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AIRBORNE GEOPHYSICS: OLD METHODS, NEW IMAGES

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ABSTRACT

"The aeromagnetic method of geophysical surveying has been established in less than two decades as a powerful method in mining and petroleum exploration. Many economically important discoveries can either directly or indirectly be credited to the aeromagnetometer.… Although much of the world has been covered by surveys, the program seems less than half done. With more emphasis on detailed surveys, comprehensive interpretation, and sensitive instruments, the future of aeromagnetics seems bright."—Reford and Sumner (1964).

A generation later, airborne geophysics is more than fifty years old but the headlines need very little editing; aeromagnetics can justify itself even more soundly and has still a youthful vitality and positive outlook on the future. In detail, however, the practice of the art has changed beyond the recognition of the pioneers, thanks largely to the wide range of innovations made possible by modern electronics. Instantaneous navigation and position fixing (thanks to GPS) has eliminated the most laborious and tedious work of earlier years and delivered flight-paths of long-desired regularity and accuracy—regardless of terrain accessibility anywhere in the world, except the most rugged mountains. Digital data compilation using current software and hardware takes visualisation of survey results from its original status as end-product contours—perhaps only available months after demobilisation—to attractive images which can even serve the role of same-day quality control of survey operations; if the data will stand up to the rigours of computer enhancement and image processing, then the quality is okay. An excellent and up-to-date review of current capability in aeromagnetic and gamma-ray spectrometry is given by Gunn (1997).

In a world that looks increasingly to databases and geo-information management, geophysical layers such as magnetic anomaly maps and even, recently, digital elevation models, are much sought after by those seeking the greatest value from (pre-)existing information in any exploration undertaking. Nobody disputes the value of such data, both for exploration and for the public good. However, a logical division between the responsibilities of government for the production, archiving and distribution of public domain (regional) data and the desire of private enterprise for exploration project-oriented data to retain confidentiality, at least temporarily, is not always clear. In some areas, recent government investment in airborne surveys as a stimulus to exploration has proven very successful.

INTRODUCTION

The original stimulant for the development of many geophysical methods was the dream of spontaneous discovery of hidden mineral deposits through their betrayal by a geophysical anomaly arising from a rock property that sets the ore body apart from its host rock—'anomaly spotting' or 'bump-finding'. History and reality shows that a more holistic approach pays surer dividends in exploration. As a consequence, more and more emphasis is being placed on sound management of all types of relevant geo-information, the synergistic interpretation of which plays a leading role in the process of progressive and repeated area selection and target selection that lies at the heart of successful mineral exploration. Rather than diminishing, this has increased the importance attached to data sets that may be acquired cost effectively using airborne geophysical survey platforms.

To see beyond the ground surface into the depth dimension has always been a dream of exploration and the mapping of geophysical anomalies caused by the entirety of the buried geology (rather than just

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the ore bodies) proves to be one of the most realistic methods of achieving this over large areas at modest cost. Similar objectives also seemed within the scope of remotely sensed satellite imagery when this first entered the sphere of geological application in the 1970s. While satellite images certainly fulfilled a need for synoptic overviews of large areas and stimulated the technology of image processing to optimise the visualisation of the information captured in its imagery, remote sensing's capability of penetrating the depth dimension has proven somewhat limited (O'Sullivan, 1991). It has, nevertheless, educated a large audience in the advantages of digitally processed and enhanced colour imagery at correct scale and projection over, for example, monochrome aerial photography in conventional hard copy.

The applications and enduring value of current airborne survey capability are now being (re-)discovered in this new context. As a result, while airborne geophysics has enjoyed 50 years of application, many of the most important developments in its history have taken place in the last ten years, i.e., since Exploration '87. Reliable production statistics are notoriously difficult to find, but the rate of acquisition seems to be taking a significant upturn in the 1990s (e.g., Denham, 1997). Perhaps the most significant change of the decade is that where, in earlier years, the limits were set by technological feasibility, we now enter an age in which many technological barriers have been crossed and achievements are set rather by the preparedness of the user to invest in the proven methodology. Since the surveys of the 1990s reveal such unparalleled detail in the subsurface world of exploration at costs per kilometre that are cheaper than ever in real terms, the investments are coming quite quickly.

Certainly a large part of this success has been to adopt image processing methods of data visualisation to produce geophysical anomaly images that are attractive to the non-specialist and display much of their geological information content in a way that is intuitively interpretable. The advantages of this approach are obvious, not least bringing the power of airborne geophysics to the attention of a larger user community. In one step, user reservations about contour maps—and their limitations in terms of static data display—are replaced by enthusiasm to make use of images that, even at first sight, reveal a great deal of new information about the hidden geology. There is, of course, also the danger that intuitive interpretation of geophysical images by non-specialists may neglect some of the physical laws by which anomalies are generated, leading to interpretations that are not physically valid. But this is a small (but scientific!) price to pay if the product reaches a larger market. It also puts a new onus on the geophysicist to develop visualisations in which the intuition of the intelligent non-geophysical interpreter is led to the right conclusions; in short, taking the 'physics' out of the geophysical anomaly maps and leaving in the information that is essentially geological.

Acquiring airborne geophysical data of a quality suitable for visualisation using image processing techniques is not simple, however, and many of the limitations of data quality from ten or more years ago had first to be pushed back, as addressed in the following sections. The revolution brought about by new positioning technology will be addressed first, followed by airborne magnetic anomaly mapping, since this is still almost always one—if not the main—element of any airborne geophysical survey.

POSITIONING

Probably the most tedious and laborious aspect of airborne geophysical surveys has been the procedure for obtaining the all-important x and y co-ordinates to locate the geophysical values on the final survey map. This was originally achieved with the help of maps and aerial photography, followed by transcription of strip film exposed in flight. The navigation aids that were later added included Doppler navigation and a variety of other electronic systems, as summarised by Bullock and Barritt (1989). Their summary was timely because, as they predicted, global positioning systems (GPS) based on the simultaneous ranging of at least four members of a constellation of dedicated satellites to give a precise position of an earth-based (or aircraft-based) receiver became *de rigueur* for this application once the full constellation of GPS satellites was available in the early 1990s. (For the principles, see, for example, Featherstone, 1995).

At present, receivers used typically in airborne survey aircraft can achieve accuracy of ± 15–50 m horizontal position in real-time in standalone mode (Horsfall, 1997). This accuracy is sufficient for the needs of the pilot in flying surveys with all but the closest line spacing and can be improved upon, either in real-time or by post-processing in so-called differential mode, with a second (fixed) receiver on the ground. Accuracy in x and y of ± 5 m is then readily achieveable, meeting needs for almost all airborne surveys in a most convenient way. In a cost-conscious industry, a solution that is at the same time cheaper and more effective was obviously taken up very quickly. It has brought about a more regular flight-line pattern (Figure 1) with consequently more robust data sets when subjected to image processing, faster turnaround times since all digitally acquired data are immediately tagged with their corresponding x,y co-ordinates, and a reduced need for personnel in the (field) crew with further savings of real costs.

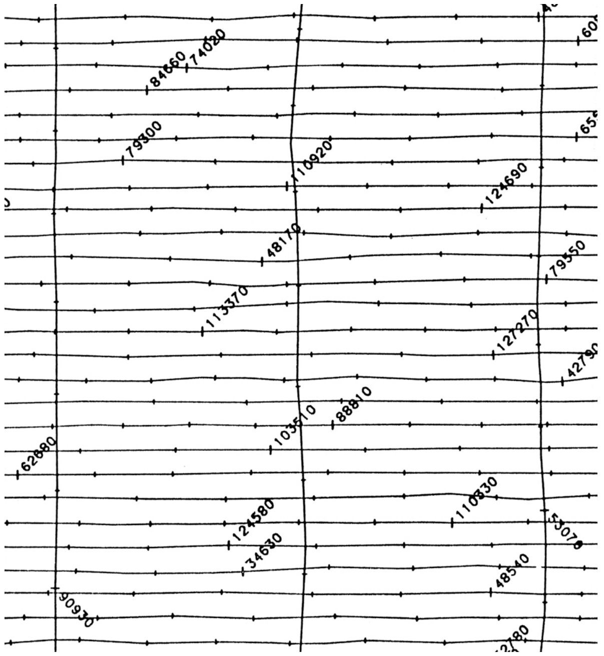

Figure 1: *Sample area of flight path map demonstrating the regularity of flight lines achievable using GPS in a survey of nominal line spacing 400 m (courtesy of the Australian Geological Survey Organisation (AGSO), Department of Primary Industries and Energy).*

A spinoff from the implementation of GPS that holds great promise is that a combination of the geocentric height of the aircraft determined from GPS (to a somewhat lower accuracy than x,y position, because the geometry of the satellites is normally selected to optimise x,y accuracy) and the ground clearance of the aircraft given by the radar altimeter gives an estimate of the geocentric distance of the ground surface at each GPS observation point. With some simple image processing of the line-based values to bring adjacent lines into agreement and some ground control points to convert geocentric to conventional heights above sea level, a digital elevation model (DEM) can be made of the terrain in an airborne survey area. This can map the topography of the survey area with accuracy and can reveal subtle topographic features as small as a few metres in altitude. As an element of useful information to any geographic database (within as well as outside of mineral exploration), a DEM is extremely useful. What is achievable as a by-product of airborne geophysical survey not only immediately exceeds the resolution that might be achieved by digitising traditional topographic contour maps, but can also provide this accuracy in remote areas where surveyed height control or contoured topographic maps are frequently unavailable. An example of what is being routinely achieved in Australia is shown in Figure 2; see Figure 3 for the location.

AEROMAGNETICS

Signal-to-noise

Hogg (1989) provides an excellent review of the capabilities of aeromagnetic systems ten years ago. Improving the quality of aeromagnetic data over that typical of the 1960s and 1970s has many facets that touch on the theory of data acquisition and sampling in a way that is seldom addressed in geophysical textbooks or in the journals. See Reid (1980)

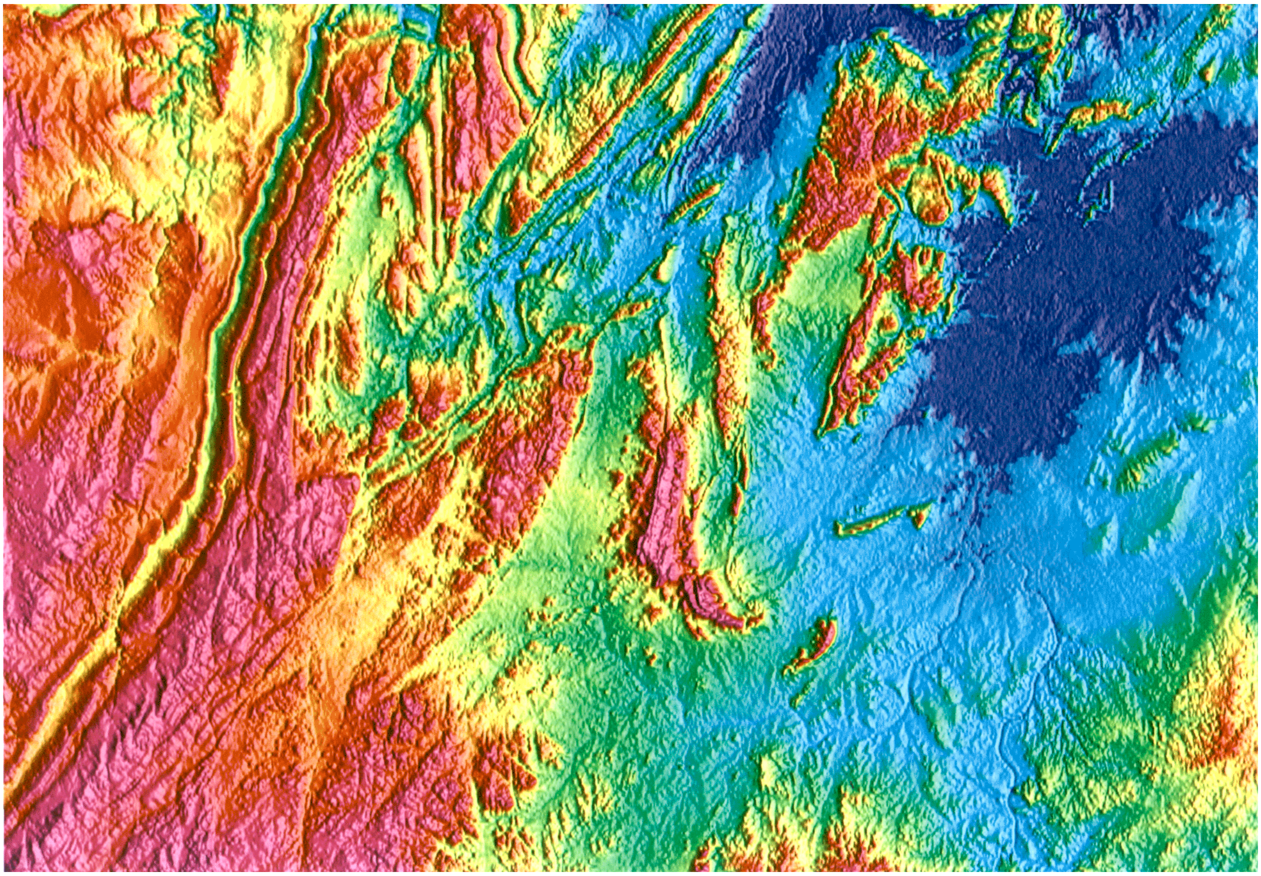

Figure 2: *Processing GPS height data from the survey aircraft with altimeter data and some ground control allows the height of the terrain to be mapped during an airborne survey, creating a digital elevation model (DEM) with an accuracy of a few metres. This figure shows a DEM from part of the Lissadell sheet, Western Australia, presented as a colour image (red = high, maximum 770 m; blue = low, minimum 33 m) with easterly illumination. The data were acquired by AGSO in 1994 on E-W lines flown 100 m above terrain and spaced 400 m apart. Terrain clearance and GPS data were sampled every second and differential GPS corrections every 5 seconds. The GPS data were converted to AGD66 and adjusted for the height of the aircraft above the ground to produce raw elevation data. These raw data were then corrected for geoid-ellipsoid separation (N value) and the height difference between the radio altimeter and the GPS antennae. The point-located data were gridded to a cell size of 90 m using minimum curvature (Mackey and Bacchin, 1994). For location of the survey area, see Figure 3. For another example, see Figure 8.*

for a solitary exception. One of these—and probably the single most important—is the ratio of signal to noise in the acquired data.

The ‘signal’ is the profile of anomalies recorded along the flightpath. The amplitude of the signal increases as the vertical separation between the sensor (magnetometer) and the sources (buried or outcropping igneous and metamorphic rocks) is reduced. Where sources outcrop (or are within a few tens of metres of the ground surface, as is typically the case in the hard-rock domain of mineral exploration), reducing the terrain clearance used during data acquisition increases the amplitude of the anomalies and, at the same time, reduces the wavelength of the anomaly from each distinct source, shrinking the horizontal dimension of each anomaly to an area closer to its source, and increasing the chances that sources separated by distances comparable to their individual horizontal dimensions appear as well-separated anomalies (Figure 4).

The ‘noise’ is anything that is not part of the signal. It can be *instrumental* in origin, can be due to *temporal fluctuations* in the Earth’s magnetic field, or of *geological* origin, usually within the overburden or surficial layers.

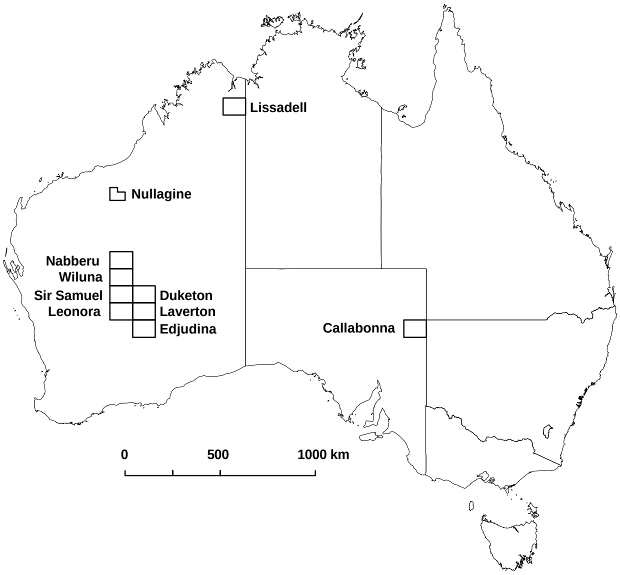

Figure 3: *Location diagram for the map areas in Australia shown in Figures 2, 6, 7, 8, and 11.*

Instrumental noise is firstly attributable to the accuracy and sensitivity of the magnetometer itself. Sensitivities of ±0.01 nT are readily obtainable from the generation of optical pumping magnetometers (Ce, He, Rb, K) presently used in most airborne systems and matched by the dynamic range of the recording systems to which they are attached. Pollution of this signal can be expected from imperfect compensation of the magnetic effect of the aircraft, commonly known as heading effect and manoeuvre noise. Technical developments have led to real-time magnetic compensators that (in calibration mode) record the effects of aircraft pitch, roll and yaw with headings in each of the four cardinal compass directions in an anomaly-free area (e.g., at high altitude) and then subtract an appropriate correction for the measured orientation and attitude of the aircraft at the instant of each magnetometer reading while in active survey mode. By this means, the figure of merit (the sum of the amplitudes of magnetic variations induced by pitch [±5 degrees], roll [±10 degrees], and yaw [±5 degrees], movements in each of the four compass directions in survey mode) has been reduced to less than 1 nT, compared to the 12 nT commonplace 20 years ago (Teskey *et al.*, 1991).

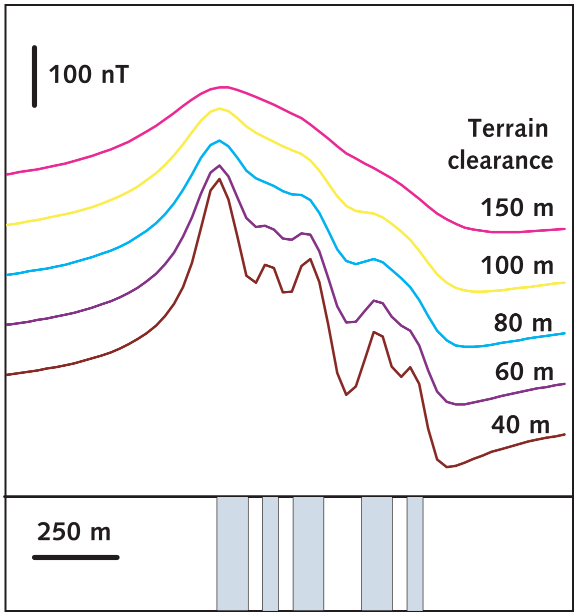

Figure 4: *Over multiple sources, each of width 50 or 100 m, separated by distances of 50 or 100 m—simulating the geological detail in a survey area of (near-)outcropping bedrock sources—the amplitude of the magnetic anomalies and the resolution of neighbouring sources as separate bodies increases as the terrain clearance of the magnetometer is reduced from 150 m to 100 m, 80 m, 60 m and 40 m. Note that resolvable detail is no smaller than (approximately) the terrain clearance.*

Any survey attempts to record variations that are related to x,y position in the survey area. Aeromagnetic surveys suffer additionally from temporal variations in the Earth’s magnetic field that must be removed from survey observations (Reeves, 1993; Milligan, 1995). The most rigorous approach to this removal in current survey practice is to run a ground base-station magnetometer of identical specification to that in the aircraft and subtract its time-synchronised output from the airborne observations. (GPS time base provides a convenient method of synchronising of both instruments). With suitable care, 90% of time variations can be removed by this method. Remaining errors are reduced by traditional adjustment of differences at intersections of regular flight lines with control or tie lines. Further fine-tuning of line-based differences is now achieved by micro-levelling, an essentially arbitrary image-processing technique that brings adjacent survey lines line into better near-DC level agreement (Minty, 1991).

Given all these precautions, the repeatability of an airborne profile is impressively demonstrated in a recent Geoterrex brochure which shows that ten accurate reflights of the same flight line (in an area of the North Sea) show that anomalies as small as 0.1 nT are consistently reproducible and distinguishable above the noise levels of the profile (Figure 5).

In this way, the combined effect of lowering the terrain clearance and reducing the noise envelope has led to the detectability of anomalies of much lower amplitude than had been possible by earlier airborne systems. Since the importance of magnetic anomalies in geological mapping has relatively little to do with the magnitude of anomalies but much to do with the ability to detect contrast between the magnetisation of adjacent rock types, the ability to map geological features is much enhanced by the ability to map anomalies of lower amplitude. In favourable circumstances, anomalies arising from contrasts within sedimentary successions can be mapped, giving an extra dimension to the application of magnetic surveys over sedimentary basins.

Sampling

The ability to detect low amplitude anomalies in profile is far from the full story of successful imaging. A digital image is built up of scan lines (flight lines), and to avoid the possibility that local anomalies are missed when their source falls between adjacent flight lines, the line spacing must not be too great. Since survey costs are proportional to the number of kilometres flown, unnecessarily close line spacing will lead directly to unnecessary cost, so care must be exercised in choosing an optimal spacing. The criterion of detection is that even the most local anomaly is sampled by one flight line which—when not fortuitously falling on the peak of the anomaly—still samples the anomaly where it has significant amplitude. Since even a point-source anomaly has a significant magnetic anomaly at a horizontal distance equal to two or three times the vertical distance between source and sensor, it follows that the line spacing for the detection of the smallest wavelength anomaly should not exceed 4-5 times the terrain clearance (assuming the worst case of outcropping point sources). For surveys flown at 70–100 m above terrain, a maximum line spacing of 400 m meets this criterion, though for particularly detailed needs where the diminishing returns associated with the extra cost can be tolerated, a spacing of as little as half this value may be chosen. Fortunately, with the important economic exception of kimberlite exploration, most magnetic anomalies are more elongate than circular and many have significant strike lengths (i.e., are 2-D). It follows that most anomalies are somewhat less demanding from the point of view of detection, particularly when flight line direction is even approximately normal to the strike direction.

However, *detection* of the smallest anomaly by sufficiently closely spaced scan lines is different from the *definition* of all anomalies by adequate sampling at points spaced sufficiently closely along each flight line. Luckily, modern magnetometers sampling ten times per second, flown at typical survey ground speeds of 60–70 m per second, give a sampling interval of 6–7 m, which offers considerable redundancy in this context. Interpolation of line-based data onto image grids of cell dimension equal to or less than the source-sensor distance (i.e., cell sizes of 40–100 m in typical mineral exploration terrain) only marginally compromises the information content of original profile data in the flight-line direction, while the relatively wide spacing between the lines provides almost two samples per wavelength for (at least) the most important wavelengths in the spectra of even shallow, compact sources in the direction normal to the flight lines. The lengthening of wavelength due to intervening overburden or weathering, together with the 2-D nature of much geology, means that little detail is lost at 400 m line spacing and 80 m above terrain. The wealth of detail revealed when these specifications are applied over areas of complex Precambrian geology is illustrated in Figure 6.

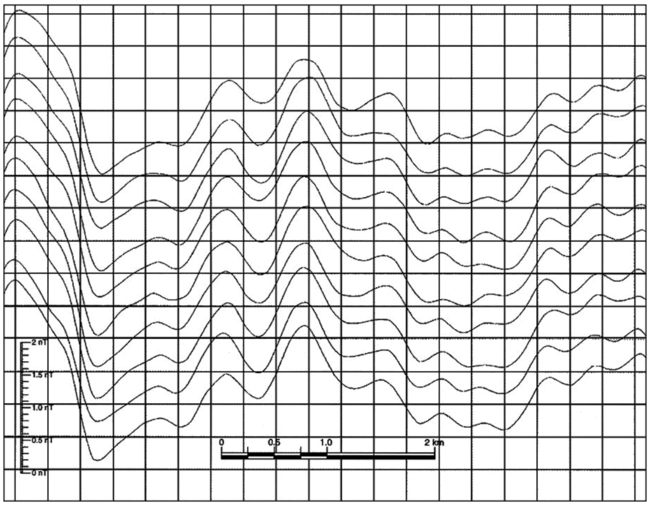

Figure 5: *The same magnetic profile flown ten times (with very close positional tolerance) to demonstrate the repeatability of small anomalies, in this case at 80 m above the sea over a sedimentary area in the North Sea. Anomalies as small as 0.1 nT (one-fifth of a vertical graticule interval) are recorded reliably at every pass (courtesy of Geoterrex).*

Magnetic gradiometers

Sumpton *et al.* (1996) summarise progress in magnetic gradiometry over shallow sources and re-address the issue of using horizontal gradients to assist the interpolation process between flight-lines in typical airborne data. They claim that the increased cost per kilometre of gradiometry can be offset by permitting a 20% wider line spacing without loss of detection capacity, even in kimberlite exploration.

GAMMA-RAY SPECTROMETRY

Darnley and Ford (1989) review airborne gamma-ray spectrometry capabilities of ten years ago. The principles and current practice are well set out in two recent summaries by Grasty *et al.* (1991) and Grasty and Minty (1995). The method seems to be entering a new era of more extended application and it would be fair to say that many potential users are probably, as yet, unaware of the capabilities of state-of-the-art gamma-ray spectrometer mapping, not only within exploration but for many other applications such as in soil mapping where the chemistry of the ground surface may be indicative.

The criteria for acquiring gamma-ray spectrometer data of the highest possible quality are quite different from those described for aeromagnetics. Nevertheless, the two systems have, in recent years, become firm partners for simultaneous data acquisition in many fixed-wing airborne systems, and the main objective of both aeromagnetic and radiometric surveys is now usually systematic geological mapping rather than direct

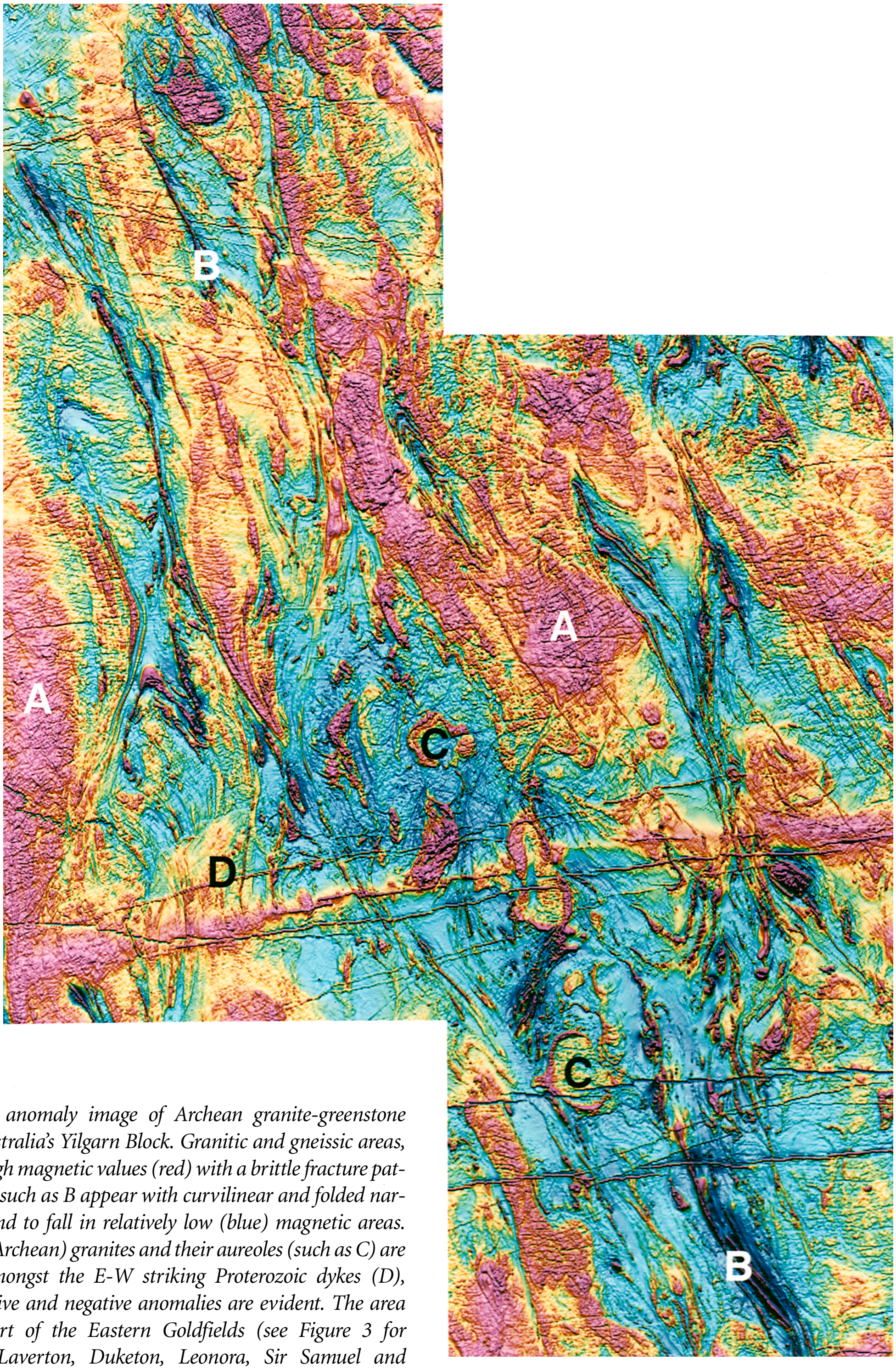

Figure 6: *Magnetic anomaly image of Archean granite-greenstone terrane in Western Australia's Yilgarn Block. Granitic and gneissic areas, such as A, appear as high magnetic values (red) with a brittle fracture pattern. Greenstone areas such as B appear with curvilinear and folded narrow anomalies that tend to fall in relatively low (blue) magnetic areas. Post-tectonic (but still Archean) granites and their aureoles (such as C) are clearly discordant. Amongst the E-W striking Proterozoic dykes (D), examples of both positive and negative anomalies are evident. The area covers a northern part of the Eastern Goldfields (see Figure 3 for location—Edjudina, Laverton, Duketon, Leonora, Sir Samuel and Wiluna map sheets), four degrees of latitude by three degrees of longitude, that is very poorly exposed. The approximately 250 000 line-km of data in this image were acquired 1984–1994 on E-W lines, 400 m apart at between 60 and 100 m above terrain by AGSO, Aerodata Holdings Ltd. and World Geoscience Ltd. for AGSO and the Geological Survey of Western Australia (Mackey et al., 1995).*

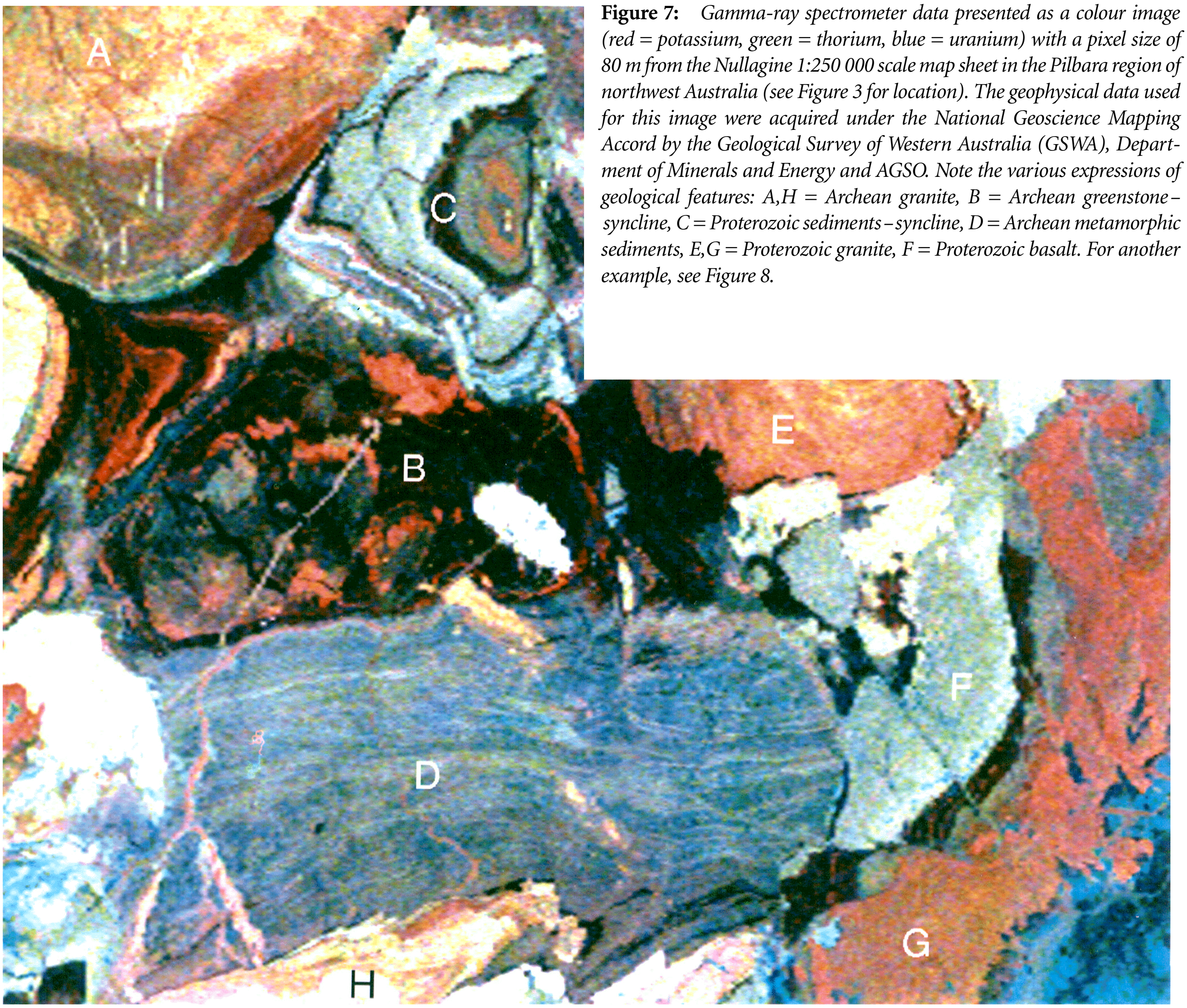

Figure 7: *Gamma-ray spectrometer data presented as a colour image (red = potassium, green = thorium, blue = uranium) with a pixel size of 80 m from the Nullagine 1:250 000 scale map sheet in the Pilbara region of northwest Australia (see Figure 3 for location). The geophysical data used for this image were acquired under the National Geoscience Mapping Accord by the Geological Survey of Western Australia (GSWA), Department of Minerals and Energy and AGSO. Note the various expressions of geological features: A,H = Archean granite, B = Archean greenstone–syncline, C = Proterozoic sediments–syncline, D = Archean metamorphic sediments, E,G = Proterozoic granite, F = Proterozoic basalt. For another example, see Figure 8.*

detection of exploration targets. The downturn in uranium exploration has, therefore, not been followed by mileage of gamma-ray spectrometry.

The main data quality trade-off in airborne gamma-ray spectrometry is the need for good counting statistics against payload weight penalties for large crystal volumes. Practical fixed-wing systems seem to have settled on 33 or 50 litres of NaI crystal (two or three packs of four crystals) as a working optimum at a one-second sampling rate. Lower terrain clearances consequent upon cohabitation with the magnetometer in current survey platforms gives a bonus as the cumulative effect of the intervening air layer is exponential; halving terrain clearance (say from 150–75 m) almost doubles the number of counts per second to be expected. At the same time, lower terrain clearance leads to a smaller footprint of investigation below the detectors and the investigation will be more heavily weighted towards ground immediately below each flight path than to ground lying midway between them. For a line spacing of four times terrain clearance, the gamma-ray path through the scattering medium will be more than twice ($\sqrt{5}$ times, in fact) as long in the second case than the first, with some consequent risk that point sources between lines will be missed or severely downgraded in amplitude. This has not been reported as a problem, while the reduced overlap of consecutive one-second footprints (consequent upon lower terrain clearance) leads to the advantage of more focused recording of boundary transits from one geological unit to its neighbour and hence greater clarity in the definition of the geological boundaries encountered along each flight line.

Thorough and systematic calibration of acquisition systems and processing of the data acquired in gamma-ray spectrometry has always been a challenge, and dividends are now being paid to those who have approached this scientifically. One of the limitations of earlier spectrometer systems has been the drift of the photopeaks within (or even outside) the elemental windows for Th, U, and K. Self-calibrating spectrometers are now widely in use to solve this problem. Systematic calibration using standard pads and flying test strips before and after each flight are capable of solving many of the most severe problems surrounding, for example, the unpredictable variation in airborne radon over the duration of a typical survey. As a result, reporting results as equivalent concentrations of K (per cent), U, and Th (ppm) is becoming

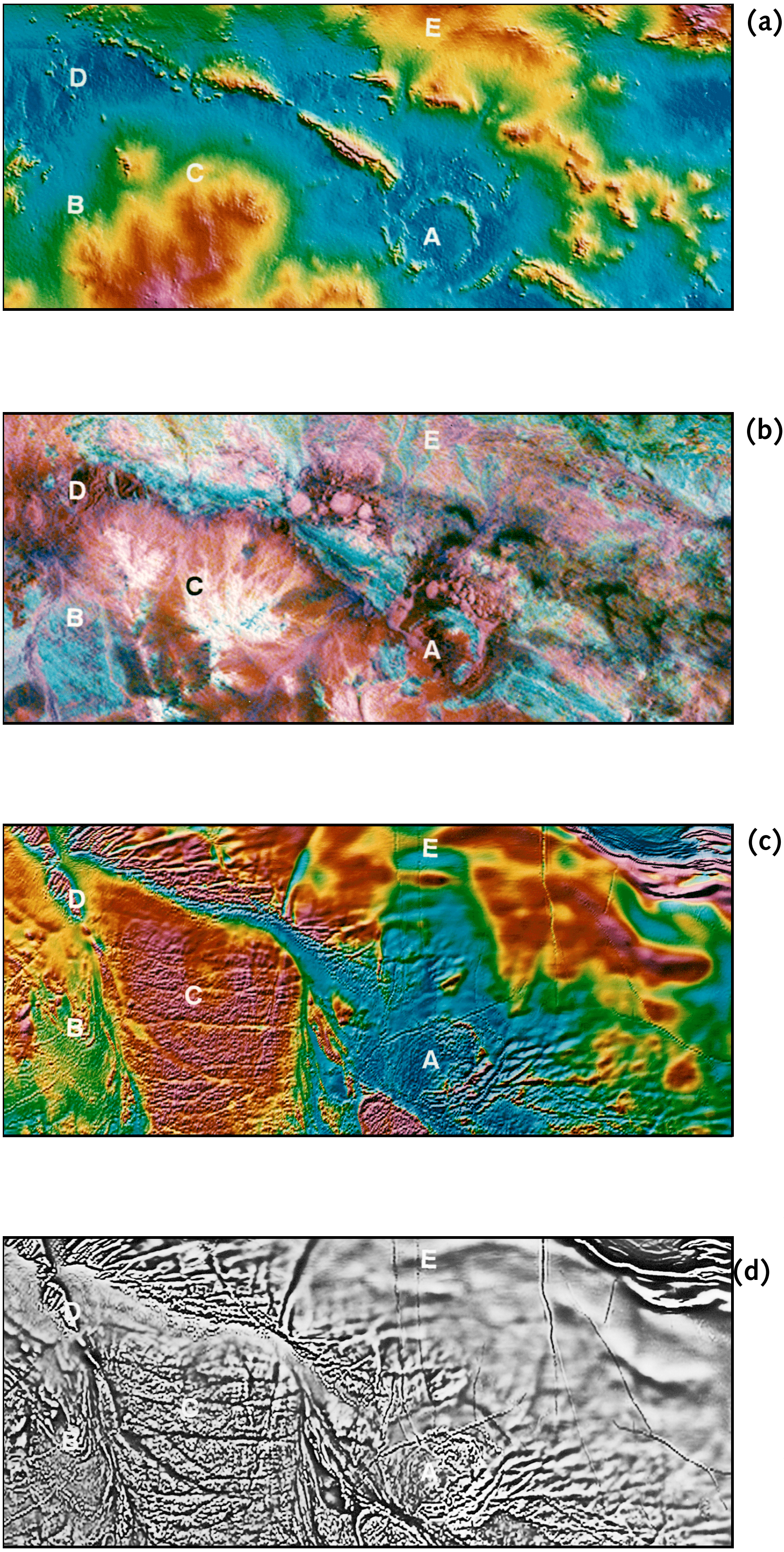

Figure 8: *The three basic data sets from an airborne survey for part of the Nabberu sheet, Western Australia (see Figure 3 for location):*

*(**a**) Digital elevation model (DEM);*
*(**b**) Gamma-ray spectrometer image, red = potassium, green = thorium, blue = uranium;*
*(**c**) Total magnetic intensity anomaly.*
(d) Total magnetic intensity in grayscale.

Note the various expressions of geological features: A – Teague Ring Structure, an early Proterozoic impact structure, B – Archean greenstones, C – potassium-rich Archean granitoid body, D – the Merrie Fault, E – Nabberu Syncline (Proterozoic). Many of the topographic ridges are Proterozoic banded iron formations. The data were acquired during 1996 by AGSO and Kevron Geophysics with 400 m line spacing, 80 m above terrain (Mackey and Franklin, 1996).

both more commonplace and more reliable, facilitating a more direct comparison between surveys of different times and specifications (Grasty and St. John Smith, this volume).

The limit to what can be achieved in processing towards noise-free data is set by the small number of counts received per second, and the worst statistics (fewest counts) are almost always to be found in the U window. With few counts, the random nature of radioactive decay gives rise to a relatively high level of noise in the profile; channels with higher count rates suffer much less in this way.

Darnley and Ford (1989) announce the beginning (at that time) of the trend away from analogue profile and contour presentations towards the use of colour images, and give some early examples which serve now to emphasise the progress that has been made in the last ten years. There are regrettably few examples of such images in the literature (e.g., Smith, 1985; Reeves, 1992) to demonstrate the improvement in technical quality over the years. Images illustrating the current capability are shown in Figures 7 and 8. There are many elements to this progress, including larger crystal volumes, but almost certainly the most important of them arises automatically once lower terrain clearance and closer line spacing are adopted for data acquisition. With hindsight, the wide line spacing of earlier years of airborne geophysics, while naturally driven by the need to reconnoitre large areas at low cost, can now often be seen as false economy, and good, detailed results come only from a more serious approach to careful sampling of the survey area.

Using the corrected output of the three channels (Th, U, and K) as input for the three primary colours of an image processing system, or as hues in the hue-saturation-value (HSV) colour model, easily produces a colour image in which the various combinations of element abundance give a characteristic colour for each rock or soil type and, as with aeromagnetic data, gives an output which potential users find attractive to study and is immediately interpretable. Unlike magnetic images, however, the colour of each geological unit in a gamma-ray image is derived from its inherent concentration of U, Th and K and thus its geochemistry. Very often, then, a good gamma-ray image of an area with residual soils has an immediate similarity with a geological map. The one-second along-line sampling interval (equivalent to 60–70 m on the ground) leads to a resolution limit in image presentation of a pixel of about 80 m, with the interpolation of 4–6 pixels between each flight line. In this respect, the resolution is comparable to that achieved in imaging magnetic anomaly data acquired at the same time.

Optimising the imaging of gamma-ray data has probably yet to reach its limit, and experimental work is still showing promising developments, exploiting colour theory and image processing technology developed in other areas of mapping and imaging. Contrast stretching of the information in each colour channel and, for example, adding the total count information to give a shaded-relief effect to the colour image resulting from the three elemental channels, all offer results that are pleasing to the eye and serve to enhance the interest of the potential user in interpreting the data (Milligan and Gunn, 1997). While many combinations and elemental ratios were attempted in the earlier years, direct plotting of elemental abundances now seems most common and most easily understandable, though even the colour to be attributed to each element is not yet adopted universally by convention. In North America, the subtractive colours of printing seem to be have been used most often with U as yellow, Th as cyan and K as magenta. In Australia, the additive colours of the VDU screen have become reasonably standardised with U as blue, K as red and Th as green. In both cases, the noisiest channel (U) is ascribed to the least visible colour.

A recent study by Minty (1997) demonstrates a more rigorous approach to data processing that probably brings us closer to the limits of what can be achieved with current data and acquisition technology. Most spectrometers in current use record the gamma-ray spectrum in 256 or 1024 channels. Much of this information is not used in conventional three-channel processing and presentation, and counting statistics are typically poor in each individual channel. The entire observed spectrum is, however, the sum of the three elemental spectra and may, therefore, offer a more complete and accurate picture of elemental abundances than that traditionally obtained from just the three photopeak windows. Experimentally determined elemental spectra and calibration range data are used to invert survey-derived spectra, averaged over an appropriate grouping of channels into an optimum number of windows that best represent the information content of the spectrum, to give elemental abundances along track. The improvement in statistical scatter (noise) in each profile is demonstrated to be 12% (K), 26% (U) and 20% (Th) over conventionally processed three-channel data, with a resulting improvement in resolution of small anomalies when results are presented as images.

Where the soil layer is residual, clear patterns of the distribution of the underlying rock are often obtained, even where the surface geology is virtually devoid of outcrop. The gamma-ray image then becomes an important new source of geological mapping information. In areas of erosion and deposition, the power of the method to detail erosional and depositional processes have been scarcely exploited but can be expected to have important impact on geomorphology and stream-sediment studies. From an exploration point of view, the method still tends to disappoint in those areas where transported soils and glacial detritus cover the bedrock. Unfortunately, where chemical processes have led to lateritic, calcretic and silicic deposits in the immediate subsurface, little information on the hidden geology is to be found by gamma-ray spectrometry. Elsewhere, however, particularly in tropical terrains, the gamma-ray data may provide a good reflection of the bedrock geology, even where weathering processes have rendered geological mapping from the regolith difficult.

AIRBORNE ELECTROMAGNETICS

The last decade has also seen airborne electromagnetics graduate from a bump-finder to a geological mapping tool. A proliferation of system configurations have become available, both in the frequency- and time-domains, that were designed with particular geology, target and acquisition constraints in mind. The role of airborne electromagnetics for kimberlite exploration has increased substantially, particularly in areas such as the Northwest Territories where the pipes and their weathering products contrast strongly with the highly resistive host rock. In addition to mineral exploration, applications of airborne electromagnetic systems now include:

- mapping of environmental targets (e.g., contamination plumes, buried wastes);
- baseline mapping and monitoring of acid wastes at mine sites;
- exploration for freshwater aquifers;
- mapping of saline-contaminated soils and aquifers; and
- sea ice thickness measurements and shallow water bathymetry.

These applications — and a new appreciation of the regolith as an important contributor to mineral exploration — has lead to a considerable increase in the bandwidth of both helicopter-borne frequency-domain electromagnetic (FDEM) and fixed-wing time-domain electromagnetic (TDEM) systems. The frequency range of FDEM systems has extended higher by an order of magnitude so that shallow targets can be accurately mapped. A typical FDEM system might have three coplanar and two coaxial coil pairs, with a frequency range of 400 to 60 000 Hz. However, a system designed for shallow resistivity mapping might have five coplanar coil pairs and a frequency range of 200 to 200 000 Hz.

Similarly, the frequency range of TDEM systems has also extended higher and more attention is being paid to the on-time and early time data. On the other hand, exploration for highly conductive or deeply buried mineral targets has resulted in TDEM configurations with lower base frequencies (e.g., 25 Hz), larger transmitter moments (e.g., 490 000 Am^2) and longer pulse widths (e.g., 4–6 ms). TDEM receivers can now measure three-component data, rather than the standard X-component. The Z-component improves the response and resolution for flat-lying conductors, dip determination and depth of penetration, whereas the Y-component improves determination of the strike and location of discrete conductors (Smith and Keating, 1996). The three-component measurements also increase the signal-to-noise ratio, and facilitate the detection of conductors laterally offset from the survey line. Sampling of the TDEM waveform now reaches 256 channels, which provides possibilities for more sophisticated processing, modelling and imaging techniques.

New applications and improved data acquisition systems have pushed the display and analysis of airborne electromagnetic data forward considerably. There has been considerable progress in the understanding of the fundamental physics of the electromagnetic fields that these systems generate, and their interaction with a complex earth. Most of the work in recent years has concentrated on transformation and imaging of the data in plan and section form. Modelling of the earth as a series of one, two or three discrete layers is slowly being replaced by techniques that display 2-D sections of continuously varying resistivity or conductivity. Huang and Fraser (1996) describe a method of computing differential resistivity and differential depth for each of several FDEM frequencies, using coplanar coils. The results are then gridded to produce a differential section, and provide a better model of the earth's true resistivity than earlier FDEM modelling techniques. MacNae *et al.* (1991) use a lookup table to determine an apparent mirror image depth for measured TDEM responses at each delay time and then compute corresponding conductivity values by damped matrix inversion. Their technique can provide a generalised model earth, or be applied to halfspace and thin sheet (thick sheet overburden) models. The approach taken by Wolfgram and Karlik (1995) is to first deconvolve the TDEM system response from the data and then determine the conductivity variation with depth using integral quantities such as the cumulative conductance. The results from both of these TDEM techniques are displayed as conductivity sections in a similar form to the FDEM technique described previously.

Interpretation of electromagnetic data requires presentations that are geologically intuitive. Images of halfspace apparent resistivity or decay constant τ (tau) have proven to be effective geological mapping tools, although they oversimplify the information inherent in the data. The results from the modelling techniques described above provide better approximations to the earth's true conductivity structure, and can be presented in plan view, as well as a series of image slices at selected apparent depths. Challenges remain in effectively presenting the results from the new approaches to true 3-D modelling.

Now that modelling of stratified conductivity structure has become more routine, much of the current work is focused on the modelling of discrete conductors. The issues being addressed include interaction with a complex host, and automatic anomaly selection. Much of the work is being done through research consortia sponsored by the mining industry. The ultimate goal is to make interpretation of electromagnetic data fast, robust, geologically reasonable and open to a wider audience.

Airborne gravity

Hammer (1983) declared that "Airborne gravity is here!" This may be true for reconnaissance studies of sedimentary basins for petroleum exploration, but for mineral exploration, a better statement might be "Airborne gravity gradiometry is almost here!" The current generation of airborne gravimeters are typically adaptations of marine gravimeters (Schwarz *et al.*, 1995). The fundamental limitations of such systems are that the amplitudes of the various noise sources, particularly those induced by variable aircraft motion, are orders of magnitude larger than the signal due to geological sources. With the advent of GPS, the precision of aircraft positioning has improved and consequently the corrections for aircraft motion are more precise. Nevertheless, the resolution of current fixed-wing airborne gravity systems is of the order of 1 milligal over half-wavelengths of four kilometers (Anderson *et al.*, 1996), as the observed data require carefully applied, rather heavy filtering.

Dransfield *et al.* (1991) set out the criteria for an airborne gravity gradiometer system that would apply to mineral exploration, particularly the direct detection of moderate- to large-sized massive sulphide bodies. This is illustrated in Figure 9, where the detectability of a number of exploration targets is compared with current and planned airborne gravity systems. The principal advantage of a gradiometer over a conventional scalar gravity system is that it is not bound by the equivalence principle. Much of the motion noise is common to both the sensors and is therefore cancelled in the gradiometer measurements. As a result, the sensitivity of a gradiometer is substantially higher. Properly configured, a gradiometer can measure (directly or indirectly) all nine components of the gravity tensor. This provides a considerable wealth of data to not only locate geological targets, but also to determine their geometry.

Several research programs are currently underway to develop airborne gravity gradiometers using a variety of approaches and technologies, including inertial and GPS navigation systems, scissoring beams or vibrating strings in a superconducting environment and atomic interferometers. Little concrete information on these approaches has yet been published, as the application of such a system is projected to have considerable impact, whether deployed on a proprietary basis by mining companies or offered as a commercial service. It is anticipated that one or more gradiometer systems will be acquiring production data by 1999, although similar predictions have been made for at least the last six years. One gradiometer system is known to have been flown (Bell *et al.*, 1997). However, this test required a Winnebago containing the system being driven aboard a Lockheed C-130 aircraft, not a practical solution for mineral exploration.

Considerable work remains to develop the actual application of gradiometer data for solving exploration problems. Dransfield (1997) discusses the simplification of interpretation by utilizing the invariants of

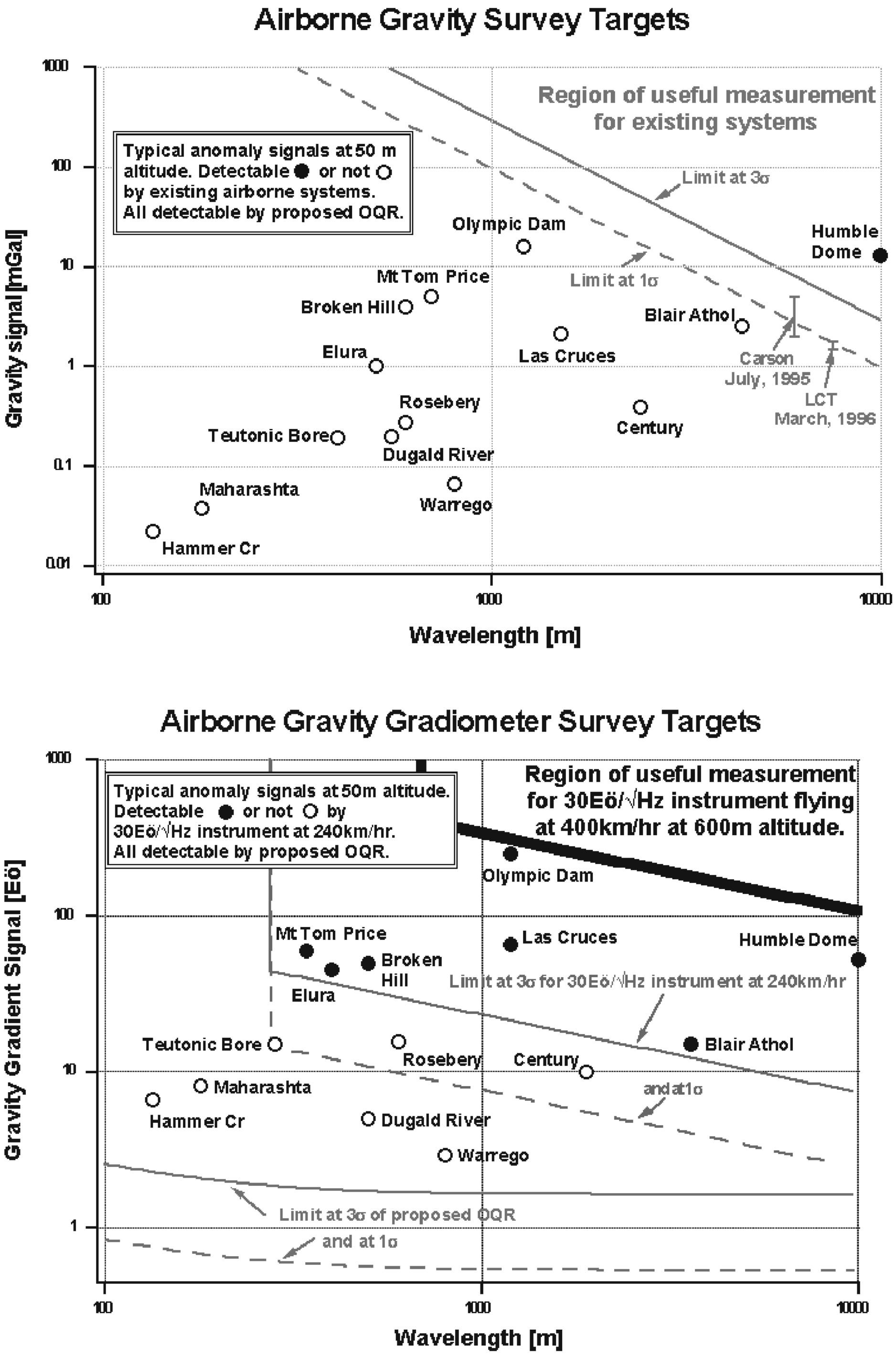

Figure 9: *The gravity signals of known mineral deposits are not detectable using existing airborne scalar gravity systems (**a**). The gravity gradiometer response of mineral exploration targets will be detectable, depending on the specifications of the instrumentation and the data acquisition parameters (**b**). For example, Humble Dome – 139 Mbbl oil, Teutonic Bore – 1.4 MT @ 16% Zn, 4% Cu, Warrego – 5 MT @ 3% Cu, 2 ppm Au, 0.3% Bi. The orthogonal quadropole responder (OQR) measures the torque of two test masses mounted on a common rotational axis and orthogonal principal axes. The gravity gradient is separated from rotational accelerations by differential and common mode measurements. The OQR gravity gradiometer system is under development by RTZ-CRA Exploration and the University of Western Australia (after Dransfield et al., 1991 and Dransfield, 1997).*

the gravity gradient tensor to reduce the complexity of the responses and the number of products that require study. Chen and MacNae (1997) point out that although gradient measurements negate the application of the Bouguer slab correction required by conventional gravity measurements, the terrain effects are magnified to the point where a sulphide target of moderate size and shallow depth can be obscured completely. Consequently, an accurate model of the terrain surface is required, as are the densities of the regolith and bedrock.

Seigel and McConnell (1996) describe an automated technique for acquiring regional gravity surveys. A self-levelling, high precision ground gravimeter is sealed within a waterproof container and lowered to a measurement site from a hovering helicopter. The entire reading and positioning process is pilot-activated and controlled. It allows for acquisition of data in areas where landing conditions are difficult, such as rugged topography, heavy forest cover or shallow water, and leads to a considerable production increase over land-based surveys.

SAFETY

The increase in airborne geophysical surveying, particularly in hostile areas (e.g., rugged terrain, high altitudes, poor infrastructure), has made aircraft and crew safety a more important issue. In absolute terms, accidents have increased in the last three years, although it is not clear whether that remains true if measured against the volume of data acquired. Nevertheless, it remains a critical issue. The International Airborne Geophysics Safety Association (IAGSA) was formed in 1995 to address safety issues on a collaborative basis. Safety concerns not only the survey contractors, but also their clients and consultants, all of whom play a role in designing airborne surveys. IAGSA is studying any safety-related data that are made available, with a view to developing standards and recommended practices for the safe execution of airborne surveys. Some end users are becoming more strict in the implementation of safety procedures by their selected contractors. The adage that airborne geophysical data are preferably acquired by "flying low and slow" is apparently wearing a bit thin and is, in any case, not always consistent with theory or system limitations.

Airborne geophysical platforms and instrumentation design are being adapted to address the requirements of clients, from both an economic and safety point of view. Lightweight, frequency-domain, helicopter electromagnetic systems have been developed for acquiring data in high altitude mountains, with the requisite reduction in transmitter power and receiver bandwidth. Low altitude magnetic surveys (20 m above ground or less) are being acquired using stinger-equipped helicopters or crop-dusting planes, aided by the miniaturisation of the necessary electronic equipment in recent years. The implementation of low cost, low altitude aeromagnetic surveys using an unmanned air vehicle (an aerosonde) has received considerable attention (CRC AMET, 1996).

DATA VISUALISATION AND INTERPRETATION

Visualisation as images

For data collected in an airborne survey and corrected appropriately, the first step towards visualisation is the process of gridding, i.e., interpolating the data that are originally characterised by closely spaced observations along comparatively widely spaced lines into a grid of points spaced equally in x and y. This was traditionally the first step in the generation of contours by computer routines (Figure 10a) and is no different when the switch is made to image presentation, except that a smaller grid cell size may be required. Some problems of sound gridding remain, centred mostly around the difficulty of reconciling the along-line detail with the relatively sparse information available across line (e.g., Hogg, 1989). Minimum curvature methods still appear to be the most popular here and some new approaches to ameliorating the consequences of wide line spacing include the use of Radon transforms (Zhou, 1993). However, simply adopting more rigorous survey specifications has already reduced the problem very considerably in many cases.

Once data are interpolated to a grid of suitable dimension, an image of aeromagnetic survey data can easily be created by ascribing to each element in the grid an appropriate shade of grey on a VDU screen (Figure 10b). The optimum use of the available grey levels can be made by contrast-stretching such that each grey level appears in about as many pixels as all other grey levels. With the normal spread of total field values encountered in aeromagnetics, this results in small changes in value between different grey levels near the centre of the range with much larger intervals at the highest and lowest scale ranges. Normally this is quite satisfactory in emphasising small anomalies that differ little from average background values.

However, in most cases the grey-scale presentation can be improved upon by exploiting the predisposition of the human eye to interpret grey shades as relief of a white surface that scatters incident light in all directions. The result is often referred to as *shaded relief* and, of course, is dependent on the azimuth of the incoming illumination. This can be simulated very easily by calculating horizontal derivatives of the grid in two orthogonal directions (e.g., N–S and E–W) and blending them according to the desired illumination direction (Figure 10c). On screen this can be done interactively to help the user choose the most revealing illumination direction (usually illumination from the northerly quadrant produces a most convincing effect on the eye) or to seek out subtle anomalies that only appear under certain illumination conditions. A simple positive anomaly under northerly illumination is bright on its north flank and dark on its south. Coincidentally, this situation also arises when data from mid-southerly latitudes are displayed as a simple grey scale image, since typical anomalies at these latitudes have a positive part to the north (bright) and a negative part to the south (dark), simulating the shaded relief effect already in the grey scale image. This, and other factors, can cause some confusion among inexperienced users confronted with the two styles of presentation.

Use of colour also has many merits. The colours of the natural colour wheel (red-yellow-green-cyan-blue-magenta-red) are now adopted almost universally, with red for the highest anomaly values and blue for the lowest (Figure 10d). Again, contrast stretching can ensure optimum use of the available colour levels and the effect is to make magnetic highs and lows immediately recognisable as such. From the point of view of interpretation, a drawback of colour is that it tends to emphasise regional variations in the anomaly *level* as changes in predominant colour from place to place. This is not straightforwardly related to near-surface geology and may cause confusion. While the views of users obviously differ, many would agree that the most satisfactory presentation is a combination of colour and shaded relief (Figure 10e) and while the advantages of the combined image over pure shaded relief can be debated, most will agree that either one is superior for the serious interpreter to colour alone. Taking colour theory a stage further, a most satisfactory method has been based on the so-called HSV colour model

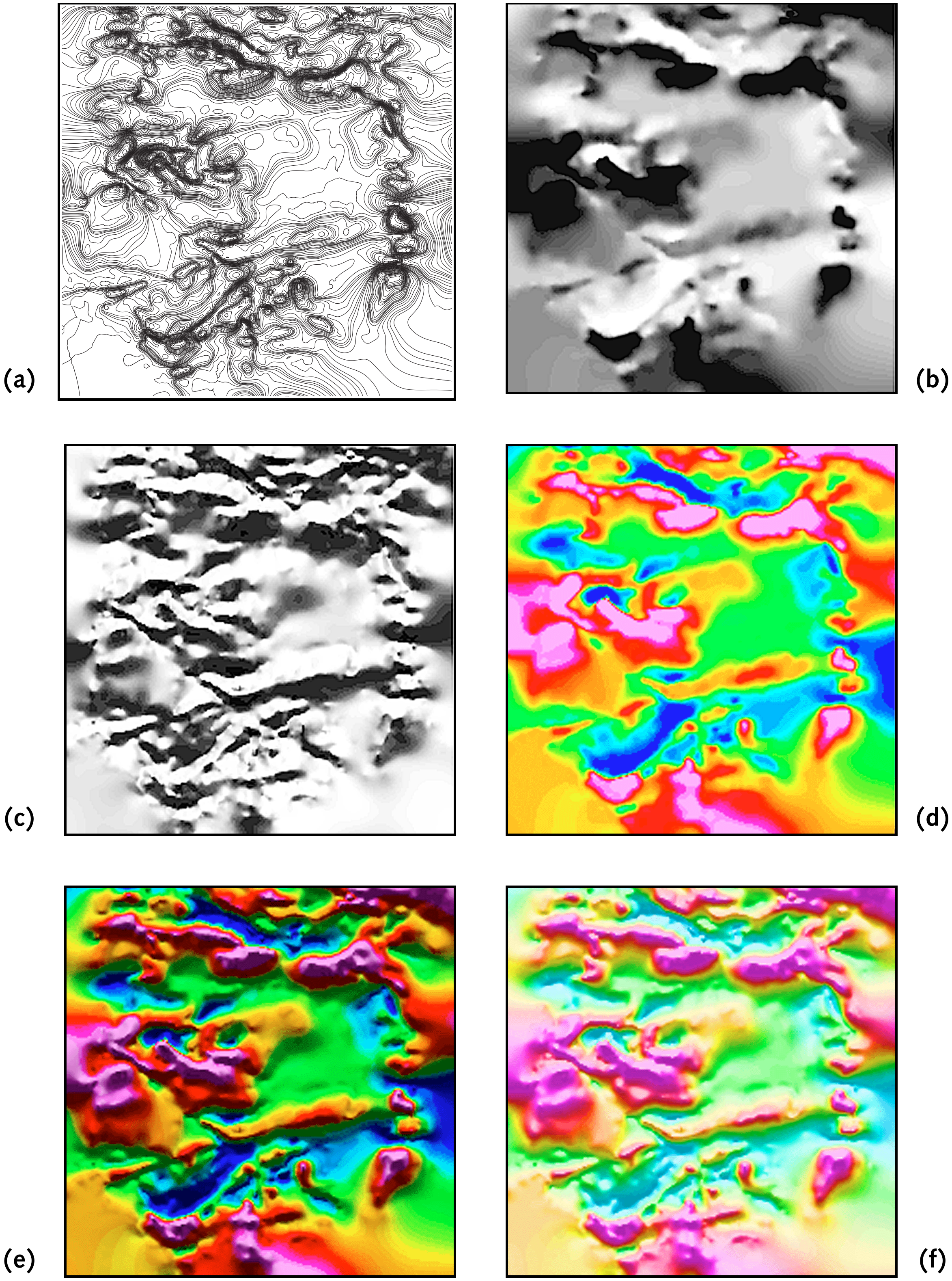

Figure 10: *The stages in the development of an optimum presentation of magnetic anomaly data as an image, as explained in the text. (**a**) Contour map; (**b**) grey-scale image (black = high, white = low); (**c**) shaded relief image with northerly illumination; (**d**) colour raster image (red = high; blue = low); (**e**) combined shaded relief and colour raster image (i.e., c + d); (**f**) shaded relief image using the HSV colour model.*

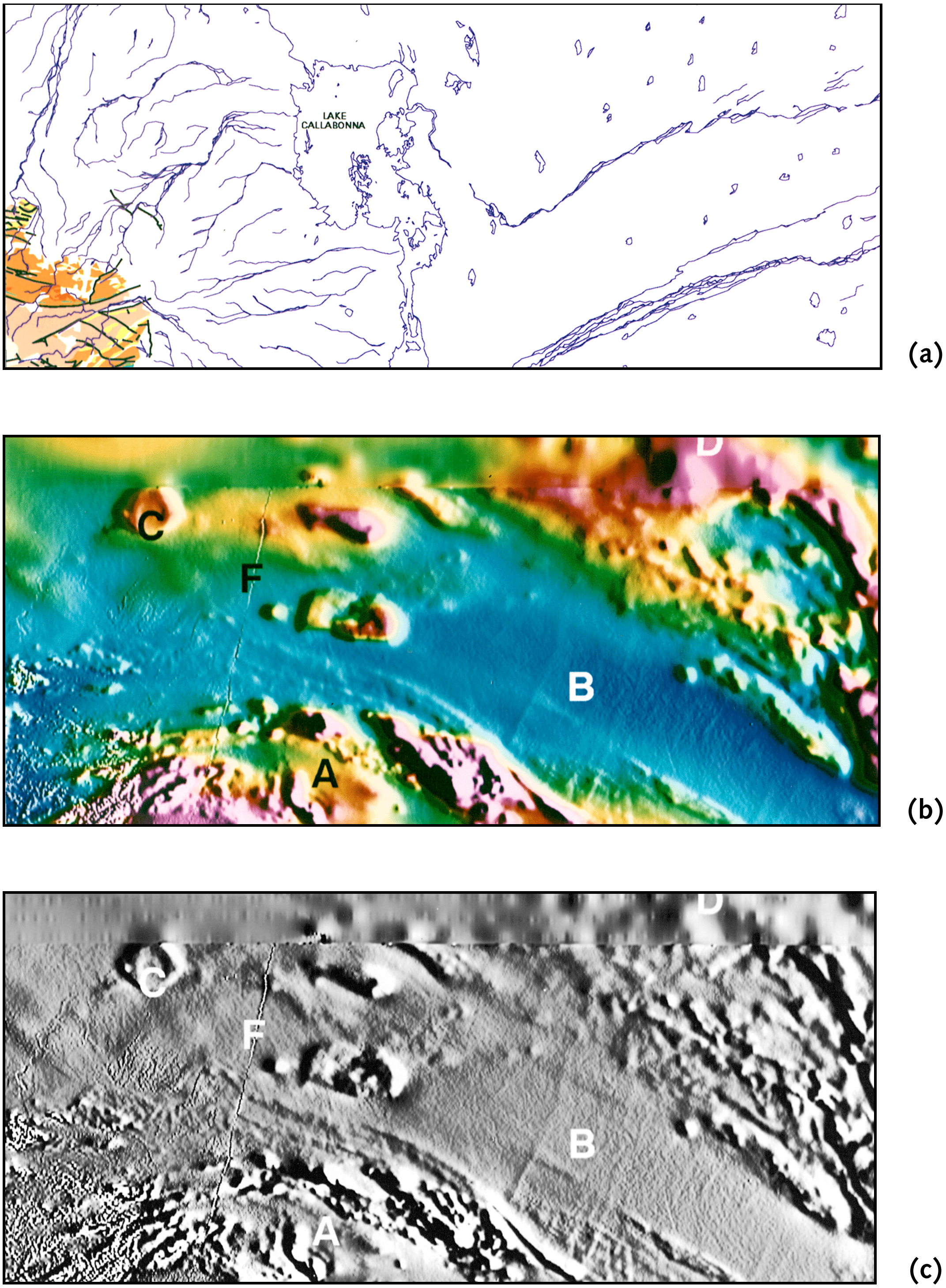

Figure 11: *Extending geological mapping into areas devoid of outcrop using magnetic images—part of the Callabonna sheet, South Australia (for location, see Figure 3). (**a**) Outcrop geology; (**b**) Total magnetic intensity anomaly (TMI); (**c**) 0.5 vertical derivative of TMI. Some of the geological features are: A – Northern part of the Mount Babbage Inlier of the North Flinders Ranges, Proterozoic metamorphic and intrusive rocks, B–Metasedimentary and volcanic rocks of unknown (Proterozoic?) age, C – intrusion, F – gas pipeline. Flight lines oriented E-W, 80 m above terrain and 400 m apart were flown by AGSO in 1995 (Mackey and Richardson, 1996).*

(Milligan *et al.*, 1992) that allows the bright side of anomalies to be highlighted as well as shading the darker sides. This gives the image an overall brighter aspect than simple addition of colour and shaded relief rasters (Figure 10f).

The methods of image visualisation summarised above may be applied to original data or to data that has been subjected to one or more of the familiar processes that have often in the past been applied in the wavenumber or Fourier domain that exploit the Laplacian properties of potential fields. These include the calculation of derivatives (first, second and higher, vertical or horizontal), upward and downward continuation, regional, residual or bandpass filtering, migration to the pole or equator and susceptibility mapping (Grant, 1973). All offer enhancement of certain types of feature that have often been exploited in the past to assist the interpreter. The advent of higher quality data and the presentation of data as images that appear largely self-explanatory, together with Fourier domain processing, offer a wide range of visualisation possibilities (Milligan and Gunn, 1997). Some further examples are given in Figure 11.

Hardware and software

Ten years have seen the hardware and software that comprise airborne geophysical data processing systems change radically. The dedicated processing centres and the mainframe computers of the contractors of ten years ago have been largely replaced by relatively inexpensive workstations and personal computer (PC) systems and networks that enable the data user to process and interact with his data in a much more hands-on fashion. All the image processing functions described above are easily accessible to users equipped in this way. In particular, the PC that was only in its infancy ten years ago is now ubiquitous, its very success creating a market for affordable software, the development of which is largely driven by the requirements and investments (through software purchases) of the end user. The developments therefore have become much more demand-driven and the near monopolies of the old-style processing centres have virtually disappeared. We now stand at a point in time when the only real dichotomy lies between the users of workstations (often within cultures that have a history in mainframe computers) and the users of PCs (most of whom have become computer-oriented only since the PC arrived on the scene). With the power of the Pentium PC architecture and the common environment provided by Windows NT, a convergence in even this area seems likely within a few years. Most noticeable from the user's point of view is that sufficient processing capacity is now usually found at the flying base in the field for much, if not all, data processing to be done there, leaving relatively little for the processing centre after demobilisation. The resulting faster survey turnaround and early delivery of final products is welcomed by all.

Processing and interpretation

Some innovations in data processing and interpretation appear to have found favour amongst users. These include Euler deconvolution (Reid *et al.*, 1990) which, packaged in software systems that can handle gridded data sets, offers one of the first practical ways of extracting believable source-depth information from gridded gravity and magnetic data. It also has proven very good at recognising lineaments, so adding some physical credibility to the fracture patterns and displacements that interpreters have often drawn on maps but which have often failed to convince the sceptical user (Figure 12). The method still has scope for refinement, however, and the multiplicity of solutions produced when applied without sufficient care or knowledge can confound the unwary. But as a method of quantitative interpretation that also offers considerable assistance in qualitative understanding, it seems a very appropriate tool in an interpretation environment that will not foreseeably become fully analytical but which would gain scientific stature by being less than fully subjective.

The revival of the analytic signal technique (Roest *et al.*, 1992) and its implementation in accessible software has also become popular and successful, and has offered new and promising solutions when applied to data at very low magnetic latitudes that do not permit reliable pole reduction (MacLeod *et al.*, 1993).

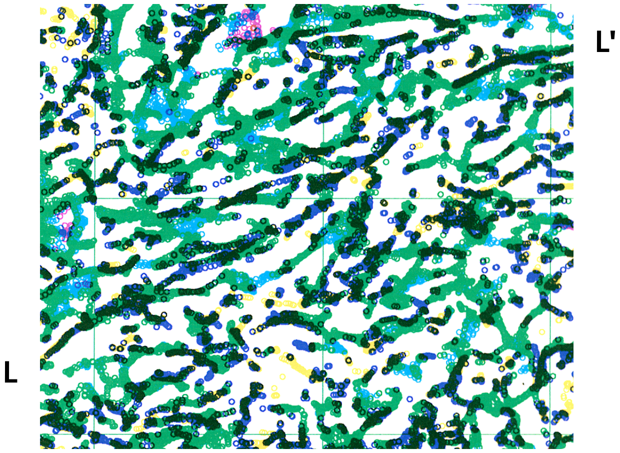

Figure 12: *Solutions of Euler deconvolution trace clearly the Lurio fault zone (L-L') in northern Mozambique.*

DATABASES OF OLD DATA

The advantages of image presentation (before or after Fourier domain and/or image processing of the data raster) are not confined to new data of the highest quality. Some of these advantages can be enjoyed for older data, particularly where large numbers of old surveys are retrieved, digitised where necessary, and assembled to give a synoptic overview of an area as large as a continent (Barritt, 1993). Such compilation activities have been a feature of the last ten years and are reviewed by Fairhead *et al.* (this volume). It is a testimony to the value attributed to aeromagnetic coverage that, even on continents where there has been no systematic plan of regional coverage, the surveys that have been carried out for the various objectives of national governments, mining and petroleum companies have led to a coverage that approaches completeness at a reconnaissance scale in most parts of the world. Even the oldest data acquire a new lease on life when digitised and viewed at regional scale. The coverage is most thorough and complete, however, where national governments have planned this over many decades, as in Canada, Australia and the Scandinavian countries. This also signals the presence of an excellent database for exploration purposes that contributes to those countries continuing to be viewed favourably for exploration investment.

From the viewpoint of global geology, such information is also usefully supplemented by the regional gravity and magnetic coverage of the oceans, the former from Geosat (e.g., Marks *et al.*, 1993), the latter from compilation of marine magnetic anomaly data (e.g., Roest *et al.*, 1996).

Unfortunately, data from other geophysical methods are unlikely to offer much completeness of coverage to merit regional compilation in the foreseeable future, with the exception of radiometric data and, to a lesser extent, electromagnetic data in some localised parts of the world. Even more so than with aeromagnetic data, the variability in acquisition systems and parameters—and in the original compilation techniques used—present challenges in preparation of coherent regional data sets. However, techniques such as back-calibration of radiometric surveys have proven remarkably successful in mitigating these problems.

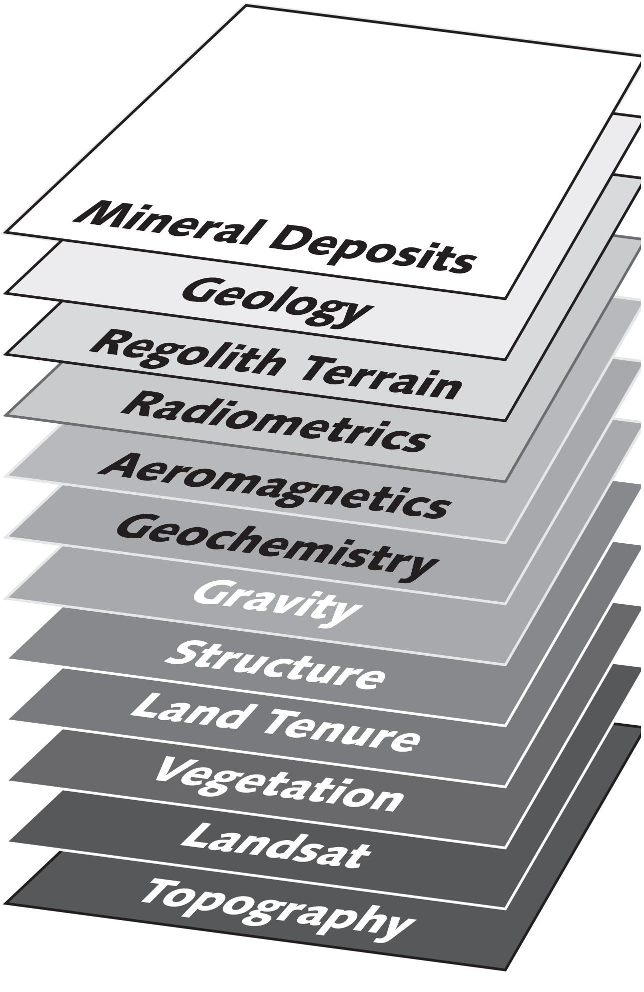

Figure 13: *Some of the key data layers that are often used in an exploration area. Of these, topography (DEM), aeromagnetics and radiometrics are derived from airborne geophysical survey. Gravity data are still collected conventionally on the ground, but would be a powerful addition to airborne survey capability (courtesy of AGSO).*

Finally on this topic, compilations serve to highlight those virgin areas where the airborne geophysics of the recent decades has yet to be applied. Most such regions result from conditions of civil instability or regimes ill-disposed to foreign investment. Where appropriate political situations now prevail, opportunities to use the latest airborne technology in new areas seem so promising as to attract exploration investment for mineral exploration very easily. This may be seen as a result—or may be sometimes even as a cause—of the recent and rapid globalisation of mineral exploration expenditure.

DATA INTEGRATION

The move towards restoring and digitising historical aeromagnetic data should be seen as part of a trend that has emerged in the last ten years to better manage all available information that may be relevant to exploration. This has been supported by emerging computer technology to facilitate the management of x,y-referenced data under the generic name of geographic information systems or GIS. While its origins can be traced back several decades, it has only recently emerged onto the mass market where large numbers of users can begin to benefit from it with minimal tuition. It follows a curve of increasing user-friendliness and intuitive interaction that will surely make GIS ubiquitous in time and we will shortly wonder how we ever achieved anything without it, in the same way that word processing software has already highlighted the limitations of the humble typewriter. Accounts of GIS development and application can be found elsewhere (e.g., Bonham-Carter, this volume; IAEA, 1994; AGSO, 1992). For purposes of the present paper, the important point to note is the large number of GIS *layers* of exploration relevance that may be obtained from (airborne) geophysical surveys (Figure 13).

The realisation that all types of data are potentially valuable is no more than the practical manifestation of a truly scientific approach to mineral exploration in which, ultimately, models of ore genesis are created and then used as exploration tools in searching for the geological environments in which such models may have been operational. No better evidence of this is to be found than the investments that have been made by the mining majors in their databases in recent years. Hand-in-hand with the globalisation of exploration investment, these databases are naturally becoming more and more global in nature, and senior exploration executives have even been known to allude to the thought that "the next mine will be found inside our computer system."

While this might be seen as a triumph for the scientific approach to mineral exploration, it is not without its dangers. The more the value of global databases is appreciated, the greater the need for data and the greater the perception that such data provide an important part of a company's competitive edge and so should be held confidential. The threat is that government and academic geoscientists will become increasingly remote from the cutting edge of exploration science and starved of the data that are needed to further develop the science itself.

Particularly challenging is the role of national geological surveys in this context. Their traditional role as custodians and publishers of data and maps at a national level is now open to the application of many technologically advanced alternatives to the long-established media of paper maps and reports; digital data delivery will soon be *de rigueur*, and the expectation of the mining companies will be high. Surveys also have a 'public good' role to play, and their function here is on a much longer time scale than that of exploration interests which may come and go over periods shorter than decades. The wisdom of public expenditure on geoscience has been much questioned in recent years and, very often, political expediency—also on a short-term time scale—threatens in some cases to push the needs of sound geoscience into second place, with consequences that may be devastating in the longer term.

Within airborne geophysics, it is now obvious that the results of systematic mapping programmes—that were started almost fifty years ago in some countries (e.g., Canada, Australia)—have become an important part of the national database, not to mention the national investment climate for exploration. In Australia, the approaching completion of the reconnaissance aeromagnetic coverage was seen as the appropriate time to employ the new level of technological sophistication to commence a more detailed national airborne geophysical coverage (Woods, 1991; Richards, 1993). This has accelerated during the 1990s as government investment in airborne geophysics (both federal and state) has led to new and revived interest in exploration acreage, the taxpayer's dollar being returned immediately by new investment as well as the longer term prospect of new mines, employment and prosperity (Denham, 1997; Crabb, 1996). What now seems evident is that company exploration databases must be matched in quality at a regional scale by national databases and archives that are openly available to all those who may need them—for groundwater and environmental purposes as well as for exploration, both now and in the future.

In the developing countries that make up a large part of the world's land area—and an ever-increasing share of active exploration acreage—the challenge is even greater. While the new inward investment of exploration dollars is very welcome, the expectation of the explorers to access national databases is often frustrated by geological survey departments that are desperately underfunded and largely unfamiliar with current information technology. International aid funding was often available during past decades to fund major airborne geophysical programmes in many of these countries, in Africa, South America and Southeast Asia, for example. The aim then was to stimulate the sort of exploration boom that has finally materialised in the 1990s. Now, however, international funding of this sort has become hard to find to serve the present pressing need to bring even existing national geoscience databases into the digital era.

THE FUTURE

To forecast the future is always difficult and, after a decade of great change in airborne geophysics, it is tempting to think that developments in the coming decade will be more modest. The capability of present survey systems offers such enormous potential that the immediate emphasis is more likely to be on application rather than innovation; coverage of more and more acreage with existing systems rather than the development of new and better systems. An exception might be the arrival of practical, low-cost airborne gravimetry to add a much-needed new dimension to the classic airborne survey toolkit. Airborne induced polarisation may be farther off on the horizon. Systematic and detailed coverage will certainly serve to answer more geological uncertainties in the longer term.

The recognition that high resolution geophysics, particularly aeromagnetics, provides an important mapping tool for intrasedimentary geology has lead to a significant increase in surveying over basins, both onshore and offshore, in recent years. The work offshore is anticipated to increase as the definition of Law of the Sea boundaries and economic zones is becoming increasingly important. The exploitation of offshore mineral resources is coming closer to hand, which will lead to a new realm for mineral exploration. Offshore surveys would seem to be the natural proving ground for the aerosonde.

For the user, the competitive environment for survey contractors keeps costs down to a level where, in real terms, airborne geophysics gets cheaper and cheaper. Quoted prices in Australia for combined aeromagnetic and gamma-ray spectrometer surveys, for example, are now routinely much less than US$10/km. While this is good for the user, the margins available for technological innovation and applied research remain minimal and it is a remarkable testimony to the dedication of the airborne geophysical community as a whole that we have reached the present level of sophistication with so little investment of soft money.

Unless the applied earth sciences can attract more of the government money that goes regularly, for example, into prestige projects such as satellites and astrophysics, the future of effective applied earth sciences in the universities and government surveys looks difficult. A shortage of well-informed new applied geoscience graduates and the neglect of national databases may be the sad keynote of the new millennium.

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