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Application of aeromagnetic surveys to sedimentary basin studies

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While aeromagnetic surveys have been mainly used in the past for mapping depth to magnetic basement of sedimentary basins and for delineating igneous units within the sedimentary section, the advent of high-resolution surveys flown close to the ground with close line spacing has revealed the existence of significant magnetic anomalies arising from sedimentary layers and their structure. As a result of these developments, aeromagnetic surveys now have greater relevance to sedimentary basin studies.

Introduction

The aim of this paper is to explain the types of aeromagnetic responses that arise from the various geological features associated with sedimentary basins and how these responses can be interpreted in the context of basin studies. The discussion is directed to petroleum exploration, but features relevant to mineral exploration are mentioned and, in any case, the generalities presented apply to virtually any study of sedimentary basins. In this paper, a sedimentary basin is any depression that has accumulated sediment, and no attempt has been made to distinguish between sedimentary basins of different origins and structuring.

All rock units are magnetic, but not all give rise to readily observable magnetic effects. The magnetic responses described here are those that may be expected to be detected with airborne surveying systems recording the magnetic field with a precision of ± 0.01 nT at a survey altitude of approximately 100 m above ground or sea level. Acquisition systems with such precision have become standard during the past five years, with the installation of optically pumped caesium and helium vapour magnetometers, improved compensation systems to remove the magnetic effects of survey aircraft, and the use of GPS navigation, which allows flight-line positioning to ± 10 m or better. These improvements, combined with rapid digital sampling at intervals of about 8 m, survey lines at spacing of 500 m or less, and post-processing of data with microlevelling techniques, have resulted in data that can be contoured at 0.1 nT intervals. Horsfall (1996) and Luyendyk (1996) describe the acquisition and processing systems currently being used to produce such results.

While older aeromagnetic surveys over sedimentary basins, acquired with less rigorous parameters, were able to define the major magnetic features associated with sedimentary basins, data from this new generation of acquisition are able to map fine structural and sedimentary detail previously undetected. This detail is normally enhanced by a comprehensive range of data filtering and transformation routines complemented by imaging techniques (Milligan & Gunn 1997).

Overview

A diagrammatic overview of the types of rock units likely to cause magnetic responses in sedimentary basins is shown in Figures 1 and 2. Details of the magnetic responses of these units and their relevance to hydrocarbon exploration, together with specific examples, are elaborated in the following sections. Clark (1997) reviews the magnetic properties of rocks and minerals. His paper can be used as a basis for estimating the relative magnetic responses of the magnetic units illustrated.

Figure 1 shows three hypothetical basin cross-sections drawn to include geological features likely to give rise to magnetic responses in sedimentary basins. The sections are based on actual depth-converted regional seismic sections across the Bonaparte Gulf Basin of northwestern Australia (Gunn 1988)—extra geological units and structures have been added for the purposes of this paper. The Bonaparte Gulf Basin has been interpreted as a failed Devonian–Carboniferous rift that underwent differential extension (Gunn 1988), and the three sections cross areas of different extension. Figure 2, illustrating the areal distribution of the magnetic units, is also based on the Bonaparte Gulf Basin, with extra features added for the purpose of illustration.

From the figures it can be seen that superposition of magnetic units can occur and, consequently, any magnetic field observed over the sedimentary basin may include the combined effects of several magnetic markers.

The following sections describe specific examples of magnetic responses of the features illustrated in Figure 1.

Basement

The basement is the assemblage of rocks that underlies a sedimentary basin. If it contains numerous magnetic rock units, such as igneous intrusions or extrusives, magnetic sediments or magnetic metamorphic units, these can provide information on the morphology of the sedimentary basin and its structure.

If the magnetic units in the basement occur at the basement surface, then depth determinations for these will map the basin floor morphology. This approach has been used for several decades to locate sedimentary basins with economically significant thicknesses of sediment. The initial delineation of the Gippsland Basin (Haematite Exploration 1965) and the Bonaparte Basin (Reford & Butt 1983) are classic examples of the successful application of this technique.

The flight-line spacing of most of the older aeromagnetic surveys was of the order of several kilometres and while this was appropriate for proving the general shape of basins, closer spacing allows the definition of structures and features on the basement surface with direct relevance to hydrocarbon exploration.

Depth to basement, faults in the basement surface, and the relief of the basement surface have direct relevance to the depositional and structural history of the area. Many examples exist of positive basement blocks being directly related to hydrocarbon traps. Often they are overlain by sediments whose depositional isopachs and/or structure reflect the underlying basement structure. Such an example occurs in Joseph Bonaparte Gulf of northern Australia. Gunn et al. (1995a) have demonstrated that this area, which contains the remnants of a failed Devonian–Carboniferous rift, was originally underlain by an extensive subhorizontal sheet of Proterozoic sills and/or lava flows and that the present morphology of the sheet can be used to map transfer faults associated with Devonian–Carboniferous extension as well as a series of tilted blocks and horsts created by the extension (Fig. 3). Even though the magnetic data in this example are mapping structures at the base of the sedimentary section, correlations with seismic data show that the structures and their bounding faults are reflected in the overlying sediments.

'Basement grain' or the trend of basement faults and structure is frequently the main determinant of the primary

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fractures that develop to accommodate basin extension. For example, in the Viking Graben of the North Sea many transfer faults trend northeasterly, parallel to the grain of the underlying Caledonian basement. This feature is obvious in various structural maps compiled by Abbotts (1991) for the Viking Graben hydrocarbon fields. Transfer faults can be extremely difficult to recognise in seismic data, but the trends are often readily apparent in aeromagnetic data.

Basement structures may even contain hydrocarbon accumulations. The Clair Field in the West Shetlands area of the UK continental shelf (Coney et al. 1993) contains several billion barrels of oil in place, a large proportion of which is reservoired in a basement block of fractured Lewisian granite basement. The granite is magnetic and its form can be deduced from airborne data.

Granite can act as provenance for superior quality reservoir rocks. The author has noted situations in the North Sea where localised good high-porosity reservoir sandstones on the Viking

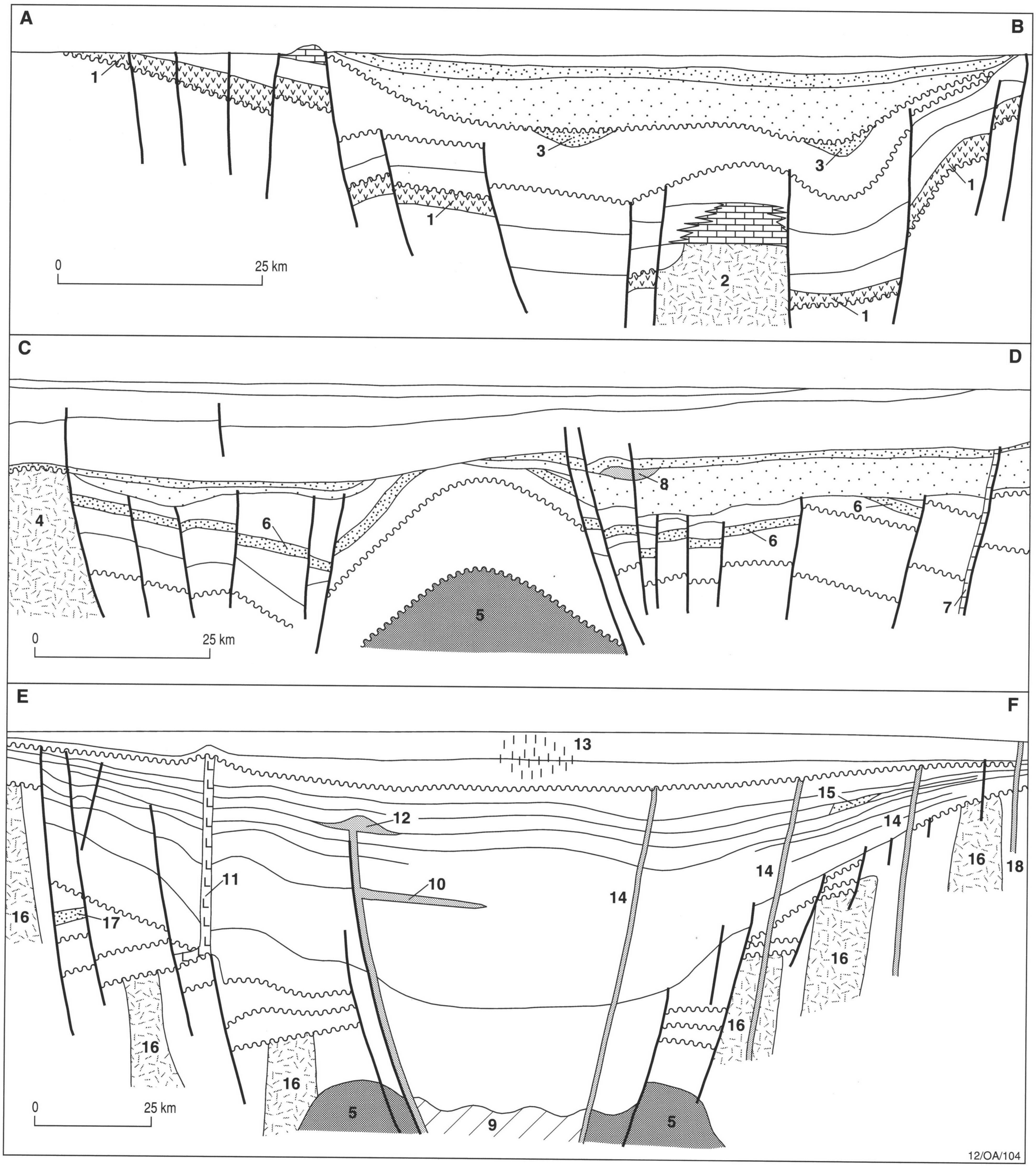


Figure 1. Basin cross-sections illustrating units and structures that can cause observable magnetic responses in a sedimentary basin. (1) Pre-existing flood basalts. (2) Magnetic basement high formed as a result of intrusion, erosion or structuring. (3) Detrital or chemically precipated magnetic minerals in palaeochannels. (4) Magnetic basement flanking the sedimentary basin. (5) Mid-basin crustal intrusion. (6) Magnetic sedimentary unit. (7) Magnetic minerals precipitated in a fault plane. (8) Intrasedimentary volcanics. (9) Oceanic crust. (10) Igneous sill. (11) Salt diapir. (12) Buried volcanic centre. (13) Diagenetic magnetite or pyrrhotite formed by hydrocarbon plumes. (14) Igneous dykes. (15) Detrital magnetic minerals in bar and fan systems. (16) Intrabasement magnetic bodies. (17) Magnetic massive sulphide gold–copper–silver–lead–zinc deposits. (18) Kimberlite and lamproite intrusions.

Graben of the North Sea have been derived from proximal granites next to the graben. Granites are commonly mappable with aeromagnetic data. However, identification with aeromagnetic data of basement lithology to predict the type of sediment in basins is rarely attempted, despite the potential of this approach.

Intrabasement intrusions and the possible generation of oceanic crust

The above discussion assumes that all intrusions associated with the basement subcrop at the basement surface and, consequently, depth determination of their tops will map the base of the sedimentary section. Obviously, this is not always the case and, to avoid errors of interpretation, every effort must be made to identify such basement features.

As well as features of the original basement that do not subcrop at the base of the sedimentary section, there may be intrabasement intrusions contemporaneous with or younger than the sediments overlying the basement. Such intrusions may be the result of crustal extension associated with the basin formation.

Gunn (1997b) reviews igneous intrusion processes associated with crustal extension, noting that a precursor to crustal splitting appears to be the intrusion of a series of major igneous bodies along the axis of the extension. These cause major magnetic anomalies, typically circular or elliptical and with apparent depths below the basin floor. Gunn cites examples of anomalies which may be of this type beneath the Bass and Canning Basins in Australia.

As basin extension progresses towards crustal rupture and generation of oceanic crust, the axial intrusions coalesce into a continuous axial dyke. If crustal splitting occurs, it apparently does so along the axis of the dyke or close to it, such that fragments of the dyke remain along the edges of the continental crust flanking oceanic crust. These fragments of the axial dyke cause linear 'continental margin magnetic anomalies', which may actually occur landward of the continental slope as a result of sediment progradation.

If oceanic crust is generated and preserved under sediments it may be expected to be distinguishable by the characteristic magnetic stripes caused by remanence of different polarity in the sea floor. In practice, the magnetic character of oceanic crust close to the continental–oceanic transition rarely exhibits such lineations; instead there is a 'quiet zone' up to several hundred kilometres wide. The quiet zone appears to be attenuated crust with a character intermediate between true continental crust and true oceanic crust.

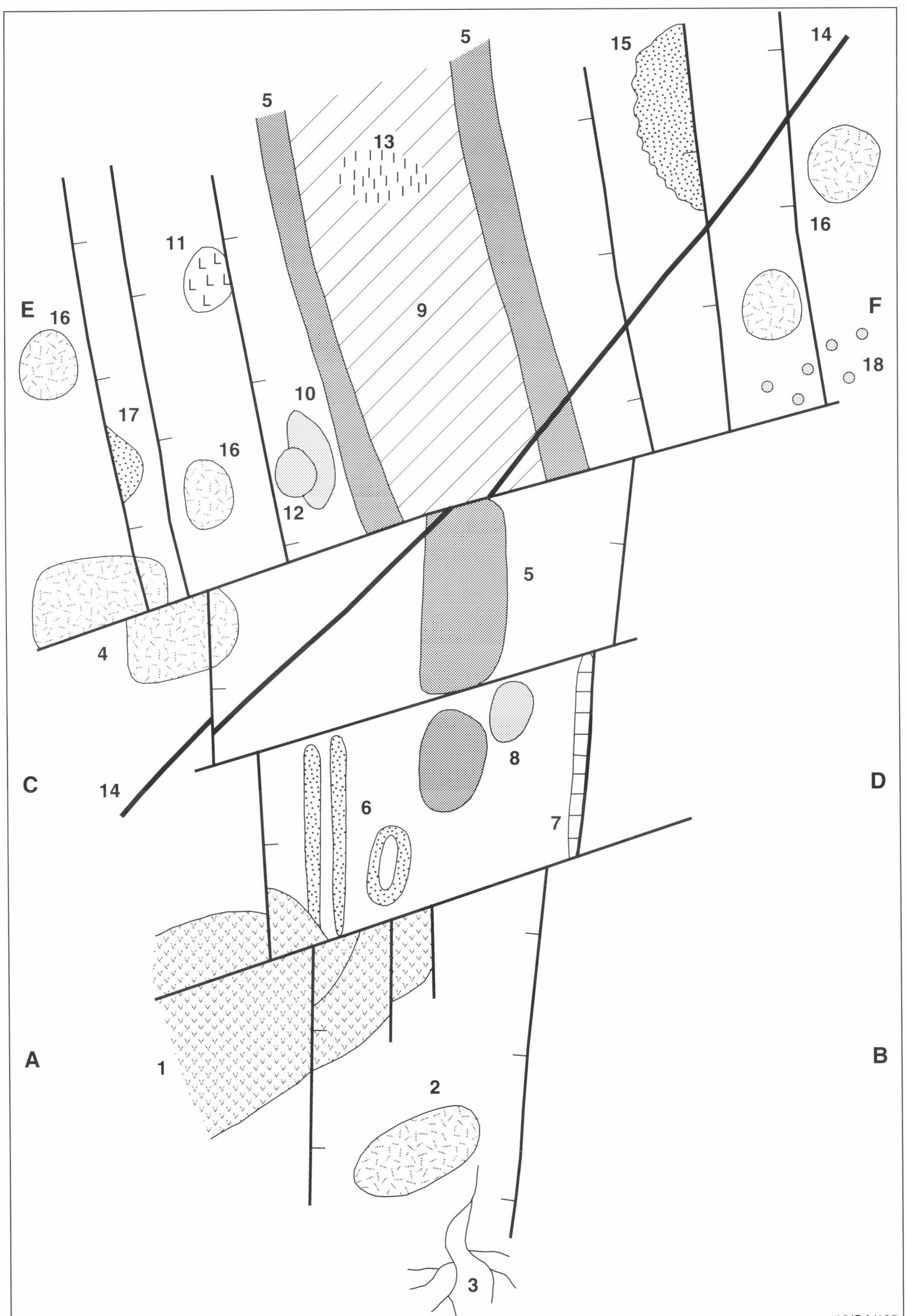


Figure 2. Types of areal distribution of units and structures that can cause observable magnetic responses in a sedimentary basin. The location of sections across this hypothetical basin, as illustrated in Figure 1, is indicated. See Figure 1 for an explanation of the various elements.

Sedimentary section

In general, magnetic anomalies caused by non-igneous sources within sediments are typically much weaker than those due to basement igneous and metamorphic rocks, which generally contain much greater concentrations of magnetic minerals.

Sedimentary layers may be magnetic if they contain enough magnetic minerals. However, they must have structural relief for them to give rise to a magnetic anomaly, as horizontal magnetic sheets only have anomalies at their edges. Small concentrations of magnetite in a sediment can produce an observable magnetic response.

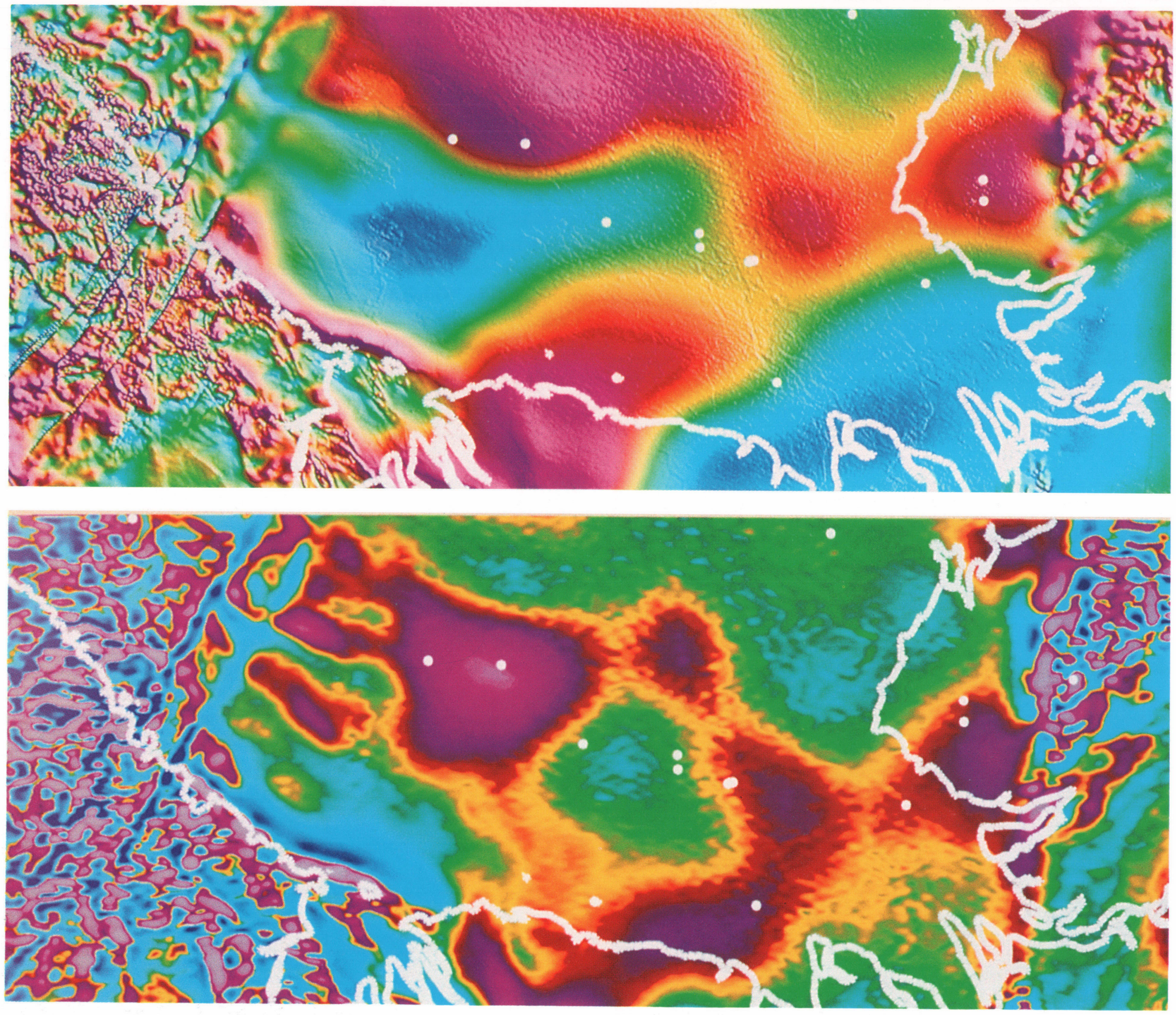
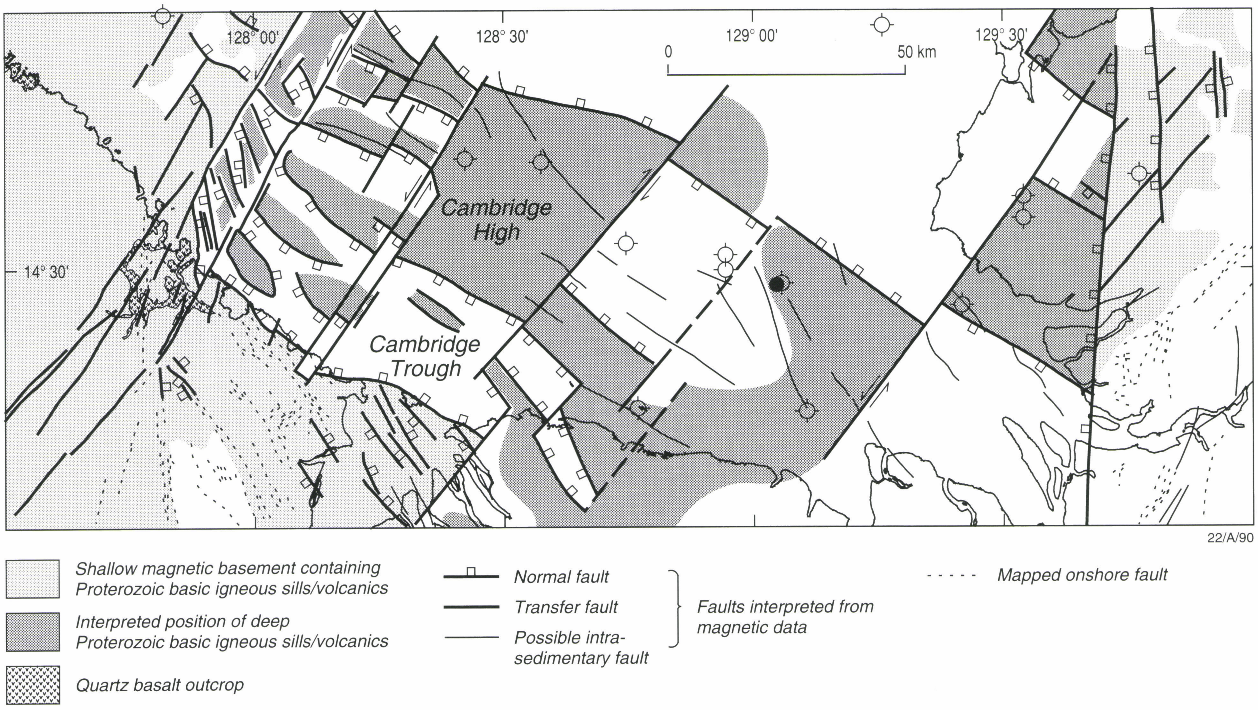


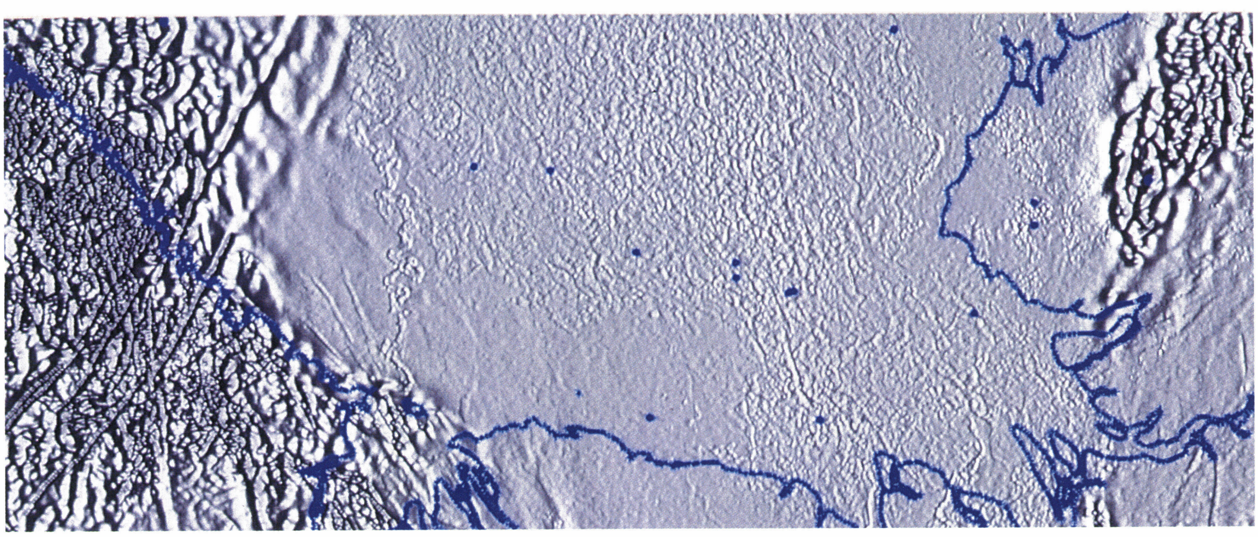
Figure 3. (A—top) Colour image of magnetic intensity of the southern portion of the Joseph Bonaparte Gulf in northwestern Australia. The red portions of the image are due to an extensive sheet of Proterozoic volcanics, whose present geometry reflects Palaeozoic structuring in the area. (B—bottom) Colour image of the vertical gradient of total magnetic intensity. This image resolves the detail in structure of the deep magnetic sheet. The high-frequency disturbances evident in the image are due to shallow magnetic markers (depicted in Fig. 3C), whose effects have been suppressed by filtering to emphasise the structure of the deeper unit. (C—top right) Interpretation of the above images (from Gunn et al. 1995a). The interpretation is consistent with seismic sections in the area. (D—bottom right) Grey-scale image that is the result of applying bandpass filtering to the data of Figure 3A. The image shows the distribution of magnetic minerals on or close to the sea floor. Palaeodrainage systems are evident. The narrow linear northwest-trending anomalies on the western margin of the gulf are due to submarine sand ridges.

Fishman et al. (1989) presented a detailed study of a Jurassic sandstone with a magnetic signature caused by detrital magnetite. Generally however, in sedimentary environments, detrital magnetite is rapidly oxidised to hematite, which is markedly less magnetic, although hematite can, in sufficient concentration, produce an observable magnetic effect.

Magnetic anomalies may be caused by disseminated pyrrhotite in shale and siltstone, such as occurs in turbidite sequences in the Cobar area of New South Wales (Clark & Tonkin 1994). Ilmenite may also give a weak magnetic response, and ancient beaches are known to contain enough of this mineral to give a weak but observable response (Mudge 1994). Maghemite, a weathering product with a similar susceptibility to magnetite and which is extremely stable under oxidising conditions, is often preserved in lateritic palaeoweathering surfaces and stream channels. Spectacular bifurcating magnetic anomalies in the Cobar area of New South Wales have such sources (Sheard et al. 1991). Figure 3 shows magnetic responses of palaeochannels defined by Gunn et al. (1995a) in the Joseph Bonaparte Gulf.

Aeromagnetic surveys over sedimentary basins, with close line spacing (~400 m) and sensitive instruments recording with noise envelopes no greater than ± 0.1 nT, almost invariably map coherent low-amplitude anomalies from sources within the sedimentary section. A series of examples published in *Preview* (1993) illustrate situations where aeromagnetic data appear to be mapping structure caused by folding and faulting as well as responses caused by intrasedimentary units. Figure 4, (from Gunn et al. 1995b) shows examples of the apparent delineation of channel systems, barrier bars, down-to-basin normal faults, transfer faults and reactivated basement faults in an area of the offshore Otway Basin. Cathro (1995), has confirmed many of Gunn et al.'s interpretations in the Otway Basin by correlating magnetic anomalies with seismic reflection responses (Figs 5, 6). Other examples of mapping magnetic intrasedimentary detail have been published for the Timor Sea





(Wellman & O'Brien 1991) and the Perth Basin (Heath et al. 1994).

In many of the above examples the true nature of the sources of the magnetic anomalies is unclear. For example, in many of the responses identified as arising from faulting this could either be due to dislocations of magnetic units or from the magnetic effects of magnetic minerals precipitated in fault planes. More research is required to understand the magnetic properties of sediments in relation to depth of burial, fluid migration and diagenetic changes. It is probable that the magnetic properties of sediments evolve in relation to basin development and that a knowledge of these relationships could allow details of thermal gradients, burial history, metamorphism, redox potentials, hydrocarbon maturation and fluid flowpaths to be estimated.

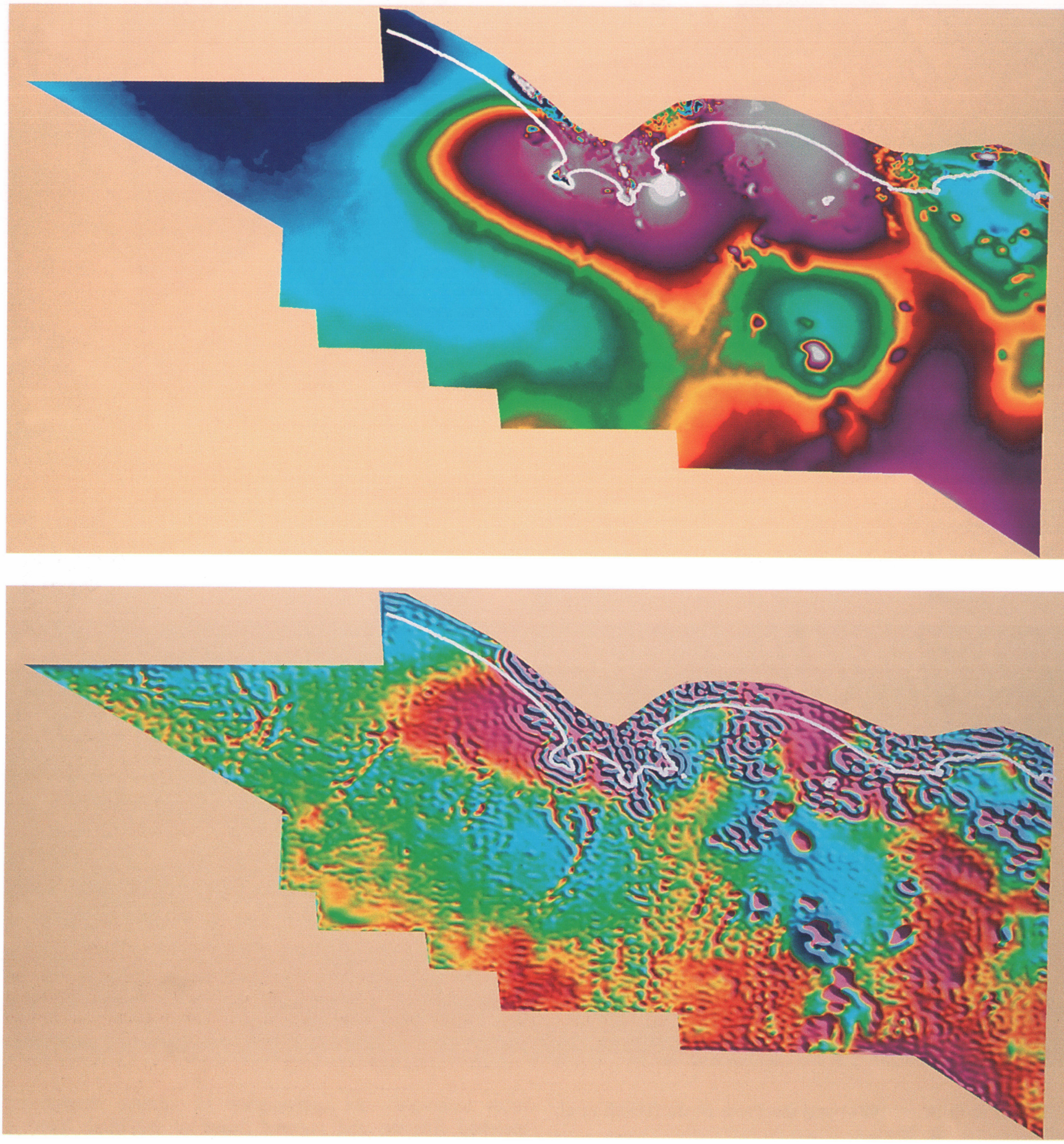
It should be noted that because of the weak and, therefore, subtle nature of the majority of the intrasedimentary responses, some form of data enhancement is normally required to clearly delineate such features relative to strong regional gradients and the more intense magnetic anomalies due to basement features, igneous intrusions and extrusions. Typical enhancement techniques are computation of vertical derivatives, matched filtering and various forms of bandpass filtering (Milligan & Gunn 1997).

Salt diapirs

Pure 'salt', comprising halite, gypsum and anhydrite, is diamagnetic, i.e. it has a negative magnetic susceptibility and, as a result, normally has a negative magnetic contrast relative to enclosing sediments. In such situations, high-sensitivity magnetic surveys map salt domes and salt ridges as magnetic lows. There are exceptions to this generalisation, such as the Paqualin salt diapir in the Timor Sea (Smith & Whitehead 1989), which has bands of diagenetic magnetite within zones of anhydrite and halite, resulting in a positive magnetic anomaly over the diapir.

Igneous units

In general, igneous rocks have a higher content of magnetic minerals, especially magnetite, than sediments and can be identified and mapped in sedimentary basins from magnetic data. Igneous features, such as intrusive plugs, dykes, sills,



lava flows and volcanic centres, can occur at any stage of a basin's evolution and, therefore, be preserved at any level in the sedimentary section. Such features are significant in understanding the history of a basin and assessing its petroleum prospectivity.

Gunn et al. (1995b) have used aeromagnetic data to identify a phase of extrusion of basic igneous material during the earliest stage of extension of the Otway Basin in southeastern Australia. Structuring of the basin, postdating emplacement of this originally horizontal, contiguous magnetic sheet, is indicated by the magnetic effects of the present-day fragments of the sheet. Transfer-type extensional faults and down-to-basin normal faults can be recognised (Fig. 4).

Significant volcanic activity in the North Sea Jurassic rift system was restricted to outpourings of the Rattray volcanics in the vicinity of a triple junction (Latin et al. 1990). These are unconformably overlain by Middle Jurassic reservoir rocks, and definition of the present structure of the volcanics is of direct significance to exploration. Platt & Walker (1995) have given examples of magnetic data mapping these volcanics.

Late Tertiary to Recent volcanics and intrusives are prolific in the Otway Basin. Aeromagnetic data presented by Gunn et al. (1995b) clearly delineate these features (Fig. 4). Figure 7, from Cathro (1995), shows correlation of an igneous sill, evident on seismic data, and its magnetic expression.

Igneous intrusions can produce structural closure and, here, magnetic anomalies can be indicators of hydrocarbon traps, such as in the Canning Basin (Reeckman & Mebberson 1984), the Wilga Park gas discovery of the Gunnedah Basin (Hamilton et al. 1988), and the Omaha Oil Field in Illinois (Sparlin & Lewis 1994). They can also be important loci for reef development—e.g. the Sentry Bank reef in the Philippines (King & Morton 1987).

Intrusions are not always recognised as such on seismic sections and at various times have been mistaken for simple anticlinal domes, salt and shale diapirs, and carbonate reefs.

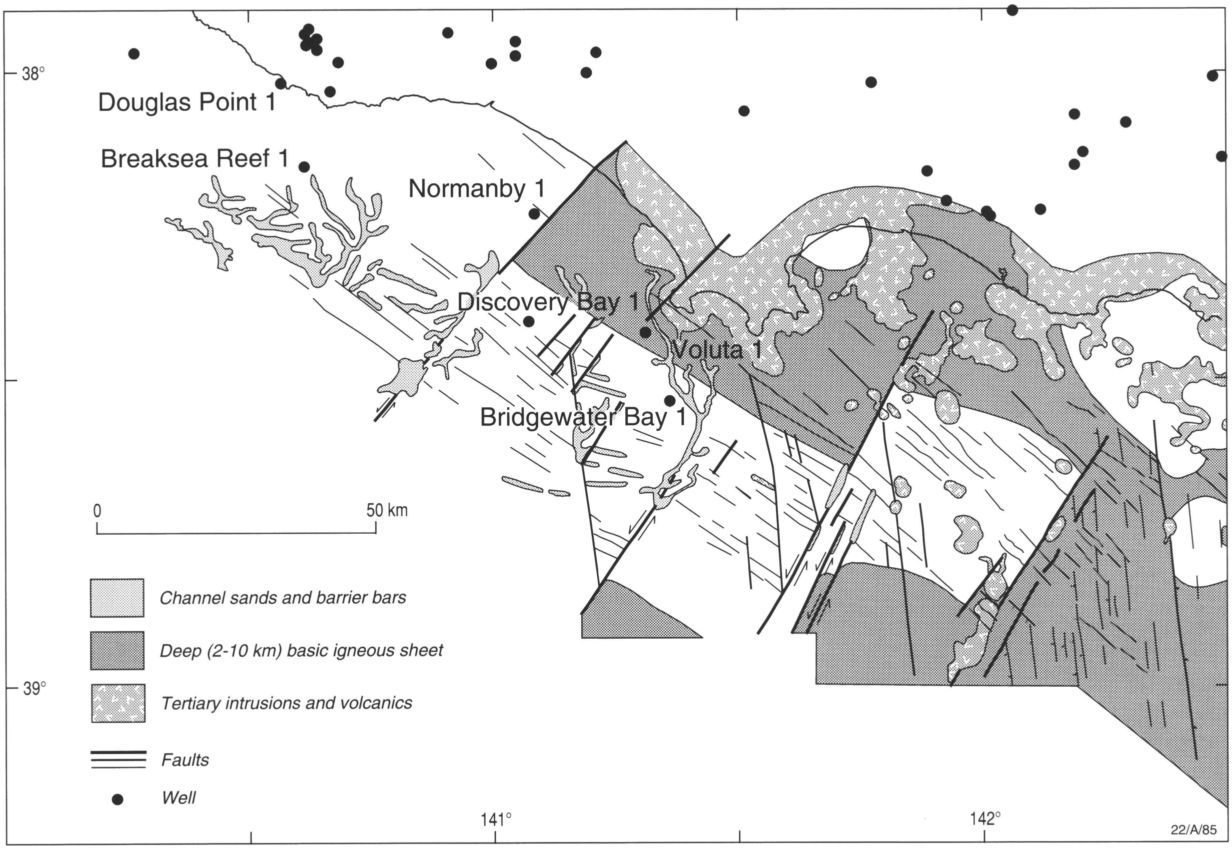


Figure 4. (A—top left) Non-illuminated colour image of total magnetic intensity of the offshore Otway Basin in southeastern Australia. Computer modelling indicates that the purple areas correspond to a sub-horizontal magnetic sheet, which can be interpreted as an extensive basic igneous event associated with the extension that initiated basin formation. The geometry of this sheet can be used to map the present day basin structure. (B—bottom left) Colour image of the vertical gradient of the above image. The vertical gradient resolves fine detail that has been interpreted to indicate volcanics, igneous intrusions, faults, channels and barrier bars. (C—above) Interpretation of the above images (after Gunn et al. 1995b).

Many dry holes have been unintentionally drilled on volcanic centres and intrusive plugs. The Tookoonooka–1 well in the Eromanga Basin of southwestern Queensland, for example, was drilled on a structural culmination, subsequently interpreted as overlying a Jurassic volcanic centre that significantly influenced Mesozoic sedimentation within a radius of 50 km (Young 1987). Jurassic volcanic rocks were not expected in this area, but could probably have been predicted from existing aeromagnetic data of the area, which show the anomaly of a classic plug-type intrusion at the location of Tookoonooka–1 (Fig. 8).

Seismic studies on the northeastern margin of the Joseph Bonaparte Gulf detected doming associated with high-amplitude seismic events within Triassic formations. Further seismic detailing associated with a marine magnetometer survey showed that the doming and high-amplitude responses are associated with igneous sills (Gunn 1987). This was the first indication of igneous activity this young in the area. The only way to avoid such surprises is to conduct magnetic surveys.

The thermal effects of igneous intrusions can cause maturation of hydrocarbon source material without associated changes in vitrinite reflectance (Reeckman & Mebberson 1984) and, thus, it is important to be aware of the existence of any igneous units that may cause such effects.

Kimberlite and lamproite diatremes may penetrate sedimentary sections and the magnetic expressions of many of these can be recognised as small sub-circular anomalies with amplitudes of the order of a few nanoteslas; e.g. a cluster of lamproite pipes on the Lennard Shelf of the Canning Basin (Jenke & Cowan 1994). Such intrusions, which are normally only a few hundred metres across, can often be distinguished from classical volcanic vents by their size and isolation; however, not all such features have magnetic responses.

Magnetic features related to hydrocarbons

Anomalous magnetisation may result from hydrocarbon seepage and the effects of this magnetisation may be detectable as a series of localised irregular high-frequency anomalies (Machel & Burton 1991; Henderson et al. 1984). Machel & Burton (1991) presented a comprehensive analysis of the geochemical, microbial, sedimentological and hydrogeological processes that control the formation of such magnetic mineralisation. The anomalous magnetisation is located in relatively reducing geochemical plumes. The magnetic minerals, magnetite and/or pyrrhotite, may be formed and hematite may be dissolved or replaced. Consequently, hydrocarbon seepage can result in positive or negative magnetic anomalies, or no anomalies at all, relative to the magnetisation of the country rock prior to the seepage. Machel & Burton's analysis identified a range of variables that influence the diagenetic changes affecting magnetic mineralisation. The interface between oxidising and reducing environments, which is normally the watertable, is characteristically the region where the most obvious transformations occur. This is frequently near the surface and, as a consequence, normally some distance above the hydrocarbon source. Previous watertable levels may have resulted in the formation of magnetic minerals below or above the present watertable.

While hydrocarbon seeps may migrate vertically and form magnetic minerals directly above hydrocarbon sources, lateral

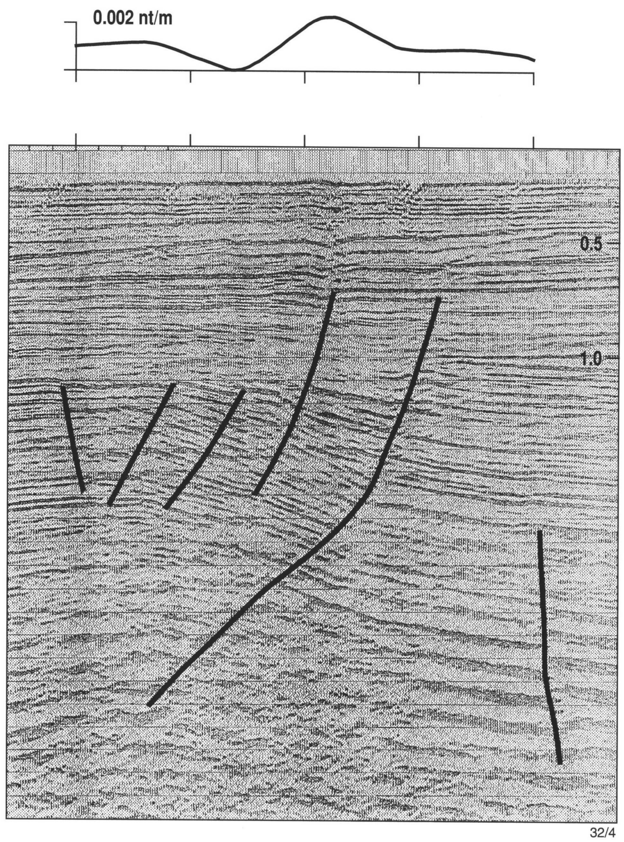


Figure 5. Correlation of magnetic and seismic responses of faults in the Otway Basin (after Cathro 1995).

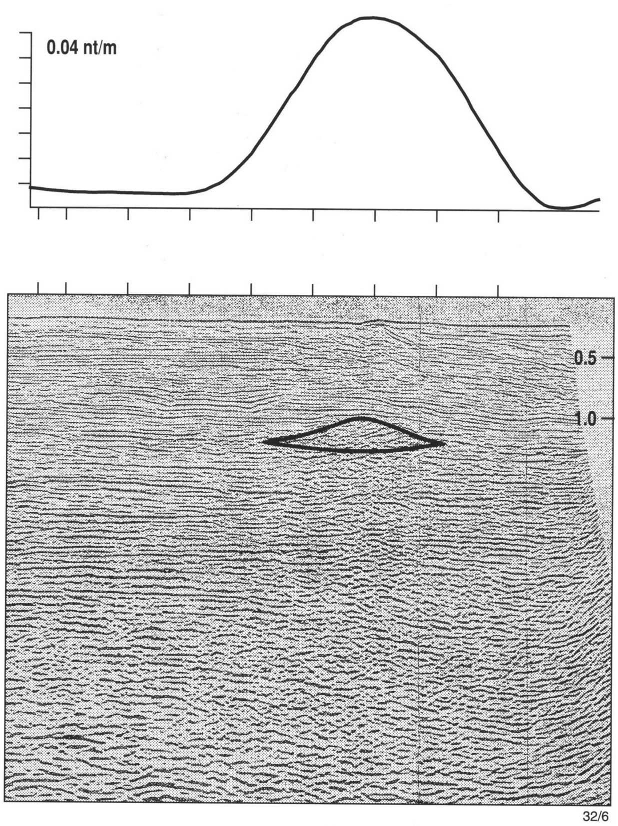


Figure 7. Correlation of magnetic and seismic responses of an igneous intrusion in the Otway Basin (after Cathro 1995).

groundwater flow may cause diagenetically formed magnetic minerals to be deposited away from the hydrocarbon accumulations from which the seeps originate. Figure 9 shows a correlation of high-frequency magnetic anomalies with hydrocarbon fields. These examples appear to indicate situations where vertical migration has occurred.

Magnetic features related to mineralisation

Isolated magnetic anomalies, generally circular or oval in plan and several hundred metres across, and with amplitude of tens to hundreds of nanoteslas, may arise from accumulations of magnetite and/or pyrrhotite, which may be associated with economic grades of copper, lead, zinc, silver and gold. Such deposits, e.g. the Abra deposit (Fig. 10) in the Bangemall Basin of Western Australia (Boddington 1990), which precipitate from mineral-bearing solutions, are frequently located within or adjacent to major faults. Gunn & Dentith (1997) reviewed the characteristics of such deposits, which are much more numerous than most people realise, and likely to occur at depth in many unexhumed sedimentary basins.

Conclusion

High-sensitivity aeromagnetic data are a valuable tool in studies of sedimentary basins. Current interpretation techniques concentrate on defining geometric attributes such as the depth and structure of magnetic units. The author is convinced it should be possible to extend the range of lithological and geochemical information that can be extracted from the data. Systematic studies relating the magnetic properties of sediments to their diagenetic history, depth of burial, and lateral facies changes are required if the interpretation methodology is to progress.

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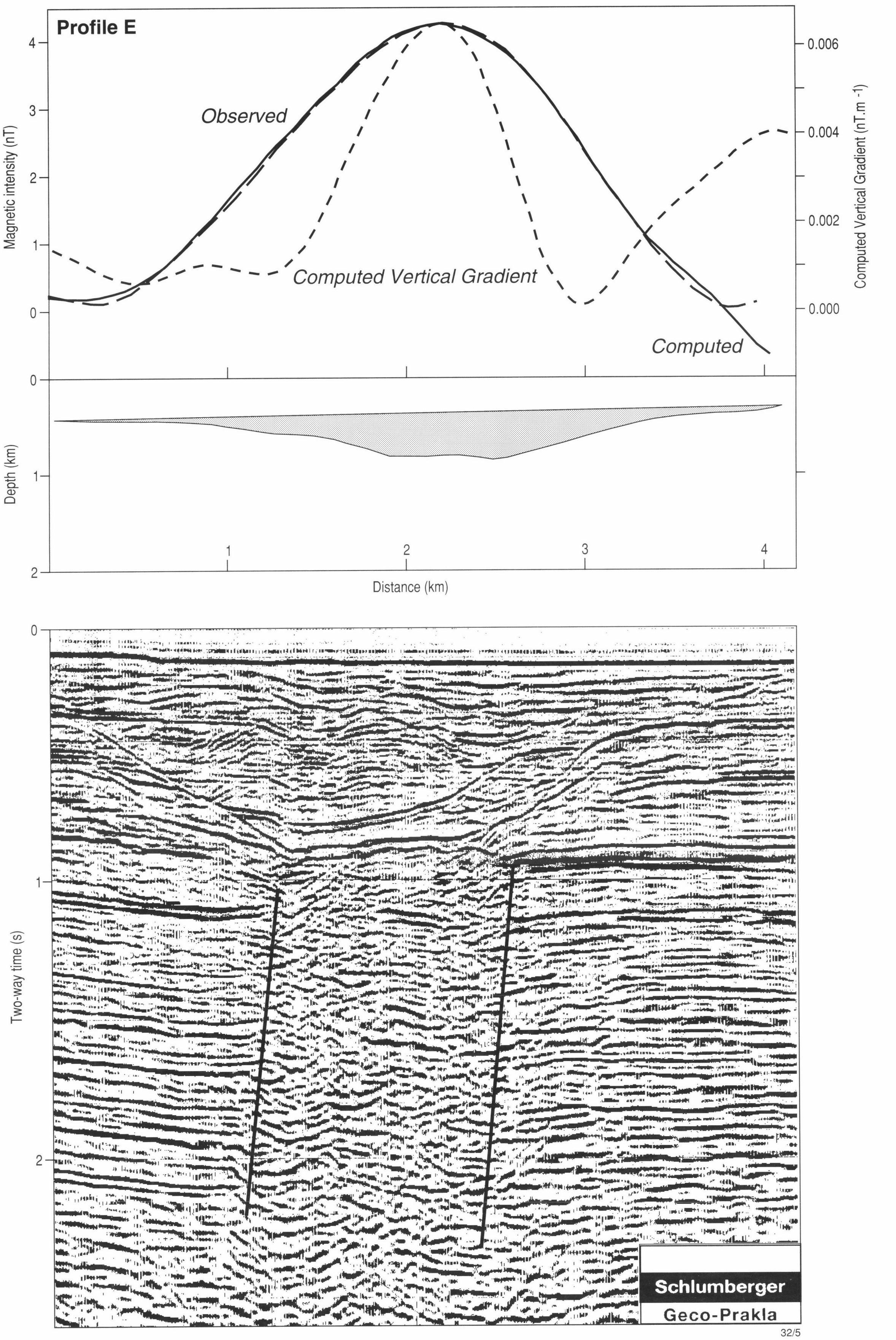

Figure 6. Correlation of magnetic and seismic responses of a channel in the Otway Basin (after Cathro 1995). Seismic data reproduced courtesy of Geco-Prakla.

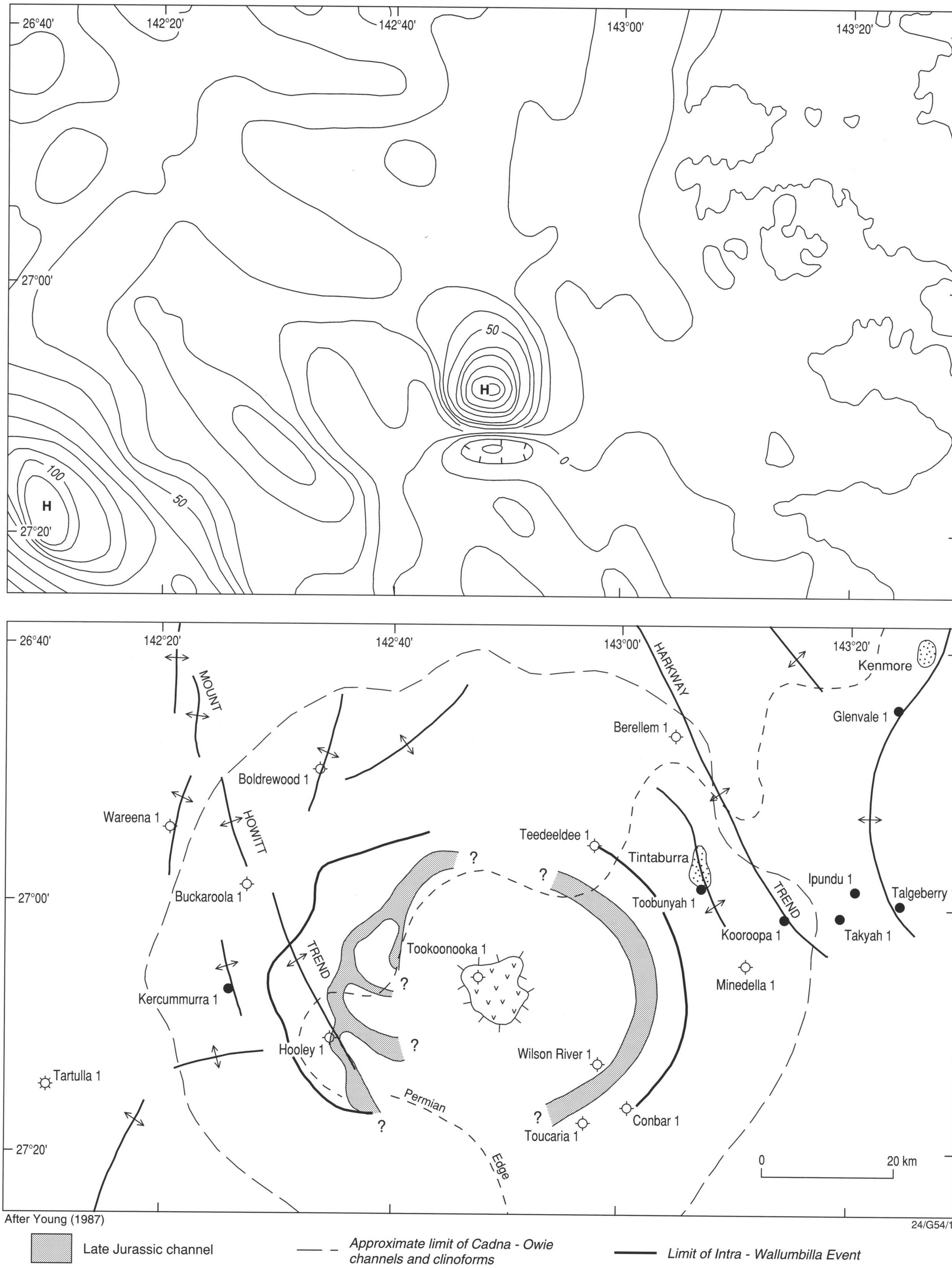

Figure 8. Sedimentary features related to the buried Tookoonooka volcanic complex (after Young 1987) and the magnetic response of the complex.

Figure 10 (facing page). Magnetic response of the Abra massive sulphide copper–lead–zinc deposit hosted by sediments of the intracontinental Bangemall Basin in Western Australia (after Boddington 1990).

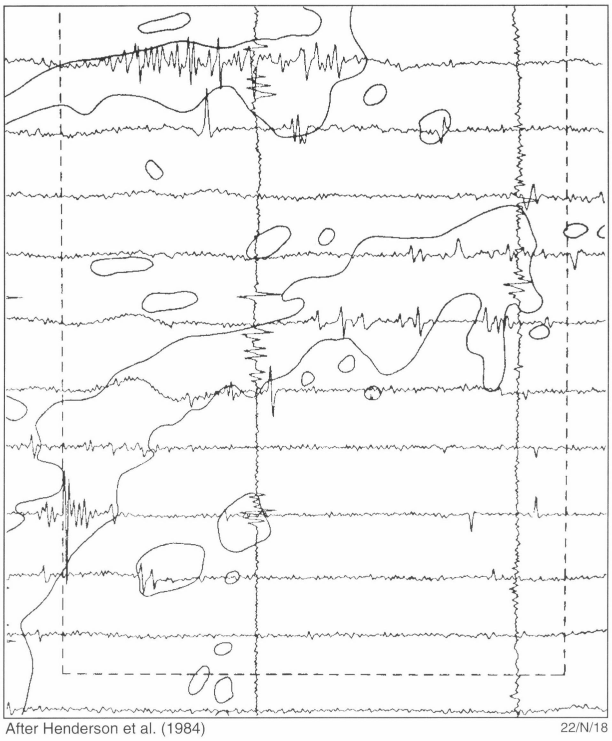

Figure 9. High frequency anomalies associated with hydrocarbon fields (after Henderson et al. 1984).

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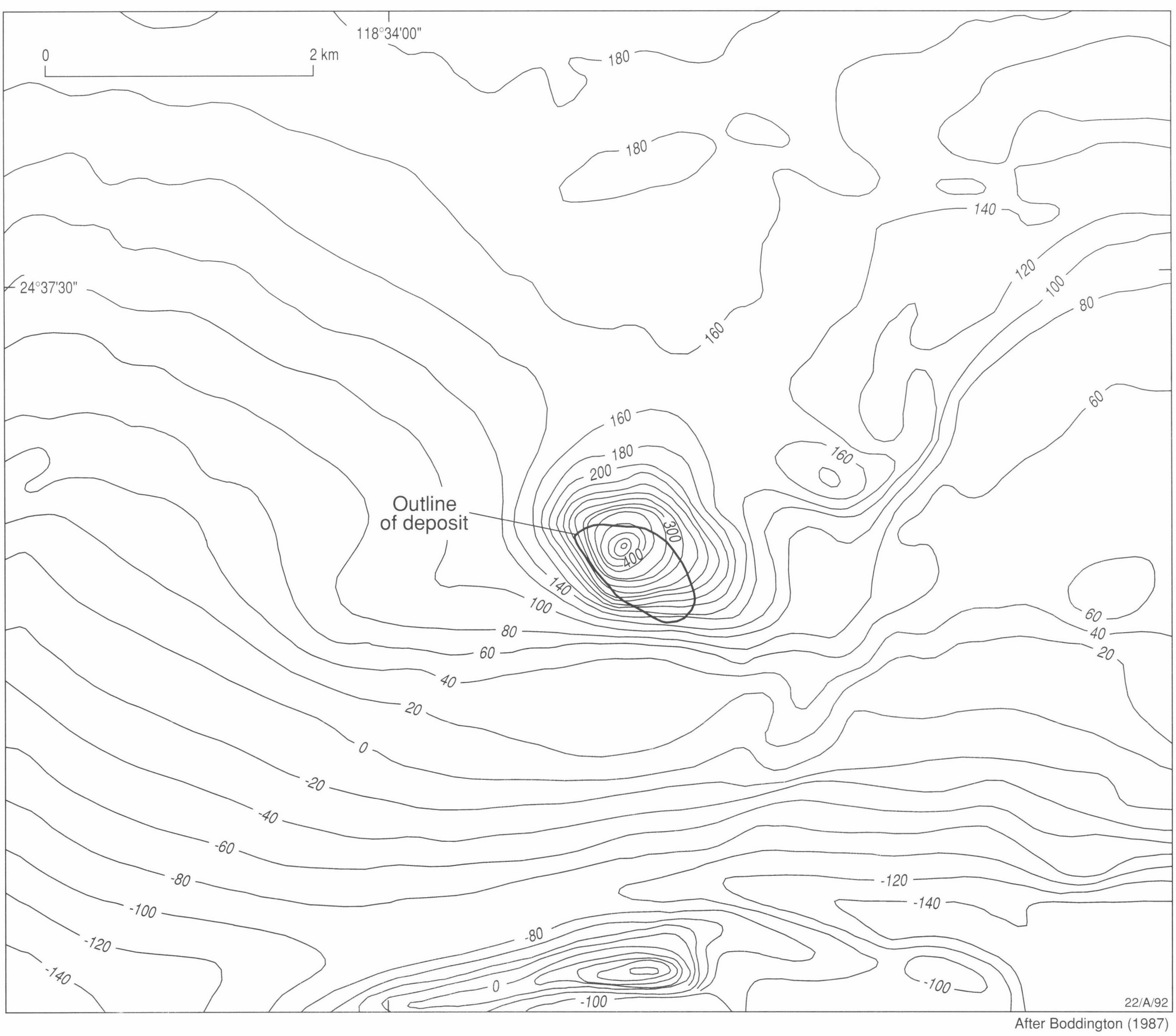

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