Bureau of Mineral Resources, Geology & Geophysics

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Vulcan Graben, Timor Sea: Regional Structure From a Magnetic Survey

Project 221.04

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SUMMARY

In late 1989 the Australian Bureau of Mineral Resources, Geology & Geophysics (BMR) carried out a regional aeromagnetic survey by contract over the Vulcan Graben region. Elongate short-wavelength anomalies, with wavelengths of 3 to 12 km, amplitudes of 0.2 to 2.0 nT, and with generally northeast strikes, can be correlated for distances of up to 100 km on the basis of their shape and amplitude. Their source appears to be principally at depths of between 0.7 and 3.0 km. Some of the relatively larger amplitude and wavelength anomalies overlie major northwest-dipping normal faults which have been mapped using seismic data. All of the elongate anomalies are thought to be due to structures or magnetic precipitates associated either directly with NE-trending normal rift faults, or with faults in the post-rift sediments which are related to rift fault reactivation. ENE fault trends, which developed in the Neogene as a result of the collision with Timor, do not appear on the aeromagnetic data.

Numerous northwest-trending faults have also been mapped. These have a spacing of approximately 10 to 25 km. They are thought to be strike-slip because some offset the major northeast-trending normal faults. The northwest trending faults may be due to the reactivation of Palaeozoic trends, the reactivation of Mesozoic transfer faults, or possibly some may be younger and independent of the earlier faults. Some of these faults have previously been mapped on seismic profiles and correspond to seismic 'bad data' areas. These faults may have a major role in the entrapment of hydrocarbon accumulations in the Timor Sea, with most of the significant fields being close to a northwest-trending fault or its extension.

In the Timor Sea, high resolution aeromagnetics has proven to be a relatively cheap and cost-effective tool which both complements and supplements the existing seismic data. It should prove equally useful in other areas with extensive seismic coverage. In frontier areas, it should rapidly define the geometry of the major tectonic elements of the basin, allowing for better positioning of seismic programs.

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1. INTRODUCTION

1.1 Project rationale

In this Record, we present the results of a regional aeromagnetic survey that the Australian Bureau of Mineral Resources, Geology & Geophysics (BMR) conducted (by contract) in the Timor Sea in November-December 1989. There were a number of reasons for undertaking the survey. Firstly, very little ship- or air-bourne magnetic or gravity data are publicly available in the area. The only previous aeromagnetic surveys are a reconnaissance survey by Arco in 1965 and a survey over the Paqualin structure (Smith and Whitehead, 1989). It was thought that a regional high-resolution aeromagnetic study would assist in the understanding of the tectonic architecture of the Vulcan Graben region, which recently has been the subject of considerable debate (Nelson, 1989). Secondly, the BMR plans to conduct two research cruises in the Timor Sea in late 1990. These seismic reflection cruises will focus on both the deep and shallow crustal evolution of the region and a comprehensive aeromagnetic data set was considered an important adjunct to those programs.

2. STUDY AREA, REGIONAL GEOLOGY AND TECTONIC EVOLUTION

The Vulcan Graben is located within the Timor Sea on the far northwestern Australian margin and lies approximately half-way between the Kimberley Block and Timor (Figure 1). It is presently one of Australia's most active petroleum exploration areas, with a number of significant oil discoveries, including the Jabiru, Challis/Cassini, and Skua fields. It is flanked by two major elevated blocks, the Ashmore Platform to the northwest and the Londonderry High to the southeast (Figures 1 & 2). The Vulcan Graben itself is sub-divided into a series of NE- and ENE-trending sub-grabens (Figure 2) which are separated by intra-graben terraces (Patillo and Nicholls, 1990).

The tectono-stratigraphic evolution of the Vulcan Graben, the Ashmore Platform and the Londonderry High has been sub-divided into three megasequences:- the pre-rift, the syn-rift and the post-rift megasequences (Patillo and Nicholls, 1990). The pre-rift megasequence consists of latest Permian to Middle Jurassic sediments and is truncated on a regional scale by a late Callovian Unconformity. The overlying syn-rift megasequence, which is largely restricted to the Vulcan Graben 'proper', is comprised of late Callovian to early Valanginian siliciclastics. Intense faulting during this time introduced a strong E-NE orientation to the graben. Syn-rift sedimentation was terminated in the Valanginian by a period of uplift and substantial erosion:- erosion was particularly pronounced on the terraces and horsts within the Vulcan Graben and on the flanking platforms such as the Londonderry High. Sands immediately subcropping the Valanginian Unconformity host the Jabiru and Challis hydrocarbon accumulations, and range in age from Late Jurassic at Jabiru to Middle to Late Triassic at Challis. Overlying (post-rift megasequence) claystones provide the seal. The variability in the age of the reservoirs reflects the highly variable amount of erosion of the fault blocks during the Valanginian.

The post-rift megasequence overlies the Valanginian Unconformity, and consists sediments ranging in age from late Valanginian to Quaternary. This sequence reflects the thermal subsidence phase with the development of a passive continental margin, with the sequence becoming progressively more marine with time. During the Late Miocene, the northward-moving Australasian plate collided with the Eurasian plate, introducing a compressional regime in the Timor Sea. This collision reactivated many of the rift faults and introduced east-northeasterly fault trends, particularly within the post-rift megasequence in the more northerly part of the Vulcan Graben, where the collisional effects are most pronounced, and ENE-oriented faulting is intense. The collision also resulted in the formation of the Cartier Trough and mobilised the Palaeozoic salt which is present within the Paqualin and Swan Grabens (Figure 2) (Patillo and Nicholls, 1990).

3. AEROMAGNETIC SURVEY

Our survey covered the Vulcan Graben region (Figures 1 & 2) and part of the Eider Trough to the east of the Jabiru Terrace. The flight line spacing was 2.5 km, the tie line spacing was 15 km and the flight altitude was 150 m. The flight lines were oriented along 130^{o}, at right angles to the known structure. An attempt was made to measure the anomalous magnetic field along flight lines to a precision of 0.1 nT. The survey (20 000 line-km) was flown by 'Austirex' under contract during November and December 1989.

The observed aeromagnetic anomaly map has anomalies with a wavelength of 50 to 100 km, amplitudes of 30 to 240 nT, and predominantly easterly trends. This trend may reflect dominant east-trending structuring, but it is more likely due to the preferential enhancement of east-trending structures relative to structures in other directions at low magnetic latitudes.

Arco (1965) calculated depth to magnetic basement, apparently mainly using graphical methods. Their shallowest depths are about 3.5 km at the southern corner of the area while their greatest depths are about 6.6 km near the centre of the Vulcan Graben. New estimates of the depth to magnetic basement were made using the Vacquier method and our new aeromagnetic data. The two sets of depths are roughly consistent, with depths to magnetic basement of 6-7 km within the Vulcan Graben and 3-5 km on the graben margins.

3.1 Short-wavelength anomalies

The short-wavelength anomalies of greatest interest had wavelengths of 3 to 12 km and amplitudes of 0.2 to 2.0 nT. There is a major problem in separating these anomalies from the longer wavelength anomalies, not because the wavelengths were similar, but because the amplitude difference means that the leakage of long wavelength components must be 0.1% or less. The preferred filter was the residual to a mean of 6 km length:- this 1-D filter was applied to the flight line profiles (Figure 3). A 1-D band-pass filter was found to be unsatisfactory:- in order to get low leakage the filter length had to so long that much of the flight-line profile was lost. Filtering in 2-D was attempted using a ring filter of diameter 6 km, applied twice. Filtering of the grid gave unsatisfactory results because:- 1) the errors in levelling (up to 0.2 nT) were about the same amplitude as the smaller short-wavelength anomalies, so the effects of poor levelling tended to mask the effects of (interpreted) cross-strike faults; and 2) gridding destroyed the detailed information on anomaly shape that provided a major control on anomaly correlation.

Figure 4 (and Enclosure 1) shows the northeast-trending short-wavelength anomalies that are present over most of the area. These have been correlated between profiles on the basis of their amplitude and shape using the plan of the flight line profiles (Figure 3); adjacent anomalies are generally sub-parallel. Only the positive anomalies have been mapped over most of the area, because they have a greater or equal amplitude compared with adjacent negative anomalies. Negative anomalies have been mapped where they have greater than about 0.4 nT amplitude, or they are greater in amplitude than the adjacent positive anomalies. Anomaly amplitude is generally less in the centre of the Vulcan Graben than elsewhere. The correlations of the more prominent short-wavelength anomalies are shown in Figure 4 by double lines. Correlations were made primarily using flight-line profiles, though contour maps showing 6 km and 30 km wavelength anomalies were also used. The trend of the anomalies ranges from east to north, with the average near northeast. There are well-defined areas within which the trend is consistent for an area 30 to 50 km across.

The depth to source of the short-wavelength anomalies has not been calculated. Their wavelength ranges from 3 to 12 km, with what appear to be composite anomalies, suggesting that the magnetic sources are spread out vertically over a depth range between 0.7 to 3 km. The dominant sources appear to be between a depth of 1 to 2 km. Arco (1965) calculated the depth-to-source to be 0.6 to 2.3 km, with a mean of about

1 km.

If an average magnetic source depth of 1.0-1.5 km is assumed, then the source would lie within:-

i.) the pre-rift (predominantly Triassic) megasequence on the Ashmore Platform and Londonderry High. It could lie within the Permian over parts of the Londonderry High.

ii.) the Triassic to Late Jurassic on the terraces within the Vulcan Graben.

iii.) the post-rift megasequence in the sub-grabens within the Vulcan Graben.

The cause of the short-wavelength anomalies is difficult to determine and each anomaly may be due to a number of sources at a range of depths. The possible sources include:- latest Jurassic to earliest Cretaceous basalts and volcaniclastics on the Ashmore Platform (as penetrated in the Ashmore Reef 1 and Mt. Ashmore 1B wells) (Patillo and Nicholls, 1990); laterization during deep weathering during Valanginian Unconformity time, as evidenced by probable laterites in the Triassic at the Challis field; magnetite, possibly associated with salt diapirism, as seen in Paqualin 1 (Smith and Whitehead, 1989). As these types of sources result in irregular and short length anomalies, they are not thought to be the major cause of the more prominent anomalies, which are straight and very elongate.

The magnetic anomalies are interpreted to be caused by structures associated with the NE faults which cut the pre-rift and syn-rift megasequences, since the anomalies correlate well with the faults shown on the structural elements map (Figure 5). Generally the magnetic and structural elements trends are consistent:- the major faults correlate with major magnetic anomalies and minor faults with minor anomalies (Figure 5). The major discrepancy is that no anomalies correlate with the SE-dipping faults along the northwest margin of the graben. The magnetic trends also correlate with the faults shown on the Valanginian and Callovian structure maps (see Figures 11 & 12 of Patillo and Nicholls, 1990), but not the ENE-trending faults which formed in response to the collision with Timor. This is somewhat puzzling, since the Valanginian (and deeper structure) would seem to be too deep to host the magnetic source in the grabenal areas within the Vulcan Graben. The preferred interpretation is that the northeast-trending anomalies are predominantly due to the truncation of sediments by unconformities and faults, and possibly to magnetite precipitation from fluids flowing along fault planes, specifically either along the northeast-trending rift faults within the pre-rift and syn-rift megasequences, or faults in the post-rift megasequence caused by the reactivation of rift faults.

3.2 Northeast component of long-wavelength anomalies

Initially the contractor used a 30 km wavelength 1-D filter along the flight lines which did not sum exactly zero. Maps contouring this data give directionly filtered long-wavelength anomalies. The sources of these anomalies is inferred from their wavelength to be in the pre-rift megasequence or basement. The magnetic highs have directions and extent such that they generally overly the correlated and stronger short-wavelength magnetic anomalies (Figure 5 and Enclosure 2). The positions of these magnetic highs are therefore consistent with the correlations between individual segments of the stronger short-wavelength anomalies and between these correlated anomalies and the major rift faults. Magnetic highs correlate with northwest-dipping normal faults whereas magnetic lows correlate with southeast-dipping faults.

3.3 Northwest-trending features

The northeast-trending anomalies are interrupted by northwest-trending features along which the amplitude of the anomalies is relatively low. These commonly offset the northeast-trending anomalies (Figures 3 & 4; Enclosure 1) by between 2 and 5 km, and they are interpreted to be faults. These NW-trending faults have a spacing of 5 to 25 km and range from 10 to over 200 km long. The offsets are generally sinistral in the southwest of the area and generally dextral in the east. The direction of these faults is very consistent; most are straight and trend at about 305^{o}.

The northwest-trending faults may be due to the reactivation of transfer faults that originally formed during Mesozoic extension, the reactivation of Palaeozoic trends, or possibly some may be late-stage and independent of earlier faults. These northwest-trending faults have not been mapped using seismic data profiles, although some northwest-trending zones of poor reflection/character change have been recognized that are presumed to be faults. The observation that the major northeast-trending anomalies end at these northwest-trending features is consistent with a transfer fault interpretation. Some of the northwest-trending faults appear to be the major boundaries between areas of different structure. These possible major faults are indicated by double lines in Figure 4 and Enclosure 1.

The northwest-trending faults may have a major role in the entrapment of major hydrocarbon accumulations in the Timor Sea, since all of the significant oilfields in the Vulcan Graben are located close to a northwest-trending fault or its extension (see Figure 4 and Enclosure 1).

On the basis of the short- and long-wavelength aeromagnetic data, the Vulcan Graben can be sub-divided into discrete tectonic provinces which have abrupt boundaries. Within each province, structure at both shallow and deep levels appears to be of a consistent trend and correlatable.

4. DISCUSSION

This study shows that an aeromagnetic survey using a high resolution magnetometer can define the structural elements of an extensional basin, the Vulcan Graben. The short-wavelength anomalies map the main northeast-trending (rift-related) normal faults and other parallel structures. The shallow, more ENE Miocene fault trends associated with the collision with Timor are not evident in the magnetic trends.

Breaks in the northeast-trending anomalies define important northwest-trending faults which may be reactivated Palaeozoic faults, Mesozoic transfer faults, or younger faults. Our work suggests that aeromagnetics may be more efficient than seismic data in delineating cross-cutting faults. The mapping of these strike slip fault systems is important for three reasons:- 1) Understanding the gross tectonic structure of the region. 2) Mapping the boundaries of continuous strata. 3) Determining their control on the migration and/or entrapment of hydrocarbons. In the Vulcan Graben, most of the significant oil discoveries are located close to one of these northwest-trending faults.

It is clear that in the Vulcan Graben, an area with extensive seismic control, that the interpretation of the pattern of magnetic anomalies both complements and supplements the seismic data in a cheap and cost effective way. A similar understanding should be achievable in other offshore areas with extensive seismic coverage. In offshore areas with poor seismic coverage, aeromagnetic surveys should allow the major normal and cross faults to be mapped, and thereby provide a framework for a more informed planning of seismic surveys. Onshore, the relevant small anomalies may be difficult to separate because of high-amplitude very short-wavelength anomalies due to the formation of magnetic minerals in the regolith.

5. Acknowledgements

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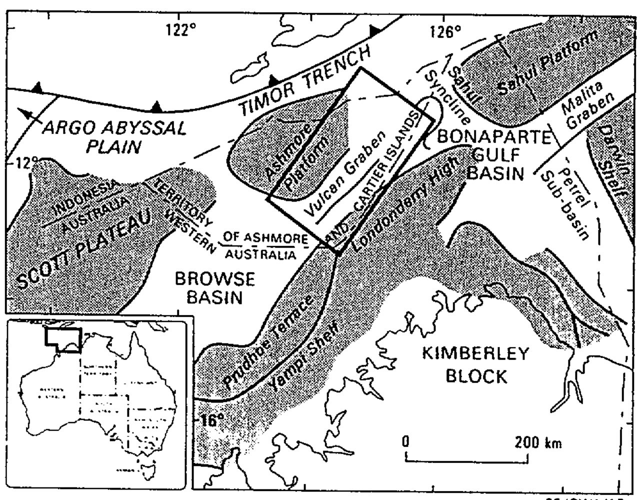


Figure 1. Major structural elements of the Timor Sea. The rectangle defines the area encompassed in Figures 2, 4 & 5. (after Pattillo and Nicholls, 1990). Structurally high areas are shaded.

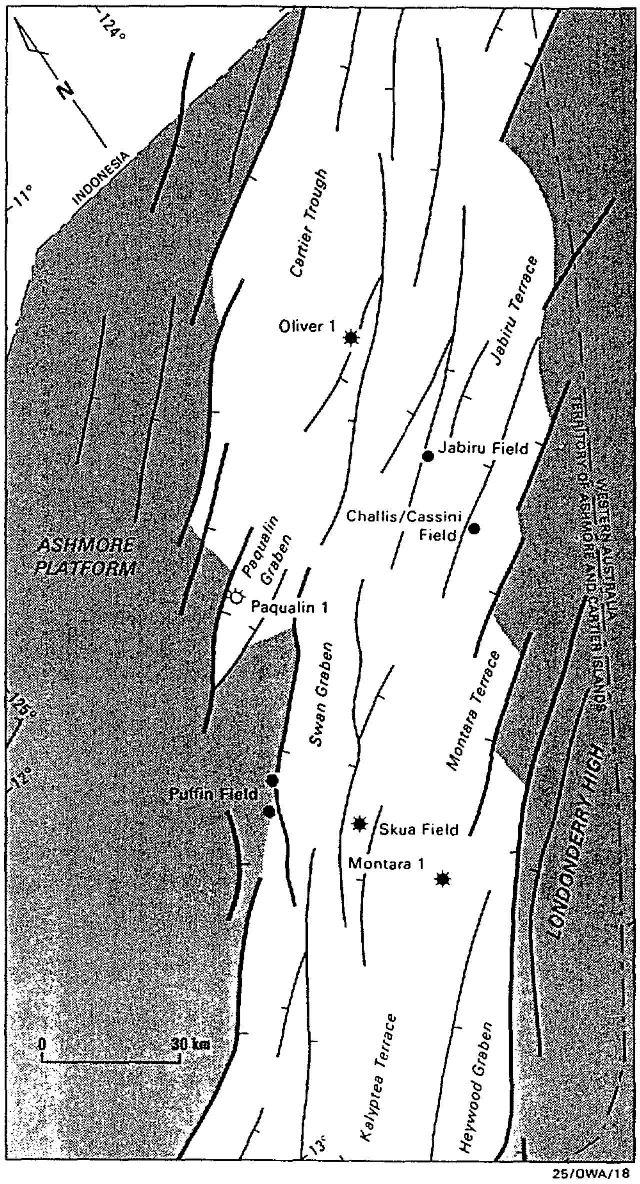


Figure 2. Structural elements of the Vulcan Graben (after Pattillo and Nicholls, 1990). Structurally high areas are shaded.

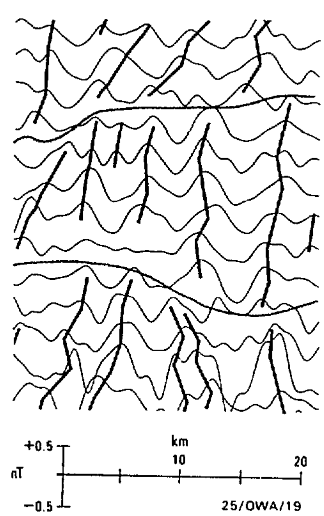


Figure 3. Example of the interpretation of profiles of short-wavelength magnetic anomalies. Thick lines show correlated anomalies, grey lines show inferred faults.

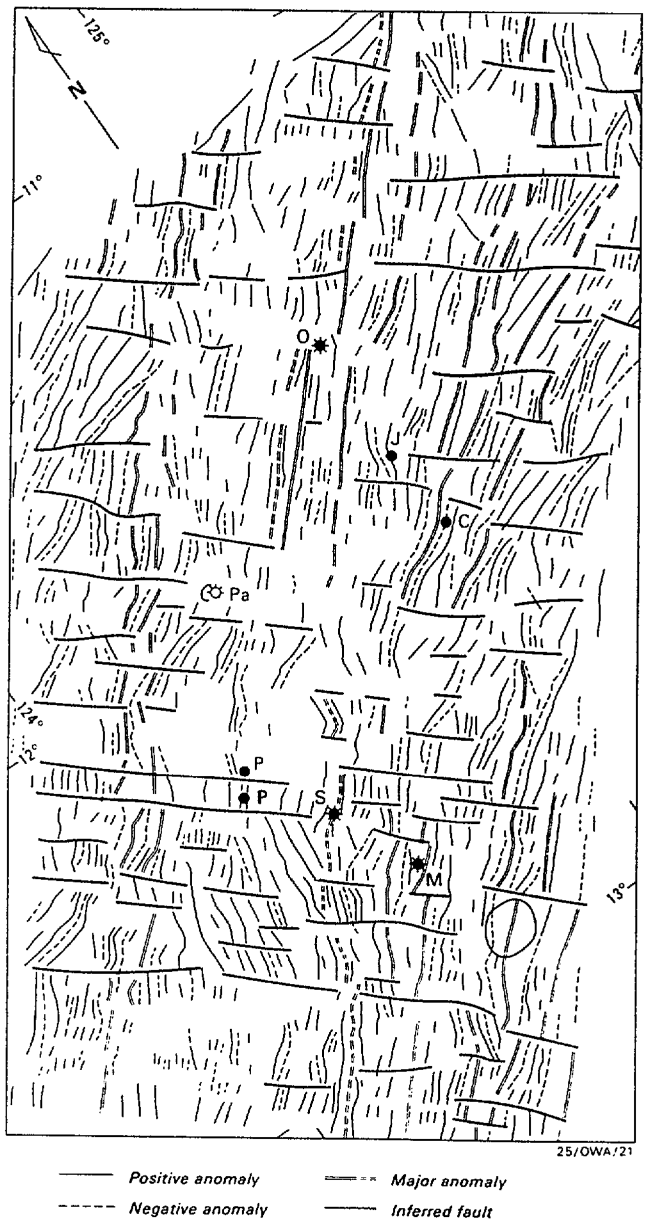


Figure 4. Interpretation of short-wavelength magnetic anomalies in the Timor Sea. Wells shown are: C: Challis/Cassini Field; J: Jabiru Field; M: Montara-1; O: Oliver-1; Pa: Paqualin-1; P: Puffin Field; S: Skua Field.

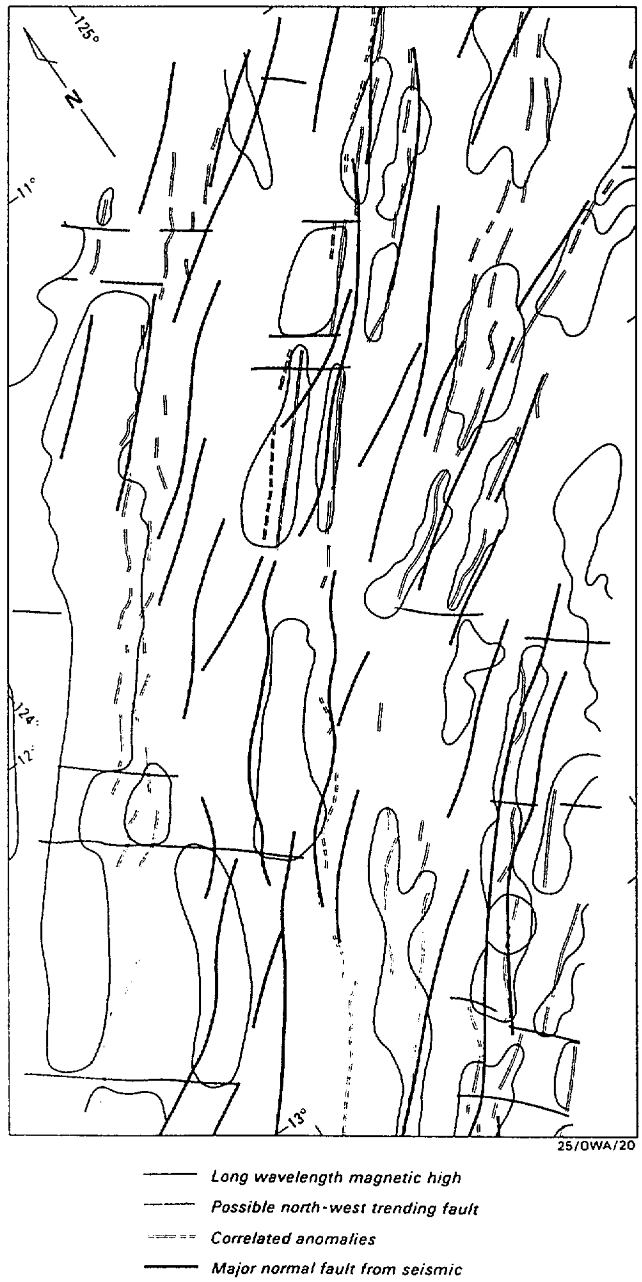
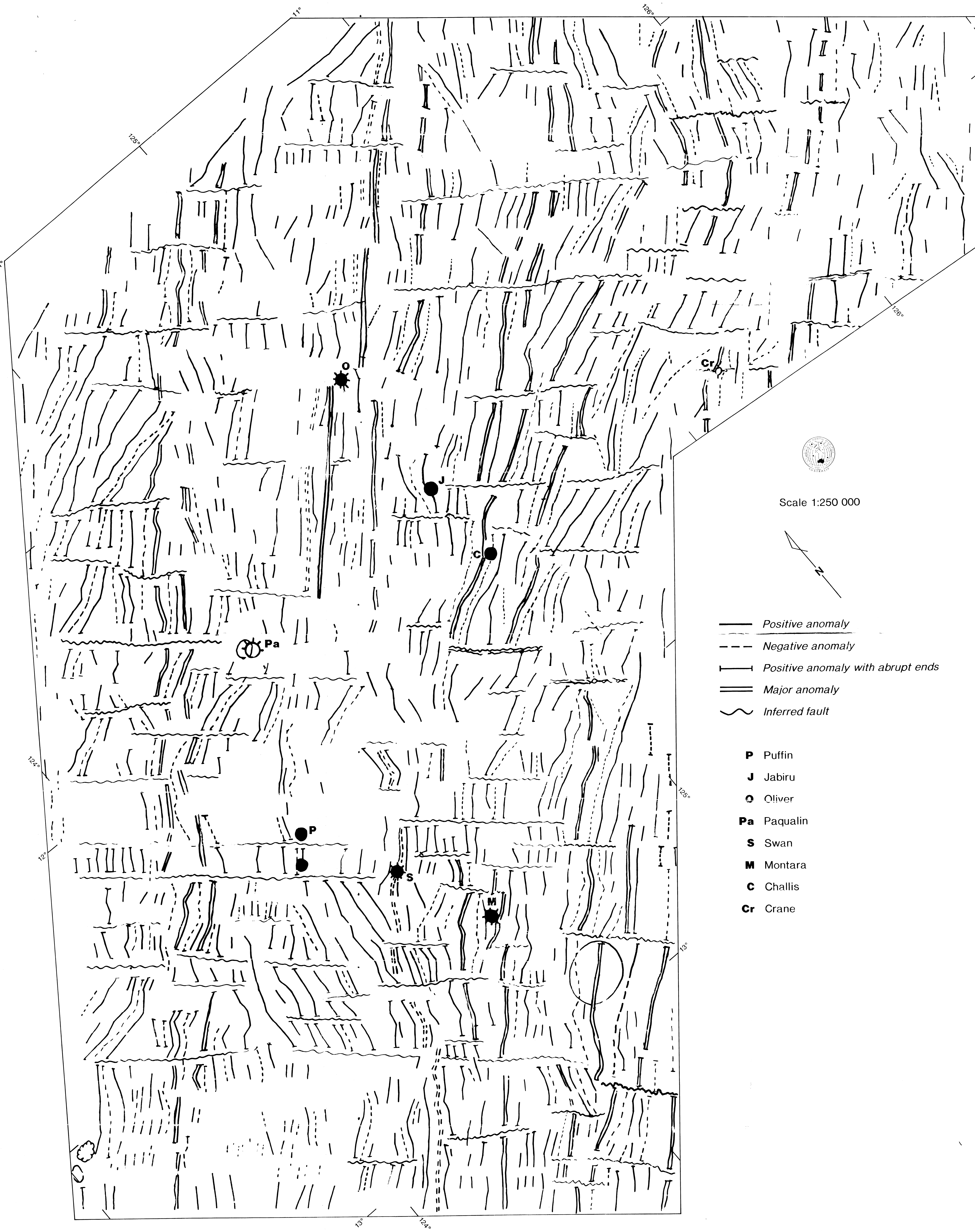


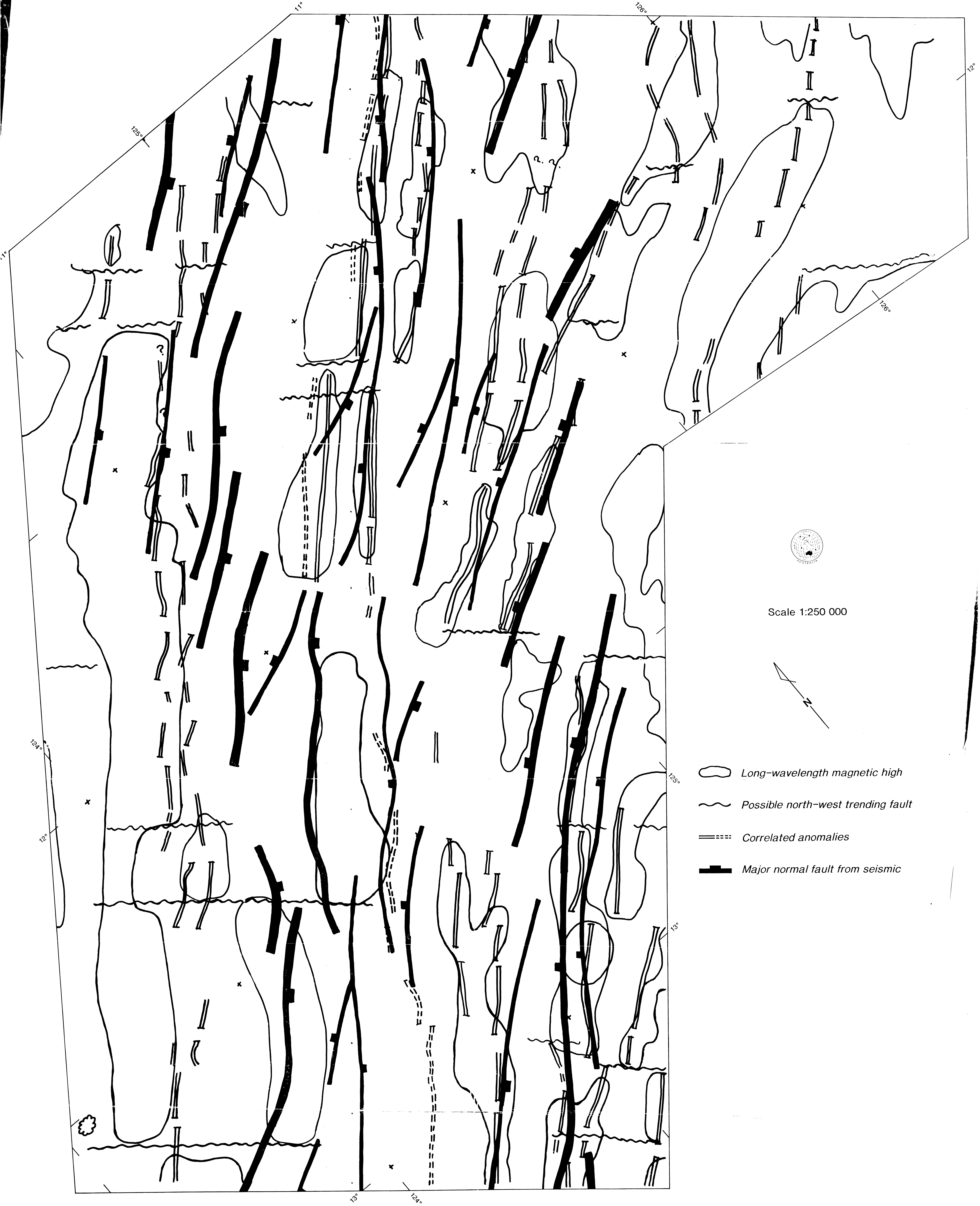
Figure 5. Comparison of the location of major normal faults, and short- and long-wavelength magnetic anomalies in the Timor Sea.

ENCLOSURE 1. **Interpretation of short-wavelength magnetic anomalies in the Vulcan Graben, Timor Sea. 1:250,000 scale, Transverse Mercator projection.**



Interpretation of short-wavelength magnetic anomalies. Oil fields shown are: C, Challis/Cassini Field; J, Jabiru Field; M, Montara 1; O, Oliver 1; Pa, Paqualin 1; P, Puffin Field; S, Skua Field.

ENCLOSURE 2. **Comparison of the location of major normal faults, and short- and long-wavelength magnetic anomalies in the Vulcan Graben, Timor Sea. 1:250,000 scale, Transverse Mercator projection.**



Comparison of the location of major normal faults, and short– and long–wavelength magnetic anomalies.