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REVIEW ARTICLE

Airborne Geophysics and the Indian Scenario

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I. INTRODUCTION

Airborne Geophysics is a powerful means available to the earth scientist for investigating very large areas rapidly. The broad view of the earth that the airborne perspective provides has been well recognised since the early days of balloon photography and military reconnaissance. Compared with ground-based methods, airborne techniques offer the advantages of rapid acquisition of data at scales that are suitable for many geophysical problems. Further, airborne surveys provide the capability of traversing regions that are otherwise difficult or impossible to cover. Airborne methods are advantageous for surveys over areas that are physically accessible but that have social, economic, or political barriers or environmentally hazardous.

Systematic and precise airborne geophysical surveys may be said to have started immediately after the Second World War with the development of an airborne fluxegate magnetometer by Vacquir (Dobrin 1952). By about 1955 countries such as the USA, Canada, Austarlia etc began using the airborne magnetometer systematically. In the following years several contracting companies made considerable R & D effort to develop capabilities for meeting the precise requirements for airborne surveys. The 1960s saw the deployment of proton precession magnetometer for aeromagnetic surveys and utilization of Doppler navigational aids for more accurate position fixing. There has also been considerable growth with regard to radiometric surveys by deploying multi-channel instruments for obtaining data on ground concentrations of potassium, thorium and uranium. The air borne geophysical techniques have undergone continuous development including transition to digital technology and refinement of the surveying methods in the 1980s and 1990s. In the case of airborne electromagnetic method (AEM) the numerous configurations that existed in the initial stages were considerably reduced and only two types of systems are mainly in vogue now. Major applications of airborne geophysics in the past decade have seen an increase in emphasis for environmental, and engineering applications, including hazard mapping.

II. A BRIEF REVIEW OF THE TECHNIQUES

The methodology for airborne geophysical surveys is basically similar to their ground counter part with the following differences. (a) The airborne instruments have to be more sensitive as the signal will be weaker due to the increased distance from the source (b) The measurements are more complex since it becomes necessary to eliminate errors from various external influences (such as the electrical and magnetic disturbances from the aircraft etc.) and (c) elaborate instrumentation is required for position location and data recording

There are three chief airborne geophysical procedures utilising magnetic, electromagnetic, and radiometric methods while a fourth one, airborne gravity, has also become an acceptable technique from the past decade or so. Airborne magnetic method has been established as a cheap and powerful tool for mapping strongly magnetic (primarily basement) structures. Improvements in instrument resolution and acquisition techniques have allowed for the utilization of the airborne magnetic methods for mapping the weakly magnetic intra-sedimentary structures and other minor features also. Airborne electromagnetic surveys are conducted utilizing either the frequency or time domain techniques. Their principal utility used to be directly searching for economic metallic conductors but latter found application as a geological mapping tool also. Airborne radioactive measurements of gamma rays originally applied for uranium and thorium exploration have latter shown much higher potential as a mapping and mineral exploration tool because of the developments in data acquisition and processing techniques. Though it is not possible to deal the subject of methodologies in detail in this review, a brief outline of the different techniques is relevant and recounted here.

II-1. AIRBORNE MAGNETICS

In 1940-41 Victor Vacquier of Gulf Research and Development Company perfected a sensitive magnetic saturation type of sensor element for airborne surveys (Reford and Sumner 1964). Also known as fluxgate magnetometer, this sensor formed the heart of the anti-submarine airborne device, Magnetic Airborne Detector (MAD) and could measure magnetic fields as low as 10^{-5} oersteds. Gulf Company later, in 1946, modified the MAD to make it more suitable for airborne geophysical surveys.

The next advancement for aeromagnetic instrumentation was in the 1950s when Varian Associates developed the Proton Precession Magnetometer, which was first used for airborne surveys in 1956 (Gimlet 1957). The Proton magnetometer measures the total field with a sensitivity of 1 nT. This is followed by the optical absorption type magnetometers (Cesium, Rubidium or Helium), which have come to airborne use by the early 1960s (Greet & Malnar 1963). These magnetometers can measure the total magnetic field up to a sensitivity of 0.01 nT and mostly employed for airborne work in recent years including magnetic gradient measurements.

The airborne magnetometer had initial success in discovering mineral deposits. However, it was soon realized that aeromagnetic anomalies were too common to be all investigated as possible mineral deposit targets and that the main application of aeromagnetic surveys was as an important aid to geological mapping for indirect exploration, and for estimating depth and structure of sedimentary basins thus providing valuable information for hydrocarbon exploration.

II-1. (a) Aeromagnetic Survey Design

Three of the most important factors to be specified for any airborne geophysical survey are the flight height, the traverse line separation and the traverse line orientation (direction). For aeromagnetic surveys, the selection of line direction depends on two main considerations, the magnetic inclination in the survey area (sometimes called the magnetic latitude of the area), and the geological strike that is significant for the investigation.

The preferred flight line direction would be north - south if the anomalies in the area were distributed randomly. Because regional surveys are conducted over very large areas usually containing various geological strike directions, a north - south traverse line orientation is usually preferred for aeromagnetic surveys. On the other hand, if the survey area is known to contain a pronounced geological strike direction and the magnetic latitude is either very high or very low it may be advantageous to orient the traverse line direction perpendicular to the geological strike direction. The advantages of this orientation arise because many of the significant magnetic features arise from linear features like dykes and or faults, and by orienting the traverse lines at right angles to these features, we can be confident that only a very few anomalies may be missed by the selected flight lines.

When dealing with an assemblage of magnetic sources the resolution is related to a ratio of the sensor height above the source to the line spacing. In hard rock environments, the sensor height will usually be the distance from the sensor to the surface; however in areas covered by sediments or other non-magnetic material, this height will be the flight height plus the thickness of the overlying non-magnetic sediments. As a rule of thumb, the line spacing should equal the sensor height for complete definition of the anomalous magnetic field. However, economic considerations may require larger line spacing. Control lines are flown to allow leveling of the survey data. In small surveys, at least three control lines should be flown at right angles to the traverse line direction. In large surveys, control lines should be spaced at intervals of five to ten times the traverse line spacing. A typical flight path lay out is shown in Fig 1.

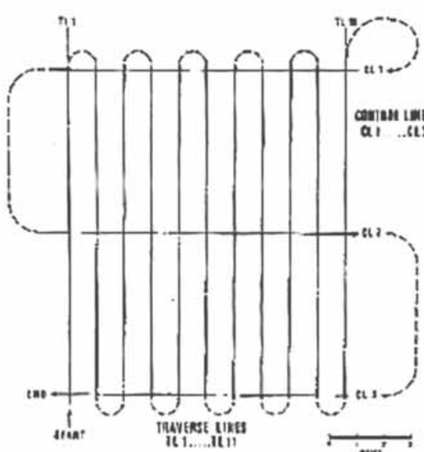

Figure 1. An ideal flight path layout

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II-1. (b) Aeromagnetic Data Processing

In any area of survey the magnetic picture ideally required is a snap-shot of the magnetic field at all locations at the same instant of time - with the earth's regional magnetic field removed. As this cannot be directly obtained the acquired aeromagnetic data has to be processed to achieve a data quality as near as possible to the ideal situation. For this purpose the data processing procedure involves a series of steps such as creation of a database for efficient data management, flight path recovery and plotting, leveling and fine leveling using base station magnetometer data and control lines. The final step in the data processing is removal of earth's normal magnetic field from the observed values (IGRF correction) and preparation of two-dimensional corrected data grid for presenting the data in profile and contour maps etc. While profile maps are useful for some interpretation methods, a two-dimensional map, usually contoured and coloured, is required to fully interpret the data in the majority of magnetic surveys. However, it is important to keep in mind that the two dimensional type of presentation is a result of considerable degradation and interpolation of the data. This is in spite of the most advanced and powerful techniques because of the unavoidable problem of most disproportionate density of data along and across the flight lines (for example, one at 10m along to one at 500m across)

Before the availability of high speed, portable personal computers, all data compilation was done long after survey flying was complete involving weeks of waiting to see the first map products. With the advent of the integrated airborne geophysical systems and PC based "in field" geophysical data compilation system, now data can be compiled in the field on a daily basis. On-site processing not only provides an excellent means of quality control but also yields map results for immediate evaluation, planning and decision-making.

II-1. (c) Aeromagnetic Data Presentation

The two dimensional display of data is the most common method of viewing and interpreting, because of the ease of use and the ability to superimpose other types of parametric data. There are several ways for 2-D display of data, viz, contour maps, colour filled contours, coloured maps and finally images. The now available digital data compilation using state of the art software and hardware takes visualisation of survey results from its original status contour maps after several days of hard manual work to attractive images on the same day of data acquisition (Fig 2).

This capability 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 (Reeves, Reford & Milligan 1997).

Realising the advantages of image presentation most of the archived old data are now getting retrieved for giving a re-look at them in its latest form. Due to the large volumes, aeromagnetic data were not generally archived as listings. Instead, they were often preserved as anomaly contour maps that 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-leveling techniques to minimize flight line related noise. This gives less accurate values than digitizing along the actual recorded profiles, but it still allows line-leveling

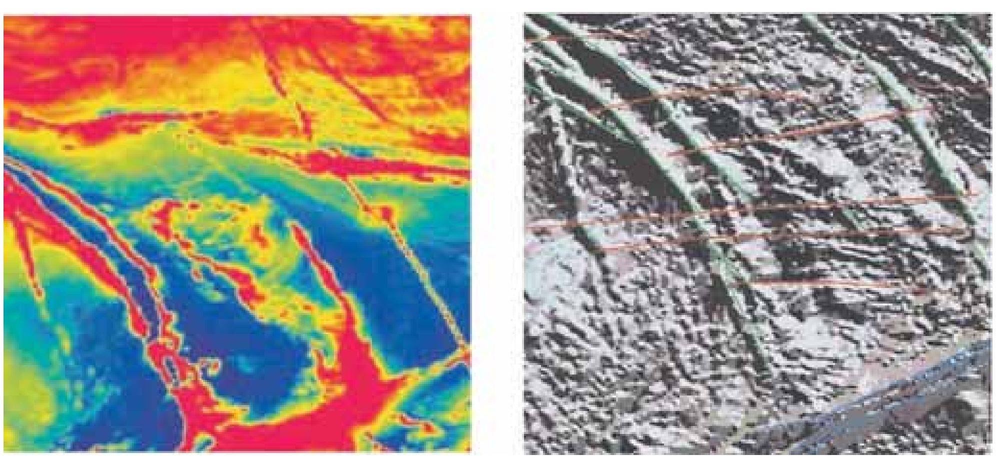

Figure 2. Example of aeromagnetic data presentation, colour map(Left) and enhanced image (Right)

techniques to be applied. In some cases the contour maps were as a result of careful hand contouring by a geophysicist. This becomes valuable as it involves an implicit geological interpretation.

In spite of the attractive image maps with various enhancements like directional filters etc., it must be kept in mind that the profile form of the original data has a value of its own. In its image form, one is only working with a interpreted subset of the real data set which is contained in the one dimensional profile information. The profile data is harder to work with but as usual there is no substitute for hard work if one is interested in getting the most out of a data set.

II-1. (d) Aeromagnetic Interpretation

Interpretation of aeromagnetic (or any geophysical) data basically involves two exercises. Firstly, the behaviour of the geophysical data and the physical nature of the anomaly picture are to be ascertained. Secondly, the geological significance of the geophysical indications has to be interpreted. The first type is generally straight forward that involves identifying various recognisable patterns directly from the map or using mathematical techniques to enhance various characteristics of the observed data and relate them to possible physical causes relevant to the distribution of the particular property of the source of the phenomena. For example, enhancing a magnetic trend on a map, and explaining it in terms of a source of 2-D geometry such as a fault or dyke. The second, type of interpretation requires much more in-depth and careful study so that the geophysical interpretation is properly correlated with the geological data to derive maximum benefit from the geophysical survey. While translating the aeromagnetic anomaly map into a meaningful geological interpretation one should bear in mind some important facts regarding magnetism of rocks. The conditions that increase rock magnetization, either increasing magnetic susceptibility or creating new magnetite , are (Grant 1985) mechanical deformation, repeated metamorphism and high temperature hydrous alteration (serpentinisation). On the other hand, conditions that decrease rock magnetism by destroying magnetite are low temperature alteration (carbonatisation, chloritisation, sericitisation), extreme oxidation (including chemical weathering and leaching) and granitisation / metasomatism

In a nutshell, the aeromagnetic maps are first interpreted to identify the source distribution and subsequently explaining them in terms of geology and structure. Several authors have discussed various data enhancement and analytical techniques for qualitative and quantitative interpretation (Roest, Verhoef & Pilkington 1992; MacLeod, Jones & Fan Dai 1993;

Cowan & Cowan 1991; Qui 1994; Zevan & Pous 1991; Li & Oldenburg 1996; Reid et al., 1990).

II-1. (e) Aeromagnetic gradiometry

Aeromagnetic gradiometry is advancement over the regular aeromagnetic surveys that measure the total field. Measurement of lateral and vertical gradients of magnetic field intensity can add a new dimension to high-resolution aeromagnetic surveys in shallow basement areas. The magnetic gradiometers have become fully effective owing to the hardware developments, particularly the highly sensitive optical pumping magnetometers (specifically the cesium vapour type) and efficient compensation devices for aircraft maneuver noise. The various aspects of aeromagnetic gradiometer surveys are well studied and reviewed by several experts in this field (for example, Cowan & Mc Bigent 1995; Hardwick 1996; Slack, Lynch & Lanyen 1967).

Practical advantages of measured gradients include elimination of diurnal problems and improved spatial resolution of small shallow sources. Transient signals have the same effect on the magnetic sensors so the effects are cancelled out in the gradients. The diurnal free total magnetic intensity can then be reconstructed by integrating the gradient data. The magnetic gradiometer data effectively enhance the smaller scale, shallow anomalies while suppressing the longer wavelength anomalies from deep-seated sources. In addition measurement of transverse horizontal gradient provides extra information between flight lines, leading to a reduction in flight line dependence of the magnetic anomalies and decreasing aliasing effects.

Since magnetic gradiometers represent additional investment in equipment and considerable incremental effort in assuring aircraft magnetic cleanliness careful consideration should be given to selecting effective configuration. Considering all the facts, the transverse horizontal gradient system (mounted on wing tips) appears to be superior to the other configurations (Hardwick 1996). Vertical gradient measurement system does not seem to be very useful as the data will be inferior to that derived from a grided total field data and may have artifacts also. Higher resolution of anomalies is obtained by lateral gradient measurements and makes possible identification of a 2-D structure from a single flight line data.

Measured magnetic gradients do provide useful information and are a valuable addition to any aeromagnetic survey. The gradient systems and processing techniques currently available have already made a significant impact that will likely redefine the aeromagnetic standards and expectations of the future.

II-2. AIRBORNE ELECTROMAGNETICS (AEM)

The successful test flight in 1948 in Canada of a wooden aircraft with an EM transmitter on the fuselage and a towed bird receiver can nominally be considered as the origin of airborne electromagnetic method (Fountain 1998). The topic of Airborne EM is very well documented and there are quite a few excellent review papers on AEM published over the years that have thoroughly explored the development of airborne EM methods from their earliest days (e.g., Collett 1986; Palacky 1991; Barringer 1987; Becker, Barringer & Annan 1987; Paterson 1971, 1973; Pemberton 1962; Ward 1966, 1970). Like their ground based counter part, the airborne EM systems also measure the secondary electromagnetic field from currents induced in conducting bodies by either active primary sources wherein the primary field is generated by the system itself or passive sources which use existing man made or natural sources (i.e. world wide thunderstorms). Figure 3 shows the scheme of airborne electromagnetic survey, employing an active source techniques can be further classified as frequency domain or time-domain.

II-2. (a) Frequency Domain System:

Airborne electromagnetic systems in the frequency domain were first developed in Canada and Scandinavia to find electrically conductive sulfide ore deposits. The early systems operated at one or more fixed frequencies with the transmitter and receiver coils attached in various ways to a fixed wing aircraft. When the receiver was located in a towed "bird" only the out of phase or quadrature component of the secondary magnetic field could be measured (Paterson 1961). Alternately, both system elements were rigidly attached to the aircraft at a fixed separation from each other so that both the in phase and out of phase components of the secondary field were measured. In these frequency domain systems, the weak secondary field from the conducting target was measured in the presence of the strong direct or primary field from the transmitter. Various schemes for bucking the primary field at the receiver were implemented in order to comply with the limited dynamic range of the electronics and to detect the secondary field. For any of these schemes there is an obvious advantage in separating the transmitter (T) as far as possible from the receiver (R) so that the primary field is weakened – increasing the T-R spacing L from 1 m to 10 m causes the primary field at the receiver to decrease by a factor of 1000. The secondary field changes vary little with increased coil separation (L) if the sub-system depth of the target, (d), is greater than this dimension. This rationale led to the development of a number of fixed - wing aircraft systems where the transmitters and receivers were affixed to the wing tips in a coplanar mode or, in the coaxial mode to fore and aft booms, which served to extend the fuselage length. Carried to extremes, this idea resulted in the two-plane system where each element was carried in a separate aircraft (Tornquist 1958).

The development of helicopter-borne (or heliborne) EM systems proceeded apace with the fixed wing equipment. Present day apparatus (such as the DIGHEM operated by Geoterrex Ltd) is based on one or more transmitter - receiver pairs that are attached to a rigid boom, which is rigged for smooth towing. Initially, these machines were built to survey in regions inaccessible to fixed-wing systems. Today, however, towed-boom helicopter systems have a strong

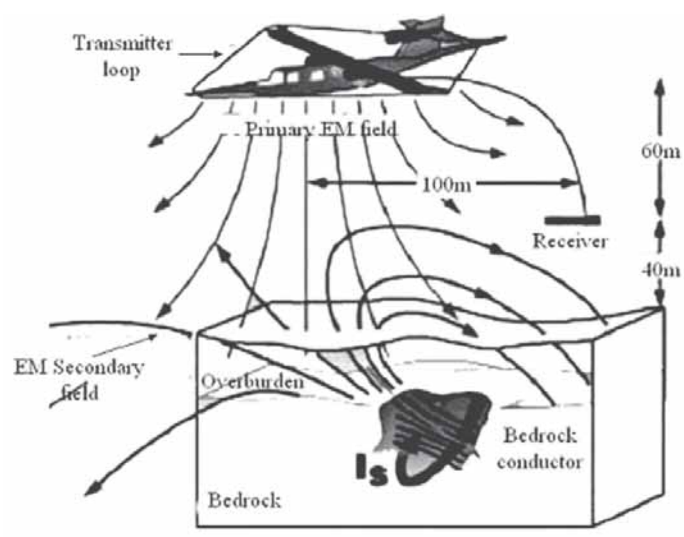

Figure 3. Schematic principle of AEM method

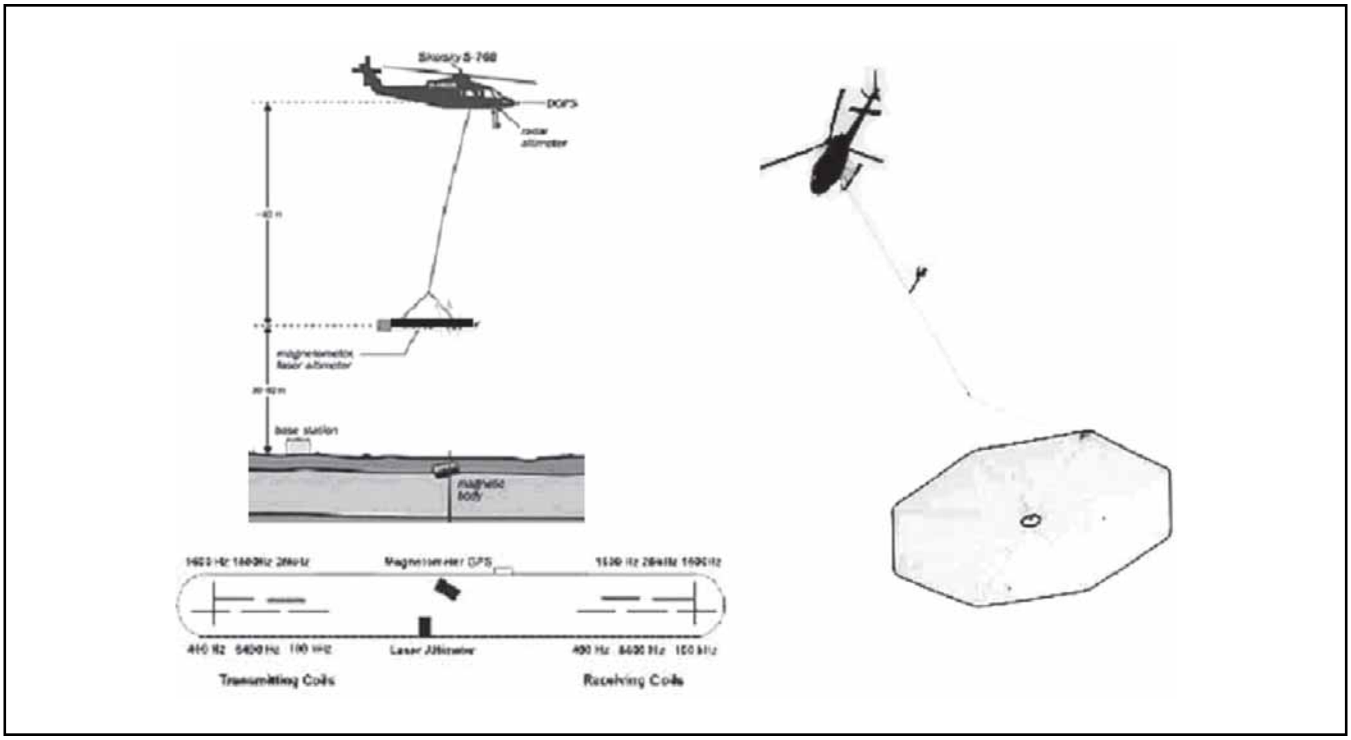

Figure 4. Heliborne FDEM and Boom with coil systems (Left) Heliborne TDEM (Right)

share of the AEM utilization because of good performance, logistic advantages and competitive operating costs. Since heliborne systems are flown close to the surface and use a small coil separation, they are very useful for high resolution mapping of shallower mining targets and for many geological applications where a surface conductivity map is the survey objective. These systems usually operate simultaneously at a number of distinct frequencies and offer a choice of coplanar or coaxial coil configurations (Fig 4).

II-2. (b) Time Domain System:

In 1960, working along different principles, A.R. Barringer introduced the time domain INPUT (INduced PUlse Transient) system. In this technique, the transmitter creates a pulsed magnetic field and the secondary fields are measured in the off time between pulses. The coil configuration is asymmetric with the transmitter in the form of a horizontal loop arranged as a rhomboid from nose to wing tips to tail and a horizontal axis receiver towed about 60 m below and 100 m behind the aircraft in a nearly maximum coupled configuration. In the resistive terrains for which this system was developed, the large separation and high moment resulted in an exceptional signal-to-noise ratio and demonstrated target detection depths in excess of 150 m subsurface. A number of field tests as well as some numerical model studies of targets in free space, attested to the superiority of this system for deep exploration. Modern versions of the INPUT system now known as Transient EM systems are presently the mainly employed electromagnetic systems for fixed wing airborne surveys.

AEM systems were first developed to detect discrete isolated conductors (i.e massive sulphide ore bodies). However, their use has evolved to include conductivity mapping, the approach appropriate to hazard mapping. Depth penetration of electromagnetic waves is inversely proportional to the square root of the conductivity x frequency product. Thus lower frequencies have greater depth penetration than higher, and by using different frequencies, to calculate conductivity of a half space or two layer model, the conductivity calculated for lower frequencies can be inferred to include a contribution from deeper material than the corresponding model calculated from higher frequencies. Conductivity can therefore be mapped in both horizontal and vertical directions. For time domain systems, the later channels correspond to lower frequencies and therefore greater depths, while the earlier channels correspond to shallower depths. The actual degree of ground penetration for a given system is dependent on power of the transmitter and the geometry and other parameters of the system.

However, frequency domain systems are usually limited to the top hundred meters or so, depending on the conductivity. Time domain systems tend to have deeper penetration but at the expense of resolution.

Helicopter borne Time domain Systems are also now developed which have an advantage of deeper penetration and thus more effective in areas of large thickness of overburden. Figure 4 shows the scheme of both the systems.

II-2. (c) Airborne Electromagnetic responses

The general objective of AEM (Airborne Electromagnetic) surveys is to conduct a rapid and relatively low-cost search for metallic conductors, e.g. massive sulphides, located in bedrock and often under a cover of overburden. This method can be applied in most geological environments except where the country rock is highly conductive or where overburden is both thick and conductive. It is equally well-suited and applied to general geologic mapping, as well as to a variety of environmental problems.

Conductivities of geological materials range over seven orders of magnitude, with the strongest EM responses coming from massive sulphides, followed in decreasing order of intensity by graphite, unconsolidated sediments (clay, tills, and gravel/sand), and igneous and metamorphic rocks. Consolidated sedimentary rocks can range in conductivity from the level of graphite (e.g. shales) down to less than the most resistive igneous materials (e.g. dolomites and limestones). Fresh water is highly resistive. However, when contaminated by decay material, such as lake bottom sediments, swamps, etc., it may display conductivity roughly equivalent to clay and when it is saline to graphite and sulphides. Conductive targets can be masked or concealed by responses from other geological conductors (termed as “geological noise”) such as lateral variations in conductive overburden, graphitic bands in metamorphosed country rock, altered (to clay facies) mafic-ultramaific rocks, faults and shear-zones carrying appreciable groundwater and/or clay gouge and magnetite bands in serpentinised ultramafics.

The Present day demand for AEM systems is for those which can measure the response of a broad variety of geological formations in a wide conductivity band such that they find utility in indirect exploration for economic minerals by mapping surface conductivity of the earth and in problems related to environmental degradation. Thus from the late 1980s the “anomaly hunting” type exploration philosophy has slowly faded out giving place to employing the AEM as conductivity mapping tool.. Currently only two types of AEM systems are generally in use (i) Multi-frequency multi-coil helicopter systems (ii) High power, broad band fixed wing EM systems operating in the Time Domain.

II-2. (d) AEM Data Presentation

The results of an AEM survey are presented in a variety of formats. The most common practice is to present the EM anomaly locations plotted on the flight path maps, or as an overlay over a magnetic map, together with a coding indicating anomaly strengths and certain parameters derived by computer-modeling the anomaly sources as vertical sheets.. The data can also be presented as profile maps. The FDEM profiles may show the in-phase and quadrature components of complimentary co-axial and co-planar frequency pairs plotted as coloured profiles on the flight path. The TDEM profiles may show the secondary field amplitudes at all, or more commonly at a few judicially selected, time channels. For the helicopter borne towed boom high resolution FDEM systems the data may also be presented as a coloured map of the apparent resistivity with embedded contours calculated from the coplanar or coaxial EM data. Such a map shows the apparent ground resistivity assuming the ground to be of uniform conductivity both laterally and vertically. These maps are helpful in outlining conductive overburden and showing discrete bedrock conductors.

II-2. (e) AEM Interpretation:

Interpretation of AEM data mainly consists of a systematic examination of the profile data to demarcate promising anomalies / anomaly zones. The next step is the analysis of the more promising anomalies using a vertical sheet as the conductor model. This is normally carried out using a computer program, after the local base level for estimating anomaly amplitudes has been carefully determined. Anomaly selection is done by judiciously using the shape of calculated models of various conductors like vertical sheets, flat lying surficial sheets, etc. Nomograms also exist by which similar analysis can be made from profile data. Both procedures produce estimates of conductance, called the conductivity-thickness product (which is the product of the conductivity of the tabular source and its thickness), and the depth to the source from the sensor. The sensor height, as recorded by the radar altimeter, is then subtracted from the depth to give an apparent depth below ground (Palacky 1981; Collet 1986; Palacky 1989).

Some interactive computer programs have also been developed and made commercially available that allow the interpreter to “pick” the anomalies directly from a display on the computer screen and immediately see the results of the conductance/depth calculation. This permits the interpreter to alter both the map scale and the profile data scale quickly to insure that all features, regardless of amplitude, are fully assessed. While the process described above does produce very useful information about the relative importance of various anomalies in the EM data, it has certain severe limitations due to the idealistic assumptions made such as steeply dipping thin sheet like bodies, non-conducting host rock etc. Moreover, removal of background value from the response of the overburden will not be accurate and becomes subjective.

The use of fast, approximate algorithms and stitched 1D inversions to transform either TEM or FEM data into conductivity-depth images has proved invaluable in the interpretation of AEM data. At least six approaches for time-domain data have been published and three or more algorithms are in use for helicopter frequency-domain EM. Conductivity depth images provide not only a visual separation between near-surface and deep conductors, but they also provide a tool for rapid estimation of layer thickness. This presentation method has transformed AEM methods from a “bump-hunting” tool used at the prospect scale, to a mapping tool (Fraser 1976).

Several workers in this field have dealt interpretation of airborne electromagnetic data. Monks and Asten (1993) developed a software package that allows interactive display and manipulation of survey data, forward and inverse modeling and characterisation of anomalies. Bergeron, Loup & Michel (1989) applied complex image theory to airborne electromagnetic data. There are various other techniques made available for AEM interpretation (for example, Eaton & Hohman 1989; Liu & Asten 1993).

It is also stressed that inversion of airborne electromagnetic data is a difficult problem (Ellis 1998) due to several reasons. Firstly, like most geophysical inverse problems, the AEM inverse problem with a finite number of noisy data is ill posed – the geo-electric property of the earth cannot be uniquely determined. Secondly, as this is a nonlinear relation between geo-electric property of the earth and observed AEM anomaly, the inverse problem is nonlinear and requires iterative solutions. Thirdly, the forward solution required by the iterative methods is itself a difficult and time-consuming problem for 2.5D and 3D models. Fourthly, AEM is characterized by enormous quantities of data and anomalies also. To generate unique solutions a-priori information must be added to the inverse problem. Joint inversion of the data from complementary geophysical surveys will be helpful.

II-3. AIRBORNE GAMMA RAY SURVEYS

Gamma ray sensors detect natural radioactive emanations, called gamma rays, from rocks and soils. All detectable gamma radiation from earth materials comes from the natural decay products of only three elements, i.e. uranium, thorium, and potassium. In parallel with the magnetic method, that is capable of detecting and mapping only magnetite (and occasionally pyrrhotite) in soils and rocks, so the radiometric method is capable of detecting only the presence of U, Th, and K at and near the surface of the ground. Typical Radio-element concentrations in some common earth materials is shown in the following Table (adopted from Hansen 1980).

Rock Class	**U (ppm)**		**Th (ppm)**		**K(%)**	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Acid Intrusives	4.5	0.1 - 30.0	25.7	0.1 - 253.1	3.4	0.1 - 7.6
Intermediate Intrusives	3.2	0.1 - 23.4	12.2	0.4 - 106.0	2.1	0.1 - 6.2
Basic Intrusives	0.8	0.01 - 5.7	2.3	0.03 - 15.0	0.8	0.01 - 2.6
Ultrbasic	0.3	0.0 - 1.6	1.4	0.0 - 7.5	0.3	0.0 - 0.8
Alkali Feldspathoidal Intermediate	55.8	0.3 - 720.0	132.6	0.4 - 880.0	4.2	1.0 - 9.9
Alkali Feldspathoidal Basic Intrusives	2.3	0.4 - 5.4	8.4	2.8 - 19.6	1.8	0.3 - 4.8
Chemical Sedimentary Rocks	3.6	0.03 - 26.7	14.9	0.03 - 132.0	0.6	0.02 - 8.4
Carbonates	2.0	0.03 - 18.0	1.3	0.03 - 0.8	0.3	0.01 - 3.5
Detrital Sedimentary Rocks	4.8	0.1 - 80.0	12.4	0.2 - 362.0	1.5	0.01 - 9.7
Metamorphosed Igneous Rocks	4.0	0.1 - 148.5	14.8	0.1 - 104.2	2.5	0.1 - 6.1
Metamorphosed Sedimentary Rocks	3.0	0.1 - 53.4	12.0	0.1 - 91.4	2.1	0.01 - 5.3

The 'Geiger counter' was the original radiation detector, recording the total count rate from all energy levels of radiation. Ionization chambers and Geiger counters were used first in field in the 1930's and their subsequently developed models were the principal instruments used for uranium prospecting for many years. In the early 1960's, a portable gamma-ray spectrometer was designed and constructed at the Geological Survey of Canada and McGill University. With proper calibration, this spectrometer was capable of providing chemical concentrations of potassium, uranium & thorium. The Geiger counter has evolved into a sophisticated 256-channel spectrometer that can be tuned to measure radiation from specific elements

By the late 1960s a team of scientists of the Geological Survey of Canada designed and developed a multi-channel radiometric instrument with its performance revolutionizing the practice of airborne gamma-ray spectrometry, making it possible to do 'geochemistry from the air'. This development of the gamma-ray spectrometer and its introduction into aircraft systems (requiring a significant increase in crystal volume) marked a new era in airborne geophysics. The International Atomic Energy Agency subsequently recommended the calibration standards and data reduction procedures that were established from this project for worldwide use (Bristow 1979; Grasty 1970, 1985; Darnley 1991; Darnley & Ford 1987).

The state of the art airborne gamma ray spectrometer surveys have become highly versatile and valuable for many applications. Some of these are (i) As a reconnaissance geologic mapping tool in most areas, as changes in the concentration of the three radioelements U, Th., and K accompany most major changes in lithology. (ii) Identification of primary geological processes such as the action of mineralizing solutions or metamorphic processes and secondary geological processes like supergene alteration and leaching that may be indicated by variations in radio-element concentrations (iii) For directly detecting the presence of uranium.

II-3. (a) Gamma Ray Data Acquisition

While many of the survey design considerations for radiometric surveys are similar to those applicable to magnetic surveys, there are some significant differences. The most obvious difference is in acceptable flight elevation, i.e. while a flight elevation of 300 meters may be acceptable when flying a magnetic survey, it would be far too high for radiometric surveys. Airborne radiometric surveys are typically flown at a planned terrain clearance of 120 m, with flight line spacing of 1000m for regional surveys and 200m to 500m for detailed surveys. Further, radiometric sensors require regular calibration of sensitivities.

The acquired data is first subjected to three corrections (i) subtraction of cosmic, aircraft and radon backgrounds (ii) stripping corrections to remove effects of Compton scattering and (iii) attenuation corrections to remove variations from nominal survey flying height before the conversion of counts to equivalent ground concentrations using sensitivities, (Grasty, Glynn & Grant 1985).

Gamma-ray spectrometry data are represented by the four variables, the total count, potassium, K (%), equivalent uranium, eU (ppm) and equivalent thorium, eTh (ppm). Although potassium concentration is measured directly, ground concentrations of uranium and thorium are obtained indirectly from measurements of daughter products, hence the term 'equivalent' is used for U and Th values. The ratio values eU/eTh, eU/K (ppm/%), eTh/K (ppm/%) are also derived from the data which are useful in the final interpretation.

II-3. (b) Gamma Ray Data Presentation

The airborne radiometric data used to be presented as contour maps separately for the three elements, potassium, uranium and thorium as well as the total count. But now taking advantage of the computer technology it has become more common to present the data in the form of ternary maps.

A ternary map is made by assigning one of the primary colours to each of the element abundances. For example, Thorium is assigned green, Uranium is blue and Potassium is red. The total count rate is used to assign an intensity scale to each of the elements and the resulting colours are then combined to produce a coloured map. Thus, bright blue areas on the map show areas where the uranium count is very high relative to both of the other element count rates; bright red indicates areas of high potassium count rate, etc. Colours other than the three primary colours indicate areas with various well defined proportions of Th, U, and K. Generally, the different colours on the map correspond closely with different rock types when compared with geological samples collected on the ground. In fact, the ternary map has proven to be so useful that, along with contour maps of the total count and of each of the element abundances, it has become a standard method of presenting airborne radiometric data. Fig 5 shows a typical example of a ternary image. Geologically the area is part of a typical Archaean craton over a region where the basement is comprised of granites, gneiss

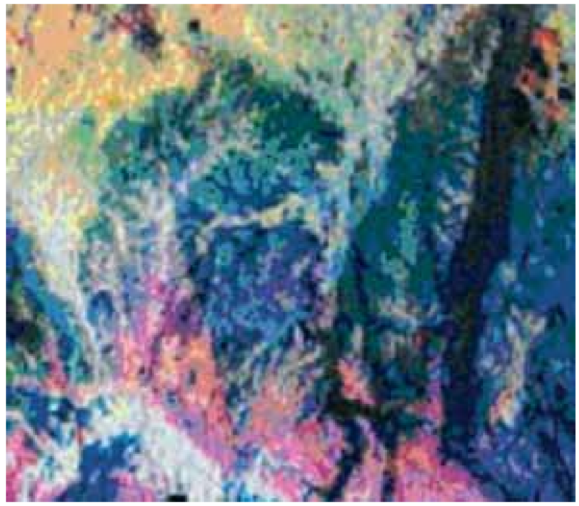

Figure 5. An example of ternary image of gammaray apectrometer data ove an Archaean craton province

complexes and greenstone belts consisting of mafic and ultramafic rocks, banded iron formations and sediments.

In simplistic terms, the gamma-ray spectrometric response shown in the ternary image shown in the above figure can be classified as follows: Red (K): regions associated with exposed granitic bedrock. Green (Th): various ferruginous materials at the surface. Blue (U): calcrete, calcareous sediments and soils. Black to brown:(Low in K, Th and U): dry in-situ soil and exposed bedrock. These areas correspond to greenstones and some sand plains. White to yellowish (High K, Th, U}: geomorphic active areas with exposed weathered granite and sediments derived from granite.

II-3. (c) Gamma Ray Interpretation

Potassium (K), uranium (U) and thorium (Th) are the three most abundant, naturally occurring radioactive elements. Potassium is a major constituent of most rocks and is a common alteration element in certain types of mineral deposits. Uranium and thorium are present in trace amounts, as mobile and relatively immobile elements, respectively. As the concentration of these different radioactive elements varies between different rock types, the information provided by a gamma-ray spectrometer may be used to map the rocks. Where the ‘normal’ radioactive element signature of a host rock is altered by a mineralizing system, corresponding radioactive element anomalies provide direct exploration guidance

Often, depending on the complexity of the geology, subtle variations in K, U and/or Th may not be readily apparent. For these reasons, the proper interpretation of gamma-ray spectrometry data requires the examination of all of the measured variables and associated derived products. Ratio maps can enhance or reinforce subtle variations in the measured variables. U increases in a general way – ultrabasic to basic to acidic. K – Th relation is significant as indicator of geological processes and points to chalcophyle as well as lithophyle mineralisation. U and Th being lithophyle elements they can serve as pathfinders for Li and rare earth element groups. Poriphery copper often associated with K-enrichment in host rocks. Increase in K concentration and raise in Th/K ratio points to zinc mineralisation and auriferous sulphides. Fall in U/Th points to areas of carbonotite and kimberlite occurrence possibility

In suitable areas, i.e., areas with reasonably low soil moisture content, maps of the ratios are useful as aids in mapping the surface geology of the area. Galbraith & Saunders (1983), demonstrated that radiometric classification of formation data and outcrop data into lithological categories can be accomplished. In such type of exercises the ternary maps are particularly valuable.

Airborne gamma-ray maps reflect the geochemical variations of K, U and Th in the upper 30cm of the earth's surface. This thin layer is subject to weathering which leads to the loss of the radio-elements. Mineralising process may also alter radioelement content. K may increase in altered rocks. Th may show increase or decrease during hydrothermal alteration. Detailed interpretation of aerial gamma-ray survey requires the delineation of major geological units and examination of subtle variations with the aid of other data (Charbonneau & Ford 1979).

It is extremely important to remember that terrestrial gamma rays emanate from the ground surface, not from depth. A few inches of overburden, including soil, are sufficient to absorb 100% of the emissions from the rocks beneath. Therefore, unlike the aeromagnetic method, the radiometric method is capable of yielding information only on what lies at the ground surface. The merit of radiometrics is as a geological mapping device that has the ability to provide chemical information on rock outcrop by remote sensing. Even though residual soils, which have not been moved, retain only some of the radioactive elements that were present in their parent rocks, their relative abundances tend to remain indicative of the parent, and thus the underlying parent rock can sometimes be mapped through a thin layer of residual soil.

II-4. AIRBORNE GRAVITY SURVEYS

Measurements of gravity at discrete points on ground surface and continuously recording it over the sea by ship borne gravimeter has been in practice for a long time. Airborne gravimetry is an important new technique within this field. Considerable effort has gone into the development of an instrument system suitable for airborne surveys, which have definite advantages as already mentioned. In order to carry out gravity measurements also from the air, by helicopter or airplane, initially the proved marine gravimeter has to be further modified so that it can also be used as a part of an airborne gravimetric measuring system(Schwarz & Wei 1994; Vallient 1992; Olesen, Forsberg & Gidskehang 1997).

Subsequently other and more advantageous methods have been developed (Malcolm et al 2000). A gravity sensor installed on a moving platform measures the sum of gravity and inertial acceleration of the system in the aircraft. Interferences caused by inertial acceleration on a normal survey flight can show 100 – 1000 times the amplitude of the wanted signal of a measured, geologically caused gravity variation, depending on the filtering of the data. The inertial acceleration, however, can be deduced from the movement of the aircraft. The flight path has to be determined by a non-inertial system, like satellite-supported GPS. Thus, the reduction of the vertical acceleration and the influence of the horizontal accelerations are important components of data processing and for this purpose ultra-modern GPS receivers and advanced DGPS post processing software are employed. Airborne gravimeter has become a viable tool in the last 10-12 years because of the development of methods of precise aircraft positioning, and efforts continue to reduce the error in this technique. Figure 6 shows a schematic of airborne gravity survey.

The airborne gravimeter consists of two main components: a gyro-stabilized platform with the gravity sensor and the rack with control electronics and power supply. Furthermore, the rack contains a high performance computer for control and data recording, a computer-controlled precision multiple altimeters and the GPS receivers. As an example, Sander Geophysics (SGL) has developed an airborne gravimeter system that uses three orthogonal accelerometers mounted on a three-axis, gyroscopically stabilized platform. The system, called AIRGrav (Airborne Inertially Referenced Gravimeter), was designed

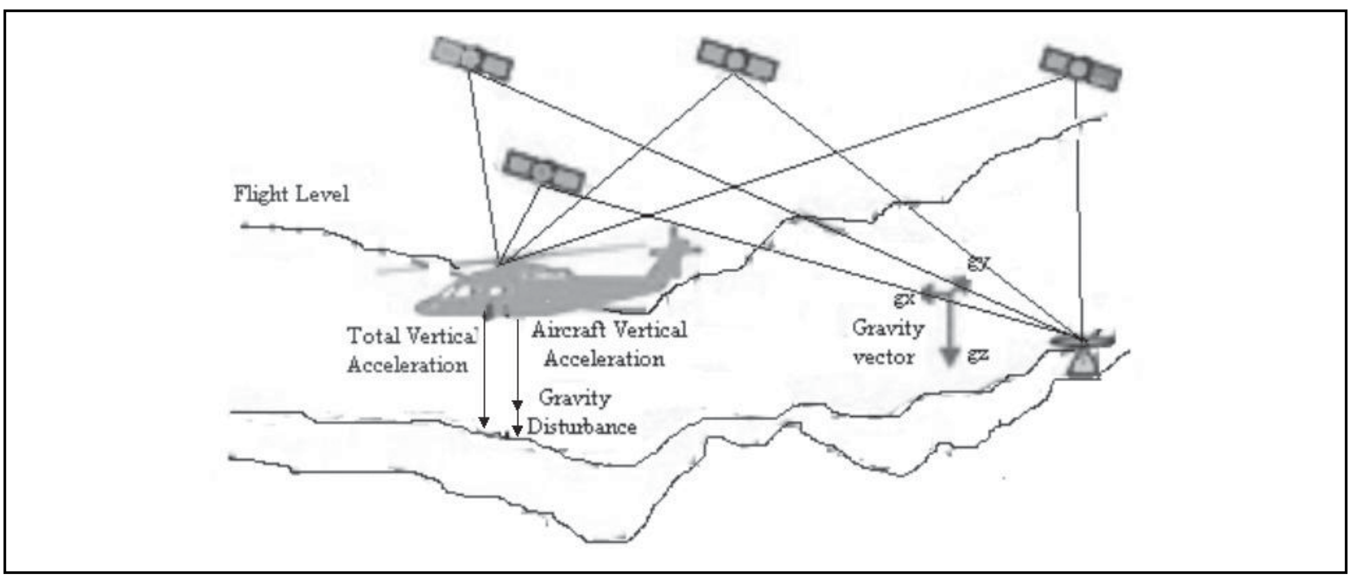

Figure 6. Schematic of Airborne gravity Survey

specifically for airborne use (Sander et al., 2005). This has resulted in an instrument with significant advantages over the modified sea gravimeters commonly used for airborne surveying; the main benefit of the new instrument is that it is more stable in attitude and less subject to noise from horizontal accelerations. During survey operations, accelerations in an aircraft can reach a value, equivalent to 100,000 mGal. Data processing must extract gravity data from this very dynamic environment. This is achieved by modeling the movements of the aircraft in flight by extremely accurate GPS measurements. Dual frequency GPS receivers are employed on the aircraft and in ground reference stations used for differential GPS processing. Figure 7 represents a comparison of ground and the airborne gravity data from test airborne gravity survey (Sander et al 2005). The image on the left is based on older ground gravity data. These data have been upward continued 500 m and filtered with a 5300 m low-pass filter to match the airborne parameters as closely as possible. The image on the right presents the airborne gravity data.

III. EMERGENCE OF AIRBORNE GEOPHYSICS IN INDIA

India also was not far behind in adopting aero geophysical technology and initiated the endeavor in the early 1950s that witnessed rapid progress since then. Chronologically, the first airborne geophysical survey in India was the aeromagnetic survey conducted as early as 1951-52 by the SADVOC Company. These surveys involved production flying of about 24000 lkm with an airborne fluxegate magnetometer in parts of West Bengal, Tripura and Orissa by M/S Fairchild Aero Corporation, USA. Subsequently in 1953-54, the Assam Oil Company conducted aeromagnetic surveys in the upper Assam valley and its western extension (Tejpur and Mangaldai areas) and Mikir Hills area. The total coverage involved was about 37,000 sq.km with a fluxgate magnetometer flown at heights of 2000’ and 4000’ above MSL respectively. The surveys produced contour maps with intervals of 50 nT to 200 nT. Later, in 1956, the government of India got about 30,000 lkm covered by aeromagnetic surveys over Ganga Valley and part of Rajasthan desert, flown by Spartan Air Services Ltd., Canada (Crompton 1959; Sankarnarayan 1975).

Contractual surveys mentioned above apart, building up of indigenous capability for airborne geophysical surveys was initiated in India in the mid fifties itself. The Atomic Minerals Division (now Atomic Minerals Directorate - AMD) of the Department of Atomic Energy occupies the pioneering position of making the earliest attempts in making earliest attempts for developing indigenous airborne surveys capability in the country. With a fabricated version of airborne scintillometer, a recording radio altimeter and a 35 mm tracking camera mounted on a ‘Dominic’ aircraft, AMD covered about 1,26,000 lkm of radioactivity total count surveys in the country during 1957-62 (Saraswat 1967). In the following years AMD’s continued R&D effort in the field has resulted in achieving tangible progress from its humble beginning and their indigenous data acquisition system has become internationally comparable (Kak, Bhairam & Dwivedi 1997). The airborne survey activity of AMD since early 1960s resulted in the coverage of nearly 500,000 lkm of multi-spectral radiometric data (Fig 8).

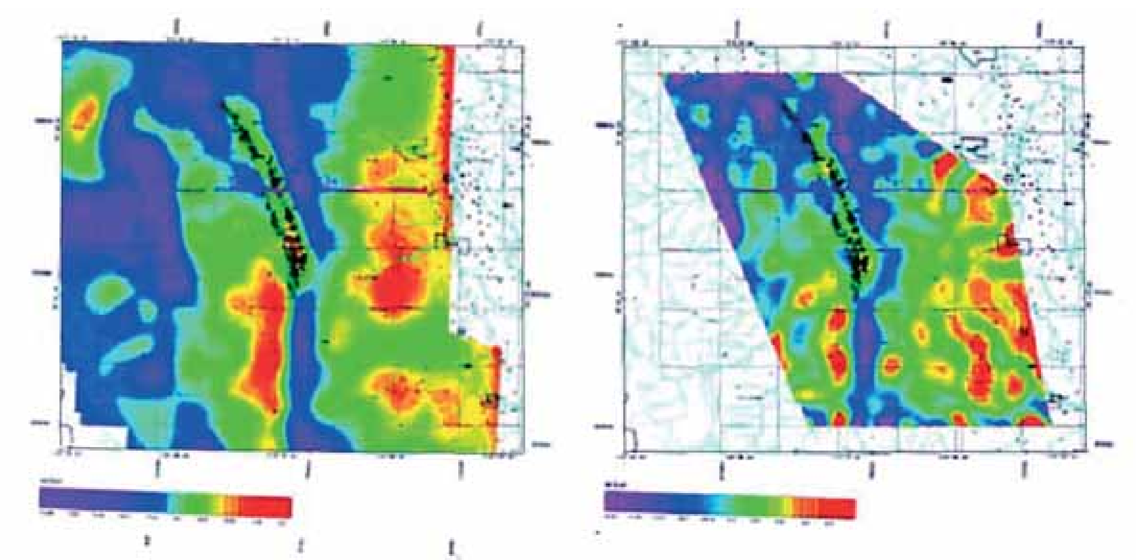

Figure 7. Comparision of Ground Gravity (Left) and Bouguer gravity(Right) After Sander et al 2005

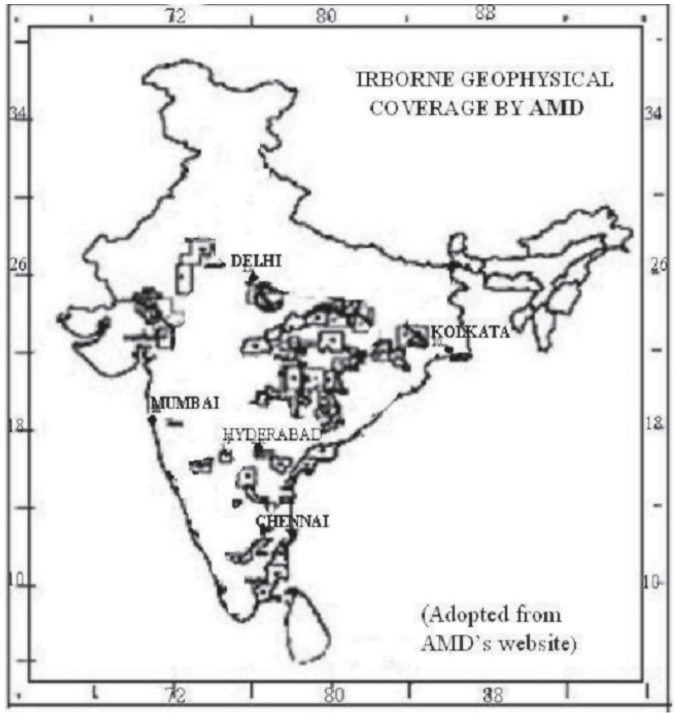

Figure 8. Airborne radiometric and magnetic coverage by AMD since 1960 (From AMD web page)

The next indigenous attempt for developing airborne geophysical survey facility was by the National geophysical research Institute (NGRI) in 1966. Suitably modifying an ELSEC proton precession magnetometer (imported from UK) for airborne work and borrowing a recording altimeter, a scintillometer and a 35mm recording camera from AMD, experimental airborne surveys were conducted by NGRI during 1967 over the iron ore belt of coastal Karnataka. These surveys involved in the coverage of 3250 sq km area with 2200 lkm of flying. Following their initial success, NGRI under took several aeromagnetic surveys sponsored by the State governments of Karnataka, MP and UP. The institute's airborne geophysical capability underwent continuous development and a rubidium vapour magnetometer and an transient EM system (modified INPUT system), both indigenously built by NGRI, along with a McPhar made 4 channel gamma ray spectrometer was in use by 1974 (Sankarnarayan 1975).

Next in chronological order in the domain of indigenous effort comes the National Remote Sensing Agency (NRSA), which started airborne geophysical surveys in 1975 in a modest way. NRSA, when it initiated the programme, used single engine Beaver aircraft and proton precession magnetometer. In due course it absorbed the technological developments in this field for establishing a modern adequate facility for airborne data acquisition, processing and interpretation (Suryanarayan, Bhattacharyya & Kamaraju 1996). From early 1980s to mid 1990s, the NRSA conducted airborne magnetic surveys for the national programme of Regional Aeromagnetic coverage of the country, which was sponsored by the Geological Survey of India (GSI).

In the mean while, in 1967, government of India undertook a project that heralded an eventful chapter of airborne geophysical surveys over the shield areas of the country. This effort also resulted in the creation of a new department, Airborne Mineral Surveys and Exploration (AMSE) by the government, which subsequently got merged with the GSI in the early 1970s. In the 1967 endeavor of government of India, there were two programmes of multi-sensor airborne surveys for basemetal exploration. The first was "Operation Hard Rock" (OHR) carried out with the assistance of the United States Agency for International Development (USAID). The second was implemented through Bureau De Recherches Geologique et Minieres and Compagnie Generale De Geophysique (BRGM-CGG) of France. Later from the late 1970s GSI undertook several airborne survey projects in the country with data acquisition carried out on sponsorship basis by NGRI and NRSA . A summary of these surveys are reproduced in the following table (from GSI's website)

Project/Year LKm/Sq.Km	Nature of Survey/Area	Instruments/Line spacing/height
Operation Hard Rocks/1967-68 1,44,462/90,395	Multisensor surveys in parts of A.P., Bihar, Rajasthan and West Bengal	Proton Precession Magnetometer, INPUT, FDEM, Gamma ray Total count500m / 130m
BRGM/CGG/1971-72 1,43,507/76,460	Multisensor surveys in parts of Gujarat, Karnataka, M.P., Maharashtra and Rajasthan	Proton Precession Magnetometer, INPUT, Gamma ray Total count 500m/130m
Narmada-Son Lineament (NSL) Project/1978-79 37,338/90,924	Aeromagnetic survey by NGRI for GSI in parts of Bihar, Gujarat, M.P., Maharashtra and U.P.	Rubidium vapour magnetometer 1km/120m
Op. Anantapur/1979-81 33,040/29,300	Aeromagnetic survey by NGRI for GSI in parts of A.P. and Karnataka	Rubidium vapour magnetometer 1 km/120m
Op. Cuddapah/1981-82 24,630/22,760	Aeromagnetic survey by NGRI for GSI in parts of A.P.	Rubidium vapour magnetometer 1km/120m
National Aeromagnetic Survey Mission/1980-95 3,73,189/13,68,894	High altitude aeromagnetic survey by NRSA for GSI in the area south of 24^0 N (excluding Deccan Trap area)	Proton Precession and Cesium vapour magnetometers4 km/5000', 7000' & 9500' above MSL

The GSI has thus made substantial progress in the deployment and utilisation of airborne geophysical surveys for aiding geological mapping and mineral exploration. The total regional aeromagnetic coverage by GSI through NGRI, NRSA as well as their own system is about 16,50,000 sq.km

IV. GROWTH OF INDIAN AEROGEOPHYSICAL CAPABILITIES

IV.1. GSI procures a state-of-the-art system

During the mid 1980s, after a few years of acquiring airborne geophysical data through contractual surveys, GSI decided to have its own full capability including trained manpower by procuring a multisensor airborne geophysical survey equipment along with a dedicated aircraft. The GSI's airborne system was purchased as a comprehensive package from M/S Scintrex Ltd. of Canada, on a turnkey project basis. The multisensor system consists of a cesium vapour magnetometer unit, a three frequency vertical co-planar electromagnetic unit – TRIDEM, and a 50 liter crystal, 256 channel gamma ray spectrometer, a Doppler navigation system, a digital data recorder on magnetic tapes and a video flight path recovery system along with other accessories. The equipment was fitted on a De Heviland Twin Otter aircraft (Fig 9). Supporting this a Geophysical Mapping Centre (GMC) has been established, equipped with a VAX 11/750 computer system and software packages and other accessories for processing data and generating different data products like contour maps, profiles, etc.

The GSI's airborne system, excluding the electromagnetic unit TRIDEM, has been subsequently up graded during 1998-99. The upgradation consists of installation of Mac-3 airborne cesium magnetometer and a PGAM-1000 gamma ray spectrometer. These have been integrated to function under a PDAS-1000 data acquisition system which also houses a plug-in processing modules for the magnetometer, multi-channel spectrometer and DGPS. This upgraded data acquisition system is supported by upgraded Geophysical Mapping Center which is currently equipped with state-of-the-art PC based hardware and software packages for data processing and producing contour maps, imagery etc as well as for interpretation (Krishna Rao & Ramachandra 2001). The Twin Otter Airborne Multi-sensor geophysical survey system of GSI has so far conducted surveys in about 25 identified blocks in India for exploring for basemetals (new deposits and extensions of existing ones) in Mamandur in Tamilnadu, Aldahalli in Karnataka, Agucha, Hindoli and Bhilwara areas in Rajasthan, for gold in Gadag, Kolar-Kadiri-Ramgiri schist belts in Andhra Pradesh and Karnataka, chromite in Sukinda-Baripada areas of Orissa, PGE deposits in Deobhog and Kotri in Madhya Pradesh and diamond. These apart, the Twin Otter system was employed for regional aeromagnetic surveys in a few identified areas for aiding hydrocarbon exploration.

Figure 9. GSI's Twin Otter geophysical Survey System(from GSI's website)

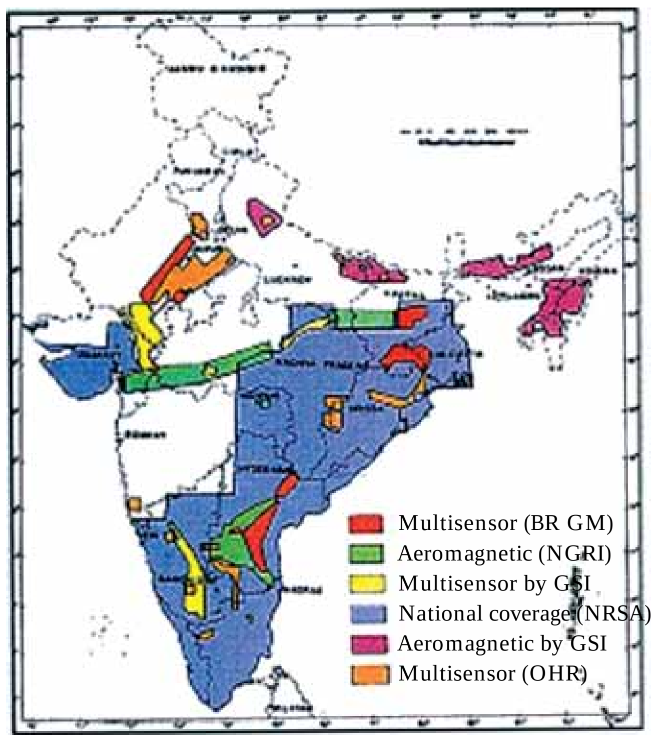

Figure 10. Aerogeophysical soverage by Geological Survey of India (after Krishna Rao and Ramachandra, 2001)

Fig 10 presents the total aerogeophysical coverage by GSI that includes earlier sponsored surveys as well as the surveys conducted by its own system. The GSI is further strengthening its airborne geophysical survey capability and is currently in the process of procuring a helicopter-borne multi sensor geophysical survey system with four sensors capable of making time domain electromagnetic, gravimetric, magnetic and gamma ray spectrometric measurements. (from GSI's website)

IV.2. NRSA upgrades its equipment

During the early 1990 the NRSA upgraded its aeromagnetic capability by procuring the latest equipment. Their new aeromagnetic instrument is installed in a Super King Air 8-200 aircraft with the sensor attached to the aircraft tail boom. The airborne system comprises a high sensitivity Cesium Magnetometer from M/s Scintrex, Canada, with associated electronics and 3-axes compensation system. The magnetometer has a sensitivity of 0.001 nT and a recording accuracy of 00.1 nT. Their latest equipment includes an upgraded data recording system, which records data from the Global Positioning System (GPS), radio altimeter, magnetometer, fiducial number, data and time of flight etc. The data is recorded on hard disk of notebook PC. The system also performs real time compensation for the magnetic effects of the flying platform. A compatible ground magnetometer simultaneously records the magnetic intensity and time for diurnal corrections. (from NRSA web site www.nrsa.gov.in).

IV.3. NGRI equips with a helicopter-borne system

During the late 1990s, the NGRI has enhanced their airborne geophysical survey capability by procuring a multi sensor system that is suitable for high-resolution surveys from a helicopter. This helicopter borne geophysical system equipped with state-of-the-art magnetic, electromagnetic and radiometric sensors is one of the most productive airborne systems. The system sensors include a Geometrics cesium vapour magnetometer G 823A, a five-frequency McPhar electromagnetic system and a 1024 channel gamma ray spectrometer. The G 823A magnetometer provides sensitivities of 0.002 nT at 1 Hz up to 0.22 nT at 100 Hz which are selectable via software command. The electromagnetic system operates with 5 frequencies with multi-coil configurations that measure the in phase and out of phase components of the secondary fields. Data is telemetered on a light weight serial cable to a data acquisition and console on board the helicopter, where it is displayed on a LCD colour screen and recorded on a removable hard disk. Pilot guidance and DGPS navigation systems are integrated into the package together with an optional gamma ray spectrometer. Other controls include laser altimeter, barometric altimeter and digital colour video imaging system. (As per personal discussions with airborne surveys group, NGRI)

IV.4. AMD Modernises its system

The continuous hardware upgradation and refinement of the data acquisition, processing and interpretation capabilities resulted in the development of high sensitivity Notebook PC-based gamma ray spectrometer with larger NaI (Tl) detector crystals. From 1997 onwards this unit, interfaced with Cesium vapour magnetometer and Global Positioning System, was flown by hiring Beechcraft B-200 aircraft of National Remote Sensing Agency.

AMD also constructed calibration pads as per IAEA standards at Nagpur airport for calibration of spectrometer and calculation of system sensitivities and stripping ratios. This is the only facility in the entire Southeast Asia. Two test-strips of natural terrain, located at Devarkonda, Nalgonda dist, Andhra Pradesh and at Malharbodi, Bhandara dist., Maharashtra, were identified. These are being used for the determination of height attenuation coefficients for each of the radioelements and total gamma radioactivity. (from AMD's website)

V. INDIAN AEROGEOPHYSICAL CASE STUDIES

Airborne geophysical surveys produce such an enormous amount of data that it may almost give a false feeling of an information overload. It is a fact, that the rich geoscientific content of aero geophysical data cannot be over exploited. The effectiveness of the aero geophysical maps, be it Magnetic, Radiometric. Electromagnetic or Gravity etc, or their combinations is undoubted as a geological mapping tool is undoubted as has been seen from many published case histories. While it is difficult to choose from the innumerable aero geophysical case histories that are available, a humble attempt has been made in this review to present some interesting examples pertaining to India.

V.1. Southern Indian granulite terrain

As mentioned earlier GSI undertook a project of regional aeromagnetic coverage of Indian Peninsula (excluding Deccan Trap covered regions) during the early 1980s. Data has been acquired by flights carried out by NRSA on contract basis, flying at 1515 m (5000 ft) barometric height generally but at higher levels of 2121m (7000 ft) and 2850m (9500 ft) over two segments having higher ground elevation. The flight lines were 4 km apart in N –S direction except for some portions where they were N25E-S25W. Reddi et al., (1988) employing a novel approach of evaluating the computed depths to the subsurface magnetic basement interpreted the data south of 12^0 N over the high-grade metamorphic terrain of southern Indian Peninsula. The authors report that the subsurface map of magnetic basement (Fig 11) brings out many interesting features which affirm the block structure of the shield separated by faults along which the blocks moved up or down in symphony with deeper and sub-crustal layers. There appears to be a close correlation between present day topography and the magnetic basement relief map thereby providing a classic instance of tectonics initiating topography.

The low pass filtered magnetic map (Fig 12) reveals further interesting information regarding the deeper crust. The prominent features in the map include a

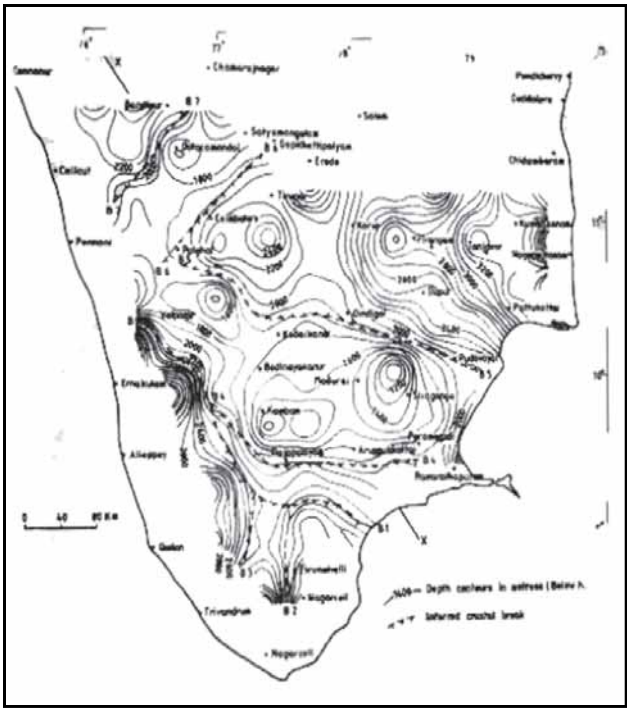

Figure 11. Subsurface relief of a magnetic basement and major crustal breaks in Tamilnadu-Kerala (after Reddi et al 1988)

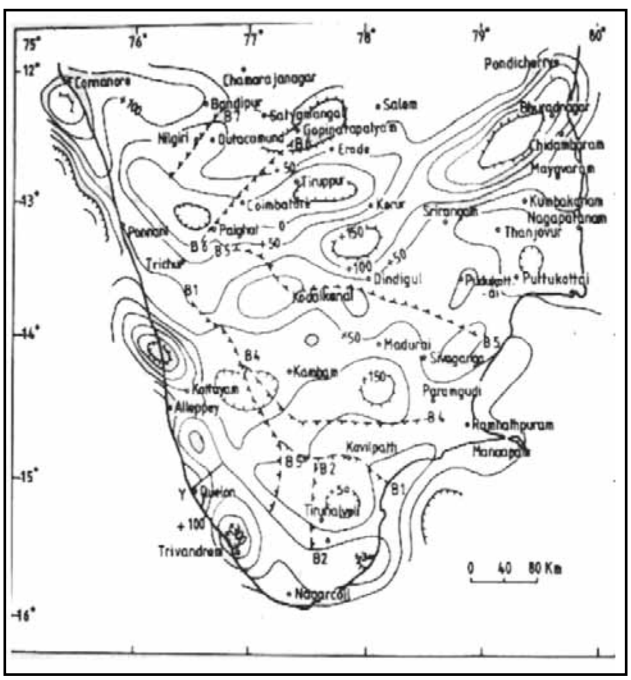

Figure 12. Filtereg (loe pass)aeromagnetic anomaly map of Tamilnadu-Kerala (after Reddi et al 1988)

series of "highs" aligned sub-parallel to the Kerala coast, forming a prominent ridge extending from Ernakulam to Trivendrum, from where it turns eastwards and the northwards and runs parallel to the east coast up to near Ramanthapuram. Reddi et al., (1988) view this ridge as one of a series of volcanic features possibly formed as a result of northward drift of Indian landmass.

V.2. Aeromagnetic Image – part of Indian Peninsula

The aeromagnetic data (both high level and low level) acquired by GSI since 1967 covering most parts of sub-Himalayan Indian Peninsula has been compiled through a collaboration project of GSI and NGRI to bring out IGRF corrected aeromagnetic anomaly contour maps and images (Mathew et al., 2001). As mentioned in earlier sections, the data is from the surveys carried out during 1967 to the mid 1990s through its OHR and BRGM/CGG Projects and contractual arrangements with NGRI and NRSA, the latter being under the National Programme of Aeromagnetic Survey. The magnetic image maps show several distinct features and patterns and a broad correlation is instantly seen between these magnetic anomalies and major tectonic features of the Peninsular Indian Shield (Fig13). Based on the anomaly patterns the map is classified into three distinct Blocks; Block-I covering area between 8^0 and 12^0 N, Block-II between 12^0 and22^0 N and Block-III between 22^0 and 25^0 N. Blocks I and III are relatively homogeneous compared to Block-II and are characterised by high density ENE-WSW to E-W trending linear (2-D) anomalies and a few locaised 3-D features. Block-III in contrast is heterogeneous and is characterized by sparsely distributed broad anomalies with a few isolated 2-D features and one or two well defined 3-D anomalies (Mathew et al., 2001).

Geologically, Block-I comprises the Southern Granulites Terrain (SGT). The aeromagnetic anomalies correspond to the major tectonic features such as Moyar-Bhavani and related shear zones, Palghat-Kaveri shear zone, the Achchankovil shear zone etc. Strong linear NE-SW trending anomaly patterns represent the Proterozoic Alkali Complex and mafic and ultramafic belts in the Salem – Dharmapuri area.

Block-II corresponds to Dharwar Craton in the south and Bastar craton in the north. The contact between the two cratons is clearly brought out by a distinct NNW-SSE to NW-SE trending anomaly along the Godavari Graben. This Block displays

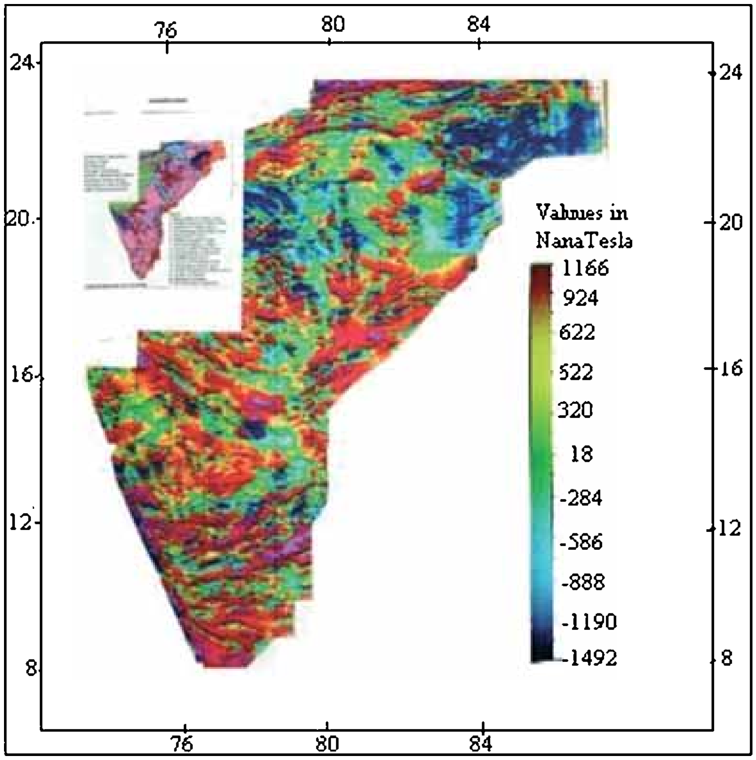

Figure 13. Aeromagnetic Image map of Indian peninsula south of 24N ,except deccan Traps (Adapted from GSI's Spl Publi. No.75-back Cover)

some interesting anomalous features related to geologic features such as the contact between the Eastern Ghat Mobile belt (EGMB) with the Bastar and Dharwar cratons, tectonic features associated with the Chitrdurga schist belt etc. The broad, but weak, WNW-ENE to E-W trending anomaly zones may correspond to the concealed structural features in the basement as the known belts in the region are in the general N-S or near N-S trend. Interestingly two major linear magnetic anomliess are seen in this Block, one trending ENE-WSW from Western Ghats to Koppal and the other trending NW-SE from Bijapur to west of Chennai. As these two trends do not have any surface geological manifestation they are being followed up by GSI employing ground surveys.

Block III covers part of Bundelkhand Craton and is characterized by dense ENE-WSW to E-W trending anomaly patterns disposed parallel to the trends of mobile belts of the Central Indian tectonic zone constituting the craton. Strong NW-SE trending anomaly zones characterise the Mahanadi graben, a prominent tectonic feature. Other linear magnetic anomaly manifestations include the Sukinda thrust and various features related to Singhbhum shear zone and the Singhbhum granitic complex.

V.3. Interpretation of Aeromagnetic image over Central India (1)

Making use of the GSI's aeromagnetic compilation mentioned above, Ramchandra et al., (2001) interpreted the magnetic patterns of the region, between 17^0 and 23^0 N and 79^0 and 86^0 E, comprising Central India, in relation with the known major geological features of the region (Fig 14). The central Indian terrain mainly exposes Precambrian rocks that are covered by Phanerozoic sedimentary sequences and Deccan Traps, with Bundelkhand craton in the northern side and Bastar Craton in the southern side. The aeromagnetic data has shown close correlation between large scale craton margins, mobile belts edges and other major geological features. The authors have made an in-depth study of these by making use of various derived maps like analytical signal, reduced to pole, high and low pass filtered maps etc. (Ramachandra et al., 2001).

V.4.Interpretation of Aeromagnetic image over Central India (2)

Rajaram & Anand (2003) also analysed the aeromagnetic data over Central India, that was

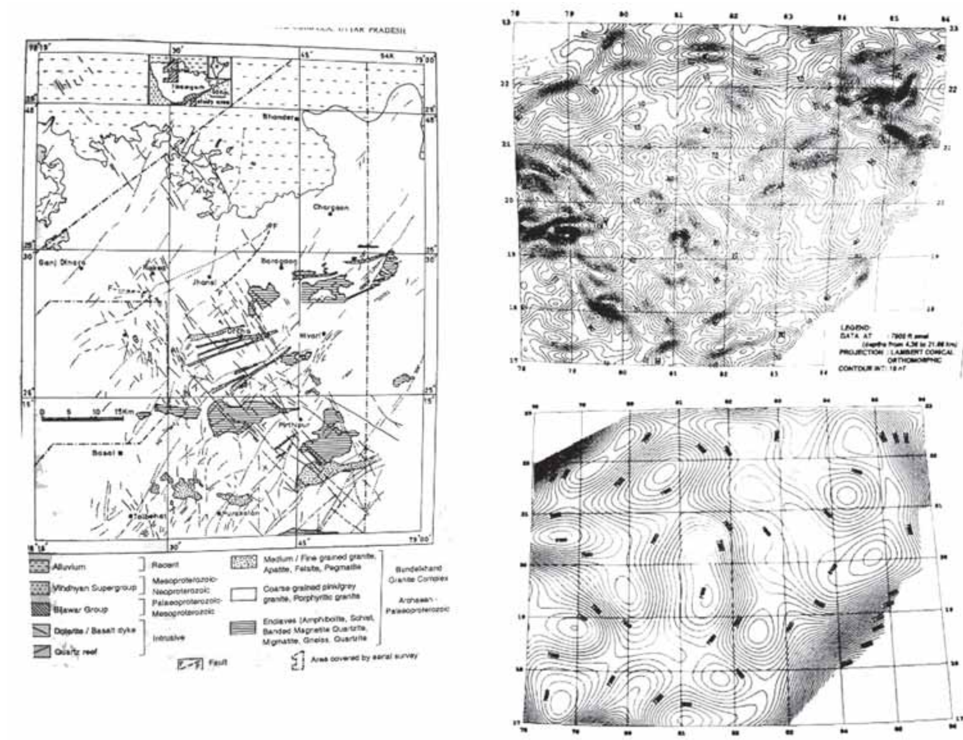

Figure 14. Left: Generalised tectonic map of Central India. Right top: Aeromagnetic total field map. Right bottom: Low pass filtered magnetic map (After Ramachandra et al 2001)

compiled by them from GSI maps, to throw light on the various tectonic blocks of the region, ranging in age from the Archean to the present. As per the authors the existing geotectonic models are based on inadequate data and studies of relatively small regions. From the aeromagnetic data, the authors derived the analytic signal and Euler deconvolution, to elucidate the subsurface structure of the region and redefine the tectonic elements. From the analysis of the aeromagnetic data the authors identified the Main Peninsular shear as a single shear defining the northern limit of the Bastar craton and EGMB, though its surface manifestation is a conglomerate of several separate faults or shears. Fig 15 shows the generalized geological map, aeromagnetic image, analytical signal map and the schematic tectonic blocks and magnetic sources as interpreted by the authors.

V.5. Bundelkhand Granite Massif-Jhansi Area

Ghosh & Ramesh Acharya (2006) presented the interpretation of the aeromagnetic data generated by low altitude airborne surveys conducted by GSI over an area near Jhansi in the Budelkhand Granite Massif (BGM). The BGM, which forms a part of the Precambrian Central Indian Shield, is highly metamorphosed and structurally disturbed. And owing to this the aeromagnetic picture is quite complex. The authors have employed a comprehensive suite of data enhancement techniques to interpret the aeromagnetic map which will be helpful in delineation of magnetic units within the supracrustals, tensional fracture-shear systems and associated acid/basic intrusives. From the enhanced magnetic maps it is observed that a high degree of correlation exists between the magnetic patterns and the surface geology indicating that the magnetic anomalies in the area are derived primarily from relatively shallow features (Fig 16) Two main regional structural patterns are evident in the magnetic contour and image maps, one trending NE-SW which are interpreted as due to the tensional fractures emplaced with demagnetized material (quartz reef, fine grained granite etc.) and the other NW-SE striking strong magnetic linear trends which are explained as due to basic dykes. An elliptical magnetic aureole has been delineated in the area of Basi-Talbehat-Purakalan, which may be further explored for tin mineralisation (Ghosh & Ramesh Acharya 2006).

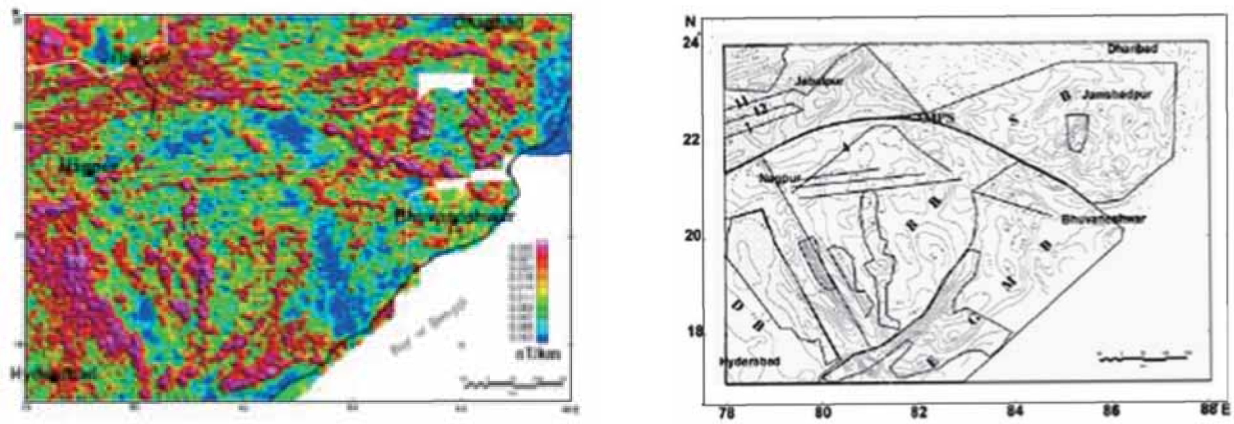

Figure 15. Aeromagnetic analytical signal map (left) and interpreted tectonic map. (After Rajaram and Anand 2003)

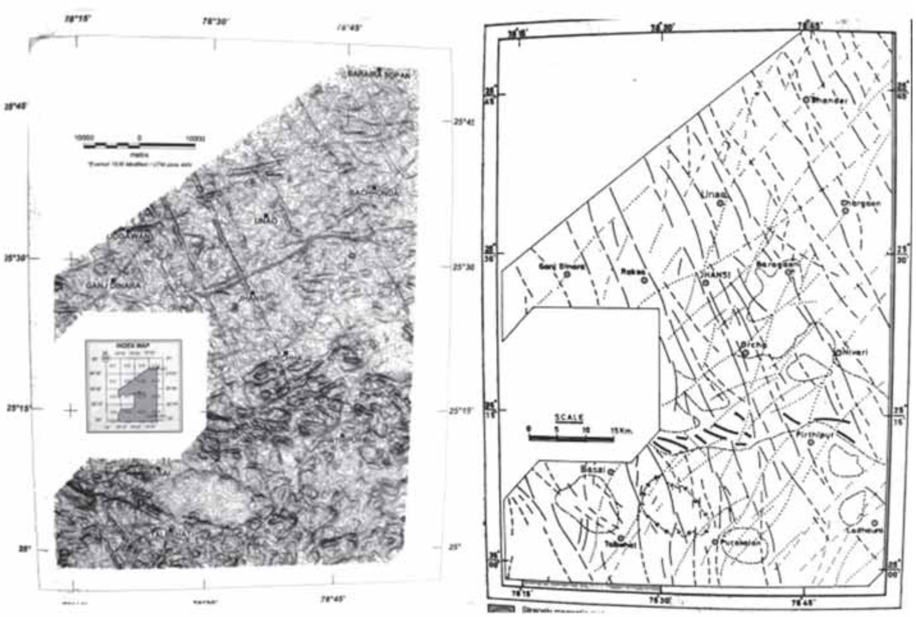

Figure 16. Aeromagnetic map (Left) and interpreted structural trends (Right). After Ghosh & Ramesh Acharya 2006

V.6. Bundelkhand Granite Massif - Lalitpur-Sagar Area

Rajendra Sarma et al., (2006) interpreted the aeromagnetic data of another part of Bundelkhand Granite Massif (Fig 17) in parts of Lalitpur district (U.P) and Sagar Districts, Madhya Pradesh. The qualitative study of aeromagnetic data helped in delineating various zones correlating with geological units, Bijawars, Vindhyans and Deccan Traps, that over lie the Bundel Khand Gneissic basement. The in depth analysis of the aeromagnetic data helped in delineating the structural set up and delineation of magnetic body-axes and discontinuities in the area. Depths to different magnetic interfaces and depth extent and other parameters of various magnetic bodies have been estimated.

V.7. Cuddapah basin

On the basis of three aeromagnetic profiles across the Cuddapah basin integrated with ground gravity, Atchuta Rao, Sankarnarayan & Harinarayan (1970) inferred three well-defined zones. The first is large broad anomaly referable to a large ultramafic body, the second is magnetically flat zone over the thick, horizontal, undisturbed part of the Cuddpah and Kurnool formations and the third zone is towards the east of the eastern boundary of the basin possibly originating from the Eastern Ghat Mobile Belt. Later Babu Rao et al., (1987) studied the aeromagnetic map over parts of Cuddapah basin on the basis of the wavelengths and amplitudes of the magnetic anomalies and their relationship with surface geology

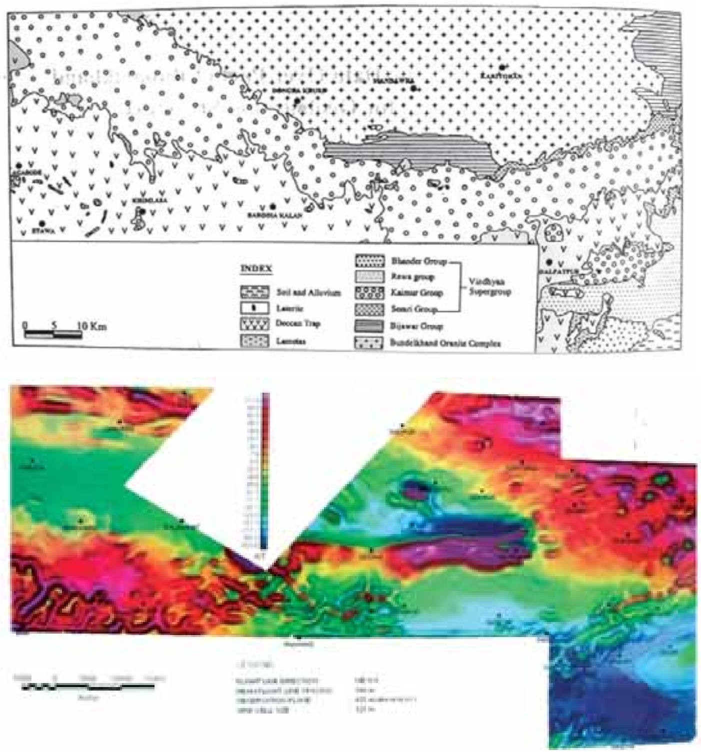

Figure 17. Aeromagnetic study of lalitpur sagar area. Top: Simplified geology. Bottom: Aeromagnetic Image After Rajendra Sarma et al 2006)

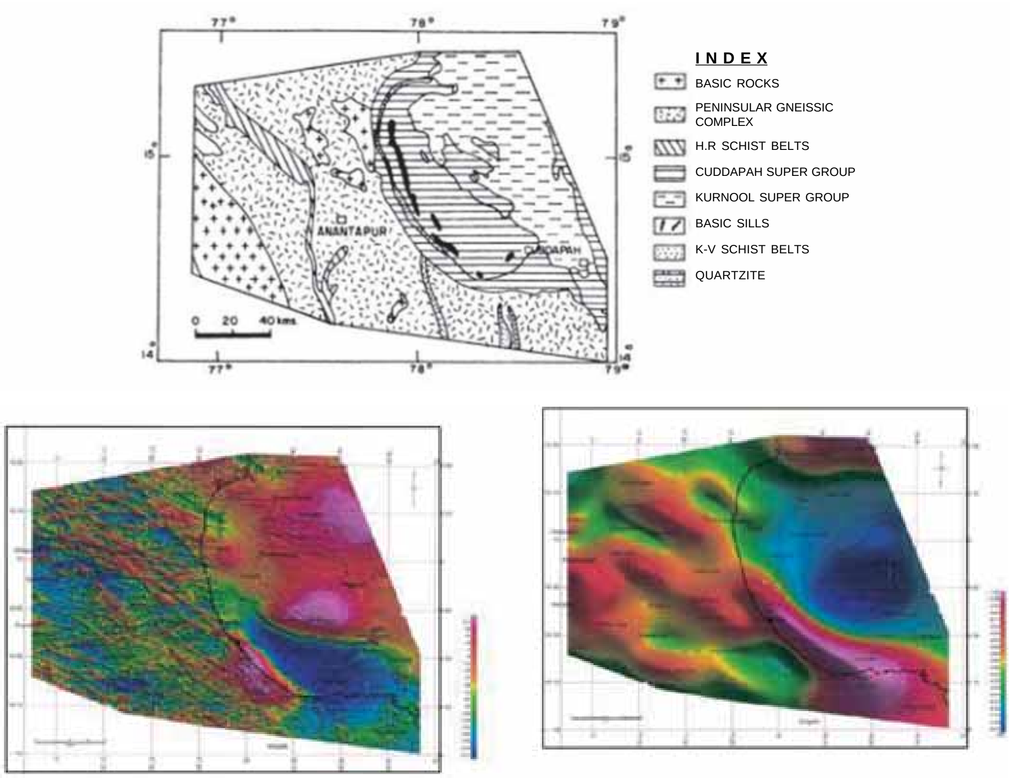

Figure 18. Aeromagnetic study of western part of Cuddpah basin and adjoining areas (after Prasanti Lakshmi and Rambabu, 2002)

to bring out various structural features. The authors carried out quantitative analysis also over a few selected anomalies by 2-D modeling.

Prasanti Lakshmi & Rambabu (2002) interpreted the aeromagnetic data over Cuddapah Basin using pseudo-gravity approach. The entire basin was covered by aeromagnetic surveys with a 1 km line spacing at a mean terrain clearance of 150 m.. The simplified geological map, total intensity aeromagnetic and low pass filtered anomaly image are shown in Fig 18.

The basement configuration of the southwestern part of the Cuddapah Basin was derived from the aeromagnetic data by transforming it into pseudo-gravity anomalies. The inferred picture shows a general depression of the basement elongated in a NW-SE direction and reaching a maximum depth of about 10 km near Muddanuru.. The central depression in basement is elongated in NW-SE direction with steep dips in the southern and southwestern sides, suggesting that the sediment filling the depression was derived from the southern and southwestern side of the basin. The basement high further north to the Banganpalle Fault may be a transition zone between Papaghni Basin and the northern Kurnool sub-basin. It seems from this basement map that the western sub-basin is bounded by faults in the north and the southwest directions. The maximum thickness of the sediment in this area is observed to be about 10 km near Muddanuru.

V.8. Chitradurga Schist Belt

Ramarao et al., (2002) demonstrated the utility of airborne radiometric data even in its primitive form. For this purpose the authors manually digitized the Radiometric total count contour map of GSI (surveys conducted through BRGM/CGG during the 1970s) in a judicious way.

The authors utilized the radiometric data as an adjunct for interpretation of the gravity and magnetic anomaly maps obtained by their regional surveys over the Chitradurga Schist Belt for structural studies. The Gamma-ray total count value at each of the location of the gravity and magnetic observation station was read by interpolation from the radiometric contour map to approximately reproduce map with denser contours. This map is visually interpreted in terms of surface geology by assuming three ranges of total count values, less than 500 for mafic rocks, 500 to 600 for gneissic rocks and greater than 600 for granite. According to the authors, a clear picture of the disposition of major rock types was brought out by this approach. Fig 19 shows the close agreement between the reproduced total count map and the Bouguer gravity map.

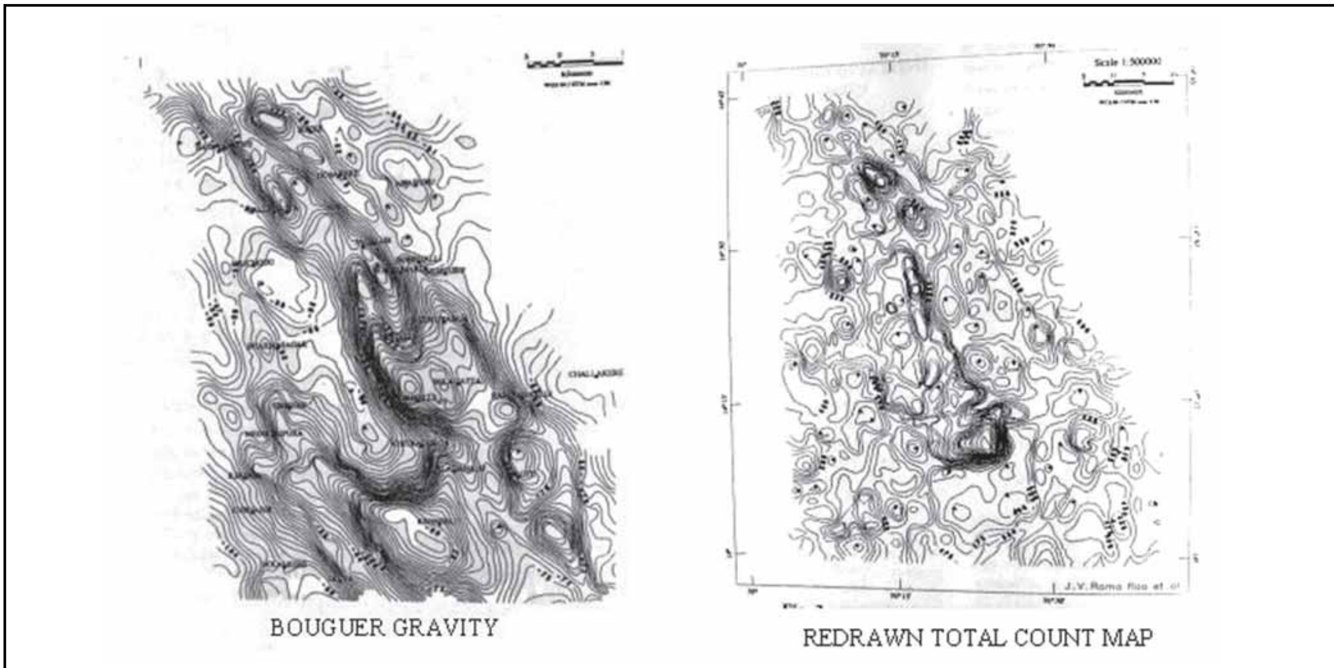

Figure 19. Comparision of Bouguer gravity (left) and redrawn (right) Total Count (by manual digitisation of old data) contour map, Chitradurga Schist Belt, Karnataka. (After Rama Rao et al., 2002)

V.9. Dharwar Craton

Anand & Rajaram (2002) presented an analysis of aeromagnetic data over the Dharwar Craton (Fig 20) to probe its structure. The source of the data are analogue degree-sheet aeromagnetic total field anomaly maps pertaining to the study area, acquired from GSI, which were digitized along contours at close interval for each degree-sheet. The digitized data has been further processed applying the necessary corrections (to bring them to a common datum of 7000 feet above MSL, removal of IGRF etc). The total field anomaly map generated from this data and the derived analytical signal map (Fig 20) confirm the division of Dharwar craton into western and eastern blocks, and are consistent with the several strike trends of the causative sources. The Chitradurga schist belt appears to divide the Dharwar craton into the western and eastern blocks. From the study the authors find that the density of the anomalies in the Eastern Dharwar is greater than that in the Western Dharwar. They suggest that the reason for this magnetic heterogeneity between the two blocks may be due to the higher grade of metamorphic rocks in the Eastern Dharwar and/or the uplifting of the Eastern block with respect to the Western block with the characteristics of the deeper crustal layer now exposed due to erosion. The third possibility may be the presence of thick sedimentary sequence in the Western block with mainly volcanics in the Eastern block.

V.10. Airborne geophysical surveys for Mineral search

The multi-sensor airborne geophysical surveys conducted by GSI through OHR and BRGM/CGG generated around 75,160 AEM anomalies attributable to bed rock conductors. Ground follow-up of these by geology, geophysics and geochemistry and drilling has since produced about 20 copper prospects and 10 lead-zinc prospects (Reddi, Murthy & Kesavamani 1995). Most of these discoveries happen to be in Rajasthan (16 copper in Banwas, Malwali etc and and 7 lead-zinc in Devpura, Kayar etc) with overall reserves estimate of about 50 m ton for copper and 33 m ton for lead-Zinc. In addition to these two copper prospects were identified in Bihar (Bhagdogrs and Khadandungri), one in Karnataka (Aladahalli) and two in Mahrashtra (Ranmangli and khapri). A lead and zinc prospect was located in each of the states of Andhra Pradesh (Gollapalli) and Maharashtra (Kolari), all these indicating reserves from 1 to 3 m ton of reasonable grade. The figs 21 through 23 (adopted from Reddi, Murthy & Kesavamani 1995) show the aerogeophysical expression of some of these prospects.

V.11. Ganga Valley

Ganga valley, the largest on shore sedimentary basin of the subcontinent with an area of over 3,00,000

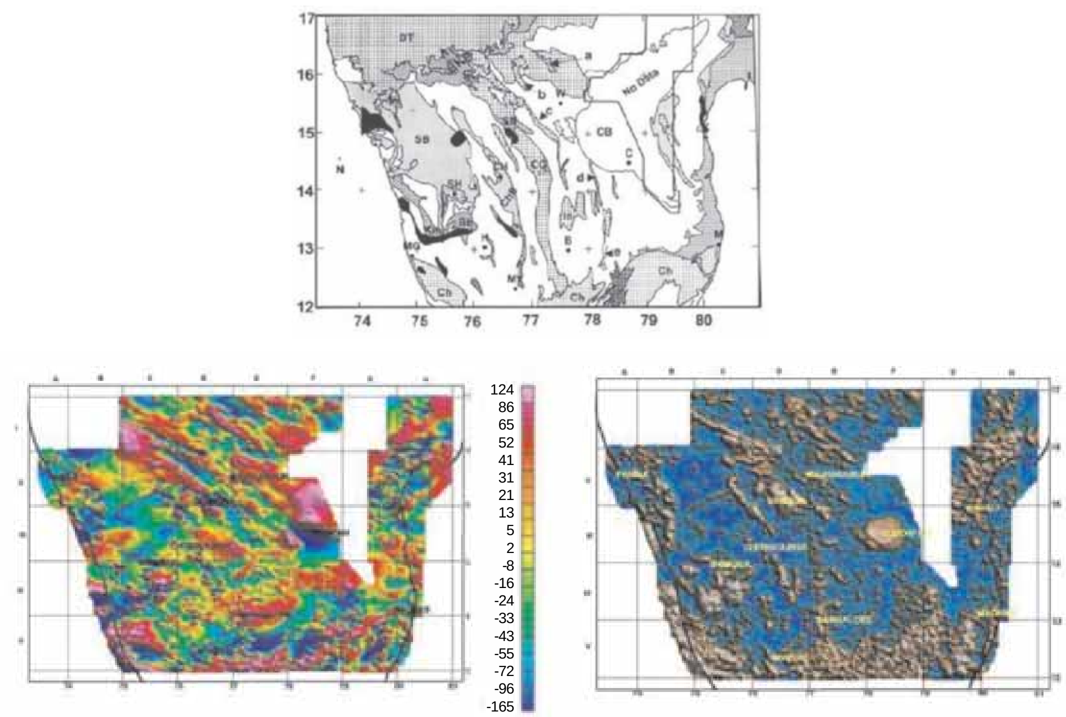

Figure 20. Aeromagnetic study over Dharwar Craton. Top shows the generalised geology. Bottom left is the toatal field and bottom right is analystical signal map (After Anand and Rajaram)

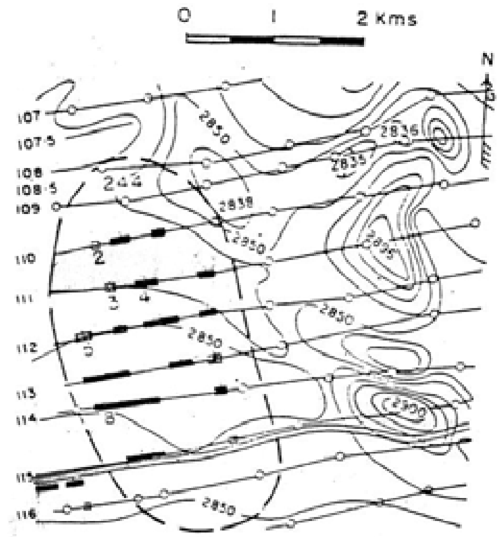

Figure 21. Airborne geophysical map over part of Kottapalli-Gollapalli area .Andhrapradesh

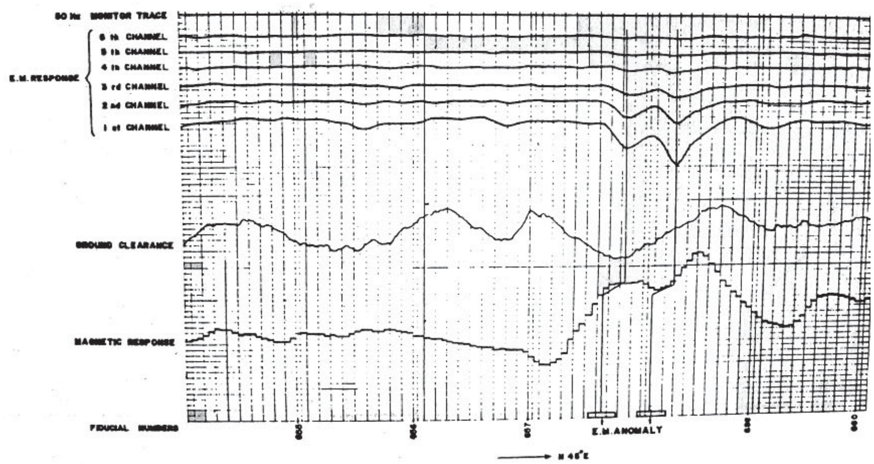

Figure 22. Aerogeophysical analogue record over Aldahalli area showing the INPUT anomaly indicating bedrock conductor

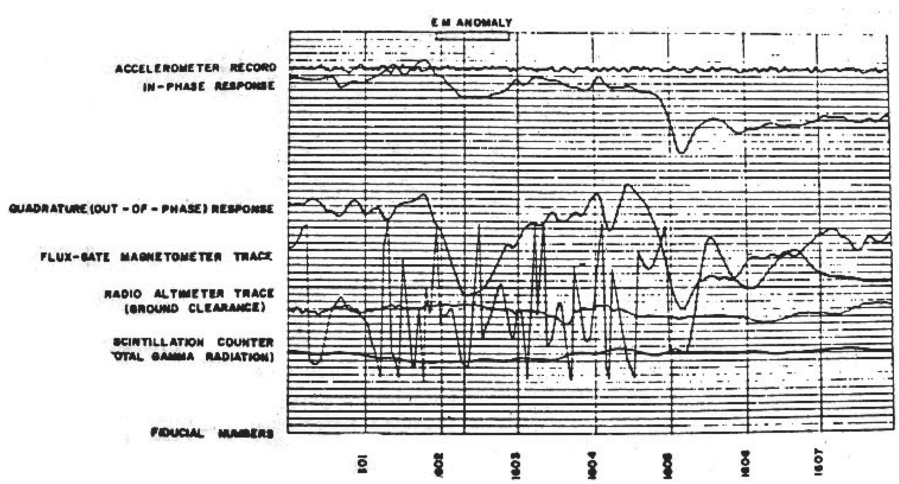

Figure 23. Airborne geophysical analogue record over Bbaghdogra area, Bihar, showing frequency domain record indicating bedrock conductor

sq.km has been explored for hydrocarbons over half a century. Ganga valley is bounded by Indus basin on the west and Brahmaputra basin in the east. Bahuleyan et al., (1999) presented the results of aeromagnetic survey conducted by GSI over part of the basin. The area proper consists of three sub-basins, which are by northerly plunging basement ridges in the west and east. The Main Boundary Fault (MBT) forms the northern boundary of the basin, while the Delhi-Aravalli systems, Bundelkhand granitic complex and Satpuras distinguish the southern margin. The airborne surveys conducted at 700m barometric altitude and flight line interval of 2 km were taken up on contract basis for Oil India Limited. The authors prepared various types of derived maps (To name a few: Reduction to Pole, vertical component, Downward continued etc.) and of these the total field and the vertical component maps are reproduced in Fig 25. From these maps they observed that (Bahuleyan et al., 1999) the Moradabad-Haldwani fault divides the area into two zones. The southern zone appears to be underlain by basement rocks of much lower magnetic susceptibility compared to the northern zone. This suggests that the northern basement is of high mafic composition indicating its basic nature. Along with these aeromagnetic surveys, low level (70m height and 1 km spacing) multi-sensor surveys over a few sub-blocks of interest.

While the above airborne surveys might have brought out many subtle features that are significant on the point of view of hydrocarbon exploration, they are not presented in the paper owing perhaps to their confidential nature. The IGRF corrected total field map and the derived vertical component map are shown in fig 24.

VI. PROSPECTS OF AIRBORNE GEOPHYSICS

Airborne geophysical methods that got initiated in the mid 1940s established themselves by the early 1960s holding a strong ubiquitous role in all mapping and exploration activities. The methods have seen continuous growth in the following decades and, in fact, gone beyond comparision with those during the pioneering times. This is due to the wide range of innovations that have become possible due to the modern electronics, navigational methods, computing power and the various attractive techniques developed for data presentation. From the old "bump selection" or "anomaly hunting" type utilization the method got evolved into employing very comprehensive interpretations that look at the overall picture.

Looking into the future, not withstanding the usual uncertainties, it may be anticipated that many of the advancements in airborne geophysics will become even more accentuated and developed in the coming years, driven by their widening scope of application and need to detect and delineate deeper and/or more subtle targets.

In airborne magnetic method the commonplace term will be "High Resolution Aeromagntics (HRA)" evolved from advances in survey specifications, instrumentation, data processing and imaging

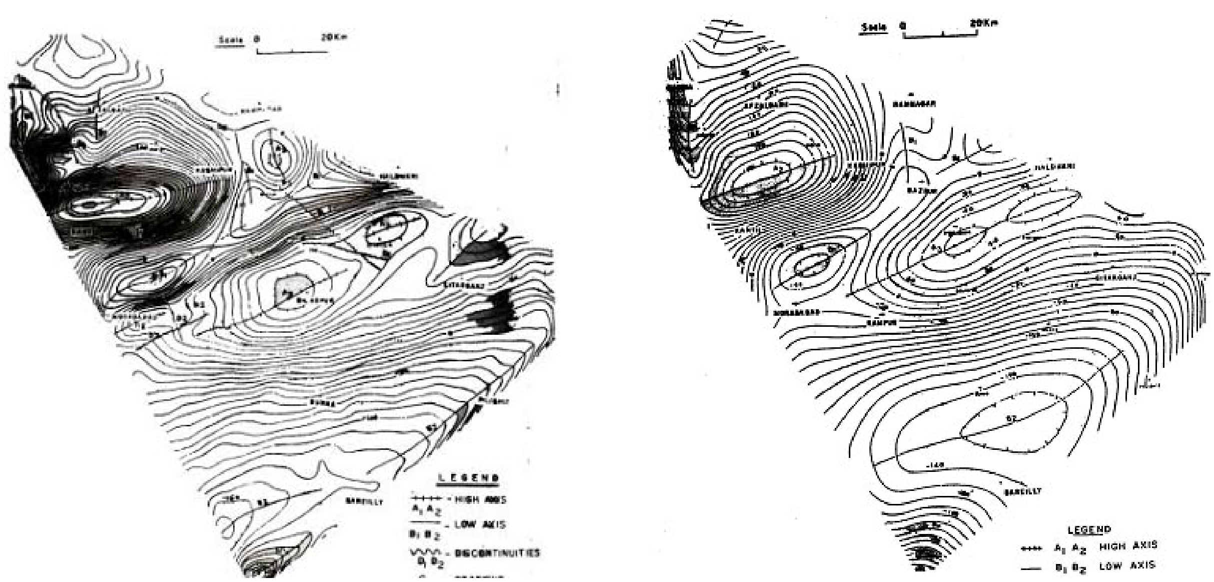

Figure 24. Total aeromagnetic (IGRF corrected) map and derived vertical field map over part of Ganga valley (After Bahuleyan et al., 1999)

techniques. HRA greatly improves the quality and geological information content of the final maps.

The heliborne EM capability now possessed by the country will enhance the scope of the method to a large extent. In addition to mineral exploration, applications of airborne electromagnetic systems will 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 off shore investigations like shallow water bathymetry.

In airborne gamma ray spectrometry, the introduction of PGAM (Picodas gamma ray spectrometer) technology has resulted in radiometric data that required fewer statistical corrections. This has brought revolutionary changes in the sensitivity and accuracy of measurements. However, interpretation of the data is commonly carried out involving no more than subjective visual classification of colour changes, either of individual elements or combined RGB composites. This interpretation does not extract maximum information from the data. Future requirement would be analysis of the data in terms of major rock types, and subdivisions of these rocks types in to components. This allows the interpreter to relate the spectrometric data into natural classification of rocks and identify areas of anomalous chemistry.

A notable addition to the spectrum of aerogeophysical methods is the airborne gravity, which has seen many practical applications during the last decade. While airborne gravity is now established as a dependable tool, airborne gravity gradiometers will become more common for detailed surveys. The principal advantage of a gradiometer over a conventional scalar gravity system is much better noise elimination. 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.

The airborne geophysics now consists of four major techniques, magnetic, electromagnetic, radiometric and gravity. Now methods like Airborne Laser Flurosensor (ALF), which detects fluorescent signals from pollution, Algae, Oil slicks etc, may come into regular practice particularly for environment related surveys.

The scope of airborne geophysics is vastly expanding but its effective utiliastion rests on firm understanding of what type of geological information already exists and what is required to be added. Orienting the surveys with all available geological inputs and interpreting the results with meaningful geological considerations establishes the technique of airborne geophysical surveys as primary method in all geoscientific studies. It is expected that the future direction of airborne geophysics in India offers exciting prospects as well as demanding challenges.

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