APPLICATIONS OF REGIONAL GEOPHYSICS AND GEOCHEMISTRY
PAPER 103

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LARGE SCALE COMPILATION OF MAGNETIC, GRAVITY, RADIOMETRIC AND ELECTROMAGNETIC DATA: THE NEW EXPLORATION STRATEGY FOR THE 90S

Fairhead, J.D.[1], Misener, J.D.[2], Green, C.M.[1], Bainbridge, G.[2], and Reford, S.W.[2]

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1. GETECH division of ULIS Ltd., Dept. of Earth Sciences, University of Leeds, Leeds, England
2. Paterson Grant and Watson Limited, Toronto, Ontario, Canada

ABSTRACT

Compilation and merging of magnetic and gravity data sets, and more recently radiometric and electromagnetic data sets, are playing an ever more important role in mineral and petroleum exploration. The digital and map products provide significant regional geologic and tectonic information. These databases are also proving necessary for government institutions that wish to promote exploration investment within their jurisdictions. The compilation projects preserve historical data that otherwise might be irretrievably lost. Innovative techniques have been developed to recover data and reprocess them into consistent, merged grid and profile databases.

INTRODUCTION

The compilation of disparate geophysical data sets has mushroomed in the last decade. It has graduated from countrywide compilations of aeromagnetic and gravity data for the more developed countries, to compilations that cover most corners of the globe, and that have branched out to include radiometric and electromagnetic data as well. These studies have proven their worth by the significant support provided by the mineral and hydrocarbon exploration industries, and the enthusiastic participation of the national institutions that have archived the historical data. These efforts happily coincided with the changes in global politics that have opened up vast new regions for exploration. State-of-the-art geophysical databases often prove to be the best initial source of geoscientific information in a given area. They also preserve a legacy of five decades of geophysical surveying, at significantly lower cost than reacquiring the data at similar resolution.

STATUS OF COMPILATION STUDIES

The status of the various completed and ongoing compilation projects is summarized in the tables and figures presented in this paper. However, the reader is encouraged to study the references for specific details on each project.

Gravity

Following the gravity experiments of Galileo Galilei (~1590), and Isaac Newton's *Philosophiae Naturalis Principia Mathematica* in 1687, it was not until the early nineteenth century that the pendulum method was developed to measure gravity. In 1910 Roland von Eotvos constructed the first torsion balance (gradiometer), which was successfully used in Czechoslovakia to map the Egbell oil field in 1915. In 1922 gradiometers were successfully used in the U.S. for oil exploration. A basic problem with gradiometers was their slow production rates of two to three stations per day. It was not until the 1930s that the much easier to use gravity meter took over, enabling an order of magnitude improvement in production rates to be achieved. The best known gravity meters are the Worden and LaCoste and Romberg instruments which use the astatic principles to measure the vertical displacement of a small mass suspended from a system of delicate springs and beams (Blakely, 1995). This last type of instrument forms the basis of most modern land, shipborne and airborne gravity meters currently in use today. The spatial coverage of these measurements, generated over the last half century, together with satellite derived gravity data over the oceans, form the basis of the data compilation studies described here.

The military importance of precisely knowing the gravity field for initialising missile gyros has, and in some cases continues, to keep national gravity data sets classified and not generally made available for

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either scientific or commercial use. The advances in satellite technology (e.g., global positioning system [GPS]) has tended to downgrade the military requirements of gravity data such that they are now available at resolutions suitable for 'frontier' exploration for the whole of Eurasia.

In oceanic areas, the spatial coverage of terrestrial gravity data is generally poor except over parts of the continental margins where the oil industry have undertaken detailed surveys. In the early 1980s the results of the radar altimeter experiments from the Seasat satellite (June 1978–October 1979) indicated that the height of the sea surface (the geoid surface or equipotential surface of the gravity field) could be measured to an accuracy of a few centimetres (variations globally are ~100 meters with respect to best fitting ellipsoid) enabling the sea surface heights to be converted into free air gravity anomalies (Olgiati *et al.*, 1995). For Seasat, the spatial coverage of tracks limited spatial (wavelength) resolution to greater than ~60 km. Even so, the plate tectonic fabric of the ocean basins was spectacularly revealed between ± 72° latitudes (Haxby *et al.*, 1983)

Subsequent satellites Geosat (1985 to 1990), ERS-1 (1991 to 1995) and Topex-Poseidon (1992 to present) have enabled the marine areas of the world between ±82° latitudes to be mapped to a resolution of ~20±10 km wavelength and amplitudes of 2 to 3 mGal accuracy (Sandwell *et al.*,1992). Since thin sea ice conforms to the geoid surface, radar reflections of the ice surface have also been used to map the gravity field over the polar regions to 82° latitudes (Laxon and McAdoo, 1994). Thus in the early 1980s the gravity field of the world's oceans became better imaged than the continents. In an attempt to rectify this imbalance, GETECH dedicated itself between 1986 to 1995 to a systematic programme of continental scale gravity data compilations funded by the oil industry. These studies have collated all available data (private and public land, marine, sea bottom, airborne and satellite derived) at a

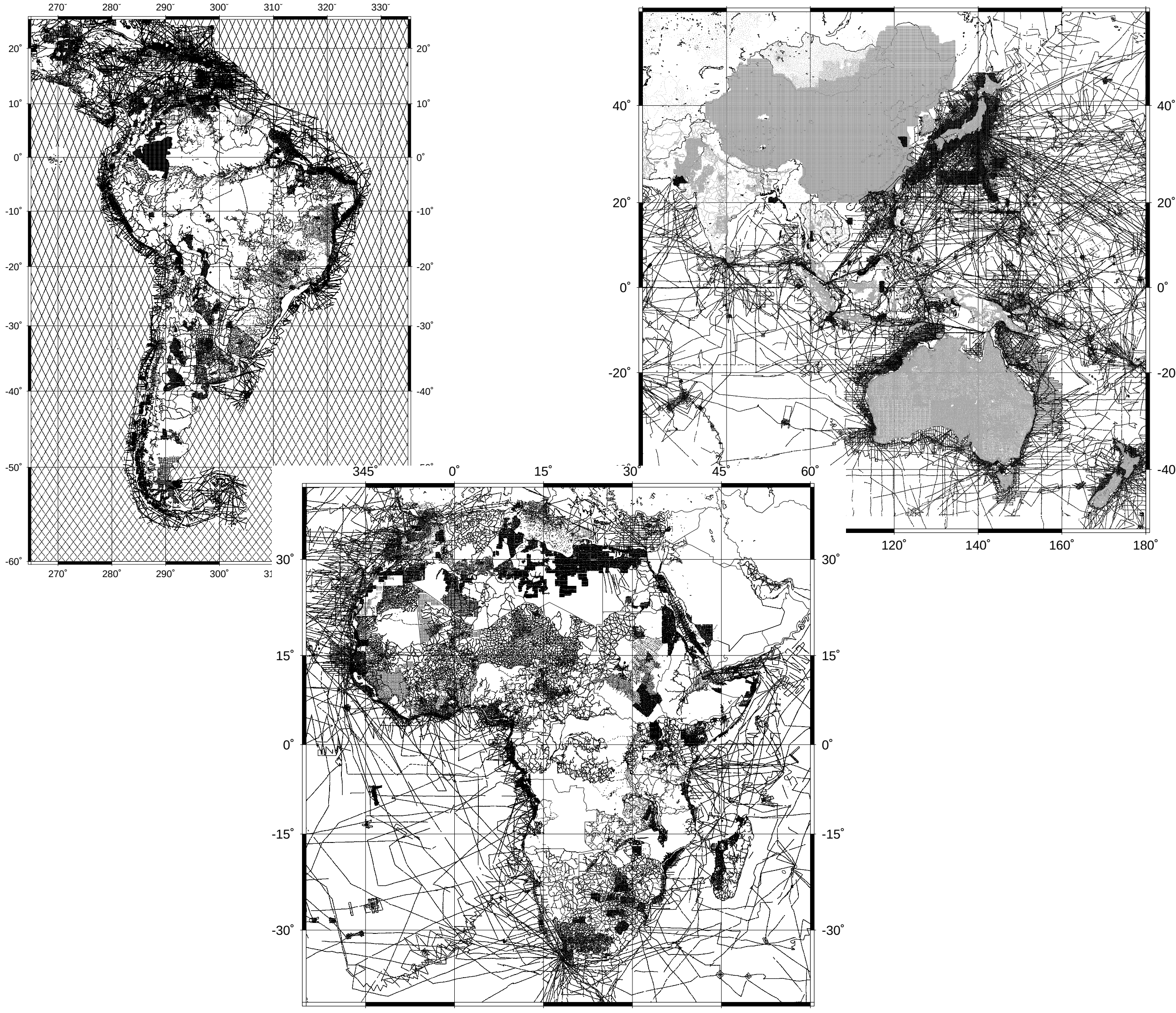
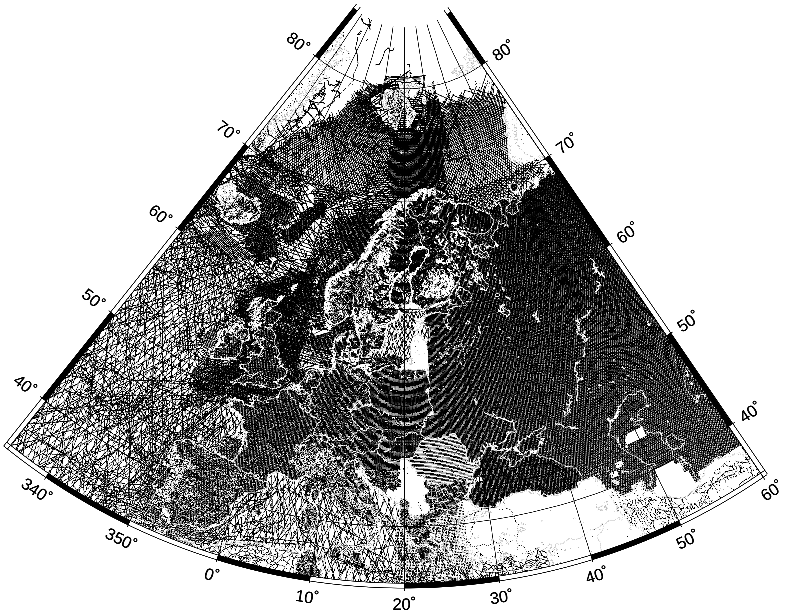


Figure 1: *Gravity data distribution maps for the land-based compilation studies (regions 8 to 12, Table 2).*

regional level (digital grids of 8 to 10 km cell size) for all continental areas except North America (Committee for the Gravity Map of North America, 1987) and Antarctica (Johnson and von Frese, 1996). Tables 1 to 3 list the major gravity compilation studies known to the authors which cover most of the earth's surface. These tables are linked to Figure 1, showing some of the data coverage maps.

The majority of land data used in these compilations (Table 2) are national data sets that have been collected in a systematic manner over a number of years or decades. The largest national surveys are listed in Table 3 (limitations on article length prevent referencing all national data sets). Some of the unlisted countries (e.g., Poland and Czech Republic) have developed data coverage as high as 5 to 7 stations per km^2! In the former Soviet Union (FSU) and China, station density is closely linked to map scale. National coverage have been achieved at 1:1 million scale where station density is one station per 25 km^2 and at 1:200 000 scale where station density is one station per 4 km^2 (western China not covered by 1:200 000 scale maps). Commercial release of higher resolution grids for the FSU is now possible and these are based on the 1:200 000 scale map data. For much of Africa, South America and South East Asia the coverage is less systematic such that there still remain large data gaps and even the 10 km (or 5′) grid is oversampling the majority of areas. Since 1991, GETECH has been involved in a programme to infill these large data gaps of central and north Brazil (Blitzkow *et al.*, 1997). The only areas in Figure 1 not covered by the compilation studies listed in Table 2 are the North Pole, i.e., greater than 82°N, which is partly covered by USSR ice (land type) measurements, the Arabian Peninsula where oil company consortia hold comprehensive data coverage, and more specifically Saudi Arabia, where Saudi Aramco hold the national gravity coverage.

In listing the compilation studies in Tables 1 to 3, the role of international gravity data archiving agencies must be acknowledged. These include NIMA (U.S.-based National Imagery and Mapping Agency,



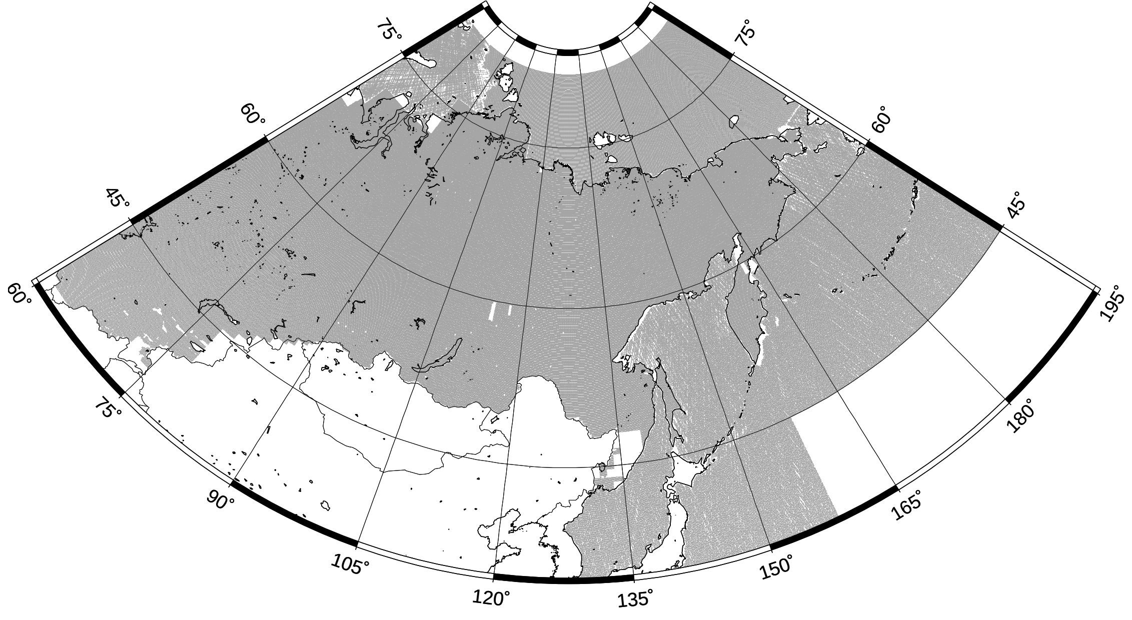


Table 1: ***Gravity compilation studies: satellite derived gravity for marine areas***

Region	Satellites	Products[1]	Co-ordinating and/or principal organisations
Global Marine ±72° latitude	Seasat and Geos-3	5′ grid (o)*	Lamont Doherty Geological Observatory of Columbia University (Haxby *et al.*, 1983)
Global Marine ±72° latitude	All satellites, missions to date	2′ grid (o)	Scripps Institute of Oceanography (Sandwell and Smith, 1992)
Antarctic to 82°S	ERS-1	?? grid	Geoscience, NOAA (McAdoo and Marks, 1992)
Arctic to 82°N	ERS-1	?? grid (c)	Geoscience Lab., NOAA (Laxon and McAdoo, 1994)
Eurasia Arctic to 82°N	ERS-1	8 km grid (c)*	GETECH (Green and Fairhead, 1994; Fairhead and Makedonskii, 1996)
Southeast Asia 60°E to 180°E & 50°S to 55°N	ERS-1 and Geosat GM missions	2′ grid (c)	GETECH (Fairhead *et al.*, 1996)

1. The symbol listed under Products makes reference to availability:
o = open file product, c = commercial product

Table 2: ***Gravity compilation studies: continental areas***

Region	Study period	Products[1]	Co-ordinating and/or principal organisations
North America	1977–1987	6 km grid (o)	USGS (CGAMNA, 1987)
Africa	1986–1988	5′ grids (c)	GETECH (Fairhead and Watts, 1989)
South and Central America	1988–1991	5′ grids (c)	GETECH (Green and Fairhead, 1993)
West -East Europe	1991–1994	8 km grids (c)	GETECH (Green and Fairhead, 1994)
Southeast Asia	1991–1995	5′ grids (c)	GETECH (Fairhead *et al.*, 1996)
North & Central Asia	1992–1995	8 km grids (c)	GETECH (Fairhead and Makedonskii, 1996)
Antarctic	1995–continuing	– (o)	BAS (Johnson and Von Frese, 1996)

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St. Louis, former known as DMA) and BGI (Bureau Gravimetrique International, Toulouse, France) who archive open file and confidential data and NGDC (U.S.-based National Geophysical Data Centre) which archives open file data. Academic institutions such as Lamont Doherty Geological Observatory of Columbia University and other U.S. institutions (e.g., Woods Hole) maintain important marine gravity and magnetic archives.

Table 3: ***Large national gravity surveys***

Country	Organisation
Former Soviet Union	Russian Army Topographic Services (Kogan *et al.*, 1994)
Canada	Geological Survey of Canada
United States	United States Geological Survey
China	No details available
Australia	Australian Geological Survey Organisation
United Kingdom and continental shelf	British Geological Survey

Table 4: ***Magnetic compilation studies***

Region	Project name	Grid products[1]	Co-ordinating and/or principal organisations
Africa	African Magnetic Mapping Project (AMMP, 1989–1992)	5′ grids (c)	GETECH, PGW and ITC (Barritt *et al.*, 1993)
Antarctica	Antarctic Digital Magnetic Anomaly Map (1995–ongoing)	– (o)	British Antarctic Survey (Johnson and Von Frese, 1996)
Arctic and North Atlantic Oceans and adjacent land areas	Compilation of Magnetic Data in the Arctic and North Atlantic Oceans (1989–1996)	5 km	Atlantic Geoscience Center, Geological Survey of Canada (Verhoef *et al.*., 1996)
Australia	National compilation (completed 1993, second edition 1996)	400 m	Australian Geological Survey Organisation (Tarlowski *et al.*, 1996)
Canada	National compilation	200 m	Geological Survey of Canada
China	China Aeromagnetic Mapping Project (CHAMP, 1996–1999)	1 km (c)	AGS/PGW/GETECH
East Asia	Magnetic Compilation of East Asia (completed 1996)	2 km (c)	Geological Survey of Japan and CCOP (Ishihara and Kisimoto, 1996)
Eastern Europe and Baltic Sea	Eastern Europe Magnetic Project (EEMP, 1995–1997)	0.5 km and optimum (c)	GETECH (Fairhead *et al.*, 1996)
Former Soviet Union	National Compilation (1951–1966) & new compilation 1993	18 maps at 1:2 500 000 scale; 5 km (o)	Ministry of Geology (Makarova, 1974; Pogrebitsky *et al.*, 1993)
Former Soviet Union	Flightline based products (1995–ongoing)	0.5 and 1 km (c)	GETECH
Middle East and India	Aeromagnetics of Arabia, India and the Middle East (AAIME, 1994–1997)	1 km and optimum (c)	ITC (Reeves and Erren, 1996)
Mongolia	Aeromagnetic Compilation completed 1994	1 km and optimum (c)	MGGEC and GETECH
North America	Magnetic Anomaly Map of North America (USA & Canada, 1977–1987)	2 km (o)	US Geological Survey (CMAMNA, 1987)
South and Central America	South America Magnetic Mapping Project (SAMMP, 1992–1996)	1 km and Optimum (o)	PGW and GETECH (Black *et al.*, 1995)
Southeast Asia	Southeast Asia Magnetic Project (SEAM, 1995—ongoing)	1 km and optimum (c)	GETECH and PGW (Fairhead *et al.*, 1996)
Western Europe	Compilation of all Western Europe	?	Wonik (Germany) and Galdeano (France)

1. The symbol listed under Products makes reference to availability:
o = open file product, c = commercial product

Magnetics

Lodestones and their property to preferentially align in a certain direction can be traced back to ancient Greece (sixth century BC). This simple device was then converted to a magnetic compass by the Chinese and this technology only reached Europe in the twelfth century AD. William Gilbert described the geomagnetic field for the first time in 1600 and in 1630, deflections of compass direction were used as a prospecting tool to locate iron ore in Sweden.

Land based instrumentation and exploration methods were subsequently developed to map spatial variations of the vertical component (ΔZ) and horizontal component (ΔH) of the geomagnetic field. It was not until World War II when Victor Vacquier and others developed fluxgate technology suitable for use in aircraft that aeromagnetic surveying became a reality. Absolute measuring instruments, the proton–precession magnetometer, were developed by Varian Associates in 1955 and rapidly became the land, sea and airborne instrument of choice due to its simplicity, reliability and its ability to measure the absolute magnitude of the total field. Higher resolution optically pumped magnetometers became widely available in the 1980s and when used with today's accurate positioning systems, GPS, enabled high resolution aeromagnetic surveys to be undertaken. These type of surveys are now standard practise in oil and mineral exploration (Merrill and McElhinny, 1983).

Aeromagnetic and marine magnetic surveys have been conducted with various survey parameters and scales over the past 40 to 50 years providing systematic coverage over discrete areas for oil and mineral exploration to the largest national surveys that now cover Australia, Canada, FSU, and U.S.A. Such national surveys have been flown to aid geological mapping and promote mineral and hydrocarbon exploitation. Digital recording and archiving of aeromagnetic data did not commence in a serious way until the late 1970s, thus the majority of magnetic surveys only exist as non-digital paper maps and/or profiles. The poor archiving and disparate nature of these data have meant they have been difficult to locate and access. Partly for this reason, a programme of systematic recovery and analogue–digital conversion of these surveys on country-wide and continental scale were initiated and in some cases is still ongoing.

Table 4 lists the major national and international data compilation studies. These studies provide technical details of known surveys and digital grids of those surveys that were made available. Figure 2 shows examples of the known data coverage.

International archiving of magnetic data is not organised as well as gravity data, with only NGDC and the Geological Survey of Canada handling open file magnetic data from other countries.

ANALOGUE TO DIGITAL CONVERSION

Analogue Data

Prior to the early 1980s many geophysical data were preserved in the form of maps, chart and listings.

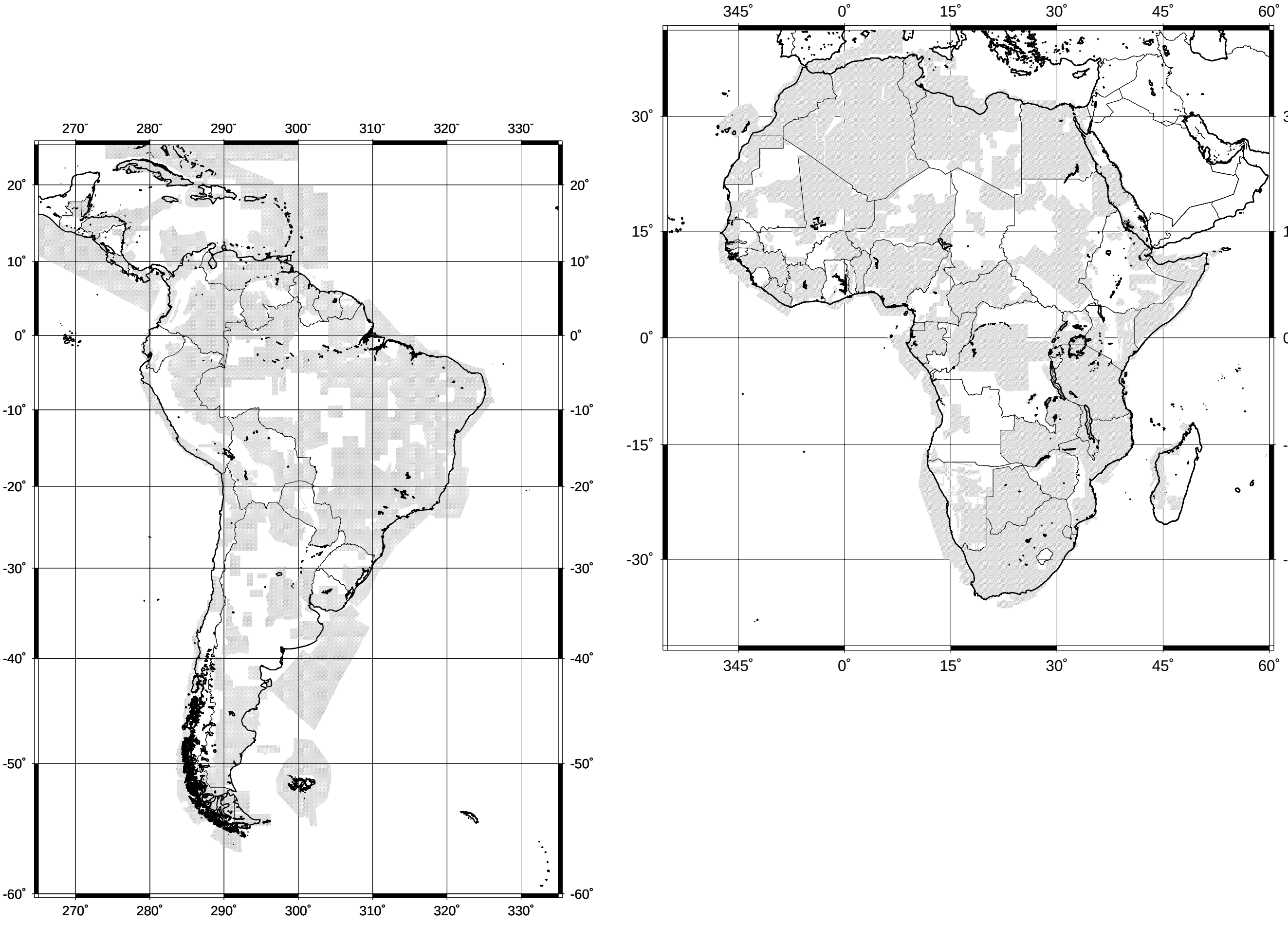


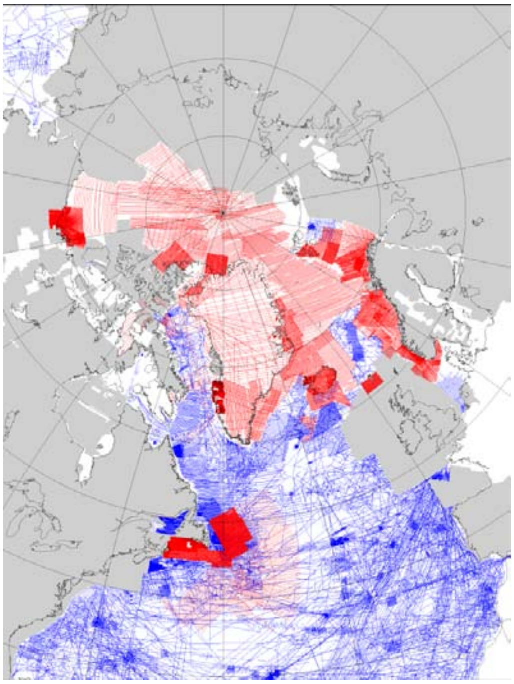
Figure 2: *Magnetic data distribution map for some of the data compilation studies.*

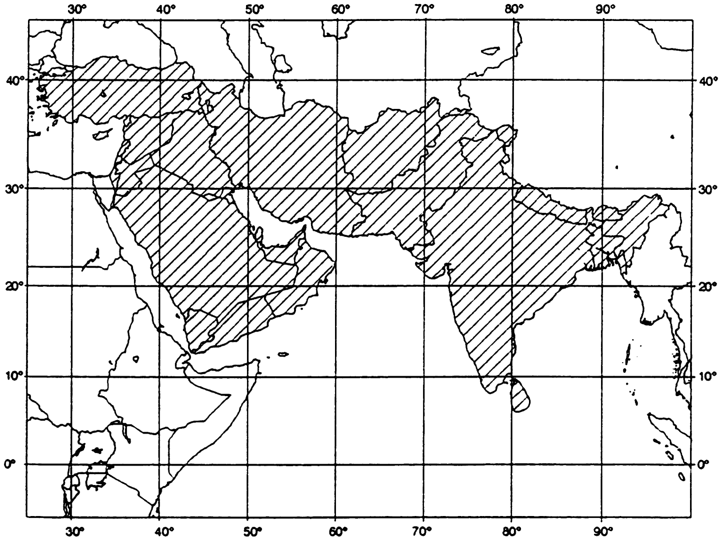
Gravity Data

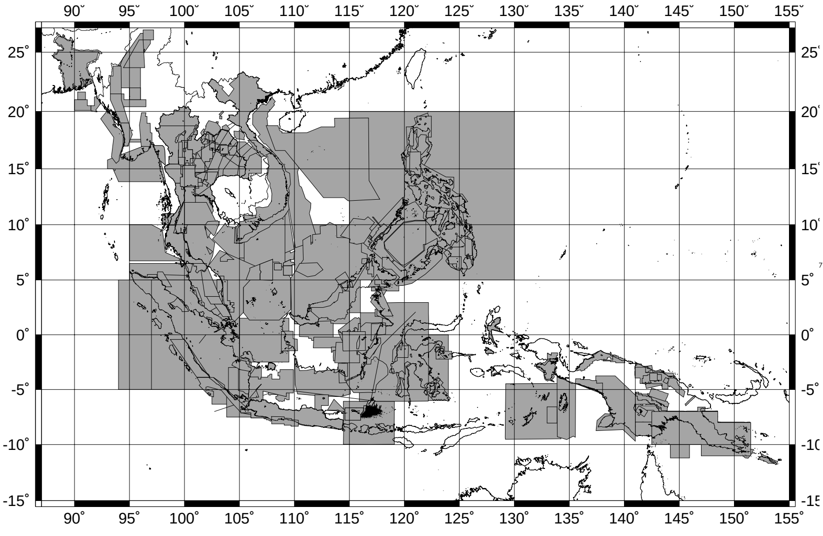
Gravity point data are generally better preserved than aeromagnetic data since the volume of data is generally less and traditionally presented as tabulated values. Such listings, often computer print outs, can be easily reentered into a computer. Since many surveys were well recorded, information relating to base station values, international gravity formulae and reduction density used were preserved. Details that are often lacking are map projection, reference ellipsoid and geodetic datum which introduce small but systematic location biases between countries using different mapping systems. This can also occur for height datum (e.g., Baltic vs. Adriatic datum) giving rise to height difference of the order of one meter in central eastern Europe. Within a single country these problems rarely occur, since common reference systems are used.

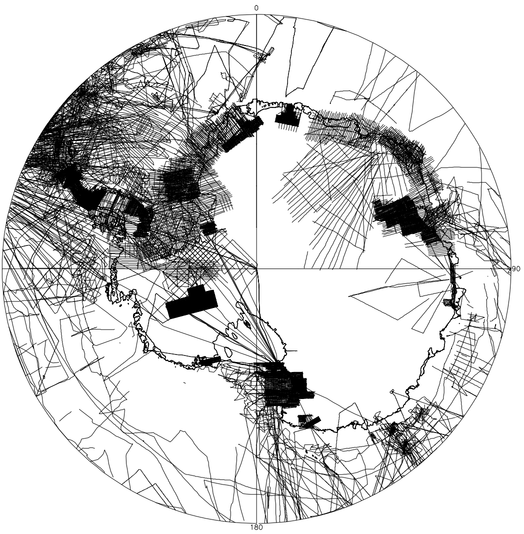
For the FSU gravity data, the numerical values of gravity and height parameters have been archived in map form as posted values alongside station locations. This is often the way oil company data were archived prior to computer generated maps replacing the draftsman's hand drawn and annotated maps.

Often gravity data have been poorly archived such that only contour maps remain and with luck, station locations are also recorded. Often reduction density and/or heights are lost making the data of limited value. The availability of digital terrain models and topographic maps does help to recover reasonable height estimates suitable for adjusting surveys to a common reduction density, but little can be done if the reduction density is unknown.









Magnetic Data

Due to the large data volumes, aeromagnetic data are not generally archived as listings. Instead they are often preserved as contour anomaly maps which represent a filtered (decimated) version of the original data. Digitising of map data will not recover the lost high frequency component but if digitising is carried out along original flight lines it is possible to enhance the quality of the final data set by applying micro-levelling techniques to minimize flightline-related noise.

Where flight line profile charts/maps have been preserved then digitising can recover the high frequency data contained in these records. This is particularly true in the case of the FSU and Chinese data.

The NGDC 1′ grid was derived from the 1:2 500 000 scale maps contoured at 100 nT (Table 4, region 9). This grid only images anomalies greater than 10 km with an uncertainty of 20 ± 10 nT. However, access to the flightline profile charts and reprocessing of the data, particularly line levelling, enables wavelengths down to 2 km and amplitudes less than 5 nT to be identified (i.e., limits of the data).

Other problems encountered with analogue data are insufficient or total lack of technical information relating to processing parameters such as datum shift, regional field removal, etc. Lack of such information ultimately dictates how these data are reprocessed and tied into the final coherent data sets.

Marine magnetic and land-based point magnetic data are generally well archived and documented. Despite the age of some land data sets, recorded as either vertical and/or total field components, if the spatial coverage is adequate, then these data can be as good as more recent aeromagnetic data. Good examples of this are found in Eastern Europe (Table 4, region 8) where ground vertical field (after transformation to total field) and total field data for parts of Poland, former East Germany and Hungary match well with aeromagnetic data in areas of overlap, such that they produce a seamless link between surveys at 0.5 km grid cell size upward continued to a common 0.5 km elevation above topography.

Digital Conversion

Gravity and other types of ground survey data has almost always been stored in a digital form, even if only as printed numbers. Airborne data was usually collected in the form of pen traces on paper rolls, representing a continuous field measurement along a survey line. The preferred method of digitizing analogue data is to read values off the original flight records or published profile maps, at some appropriate sampling interval. If the flight records are no longer available, the next best method is to extract profiles from the published contour maps by taking the value at each contour intercept along the flight lines. This may be done either by putting the map on a digitizing table, or by scanning the map and then picking points from the on-screen image. The latter method is preferred, since it enables the user to "zoom" on the image to obtain greater accuracy, and to view the extracted profile as each new point is added, so that errors may be immediately spotted and corrected. It is best to extract values along the original flight path, since the values there represent actual measurements, while the values elsewhere are interpolated. Also if the data is digitized along the flightlines, then it is possible to apply line levelling procedures to the resultant profiles (See "Magnetic Data Reprocessing" on page 812.) and thus remove flight line noise during the reprocessing. In some cases the flight path is not drawn on the maps. Then the next best option is to extract values along artificial flight lines with the same direction and spacing as the original flight lines. (Line spacing and direction information is almost always preserved even if the exact flight path is not.) This gives less accurate values than digitizing along the actual flight path, but it still allows line levelling techniques to be applied.

In some cases the published maps have been carefully hand-contoured by a geophysicist. This involves an implicit geological interpretation of the data to determine how it should be should be interpolated between flight lines. Hand-contoured data is generally smoother and more coherent than machine-contoured data, with less flight line noise or signs of under-sampling. However since it involves a personal interpretation, it may be biased or misleading. If the hand contouring is deemed to be accurate and it is considered desirable to preserve it, then the maps may be digitized along contours rather than along flight lines.

MAGNETIC DATA REPROCESSING

A number of specialized processing steps are required to produce a levelled, linked regional magnetic grid. Normally the starting point is not raw data, but rather a data set processed to the standards of the time the survey was collected (1950s to present). Thus the data will already have been edited for noise spikes and instrument errors, and roughly levelled by tying the traverse line data to values on intersecting tie lines. Also there was often an attempt to remove the background geomagnetic field, although this was not necessarily done using the modern standard values from the International Geomagnetic Reference Field (IGRF). The first step in reprocessing is to remove the appropriate IGRF field for the time and place the survey was collected. If a regional field or trend surface has already been removed, then assuming it was properly documented, the old regional can be added back, and the true IGRF can be removed.

Normally some flight line noise remains after tie line levelling, and this may not be apparent in the original contour maps of an older survey, but once the data is presented in shaded relief and derivative products are calculated, this noise becomes very obvious. A process known as micro-levelling (Minty, 1991) is used to isolate only the component of base level drift along flight lines and then subtract it from the profile data. It supplants the older de-corrugation technique in that the longer wavelength, lower amplitude noise is separated from any geological signal that is oriented sub-parallel to the flightline direction.

The data from different surveys will generally have been collected from different platforms (aircraft flying at various heights, ships, ground surveys). Therefore it is necessary to apply a height continuation algorithm to transform the measured data from each survey to an equivalent magnetic field value on a common observation datum surface. For example in the African and South American Magnetic Mapping Projects (AMMP and SAMMP) the data was continued to a common height of 1 km above the ground surface (or 1 km above sea level for the marine data) for purposes of the linked regional grid. The data for the individual surveys was also preserved at the original flying height. Some aeromagnetic surveys are flown at a constant drape height above the ground, but others are flown at a constant barometric elevation, so it is not enough to upward or downward continue by a constant distance; a variable-height continuation is required. This is achieved by upward-continuing to a series of levels parallel to the observation surface and then interpolating between the magnetic values at these different levels to get an appropriate magnetic value for the required altitude. (Paterson *et al.*, 1990) This method approximates height continuation on a point-by-point basis. A requirement of this technique is a good quality digital terrain model, whether derived from the survey data or other sources (e.g., topographic maps, gravity compilations).

Even when the data are brought to the same observation height, the link between different surveys may still be poor. Often the data for each survey is calibrated to a base station value which is assumed to measure the average background field for the area, but which in reality has been chosen arbitrarily and contains some anomalous field component. This causes random base shifts of hundreds of nanoTeslas between different surveys. Also the traverse line data will normally have been levelled to a few tie lines, so that long-wavelength noise on the tie lines (due to magnetic storm activity and instrument drift) causes the entire grid to be warped. The amplitude of this long-wavelength noise is typically 10–100 nT. On a smaller scale (~1 km or less) there will be differences at the boundary of different surveys due to uncertainty in measurement of the flight path and altitude of the survey aircraft, particularly for older surveys.

There are two ways of removing these differences between surveys and achieving a smooth link. One method is simply to take one survey as a starting point and adjust values in neighbouring surveys to fit, then add more surveys, until the whole area is linked. The other method is to take an existing low-resolution regional grid, or the national network of control lines if available (e.g., Canada, Australia, China), as a reference and level each survey to it by removing the long-wavelength component of the difference between the reference and survey grids. For the AMMP and SAMMP compilations, a combination of these two methods was employed.

In areas where a well-controlled regional grid is available (e.g., Canada), then the profile data can be levelled directly to the regional magnetic datum, and adjacent surveys will consequently match quite well along common borders (Reford *et al.*, 1990). Where this is not possible, overlapping grids that match reasonably well can be merged using inverse-distance weighted averaging. Often, however, the match is poor or there is little or no overlap between adjacent surveys. In that situation, a difference is computed along common borders, which is then filtered, extrapolated and tapered smoothly to zero at some specified distance from the joining edge (Black *et al.*, 1995). This correction surface is then subtracted from one survey to make it join smoothly with the other.

The linking procedures described give a smooth join, but also build in long wavelength distortions where there is no regional control. For the AMMP and SAMMP compilations, these distortions were minimized by filtering out wavelengths on the order of hundreds of kilometers, and replacing them with a stabilized, downward continued version of the magnetic field measured by Magsat (Barritt *et al.*, 1993).

RADIOMETRICS

Until recently, airborne radiometrics was used almost exclusively for uranium prospecting; however it also holds great potential for regional geological mapping. Airborne radiometrics is a technique which measures the concentrations of naturally occurring radioactive elements (mainly potassium, thorium, and uranium) at the ground's surface. This is done by measuring gamma radiation in the distinctive energy band emitted by each element. There is a wealth of radiometric data in national survey archives worldwide, but much of it has never been released in digital form. Usually no attempt has been made to link data from separate surveys, because true calibration information is not available (i.e., there has been no measurement of radioelement concentrations on the ground, so therefore there is no way to convert the airborne count rate to a concentration value.)

A pioneering effort was made by the Geological Survey of Namibia (Duffy *et al.*, 1994) to convert old surveys from analog to digital format and prepare linked grids of radioelement concentrations. This was accomplished by digitizing old maps, micro-levelling, and undertaking back-calibration of the data. Back-calibration consists of measuring true ground-based radioelement concentrations on a test strip within the survey area, and then comparing the concentration values to the count rate values from the airborne survey, to obtain a calibration constants for each radioelement.

A total of 2.2 million line-km of radiometric data from 42 surveys in Brazil (Figure 3) were recompiled to provide a unified database from most of the institutional data sets available in that country (PGW-CPRM, 1997). Judicious review of the original data acquisition systems, compilation procedures and survey parameters allowed preparation of radioelement concentrations for all of the data through the back-calibration of six surveys. After spike removal, and micro-levelling of flightlines and blocks of flightlines, the surveys merged surprisingly well once the new calibration constants were applied. The resultant maps show remarkable correlation with the published regional geology, and also serve the purpose to delineate areas where the radiometric data and geological mapping require reconciliation. The radiometric compilation in Brazil is a powerful complement to the earlier magnetic and gravity compilations.

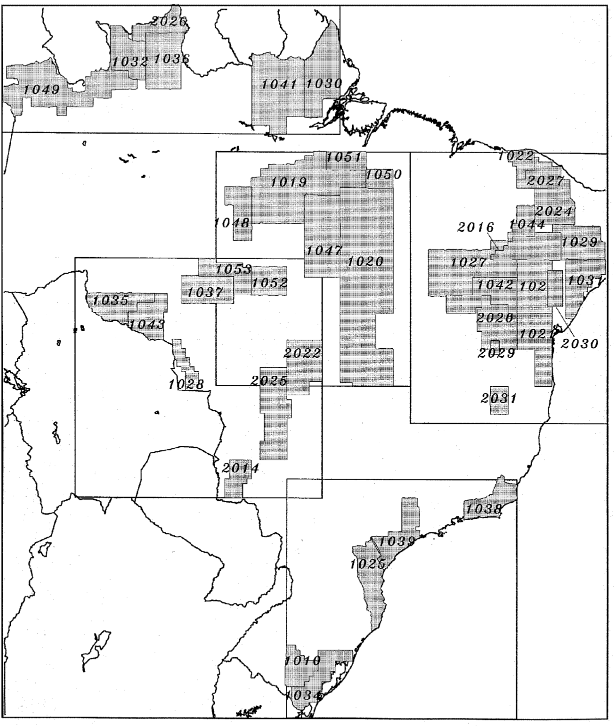


Figure 3: *Coverage map and map sheet layout for the Brazil Radiometric Mapping Project (after PGW and CPRM, 1997).*

ELECTROMAGNETICS

To our knowledge, the Ontario Geological Survey's initiative to reprocess thirty-two magnetic/electromagnetic surveys, totalling 450 000 line-km, is the only large-scale effort to date to systematically electromagnetic survey data (e.g., Ontario Geological Survey, 1997). Some of the surveys date back to 1975, and cover a wide range of fixed wing time-domain (Input, Geotem I and II), fixed wing frequency-domain (Tridem) and helicopter frequency-domain (Aerodat, Dighem) electromagnetic systems. The variety of systems presented challenges in developing consistent, low cost techniques to compute grids of apparent resistivity, and decay constant (time-domain only), as well as repick the individual anomalies. The project's emphasis on quality control of the products required a diligent effort on behalf of the participants, particularly as a result of the inevitable "surprises" encountered when historical data is systematically reworked. This applied to the magnetics as well, from which high quality second vertical derivative grids were required from surveys flown with 200 m line spacing, at 40 to 100 m above terrain. The results are helping to rejuvenate mineral exploration of Ontario's greenstone belts.

All but one of the surveys in the Ontario predate the era of GPS navigation. They were flown in areas where accurate topographic base maps were not available. As a result, the data were originally recovered, and published, using photomosaic base maps. An important aspect of the project was to transfer the flightpath to recently published topographic base maps and redigitize it. Location errors between the original and revised digital data on the order of 100 m were typical, but they exceeded 2 km in some instances (i.e., more than ten times the flightline spacing!). These errors resulted mainly from distortions in the photomosaics and provide a good lesson for explorers to ground truth anomalies, if only to locate them properly when undertaking follow-up.

EXPLORATION STRATEGIES OF THE 1990s

One immediate benefit of these studies is the wealth of information on the location, spatial extent and survey parameters of geophysical surveys. This knowledge of what, why, where and who owns such data can be immensely valuable in the speeding up of exploration decisions and making more efficient use of resources. They can play a particularly strategic role when new areas for exploration are being evaluated.

The use of such regional data sets have been in their ability to image:

- basic lithology and structure where geological mapping is inferior or non-existent;
- configuration and dimensions of geological terranes and basins, including those that straddle national boundaries, coastlines or are located in deep water close to the continental shelf break;
- internal structure and tectonic controls on geological provinces and basins, permitting sub-provinces and sub-basins to be delineated, and the regional tectonic influence to be appreciated; and
- regional anomalies and gradients, permitting a better appreciation of regional-residual separation procedures of property-size areas.

The gravity field of the Earth, deduced by the studies listed in Tables 1 to 3, provide a reliable image at 5′ (10 km) cell size, except for a number of areas already identified. In any study with irregularly spaced data, choosing a unifying grid cell size will under and over sample data; thus station, shiptrack and flightline locations are provided with most studies. Satellite-derived gravity data are adequately sampled at 5′ grid cell size.

The gravity grid cell sizes (8–10 km), and certain of the lower resolution (i.e., wide line spacing) magnetic data sets, do not permit small scale structures to be imaged or geologically modelled but they do allow exploration companies to appreciate the regional setting of a property prior to focusing into the detail that local surveys provide, enabling subtle trends and features to relate more closely and accurately to the 'bigger picture'.

Magnetic data, although more globally limited in spatial coverage, provide a confirmation of the gravity imaging where the data sets overlap. In Africa and South America aeromagnetic data often complement the gravity data when they exist in areas where gravity data are either absent or sparse. This enables structural trends, lineaments and fabric to be more widely mapped by accessing both data types. The addition of radiometric or electromagnetic data, if available, improves the geological knowledge base that much further.

A significant advantage that most magnetic projects have over their gravity counterparts is the resolution of the final products of ~1 km, to optimum resolution for many magnetic surveys within a compilation. This enables quantitative analysis of the magnetic data to map depth to basement, and susceptibility variations within the exposed or shallow basement areas for mineral exploration. Radiometric and electromagnetic surveys are typically flown at relatively high resolution, and are quite suitable for modelling and detailed interpretation.

A significant factor concerning the success of these projects has been that mining and oil companies want, and have continued to request, access to these project data sets. This is clear evidence that these data sets have, and are providing the data resource that enable them to develop new insights and understandings that are helping to shape their exploration strategies in the 1990s.

CONCLUSIONS

The recompilation and merging of geophysical surveys have played an important role in the global exploration boom of the last several years. A direct correlation between the release of airborne geophysical data, and a consequent increase in exploration activity, is evident in several countries. The projects themselves have also provided a vehicle to establish important links between industry and national institutions. In the developing world, training and transfer of technology are typical by-products.

Beyond the immediate benefit to explorationists, the ever expanding coverage provides grist for academic pursuits, such as crustal and tectonic studies, and modelling of the geoid. The technical requirements of these projects have produced tools and expertise that are applicable to the current generation of surveys as well. They have also demonstrated the need to make calibration of the instrumentation to geology a key component of data acquisition, so that merging of new data sets becomes routine.

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ABBREVIATIONS

GETECH	Geophysical Exploration Technology division of the University of Leeds Innovations Ltd., Leeds, United Kingdom
PGW	Paterson, Grant & Watson Limited., Toronto, Canada
ITC	International Institute for Aerospace Survey and Earth Sciences, Delft, The Netherlands
AGS	Airborne Geophysical Survey, Ministry of Geology and Mineral Resources, Beijing, China
CCOP	Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia, Bangkok, Thailand
MGGEC	Mongolian Geology and Geophysical Exploration Company