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Interpretation of EBAGOOLA aeromagnetic and gravity data
Record 1992/76

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GEOLOGY AND GEOPHYSICS
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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

DEPARTMENT OF RESOURCE INDUSTRIES

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A contribution to the National Geoscience Mapping Accord

NORTH QUEENSLAND PROJECT

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Minerals and Land Use Program

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ABSTRACT

Gravity and magnetic anomalies have been used to study the basement geology of the Ebagoola 1:250 000 sheet area (EBAGOOLA), Cape York Peninsula, Queensland. This sheet area is important for two reasons. It probably has the best exposure of the Proterozoic metamorphic rocks outcropping in the Coen and Yambo Inliers, these differ in age, rock-types and history from Proterozoic crust to the south and west. It is a 'continental' margin of Proterozoic crust, and it provides a well exposed section showing the reworking of this margin in the Siluro-Devonian by heating, shearing and intrusion. The apparent edge of the Proterozoic crust is the Palmerville Fault Zone. The amount of reworking decreases westwards up to 110 km away from this edge; the maximum metamorphic grade decreases from upper amphibolite to greenschist facies, the average level of the top of the granitoid intrusions decreases from above to below the present erosional level, and there is a decrease in the intensity of the D2 deformation as measured by the density of NNW-trending faults and the degree of transposition.

The sheet has meridional strips of granite separating three different Proterozoic metamorphic belts. The belt on the western margin of EBAGOOLA is thought to consist of Proterozoic greenschist-facies metamorphics and Proterozoic granitoids with some ?Permo-Carboniferous intrusions and volcanics. The belt is completely concealed beneath Carpentaria Basin sediments. The central belt (Edward River Metamorphics and Holroyd Group) is mainly greenschist-grade slate, sandstone, phyllite and greenstone, with a relatively simple folded structure. The eastern and western margins of the central belt comprise quartzite, schist and gneiss, with metamorphic grades as high as upper amphibolite facies. Granite dips under the central belt on both sides, and underlies at shallow depth extensive areas in the northern and southern parts of the belt, mostly in areas of higher metamorphic grade. The eastern metamorphic belt (Coen and Newberry Metamorphics), can be subdivided into strips with different magnetic anomaly patterns, and probably different geological histories; the only strips outcropping, in the west, are upper-amphibolite facies. It is possible that the northeastern-most strip of the eastern belt is of low-metamorphic grade, and part of a band of upper crustal rocks outcropping immediately to the north in COEN. The magnetic anomalies in EBAGOOLA also reflect the late-stage, NW-trending Coen, Ebagoola and Lukin River Shear Zones, and an extensive but poorly understood NE-trending fracture system.

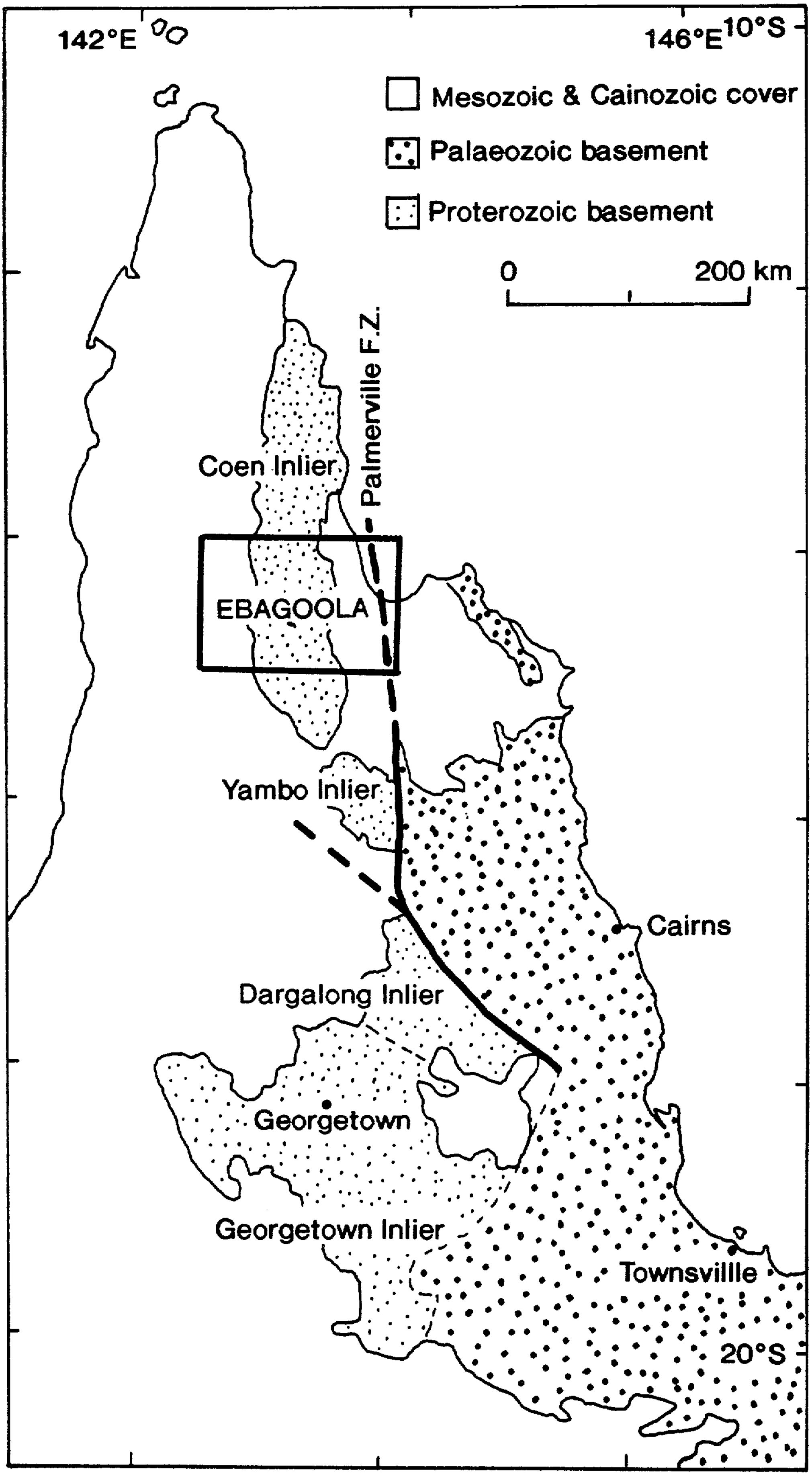


Figure 1. Location of EBAGOOLA 1:250 000 sheet area, and distribution of outcropping Proterozoic basement..

INTRODUCTION

This record gives a geological interpretation of the gravity and magnetic data of the Ebagoola 1:250 000 sheet area (EBAGOOLA)(Fig. 1) in terms of basement geology, both in the areas of exposure of the Coen Inlier, and in the area of cover. The ideas expressed are derived from study of the EBAGOOLA gravity and magnetic data, from study of gravity and magnetic surveys in the whole North Queensland Project area (Wellman, in press a), and very importantly from discussion with geologists currently mapping EBAGOOLA.

Cape York, and in particular EBAGOOLA, has a relatively low range in magnetic anomaly relative to other areas of metamorphic and granitic basement outcrop in Australia. This is due in part to the relatively low magnetic latitude, but more importantly to the absence of large bodies of strongly-magnetized rock, such as mafic and ultramafic igneous rocks, strongly magnetic granites, and granulite-grade metamorphic rocks. Because of this low average magnetization, the aeromagnetic survey of EBAGOOLA has not provided as much information on the basement geology of the area as would be provided by a similar magnetic survey in an average area of basement.

GEOLOGICAL SUMMARY

Regional geology of Cape York has been described by de Keyser & Lucas (1968), Willmott & others (1973), and Smart & others (1980), with EBAGOOLA described by Whitaker & Gibson (1977) and Trail & others (1977). Subsequent more detailed work is reported by Blewett & von Gnielinski (1991), and Bain & others (1992). The surface rocks of EBAGOOLA are Proterozoic metamorphic rocks and Palaeozoic granitic rocks of the Coen Inlier in the centre of the map sheet, and Mesozoic and Cainozoic cover rocks of the Carpentaria and Karumba Basins in the west and the Laura Basin in the east (Fig. 1 & 2). Willmott & others (1973) divided the metamorphic rocks into two types. The Coen Metamorphics in the east are mainly coarse-grained schist and gneiss, while the Holroyd Metamorphics in the west have a larger range of rock types, and are mainly of greenschist facies but range up to amphibolite facies near their contact with granitoids. These metamorphic rocks have subsequently been subdivided; the Coen Metamorphics is now the Coen Metamorphics and Newberry Metamorphics, and the Holroyd Metamorphics is now the Holroyd Group and Edward River Metamorphics; the Holroyd Group being subdivided into the Lukin and the Kalkah Structural Domains (Blewett, Trail & von Gnielinski, 1992). These metamorphic rocks are likely to be of Proterozoic age, although a very early Palaeozoic age is possible (Bain & others, 1992). The exposed granitoid rocks are part of the Cape York Peninsula Batholith, and in EBAGOOLA, Trail & others (1977) recognized Kintore and Lankelly Adamellites and Flyspeck Granodiorite. Recent dating (Black & others, in press) gives an age of intrusion of Siluro-Devonian – about 407 Ma. D1 structures associated with an early greenschist-facies event are probably upright and east-trending, while D2 structures associated with the main heating, intrusion and deformation event are NNW-trending and steeply dipping (Bain & others, 1992). Three NW-trending post-metamophic-maximum shear zones have been recognized (Willmott & others, 1973; Blewett & von Gnielinski, 1991; Bain & others, 1992) – the Coen, Ebagoola and Lukin River Shear Zones – with sinistral, reverse, movement. These basement rocks are overlain on the eastern and western margins of EBAGOOLA by a cover sequence of fairly flat-lying Mesozoic and Cainozoic platform sediments, with a minor occurrence of late Cainozoic mafic lava.

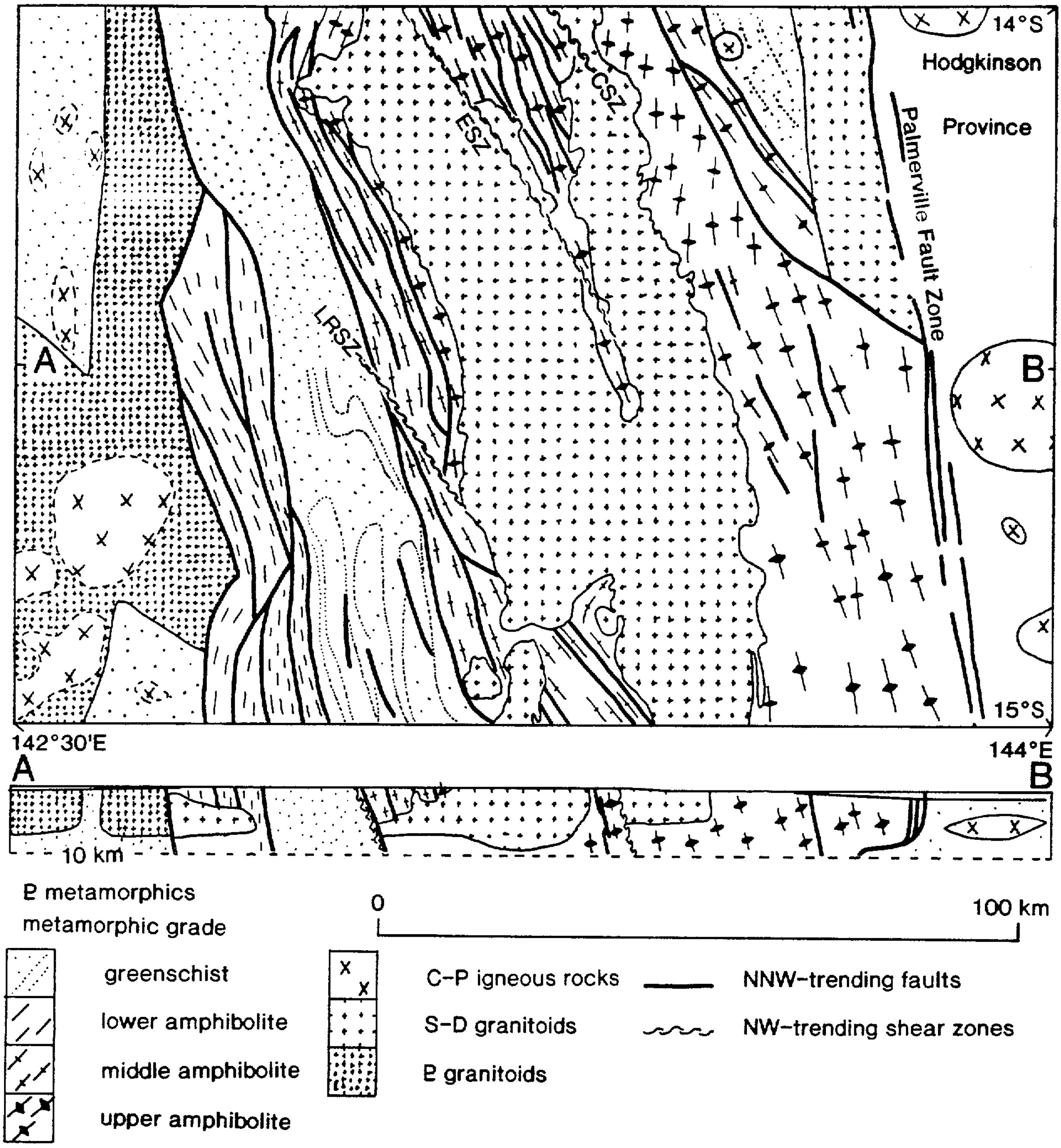


Fig. 2. Simplified map of basement geology. PFZ, Palmerville Fault Zone; CSZ, Coen Shear Zone; ESZ, Ebagoola Shear Zone; LRSZ, Lukin River Shear Zone. From Wellman (in press b).

MAGNETIC AND GRAVITY DATA

During 1973/74 BMR carried out a magnetic and radiometric survey using a fluxgate magnetometer over EBAGOOLA with a 1.5 km flightline spacing over land and 3.0 km spacing over the sea, and 150 m terrain clearance. BMR carried out similar surveys over adjacent sheets at about this time. In 1990 BMR contracted Geoterrex to carry out an airborne survey of the land part of EBAGOOLA using a cesium-vapour magnetometer, and a spectrometer at 400 m flight line spacing, and 100 m terrain clearance. The results of these magnetic surveys have been interpreted using filtered and unfiltered flight-line profiles, contour maps, and images of total magnetic intensity and east horizontal gradient (Figs. 3 & 4)(Milligan & Rajagopalan, 1992a,

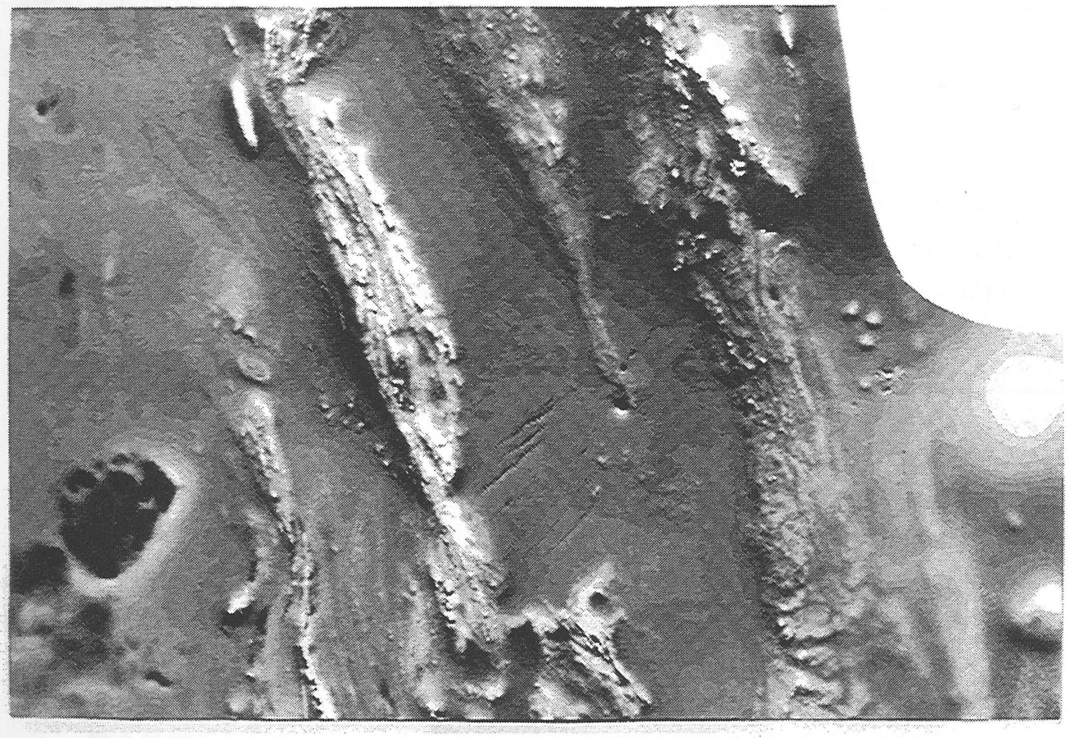


Fig. 3. Total magnetic intensity.

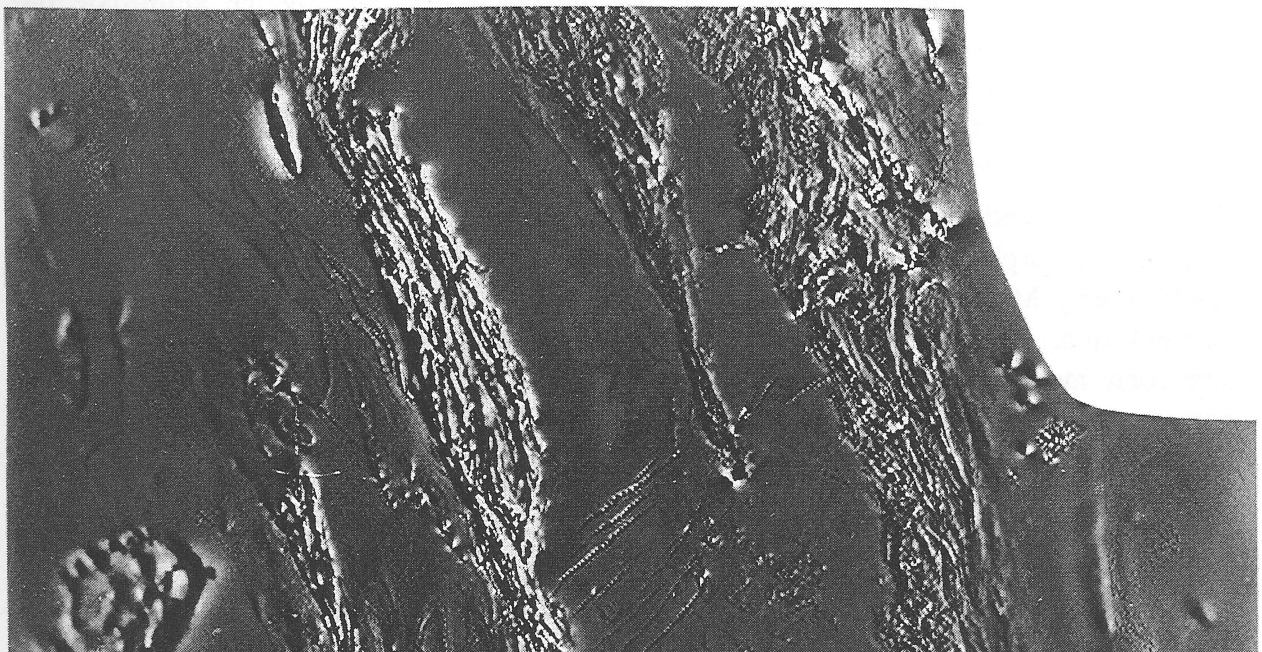


Fig. 4. East gradient of the total magnetic intensity.

b). Enhanced displays of the magnetic data were prepared to try to map adjacent granitic bodies, but magnetic anomalies due to the granites were below the noise level.

Gravity surveys over EBAGOOLA consist of an underwater survey (Goodspeed and Williams, 1959), and a helicopter survey on an approximately 11 km grid, carried out in 1966 (Shirley & Zadoroznyj, 1974). Gravity anomalies can be shown either as Bouguer anomalies (Fig. 5) or residual anomalies (Fig. 6). The Bouguer anomalies have the advantage that they have been calculated with fewer assumptions, and the disadvantage that they are dominated by a regional anomaly caused by regional topography and its isostatic compensation, that is irrelevant to upper crustal structure. The residual anomalies are optimized to show anomalies due only to the upper crust, but the parameters used in the filtering are somewhat arbitrary, and some long-wavelength, upper-crustal anomalies have been removed.

GENERAL COMMENTS

Intensity of magnetization. Geological bodies in EBAGOOLA can be classified into those of very low magnetization, normal magnetization and reverse magnetization. Very low magnetization bodies include most of the granitic rocks, greenschist-grade metamorphics, and many fault zones. Normally magnetized bodies include amphibolite-grade metamorphic rocks, and some non-outcropping intrusive rocks. Reverse-magnetized bodies are relatively rare, comprising some dykes, three 0.5 km-diameter intrusions, and bodies along the western margin of EBAGOOLA that are thought to be volcanic and intrusive bodies of Carboniferous age.

Subdivision of metamorphic rocks. Metamorphic rocks can be subdivided using changes in average magnetization, and magnetic texture. The average magnetization is given both by the amplitude of the average anomaly over the metamorphics, and by the amplitude of short-wavelength anomalies. The texture of the anomalies is due to the continuity of layering, the amplitude and wavelength of the magnetization variation across layering, the fault pattern and magnetization of the faults; the resultant pattern is modified by the attenuation due to the altitude difference between the basement surface and the survey aircraft.

Metamorphic grade. Magnetization of the Holroyd Group generally increases with increasing regional metamorphic grade from greenschist to upper-amphibolite facies. The outcropping Coen and Newberry Metamorphics are of upper amphibolite grade and have a uniform medium magnetization. Areas interpreted in this record as being underlain by granite at shallow depth have some metamorphic and some granite outcrop, anomalously low magnetization for the metamorphic grade, and low gravity anomaly.

Compositional layering. One of the major problems in interpreting the magnetic anomalies was separating magnetic anomalies due to layering and faults. Table 1 lists the criteria used to separate anomalies due to layering, faults and dykes.

TABLE 1

	Layering	Faults	Dykes
Wave-form	complex	simple	simple
Apparent body width	narrow to wide	wide	narrow
Continuity	segmented	continuous	continuous, linear
Magnetization	normal	often zero	normal or reverse
Adjacent anomalies	dissimilar	similar	similar

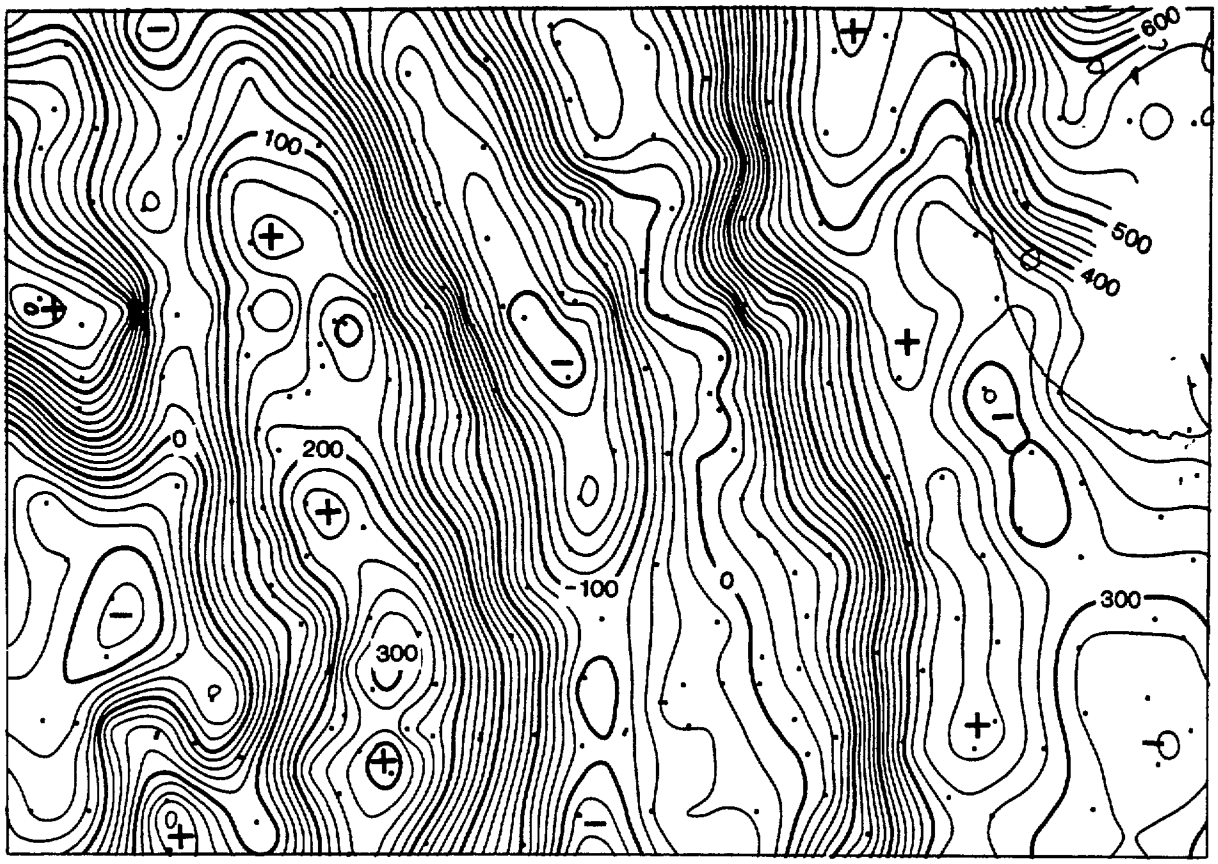


Fig. 5. Bouguer gravity anomalies, contour interval 20 $\mu m.s^{-2}$. Dots show gravity station positions (from Wellman, in press b).

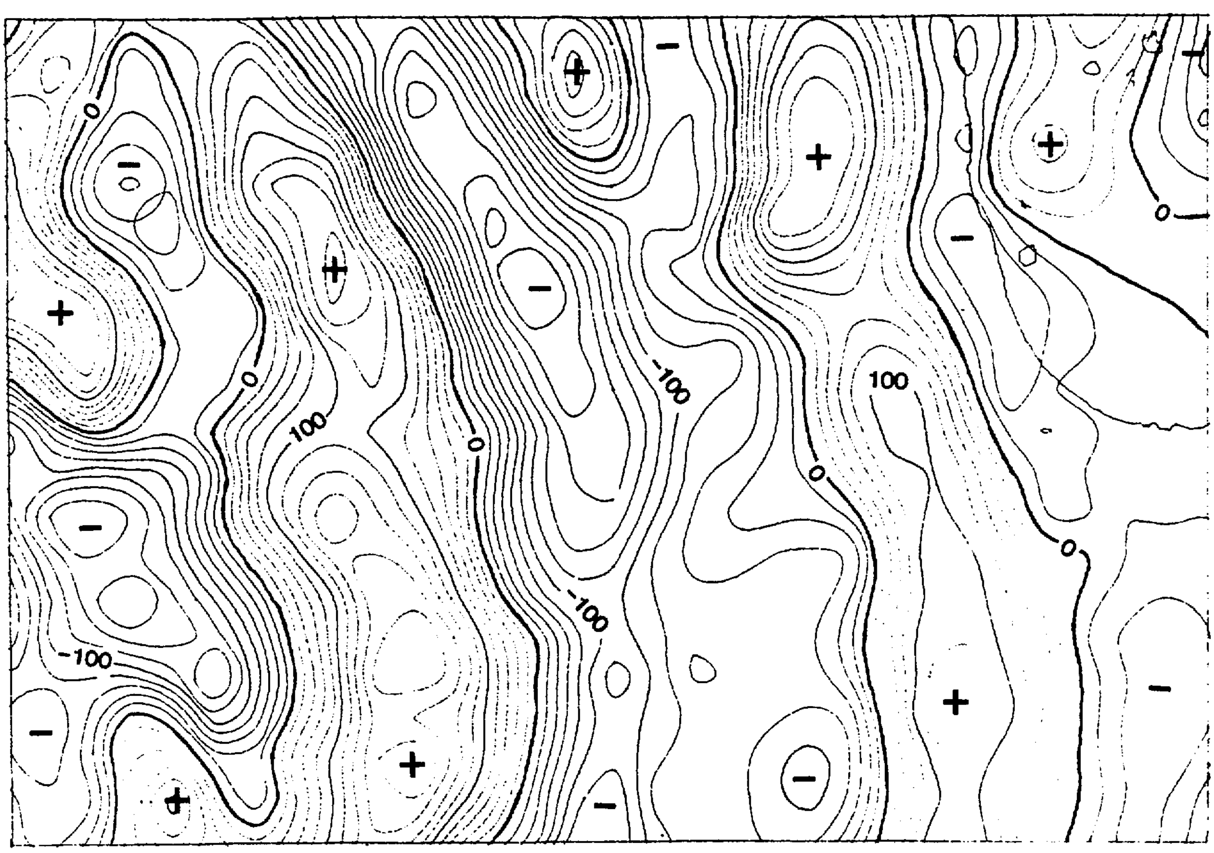


Fig. 6. Residual gravity anomaly, contour interval 20 $\mu m.s^{-2}$. Prepared by removing a 24-minute wavelength regional anomaly from the Bouguer anomaly.

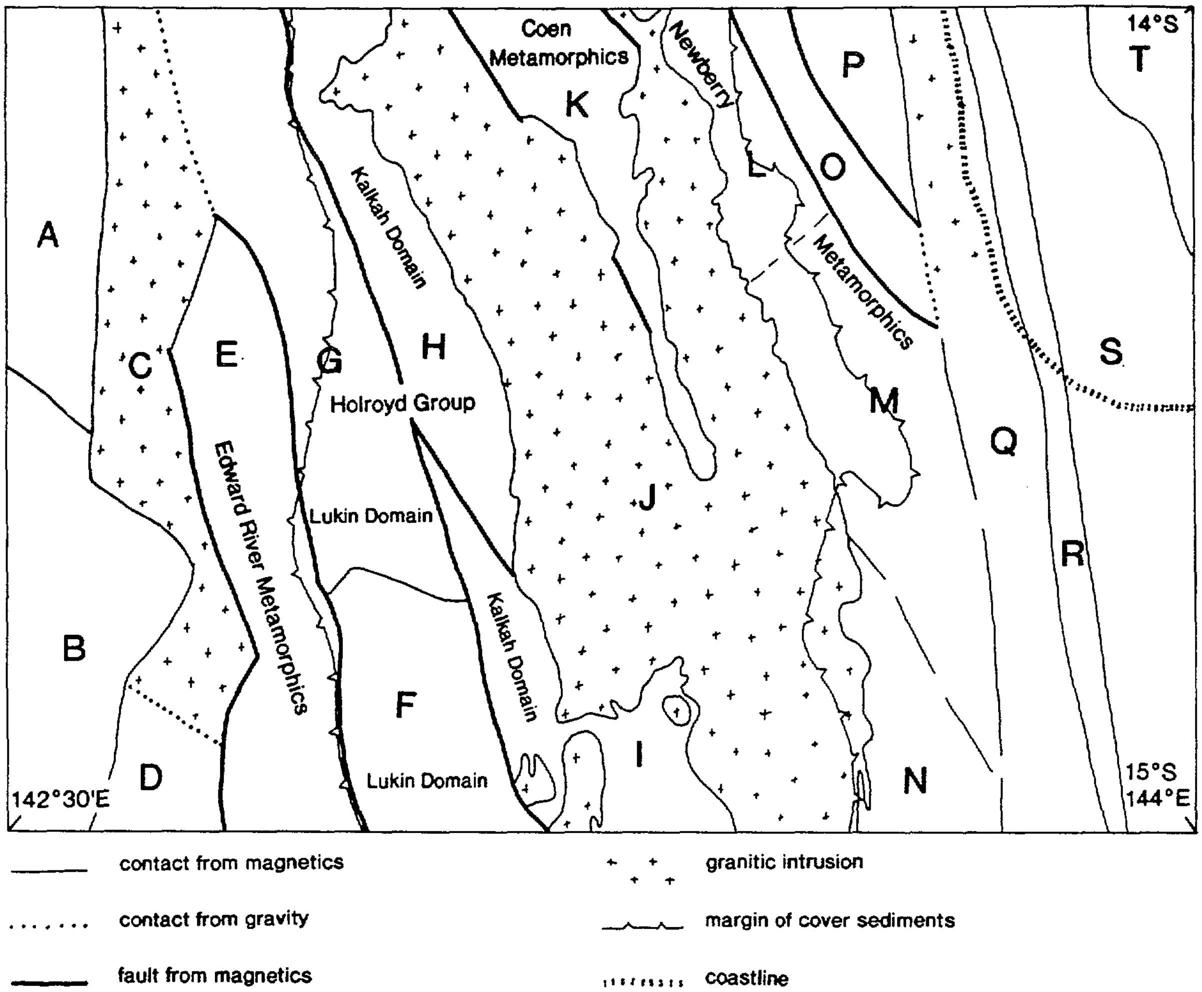


Fig. 7. Geophysical subdivisions. The letters are referred to in the text.

Granitic rocks. Within EBAGOOLA most outcropping granitoids (Fig. 7) have a magnetization (susceptibility and remanence) that in absolute terms is low, and in relative terms is much lower than adjacent sedimentary and metamorphic rocks. Hence the granitoid/metamorphic margins coincide with a steep increase in magnetic anomaly value, and truncation of anomalies due to layering in sedimentary/metamorphic rocks, and to faults. More precisely, the granitoid/ metamorphic contacts are mapped at the steep gradient between the positive and negative anomaly pair closest to the granite. Most granitoids have no changes in magnetization towards their margins, so the contacts between plutons, and the internal structures of plutons cannot be seen in the magnetic data. The main features seen within granitoids are leucogranites which produce irregular areas of positive anomaly, individual dykes, dyke swarms, isolated areas of metamorphics, and shear zones. Many minor magnetic features have an unknown cause. An important question is the structural control of the overall shape of the aggregate granitoid body. The NNW trending elongation of the aggregate body is parallel to metasedimentary layering, the axes of the dominant F2 folds, and to the major strike-slip faults. A simple model would be granitoid emplacement into a pre-existing fabric formed by these NNW-trending compressive structures. The linear margins of many of the granitic bodies is consistent with emplacement controlled in part by pre-existing faults.

Dykes. An igneous dyke is a relatively thin body that cools rapidly, and hence contains some fine-grained magnetite with few magnetic domains per grain. The result is a rock in which magnetization is dominated by a hard remanent magnetization in the direction of the Earth's field at the time of crystallisation. When dykes are metamorphosed the magnetite is modified, the strong magnetization is lost, and the dykes are generally not seen in the aeromagnetics. Hence dykes seen in the magnetic anomalies are likely to be younger than the last metamorphism. Anomalies likely to be due to dykes, are straight, of consistent profile magnitude and shape throughout their length, and with steep gradients indicating a shallow body. Anomalies due to a dyke swarm show that the dykes forming the swarm are sub-parallel, with regular spacing, thickness, magnitude of magnetization, and direction of magnetization. Most of the dykes that can be identified on the aeromagnetic images of EBAGOOLA are in areas of low magnetization. However, the most prominent dyke swarm seems to extend from the granitic area into highly magnetized metamorphics of area I of Figure 8. In area I the dykes appear to be coincident with NE-trending fractures, consistent with these dykes being of similar age or younger than the fractures.

Magnetic expression of faults and fractures. Within EBAGOOLA many of the faults and fractures are prominent on the magnetic images because the magnetization of rocks adjacent to the fault plane has been altered. This change in magnetization may be due to the process of faulting, to subsequent aqueous solutions, or to subsequent igneous intrusion. The magnetic anomalies of major fault zones are 0.5-1.5 km in wavelength, fairly linear, and have amplitudes of 1-60 nT, the anomaly being similar along strike. The magnetization can be either positive or negative relative to the surrounding material. The anomalies are smooth, so the anomalously magnetized body must have a greater depth than thickness. Anomalies of this type occur along the major shear zones (Lukin, Ebagoola and Coen), and many of the major strike-parallel faults within the belts of metamorphic rock (particularly areas H, I & M of Fig. 8).

Some faults are prominent because they form an abrupt boundary between two rock types with very different magnetizations, for example between E and F+G, and between F+G and H+I of Fig. 8.

In some areas of the Coen and Newberry Metamorphics (K, M & O) there are numerous, small-amplitude, short-wavelength anomalies that are thought to be caused by sub-parallel faulting.

Within areas of metamorphic rocks with moderate to strong magnetization there is a set of sub-parallel magnetic features, trending NE, 0.5-1.0 km wide, continuous across the metamorphic belts, fairly regularly spaced, and not displacing layering. On images there is a decrease in anomaly amplitude along these zones, and a loss of short-wavelength anomalies. The features are thought to be caused by a set of sub-parallel fractures, along which there is a decrease in magnetization of the country rock; however no such fractures were found during field mapping. In area L, anomalies of similar character, but NW not NE strike, appear to be splays of the Coen Shear Zone. A NE-trending anomaly of this type with high amplitude forms the boundary between areas L and M. The anomalies with the Palmerville Fault Zone (R, Figs. 7 & 8) comprise a set of magnetic highs about 3 km in wavelength, 2-40 nT in amplitude, with segments 10-25 km long, and trending about 350°. These magnetic anomalies are likely to be due to fault-bound slices of contrasting geology similar to those mapped to the south (Shaw & others, 1987); they are too wide to be due to material associated with the fault planes. In areas of Mesozoic sediment there are isolated, elongate, narrow, magnetic highs or lows. Some of the

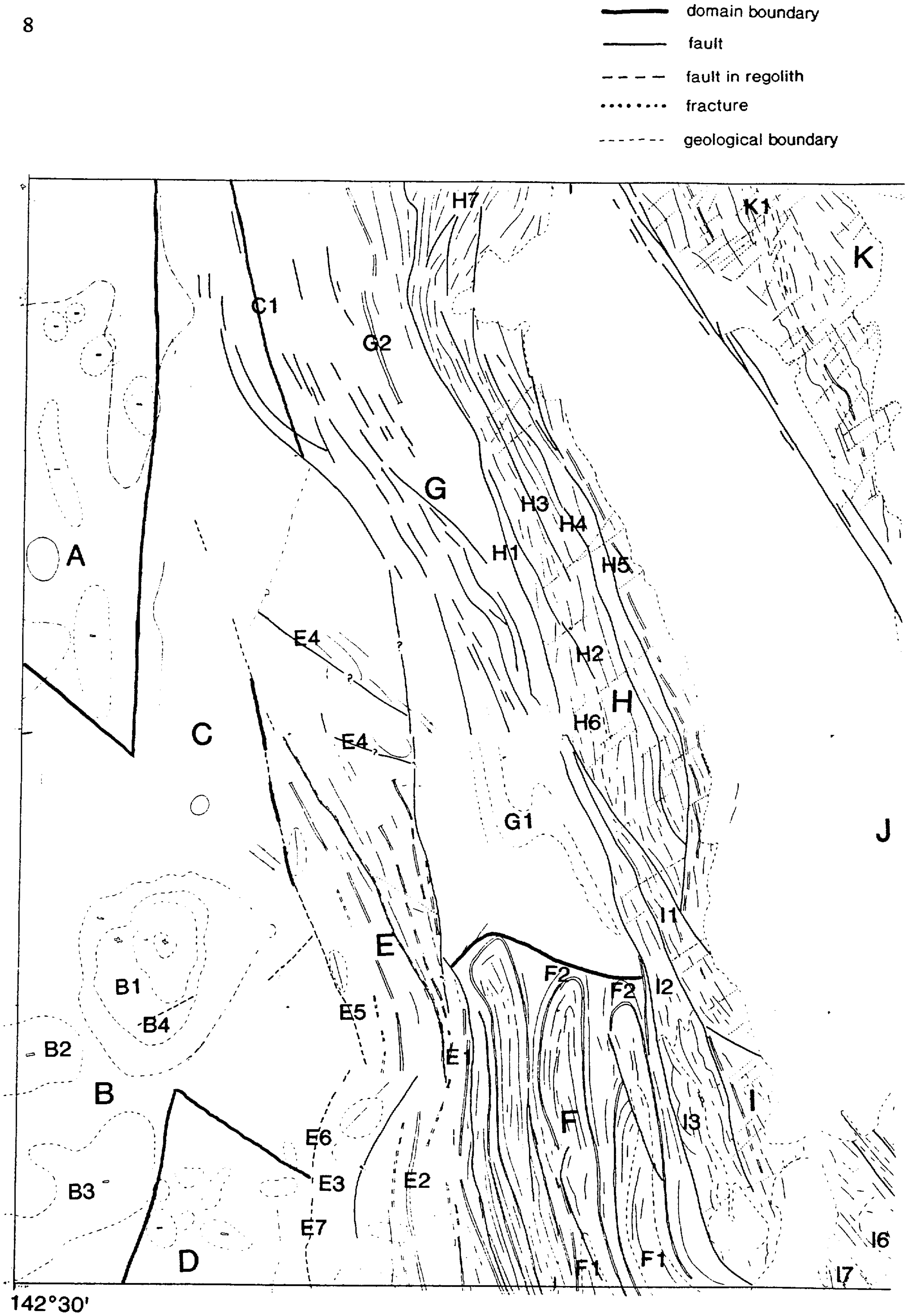
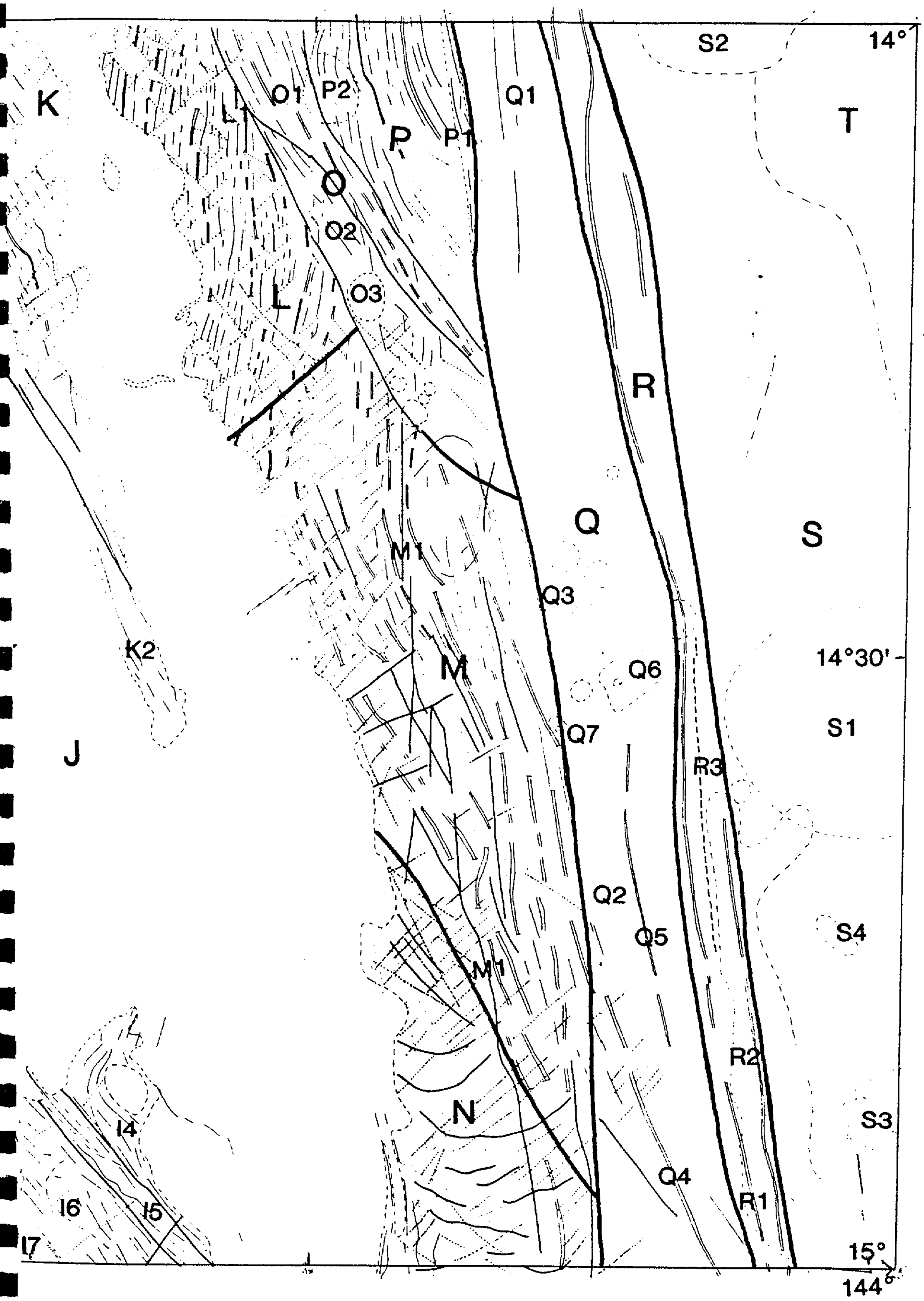


Fig. 8. Interpretation of the aeromagnetic data.

correlated anomaly, positive
correlated anomaly, negative
bedding, positive
?fault, negative
dyke



larger and more linear features correspond with previously mapped minor faults (Trail & others, 1977) – E5 and R3 corresponds with mapped faults, and B4, E6 and E7 with a mapped lineaments. Other elongate features may be faults, dykes, or narrow bands of magnetic near-surface material; many of these features are too poorly defined to be positively identified.

History of faulting. The faults are thought to be of three ages; their trends in order of age being NNW, NW and NE. Faults with NNW trends are thought to be older than those with NW trends, because they are less obvious on the magnetic images, they are often truncated by the NW-trending faults, they form the boundaries between the major rock bodies, and they are truncated by Siluro-Devonian granitoids, they do not cut them like the NW-trending faults. In the northern part of the Kalkah Domain , the NNW-trending faults appear to form steps in the amplitude of magnetic anomaly, and steps in metamorphic grade; these steps are inferred to be due to dip-slip movement on the NNW-trending faults after the metamorphic maximum. However the faults are very elongate and gently curved, so they were originally formed as strike-slip faults. These faults do not displace the granite margins, but do represent steps in metamorphic grade, so a two stage movement is proposed – a strike-slip movement prior to the metamorphic maximum, and a small (1-4 km) dip-slip or oblique-slip movement after the metamorphic maximum. On the magnetic images NE-trending zones of decreased magnetization are very common crossing the metamorphic rocks, but no corresponding fractures were seen on the ground. They are interpreted to be a post-metamorphic-maximum fracture set, that caused local demagnetization of the metamorphic rock.

The inferred history of faulting is as follows:

- Prior to the metamorphic maximum, the formation of long, sub-parallel, NNW-trending faults in the metamorphic rocks, and on the early Palmerville Fault Zone. These faults must be predominantly strike-slip because they are only gently curved and very elongate. In the Kalkah Domain the fault zones are narrow. In the Coen and Newberry Metamorphics some fault zones are wider, and composed of numerous separate faults.

- At and slightly after the metamorphic maximum and granite emplacement, the formation of the Lukin River, Ebagoola and Coen Shear Zones (Fig. 2) with NW strike. These do not significantly displace rock type boundaries, so they must have a relatively small strike-slip and dip-slip movement. At this time some predominantly dip-slip movement on the NNW trending faults. The section of the Lukin River Shear Zone between areas H and I (Fig. 2) is thought to have originally been one of the NNW trending strike slip faults because it is a major rock type boundary, and only later part of the Lukin River Shear Zone.

- Formation of the NE trending fracture system, with demagnetization of the rocks in the vicinity of the fractures. These were formed before intrusion of the northeast-trending dykes, or at the same time, and after regional cooling of the whole area.

Regolith. Very short-wavelength anomalies with speckled texture are interpreted to be due to highly magnetic iron deposits in the regolith. These anomalies are observed over part of the area of the Mesozoic rocks of the Carpentaria and Laura Basins.

Gravity anomaly interpretation. Within EBAGOOLA, to a first approximation the gravity anomalies are relatively high over the belts of metamorphic rock, and relatively low over the belts of granitic rock. The gravity anomalies reflect the relative density of parts of the upper crust, and hence of the dominant rock type. Some important observations are as follows (see Figs. 7 and 8).

- Areas A and D are gravity highs with low magnetization that are likely to be low-grade metamorphic rocks.
- There is a gravity gradient along line C1 (Fig. 8), so the rocks to the west have a lower density than the low-grade metamorphic rocks of area G, and are likely to be granitic intrusions.
- The northern part of area Q, immediately west of the Palmerville Fault Zone in EBAGOOLA, is of lower density than the adjacent crust, and has low magnetization, so the band may be granitic rocks.
- Within EBAGOOLA, and to the south, there is very little change in gravity or long-wavelength magnetic anomaly over the Palmerville Fault Zone. There are two interpretations, either Proterozoic crust extends across the fault, and underlies the Hodgkinson Basin (Shaw & others, 1987) as a continuous sheet or as fragments, or the Proterozoic crust has an edge at the Palmerville Fault Zone, and the lack of a large gravity or magnetic anomaly along the boundary is due to the two adjacent lithospheres having similar aggregate density and magnetization.

The dip of the boundary between metamorphics and granite is indicated by the offset between the boundary at the surface (given by mapped geology or magnetics) and the inflexion of the gravity residual (Fig. 9), where the inflexion point is at the change in anomaly surface from convex to concave. The western boundary of Coen Metamorphics (K), and the southern three quarters of the western boundary of Newberry Metamorphics, are mainly near vertical and fairly straight. These boundaries may be fault controlled; the boundary of the Coen Metamorphics coincides with the Ebagoola Shear Zone for much of its length. The eastern and western margin of the Holroyd Group and Edward River Metamorphics have moderate dips of granite under the metamorphics, consistent with the higher grade of the metamorphics at these two margins, and the occurrence of small areas of granitic rock intruding the Edward River Metamorphics and Kalkah Domain. The average offset of the gravity inflexion from the metamorphic/granitoid contact is about 5 km. Small areas of granite, and negative gravity anomalies, both show that the metamorphics are underlain by shallow granitic rock at the northern and southern ends of the Kalkah Domain, the northeastern margin of the Coen Metamorphics, and the northwestern margin of the Newberry Metamorphics.

The present thickness of the granitoids (h) can be estimated from the density contrast between the granitoids and metamorphic rocks (dc), and the gravity anomaly change over the granitoid/metamorphic boundary (dg), using the formula for the gravitational attraction of a slab: dg = h . dc . 0.4186. It is estimated (D.E. Mackenzie, pers comm.) that the average density of the granitoids is 2.66 t.m-3, and the metamorphics is 2.75 t.m-3. On the western boundary of the Newberry metamorphics the gravity anomaly change is 220-240 µm.s-2, so the calculated granitoid thickness is 6 km. On the eastern boundary of the Holroyd Group the gravity anomaly change is 300-400 µm.s-2, so the calculated granitoid thickness is 8-11 km. From these calculations and the distribution of gravity anomalies in Figure 6, the majority of granitoids have

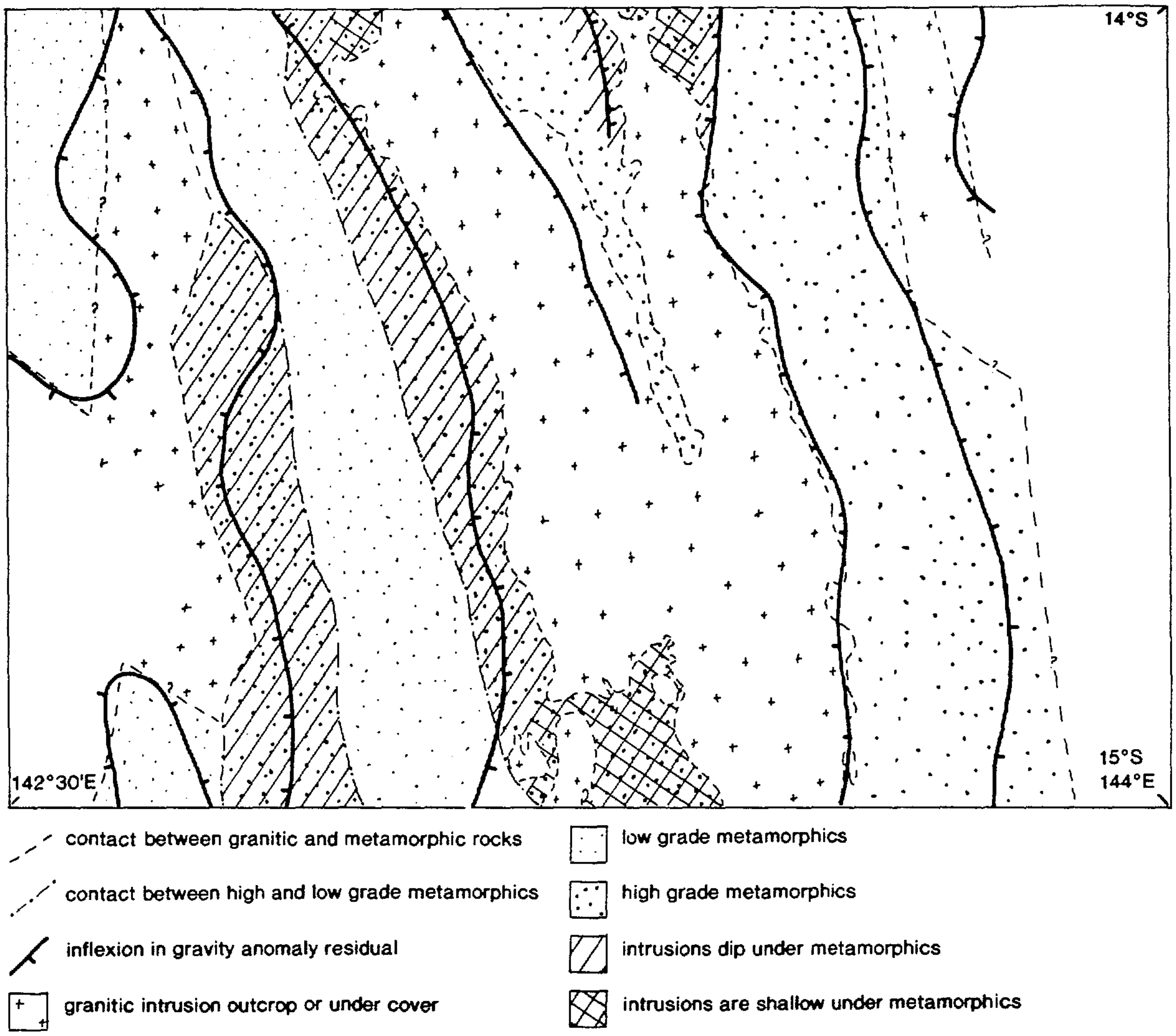


Fig. 9. Relation between surface geological contacts (from geology and aeromagnetics), the inflexion of the gravity anomaly residual, and the areas thought to be underlain by granitic intrusions.

a thickness averaging about 6 km, and there is a band through the centre of EBAGOOLA where granitoids are 2-5 km thicker.

Figure 10 shows east-west cross sections across the EBAGOOLA sheet area. The average depth to the base of the granitoids in EBAGOOLA is not known. For the purpose of drawing sections a average thickness of 7 km was adopted; this is the average of two measurements using seismic reflection of thickness of granitoids in southeastern Australia (Pinchin, 1980). Residual gravity anomalies (Fig. 6) show that the mass deficiency due to granite is greatest in a NNW trending band through the centre of EBAGOOLA. Siluro-Devonian granitoids are thought to have have tops mainly below ground level to the west below Edward River Metamorophics, at about ground level under the Kalkah Domain to within 60 km of the Palmerville Fault Zone, and generally above ground level to the east of this.

The Palmerville Fault Zone in EBAGOOLA consists of several sub-equal, parallel faults. The shape of the fault zone at depth is unknown. Shaw and others (Fig. 13 in 1987) give a model for the Palmerville Fault Zone 100 km to the south of EBAGOOLA, and this model has been used in Figure 10. However this model may not be applicable in EBAGOOLA, because the magnetic anomalies associated with the structures studied by Shaw & others (1987) do not extend north along the Palmerville Fault Zone, but extend to the northeast.

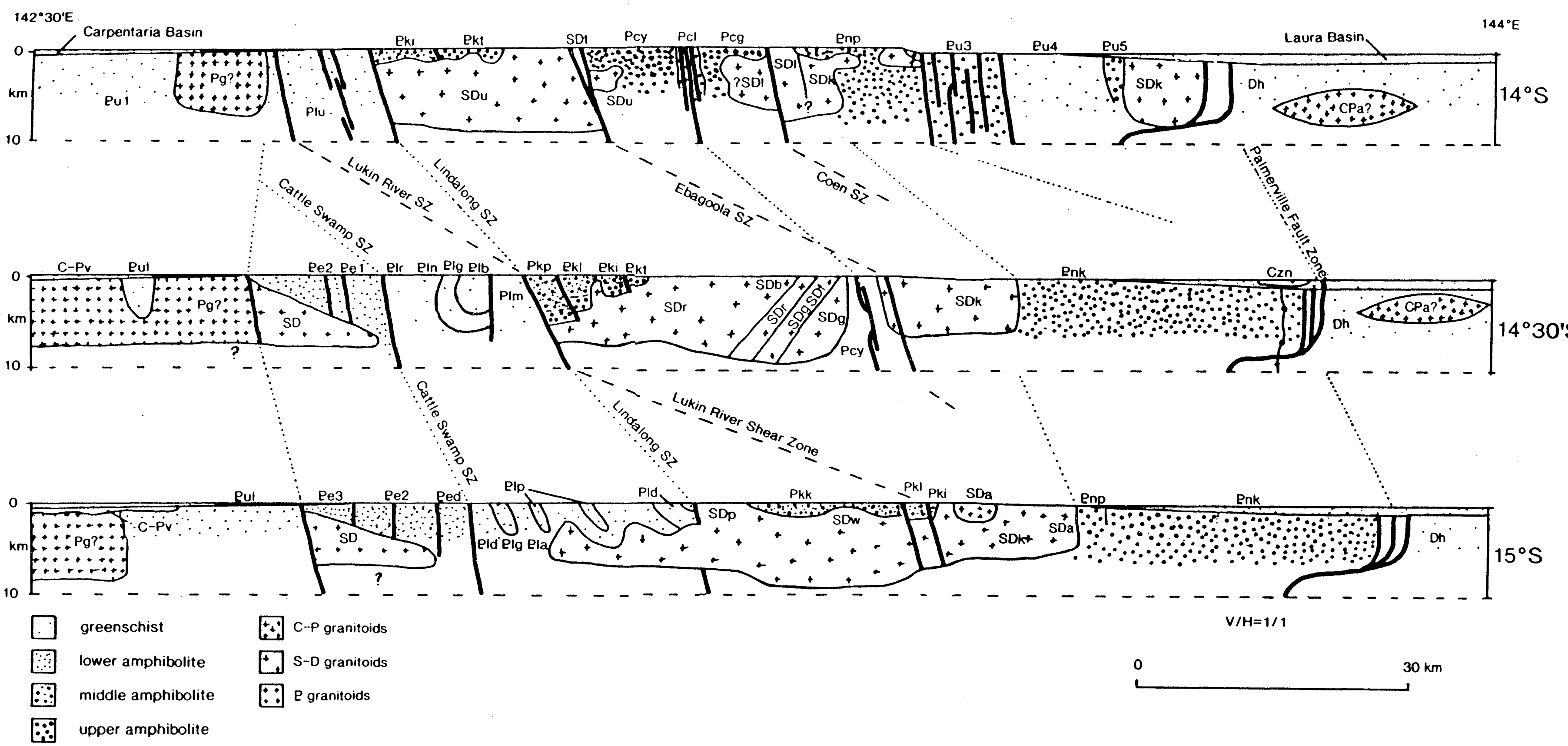


Fig. 10. Sections across EBAGOOLA at 14°S, 14°30'S, and 15°S.
The formation symbols refer to the EBAGOOLA geological map 2nd Edition, 1992.

DESCRIPTION OF MAJOR SUBDIVISIONS (see Figs. 7, 8, Table 2)

TABLE 2. ROCK TYPES OF MAJOR GEOPHYSICAL SUBDIVISIONS

	Age*	Rock type	Gravity anomaly	Magnetic anomaly	Metamorphic grade**	Name
A	Pr	metamorphics	high	low	?G	
B	Pr C-P	?granitoid intrusion & volc	low low	low negative		
C	Pr	granitoid	low	low		
D	Pr	metamorphics	high	low	?G	
E	Pr	metamorphics	high	high	LA	Edward River M.
F	Pr	metamorphics	high	low	G	Holroyd Group
G	Pr	metamorphics	high	low	G(-LA)	Holroyd Group
H	Pr	metamorphics	high	high	MA-UA	Holroyd Group
I	Pr	metamorphics	high	high	MA	Holroyd Group
J	S-D	granitoid	low	low		
K	Pr	metamorphics	high	medium	UA	Coen M.
L	Pr	metamorphics	high	medium	UA	Newberry M.
M	Pr	metamorphics	high	medium	UA	Newberry M.
N	Pr	metamorphics	high	medium	UA	Newberry M.
O	Pr	metamorphics	high	high & medium	UA	
P	Pr	metamorphics	high	low	?	
Q	Pr S-D	metamorphics granitoid	high low	low	UA- G	
R	S-D	sediments	high	high	sG	Palmerville FZ
S	S-D	sediments	high	high	sG	Hodgkinson
T	S-D	sediments	low	low	sG	Hodgkinson

*Pr, Proterozoic; S-D, Siluro-Devonian; C-P, Permo-Carboniferous.

**sG, sub-greenschist; G, greenschist, LA, lower amphibolite; MA, mid-amphibolite; UA, upper amphibolite

Area A in the northwestern corner of EBAGOOLA has relatively high density and low magnetization, and is inferred to be low-grade metamorphic rocks. Basement magnetic anomalies are of 5 to 20 nT amplitude, either circular or elongate with a north strike. The reverse magnetized bodies are thought to be minor volumes of volcanics or intrusions of generally Late Carboniferous-Early Permian age. The largest body is 2 x 12 km in plan. These thin volcanics may have high fluorine (D.E. Mackenzie, pers. comm. May 1992) and be porous, so they may be the source of the high fluorine in the Carpentaria Basin aquifers. The few normally magnetized bodies are likely to be Proterozoic rocks.

Area B in the southwest corner of EBAGOOLA is dominated by three large bodies of low density and strong negative magnetization that are inferred to be felsic Carboniferous/Permian intrusive and/or volcanic rocks. The largest body (B1) is oval in shape, 17 by 20 km in size. The anomaly consists of a marginal magnetic high of amplitude 50 nT above the regional level, and a large central low of maximum amplitude -80 nT below regional level, which may be subdivided into two concentric arcuate lows. This magnetic anomaly and gravity low is very similar to that associated with outcropping Carboniferous/Permian ring complexes elsewhere in north Queensland (Bain & others, 1992). The two other large bodies (B2, B3) are irregular-shaped magnetic lows, similar to B1 in average diameter and negative anomaly amplitude, and with a similar mass deficiency. They are inferred to be felsic Carboniferous intrusions/volcanics, but not to be ring-complexes. The gravity anomaly of area B is similar to area C, so basement is thought to be a Proterozoic granitoid.

Area C is an elongate area that is inferred to be felsic in composition because it has lower density than the lower amphibolite grade metamorphics of area E and the greenschist grade metamorphics of area G. It has low and uniform magnetization, and it has not raised the magnetization of the ?low-grade metamorphic rocks to the west, so it is thought to be a Proterozoic granitoid.

Area D has high density, low magnetization, and numerous areas of zero or negative magnetization. The rocks are thought to be similar to area A comprising low-grade metamorphics, with minor Carboniferous/Permian intrusions or volcanics.

Area E is an elongate area of generally high magnetization, and of high density, that is thought to consist of metamorphic rocks – schist and gneiss. Small outcrops of Edward River Metamorphics are of lower amphibolite grade. The eastern boundary of area E is not quite parallel to layering, and is inferred to be a major fault, the Cattle Swamp Shear Zone. Similarly the western boundary of area E is thought to be a nearly layer-parallel major fault. The minor faults and lineations along this margin displace Mesozoic rocks (Trail & others, 1977), and are probably due to reactivation of this early basement fault.

On a regional scale in EBAGOOLA and HANN RIVER to the south, area E consists of sub-parallel, discontinuous but correlatable, anomalies. The area is 18 km wide in HANN RIVER and 16 km wide in EBAGOOLA. The rocks can be divided into three north-striking bands, separated by faults of the NNW type. The eastern band (E1) is highly magnetic and most strongly layered. The eastern band is the only band exposed, it crops out in EBAGOOLA as small areas of schist and gneiss and granitoid. The central band (E2) has uniform medium magnetization. The western band (E3) has near zero magnetization except for oval areas of medium magnetization. In the north there are two NW trending magnetic lows (E4) thought to be due to faults.

Area F is an area of Lukin Domain comprising greenstone, quartzite, schist and slate folded into three large antiforms; the structures indicated by the magnetics support the outcrop patterns on air-photos and radiometrics. In addition, the magnetics shows that the mainly concealed western antiform is similar to the adjacent two antiforms. It also shows that the Lukin Domain exposed in the cores of the antiforms (at F1) are much more highly magnetic than the Lukin Domain to the north of area F. The higher magnetization may be due either to a lithological difference, or to thermal effects; these rocks directly overlie granite, as indicated by outcrops to the south in HANN RIVER. Quartzite immediately north of the greenstone, at F2, has lower magnetization than quartzite elsewhere in area F, so it may be lithologically different, or of lower metamorphic grade.

Area G is an area of Lukin Domain, mostly of low-grade, of generally low magnetization, but high density. This area extends northwest to a prominent gravity gradient, which forms the boundary with the less dense material of area C. The only useful marker horizon is a wide band of quartzite (The Gorge Formation) which forms a "z" fold (feature G1), that causes a broad, low-amplitude magnetic high with superimposed local high-amplitude anomalies. In area G there are many magnetic anomalies of wavelength about 1 km and amplitude 1 – 1.5 nT, in contrast to the granitic areas to the east where anomalies of this wavelength average about half this amplitude. These short-wavelength anomalies are interpreted to be due to layering, dykes and faulting, but individual anomalies cannot be identified and mapped using magnetics at this ground clearance and flight-line spacing. In the northern part of the area there are many gently-arcuate anomalies, up to 30 km long, and similar in anomaly shape along their length. They are probably due to magnetic material in the plane of strike-slip faults.

Area H has relatively high magnetization, and relatively high metamorphic grade. An eastward overall increase in metamorphic grade is indicated by the presence of slates and quartzites in the west, schists in the middle, and gneiss in the east. A general eastward increase in magnetization is indicated by the increases in the amplitude of short-wavelength magnetic anomalies, and the value of the long-wavelength magnetic anomaly in that direction. Eastward increases in metamorphic grade and magnetization generally occur at inferred major faults. These faults are, from west to east: H1 on the western margin of area H at the major change in metamorphic grade between Lukin and Kalkah Domains (Lindalong Shear Zone), H2 at the NNE margin of a major area of quartzite, H3 at the boundary between slate (Pkg) and schist (Pki) which is the western limit of minor granitic intrusions, H4 part way through schist (Pki), and H5 between schist (Pki) and gneiss (Pkr). Some segments of these faults corresponding with elongate, uniform magnetic lows, other segments correspond with linear gentle gradients. The magnetic lows probably indicate that the fault zone has been demagnetized. Some bodies of rock are structurally associated with the fault zone: fault H3 is associated with white patches in the radiometrics possibly due to leucogranite, and fault H4 has slivers of quartzite at two positions along its length. Extensive areas of quartzite (Pkp, Pkl) in the Kalkah Domain can be mapped on the ground, on air-photographs and Landsat images, and as dark areas on radiometric images. They cause high-amplitude magnetic anomalies with wavelength 1.5 km in area H6, and elsewhere they have similar magnetization to the surrounding rock.

In area H7 to the north, the magnetic anomalies due to lithology have north strikes in the west and north, and northeast strikes in the southeast. There appear to be at least three cross-cutting faults. There is no major increase in magnetization at the boundary between schist and gneiss as in the south.

Area I is a southward continuation of the rocks of area H, but separated from it by a major fault, the Lukin River Shear Zone. Areas H and I have a streaky, irregular radiometric image thought to indicate more deformation than the less streaky radiometrics of the less deformed areas F and G to the west; the boundary is a major NNW trending fault, the Lindalong Shear Zone. Area I1 has high magnetization relative to area I2, and slightly higher thorium than areas I2 and I3. Anomalies that can be correlated include some in the north associated with schist, and in the south associated with quartzite of the Kalkah Domain. Area I2 has low magnetization. Area I3 has high-magnetization equi-dimensional anomalies which do not correlate with mapped structures in the schist there. Area I4 is a highly magnetic area of schist. Area I5 is a strip of schist bounded by NW trending faults, that has the magnetic character of a wide shear zone. Area

I6 has low but not zero magnetization, so either the granite is magnetic in part, or there is more schist and less granite than is mapped from air photographs. Area I7 is part of a highly magnetic belt of schist that extends south into HANN RIVER. The southwestern part of I7 differs in that it has high U, Th and K.

Area J is an area of very low-amplitude magnetic anomalies that corresponds with the extent of Silurian-Devonian granitoids. The Ebagoola Shear Zone causes a positive magnetic anomaly in the northern sector, and a broad negative anomaly in the southern sector. This change coincides with the change from less magnetic Kintore Granite in the north to more magnetic Flyspeck Granodiorite in the south.

Area K magnetics have a strong northwest trend. There appears to be no systematic difference in magnetization between the gneiss and schist units, but the larger anomalies appear to be associated with the boundaries between these units. The central area of gneiss is associated with a characteristic short-wavelength (0.5 km), elongate, sinuous, small-amplitude (4 nT) magnetic anomaly which is interpreted as a wide shear zone. Elsewhere in area K there are correlatable, long-wavelength magnetic anomalies, and radiometric expressions of quartzite, that are consistent with lithology being semi-continuous for distances of 7-15 km. Elongate, semi-continuous, magnetic lows may be due to faults.

Area L magnetic anomalies are relatively low amplitude (about 10 nT), with a strong N to NNE grain. Sets of anomalies can be traced along strike, consistent with there being a well defined continuous lithological banding. In the exposed western part of the area the radiometric pattern is also consistent with this stratigraphy. There are no obvious strike-parallel faults. Crossing these magnetic anomalies, but not displacing them, are zones with NW and NE strike that are slightly negative, and are of low magnetic relief. These zones are inferred to be dip-slip faults/fractures. The NW trending set is part of the Coen Shear Zone. Area L1 has higher amplitude anomalies and may be part of area O. The similarity in magnetic character of areas K, L and M, is consistent with these areas being similar rocks of similar metamorphic grade.

Area M is a continuation of area L, the two areas being separated by a zone with irregular anomalies, that is a major, wide magnetic low, and is likely to be a major NE-trending fracture. Layering trends are generally NNW, swinging to north in the northern part of the area. Anomalies due to layering can be correlated with relatively poor confidence for up to 30 km as irregular magnetic highs with a wavelength of 3-5 km. The separation of anomalies into those due to layering, and those due to faulting is difficult. Faults, close to layering-parallel, occur as linear, uniform anomalies with a NNW trend. M1 is a series of en-echelon north-striking, nearly linear, narrow, magnetic lows that are inferred to be due to a dyke or fault with zero or negative magnetization.

Area N is gradational to area M to the east and north. The dominant magnetic features are normally magnetized, arcuate, 6-16 km in length, 40-100 nT in amplitude, with an easterly strike; they are thought to be fault controlled structures. Most of the isolated elongate NNW-striking magnetic features are due to faults. The area has relatively-high, uniform magnetization, so the rocks may be orthogneiss.

Area O is inferred to be a major NNW trending shear zone, 6-8 km wide, that truncates structures of area L and M to the SW, and area P to the NE. Sub-area O1 is a magnetic anomaly high, composed of large magnetic anomalies of amplitude 100-250 nT and 2-5 km long, that form a single line to the south and a broad band to the north. Sub-area O2 is a broad magnetic low.

Elongate short-wavelength magnetic anomalies generally are of amplitude 4-12 nT, and are inferred to be due to close spaced faulting. The difference in magnetization of sub-areas O1 and O2 is due to different modes of deformation. O3 is a circular area of high-amplitude short-wavelength anomalies due to outcropping lavas of the Late Cainozoic basanitic nephelinite of Silver Plains.

Area P is in fault contact with area O to the SW, and in contact with possible granites to the east. In general the rocks give a low average magnetic anomaly, and small-amplitude (2-6 nT) short-wavelength anomaly. The magnetic anomaly pattern is consistent with a conformable sequence, with a strike ranging regionally from NW in the south to NNW in the north. The low magnetization, and lack of disruption of layering, are consistent with a sub-schist metamorphic grade. Along the eastern margin is a narrow band (P1) of high-amplitude elongate anomalies, which by comparison with similar anomalies just north of EBAGOOLA in COEN, are interpreted as metamorphics with their magnetization enhanced by the contact effects of granites. The low metamorphic grade, the contact metamorphism, and the many small intrusions in areas P, O, and the central part of Q, are consistent with area P equilibrating in the upper part of the crust, in common with the rocks of the coastal part of COEN immediately to the north. Nearby area L is of upper amphibolite grade, so area O is interpreted to be a major fault zone separating areas which equilibrated at very different depths in the crust.

The western part of area P has a large (7 km diameter) dish shaped anomaly (P2), 75 nT in amplitude, that is interpreted as a horizontal-discoid intrusion of magnetic material below the basement surface.

Area Q has a magnetic intensity that is low or average. It is magnetically quiet at short-wavelength, due mainly to the thickness of the overlying Laura Basin sediments. Area Q1 is thought to be mainly a granitic intrusion, because gravity and magnetic anomalies are low, and there appears to be contact metamorphism in area P1. The intrusion is likely to be of Siluro-Devonian age because granites of this age, with high magnetization at their contacts, occur to the north in COEN. Area Q2 is thought to be mainly metamorphics because the magnetic and gravity anomalies are higher, and the region is traversed by elongate anomalies due to either faults or bands of different lithology.

Anomalies Q3 are due to strongly, and normally magnetized rocks in the basement, which are either equi-dimensional or vertical cylinders in shape. Anomalies Q4 and Q5 in the south, 20 and 28 km long, 2-15 nT amplitude and 3-10 km wavelength, are interpreted as due to rocks associated with faults splaying from the Palmerville Fault, but they could be layering that is continuous with layering to the NNW. Anomalies Q6 and Q7 are due to a thin layer of normally but irregularly magnetized rock. The anomalies are similar to those of the late-Cainozic basanitic nephelinite flows of Silver Plains, so the anomalies are thought to be due to related flows that are covered by late Cainozoic alluvium.

Area R is a series of subparallel elongate anomalies overlying the Palmerville Fault Zone. In the south there are two wide positive anomalies R1 and R2 due to fault structures, and off-set from these a very short-wavelength negative anomaly (R3) that overlies the previously-mapped surface trace of the fault. At this surface trace there is displacement of colluvial sand of Pliocene to Holocene age (Trail & others, 1977). In the north there are up to three subparallel wide anomalies due to fault structures. The wider anomalies in the north and south are thought to be due to fault bound slivers of marginal facies of the Hodgkinson Basin.

Area S is underlain by sediments, volcanics and granitoids of the Hodgkinson Basin. The magnetic and gravity level is relatively high, so the basin sediments close to the Palmerville Fault Zone may be relatively dense and magnetic. The dominant magnetic anomalies are discrete magnetic highs that are likely to be due to intrusions. Two anomalies (S1, S2) are of large diameter (17-27 km) positive anomalies without negatives to the south, and are due to horizontal disc-shaped bodies. Anomalies S3 and S4 are smaller, more irregular, with magnetic lows to the south of the highs, and are due to more equi-dimensional bodies.

Area T to the northeast has relatively low gravity and magnetic anomalies, so rocks may differ from area S.

DECREASE IN THE INTENSITY OF THE SILURO-DEVONIAN EVENT WESTWARDS

A simple interpretation of the geology of EBAGOOLA is that the basement is the reworked margin of the Proterozoic crust, with the edge of the crust at the Palmerville Fault Zone, and reworking decreasing in intensity westwards, and not extending past 110 km west of the Palmerville Fault Zone. Changes supporting the decrease in intensity of reworking westwards are:

- The decrease westward in the level of the top of the granitoids relative to the present basement surface as determined from geophysics. The margins of the Coen and Newberry Metamorphics generally have steep contacts with granitoids, so the top of the granitoids is above ground level in the east. The eastern margin of the Holroyd Group generally has a shallow dipping contact with granitoids, consistent with the top of the granitoids being close to the present surface. The western margin of the Edward River Metamorphics is interpreted to overlie granitoids that do not crop out, so the top of the granitoids is well below the present surface in the west.
- The effect of the Siluro-Devonian heating event is twofold, as determined mainly from geology (Blewett & others, in press):
    - — An increase eastwards towards the Palmerville Fault System in the maximum metamorphic grade. West of 110 km from the Palmerville Fault Zone the rocks are inferred to be of greenschist facies. In the band of metamorphics forming the Edward River Metamorphics and Holroyd Group, the central part (Lukin Domain) is mainly greenschist facies, the western margin (Edward River Metamorphics) where exposed is lower amphibolite facies (containing garnet), and the eastern margin (Kalkah Domain) is mainly mid amphibolite facies (containing andalusite), with a rim of rocks of upper amphibolite facies (containing sillimanite). The outcropping Coen and Newberry Metamorphics are mainly upper amphibolite facies (containing sillimanite), and most of the subcropping rock is thought to be the same grade.
    - — There is an eastward increase in the amount of heating away from the granitoids. Within the Holroyd Group and Edward River Metamorphics there was little heating away from the granitoids; granitoids underlie all rocks above greenschist facies. Within the Coen and Newberry Metamorphics rocks are of uniformly high grade, even though bands of metamorphics are wide.

- There is a general increase in the intensity of the D2 deformation eastwards, where this intensity is measured by the density of the NNW-striking faults, and the degree of transposition of large-scale folds, and the continuity of structures along strike. This is apparent both from geology (Blewett, 1992), and from the density of faults interpreted from the magnetic anomalies. Strong deformation is pervasive in the Coen and Newberry Metamorphics, is restricted to the margins of the belt of metamorphics forming the Holroyd Group and Edward River Metamorphics, and more than 110 km west of the Palmerville Fault Zone it cannot be seen on the magnetic image so is inferred not to be present.

In summary, Siluro-Devonian transpressional-deformation, heating, and intrusion extended 110 km westward from the margin of the Proterozoic crust marked by the Palmerville Fault Zone. The intensity of the event decreased westwards. Close to the Palmerville Fault Zone there was high heat flow, granitoids at higher levels than the present land surface, and pervasive faulting. To the west, the heating and faulting are more localized being concentrated close to the granitoids, and granitoids are at, or below, the present land surface. This westwards decrease in the intensity of the event is thought to be due mainly to a real decrease in intensity westwards, but due to some extent to the present land surface being now at a deeper crustal level in the east, because of deeper post-Devonian erosion.

DISCUSSION

The reworking of the Proterozoic craton margin in EBAGOOLA has many similar features to reworking described at other craton margins in Australia (e.g. Beeson & others, 1988), and overseas – the decrease in intensity of reworking inwards from the margin, the width of the margin in the range 50 to 200 km, and the transpressional-heating nature of the deformation. However, it differs from the majority of margins in the following two important respects.

- At most craton margins there are major dipole gravity (Gibb & Thomas, 1976) and major magnetic anomalies centred on the margin, due to a change in crustal structure at the craton boundary, and to volcanic and metamorphic rocks emplaced along the boundary when the younger crust was cratonized. These major gravity and magnetic anomalies are not present along the Palmerville Fault Zone, so either (a) it is not a true boundary and the Proterozoic crust extends eastwards past the Palmerville Fault Zone and under the adjacent Hodgkinson Province, or (b) by chance there is no significant difference in density and magnetization between the Proterozoic crust west of the Palmerville Fault Zone and the Phanerozoic crust immediately to the east. This second model is preferred.

- At most cratonic margins there is a reworked strip of the older crust, that has low magnetization due to metamorphism causing a decrease in magnetization (Klasner & King, 1986; Beeson & others, 1988). In EBAGOOLA the band of Siluro-Devonian activity is a zone of increased magnetization. The increase in magnetization is due to the thermal effect of reworking increasing the metamorphic grade due to the low initial grade of greenschist facies. Craton margins that have a similar magnetic pattern to that in EBAGOOLA, are the margins of similar age in eastern Queensland between New

England and East Thomson Geophysical Domains (beneath the Bowen Basin), and between East Thomson and West Thomson Geophysical Domains (beneath the Drummond Basin), as described by Wellman (1990). At these craton boundaries the reworked strip of older crust is largely under post-orogenic cover rocks; both margins have a wide band of high magnetization due to reworking/volcanism, with a 25 km wide band of low magnetization along the craton boundary. The EBAGOOLA area may provide a good model for these margins.

CONCLUSIONS

- Gravity and magnetic data have been used to map the major units of basement geology under the cover of Mesozoic sediments and thick regolith.
- A major contribution of the gravity has been to show the extent of the granitic rocks at depth, and in particular to show that some areas of basement are underlain at relatively shallow depth by granitic rocks, or have granitic rocks dipping under them.
- Three major periods of faulting are recognized from the magnetic anomalies. First, formation of mainly strike-slip NNW-trending faults, that bound the major rock units, are subparallel to regional layering, and predate the metamorphic maximum. Second, shortly after the metamorphic maximum, a small amount of reverse sinistral movement on a set of NW-trending shear zones – the Coen, Ebagoola and Lukin River Shear Zones, and on the NNW-trending faults. Third, the formation of a set of NE-trending fractures, with demagnetization on the fracture plane.
- The EBAGOOLA sheet can be interpreted as a section across the reworked margin of a cratonized Proterozoic crust, with unmodified crust in the west, crust modified by heating, shearing and intrusion in the centre, and new or thinned crust cratonized in the Palaeozoic to the east of the Palmerville Fault Zone. The intensity of reworking decreased away from the Palmerville Fault Zone, with a westward decrease in the level of the top of the granitoids relative to the present surface, a decrease in the maximum metamorphic grade and the extent of the heating away from the granitoids, and a decrease in the intensity of the D2 deformation.

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