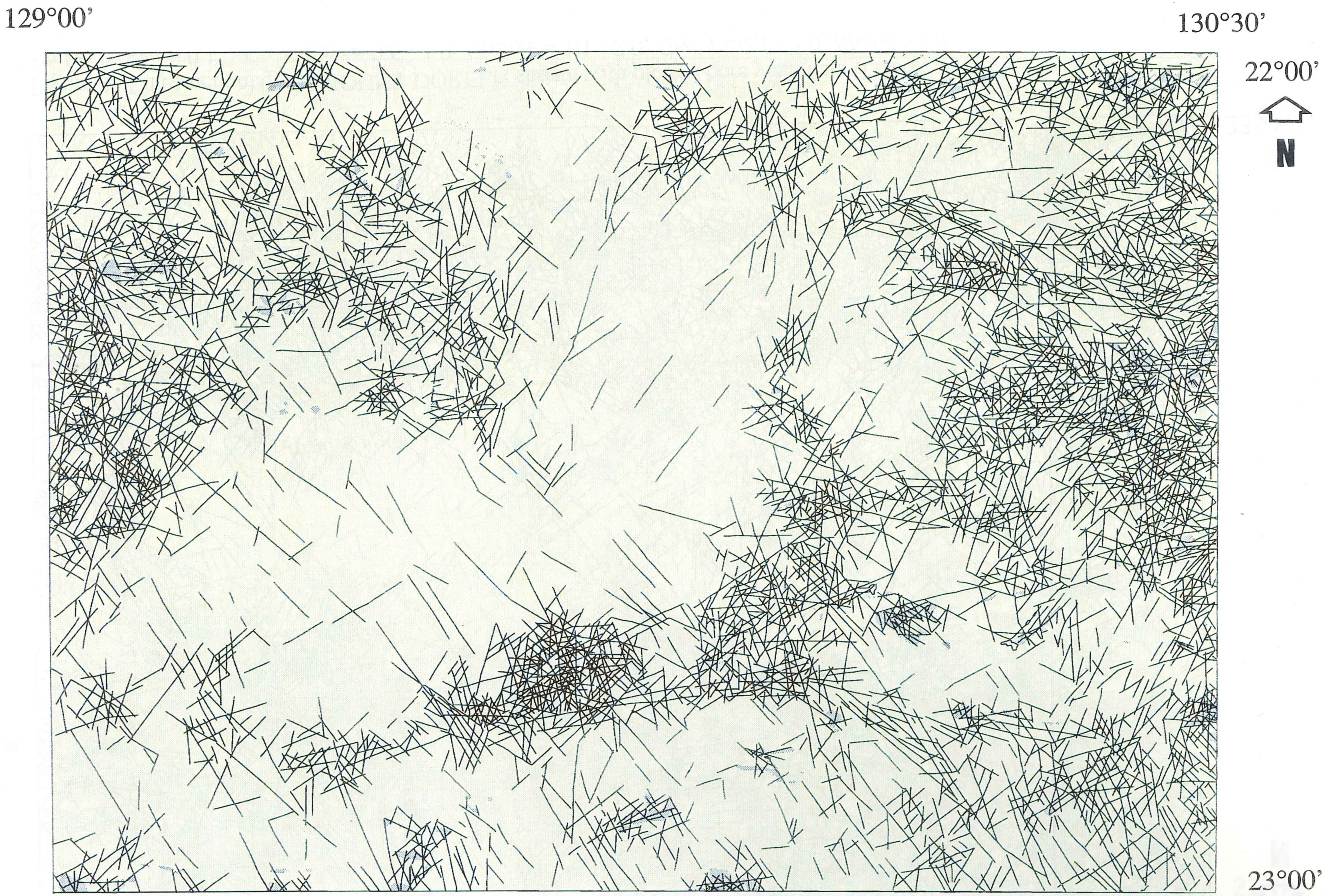

Figure 5. Lineament map for LAKE MACKAY shown against a background of simplified geology: *Grey* - Proterozoic; *Pink* = Palaeozoic; *Green* = Cainozoic.

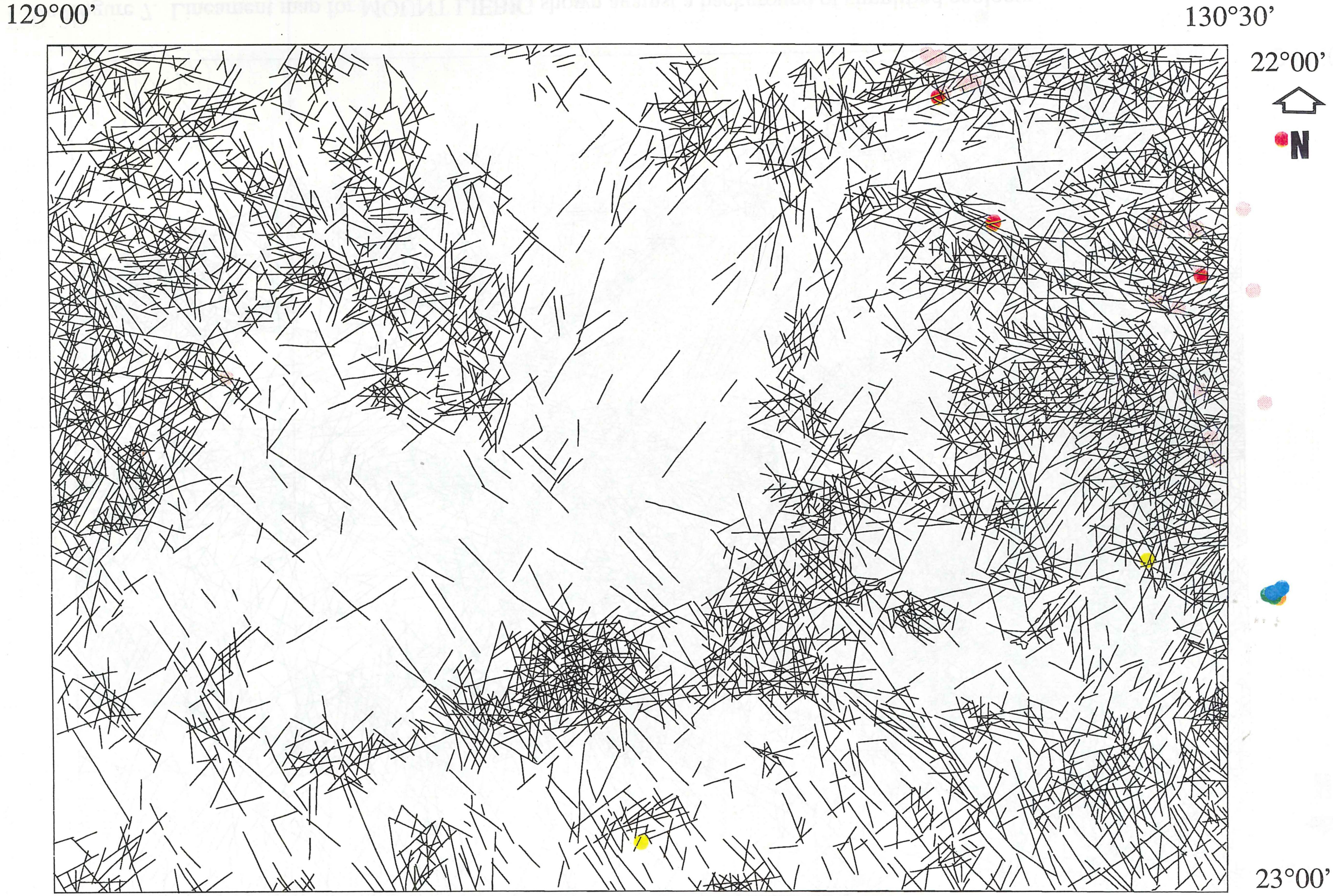

Figure 6. Lineament map for LAKE MACKAY shown with plotted bore yield data (L/sec):
Pink = 0; *Red* = 0.1 - 0.5; *Yellow* = 0.6 - 1.0; *Orange* = 1.1 - 2.0; *Green* = 2.1 - 5.0; *Blue* = >5.0.

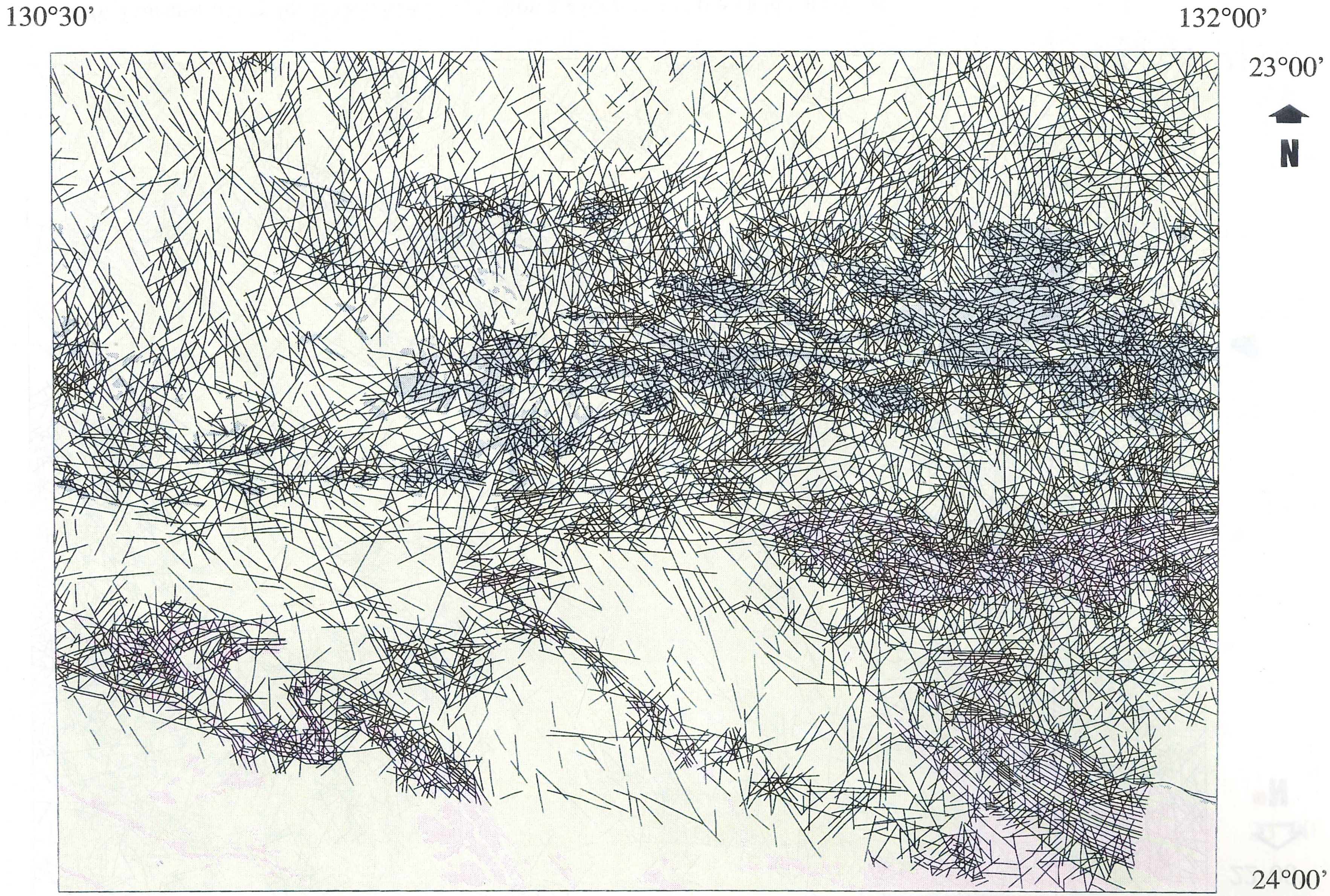

Figure 7. Lineament map for MOUNT LIEBIG shown against a background of simplified geology: *Grey* - Proterozoic; *Pink* = Palaeozoic; *Green* = Cainozoic.

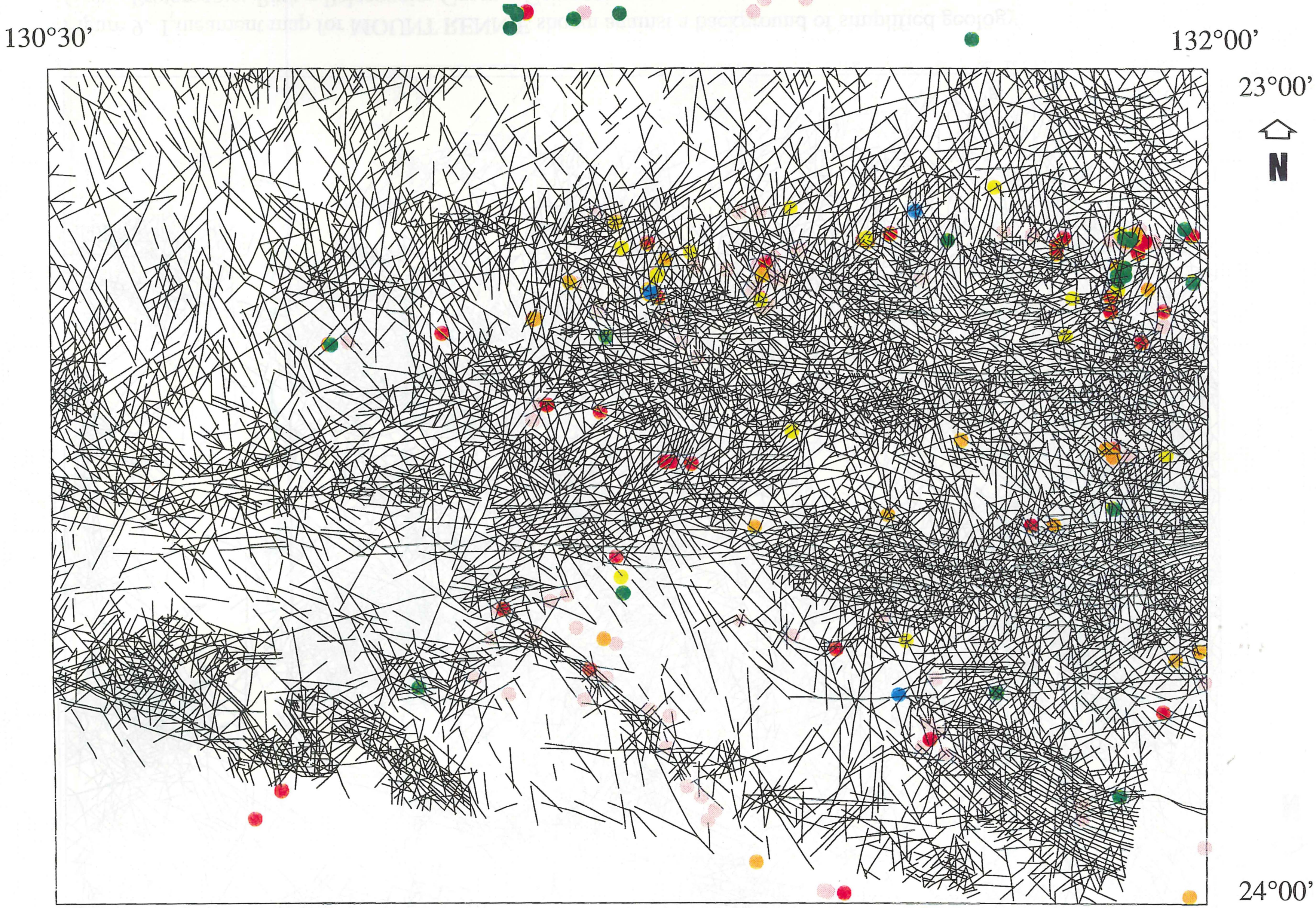

Figure 8. Lineament map for MOUNT LIEBIG shown with plotted bore yield data (L/sec):
Pink = 0; *Red* = 0.1 - 0.5; *Yellow* = 0.6 - 1.0; *Orange* = 1.1 - 2.0; *Green* = 2.1 - 5.0; *Blue* = >5.0.

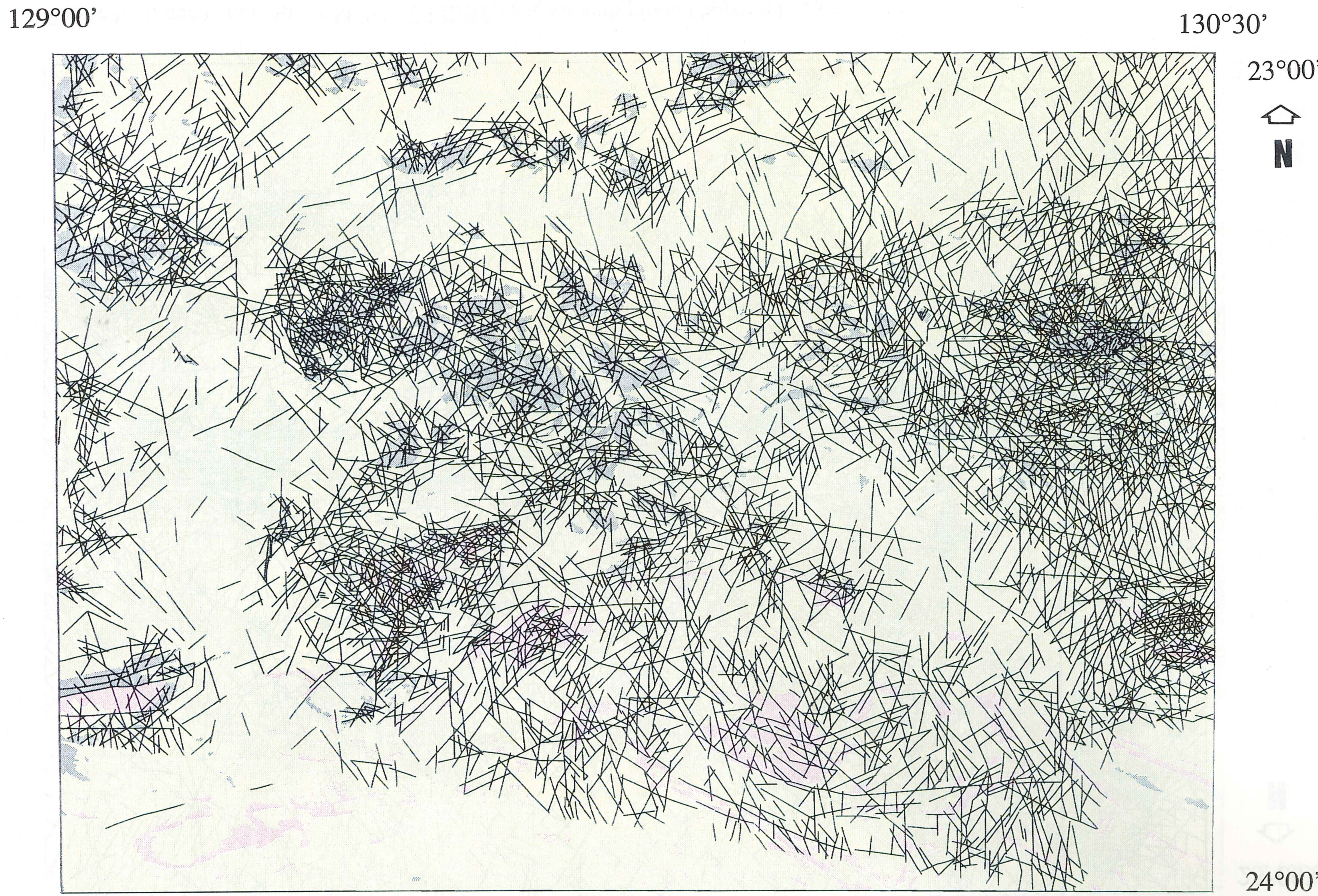

Figure 9. Lineament map for MOUNT RENNIE shown against a background of simplified geology:
Grey - Proterozoic; *Pink* = Palaeozoic; *Green* = Cainozoic.

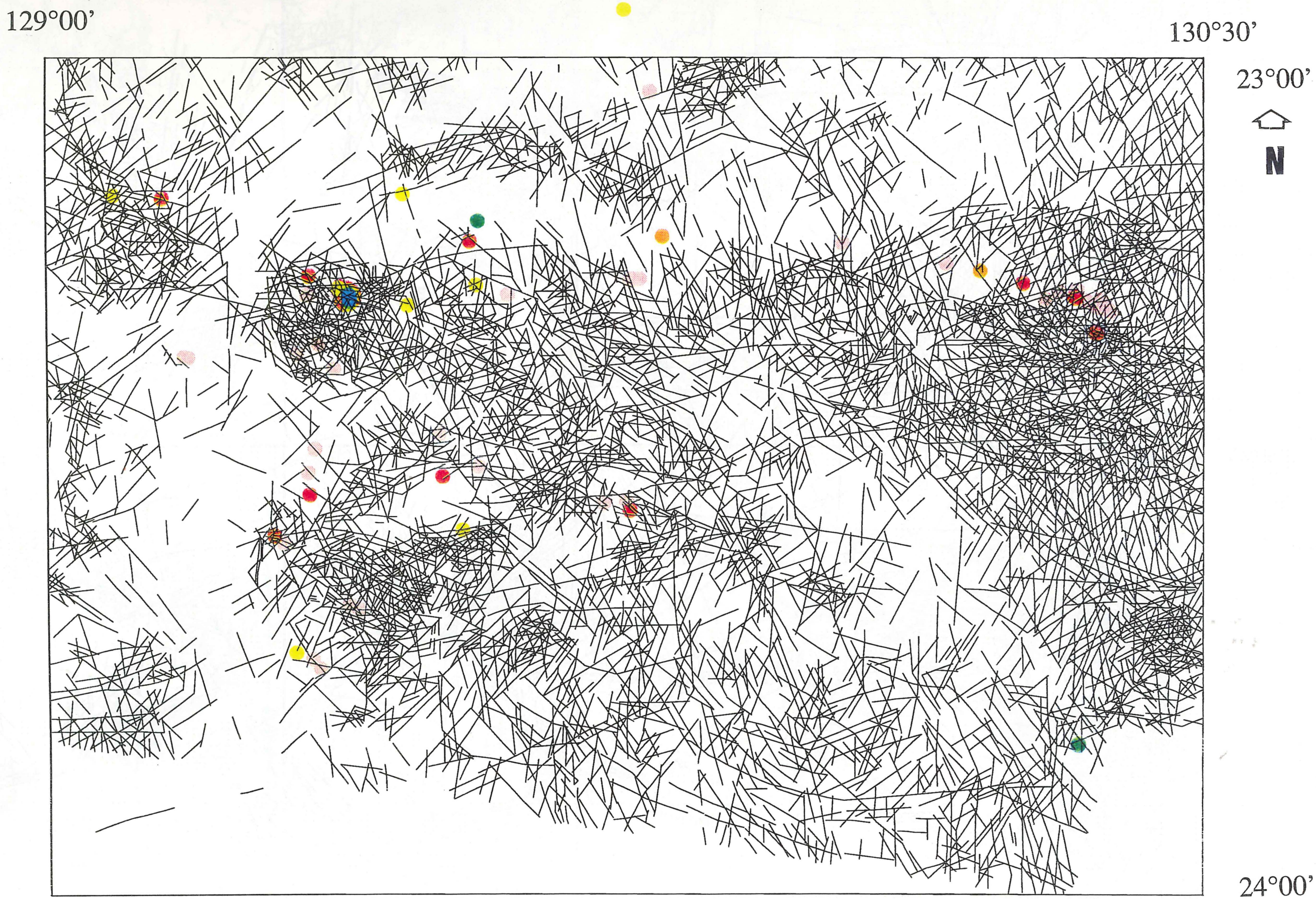

Figure 10. Lineament map for MOUNT RENNIE shown with plotted bore yield data (L/sec):
Pink = 0; *Red* = 0.1 - 0.5; *Yellow* = 0.6 - 1.0; *Orange* = 1.1 - 2.0; *Green* = 2.1 - 5.0; *Blue* = >5.0.

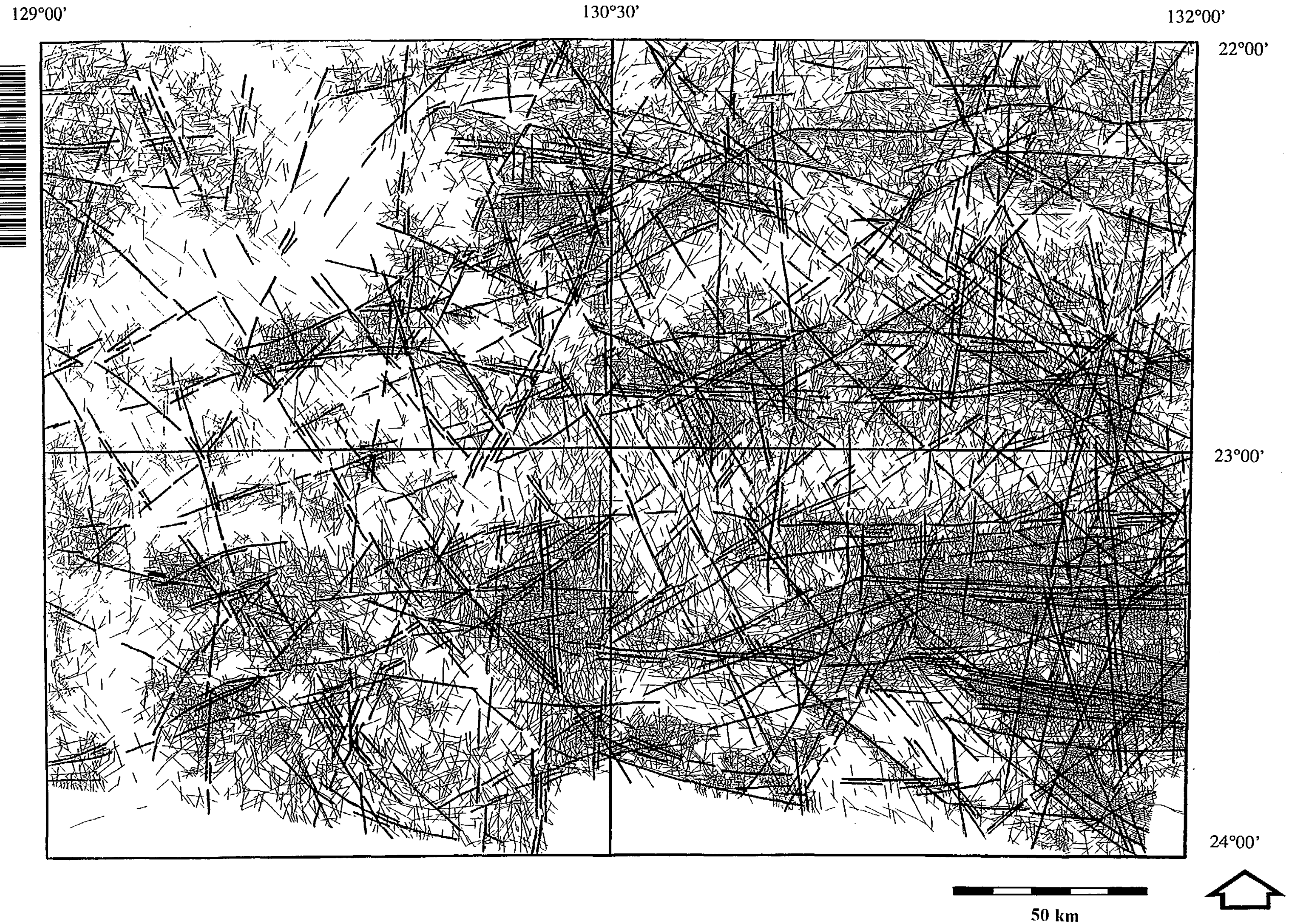

Figure 11. Lineament Synthesis Map for the whole Western Water Study area.

See text for interpretation procedure and comments.

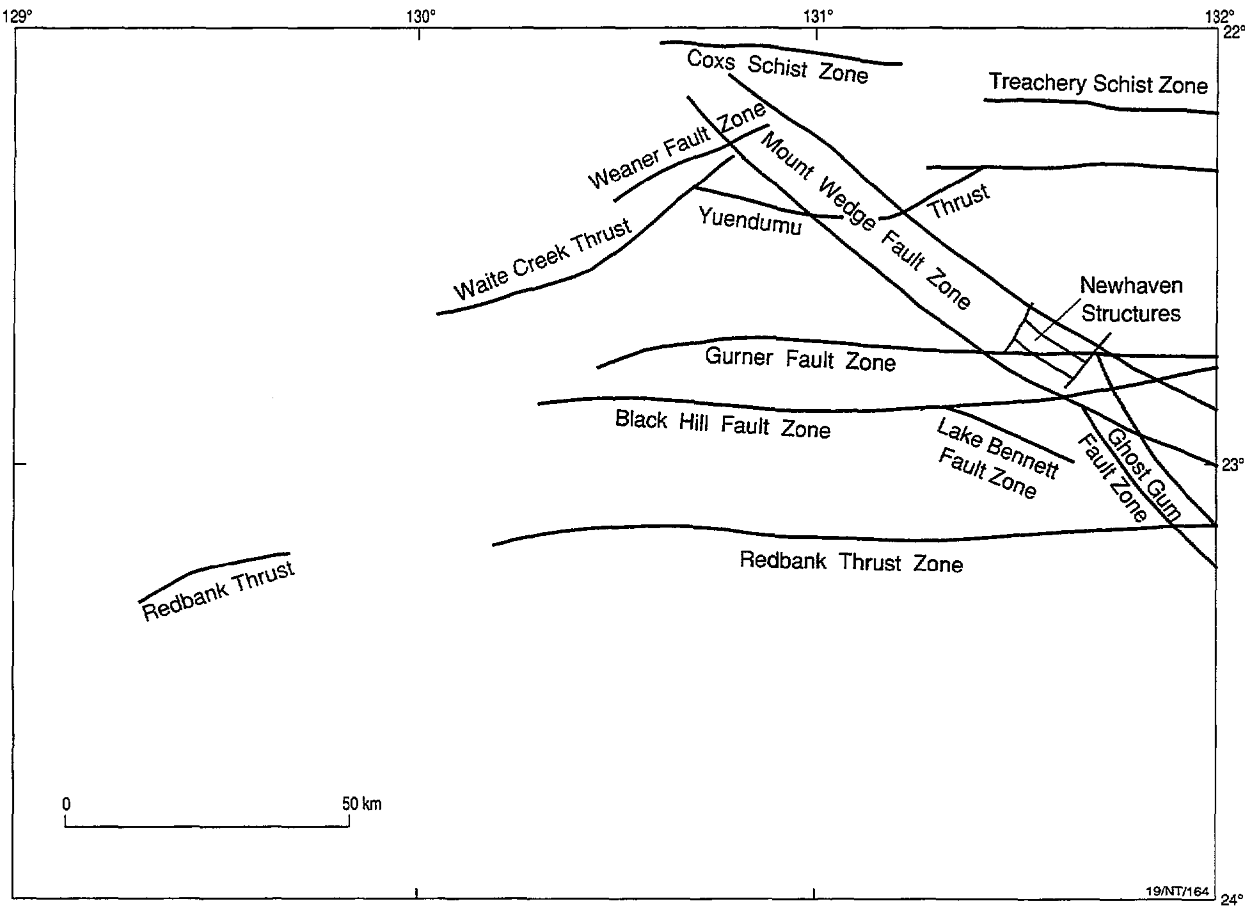

Figure 12. Named structures in the study area.