Heliborne Time Domain Electromagnetic Surveys for Uranium Exploration

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Abstract

Airborne geophysical surveys have been used extensively in petroleum, mineral exploration, and environmental mapping.Of all the geophysical methods, Electromagnetic (EM) methods, both ground and airborne are used to map the conductive ore bodies buried in the resistive bed rock. Mapping conductivity/resistivity variations can help unravel complex geological problems and identify areas of hidden potential. Besides the traditional applications to ground water investigations and other natural resource exploration and geological mapping, a number of new applications of EM have been reported. These include hazardous-waste characterization studies, precision agriculture applications, archeological surveys etc. Airborne Electromagnetic (AEM) methods have undergone rapid improvements over the past few decades. Several new airborne Time Domain EM (TDEM) systems appeared; existing systems were updated and/or enhanced. The use of natural field (passive) EM surveys continued to increase, with new or improved systems becoming available for both airborne and ground surveys. The number of large airborne survey systems with combined EM, magnetic, gravimetric and gamma-ray spectrometric capabilities also increased. In data processing, new developments in 3-D inversion and 3-D modelling of EM data on parallel and cloud computing were reported.

Atomic Mineral Directorate for Exploration and Research (AMD) of Department of Atomic Energy is one of the earliest adopters of the airborne geophysical survey technology for its exploration program. AMD successfully acquired the heliborne high resolution magnetic, gamma ray spectrometric and time domain electromagnetic geophysical data over different parts of the country with advancedsystems like time domain electromagnetic (VTEM), magnetic and gamma ray spectrometer. So far, AMD has generated 286, 275 line km of high resolution (fixed wing TDEM, Frequency Domain Electromagnetic (FDEM) and TDEM Heliborne) data over different parts of the country utilizing its heliborne geophysical system and also in association with NGRI and other Multi-National companies for its uranium exploration program. Several target areas have been identified based on integrated interpretation of these data sets using the state of the art technology and are in the process of further exploration. We highlight a few interpreted results of the acquired high resolution heliborne time domain EM data in the present paper.

Introduction

Electromagnetic (EM) methods, both ground and airborne are used to map the conductive ore bodies buried in the resistive bed rock. Resistivity of sediments are primarily determined by rock porosity, the electrical resistivity of the pore substance, and the presence of certain electrically conductive minerals (Keller, 1987). Mapping resistivity variations can help unravel complex geological problems and identify areas of hidden potential. Besides the traditional applications to ground water investigations and other natural resource exploration and geological mapping, a number of new applications have been reported. These include hazardous-waste characterization studies, precision agriculture applications, archeological surveys etc (Reeves et al., 1997 and Auken et al., 2006).

Electromagnetic (EM) methods have undergone rapid improvements over the past few decades not only in ground but also in airborne investigations. Advancement in instrumentation, development of new tools, interpretational techniques, algorithms and the availability of enormous computing power have favored innovation in geophysical industry all through. Each EM method, however, involves the measurement of one or more electric or magnetic field components by an "EM receiver," from some natural or artificial source of electromagnetic energy – the "EM transmitter". The behavior of electromagnetic (EM) fields, governed by Maxwell's equations, spans the EM spectrum from hundreds of MHz to very low frequencies approximating to DC (direct current). EM methods are broadly classified into frequency and time domain methods.

In Frequency Domain Electromagnetic Method (FDEM) an AC (alternating current) electromagnetic source induces eddy currents in conductive earth material. These eddy currents generate secondary magnetic fields. EM receivers measure both the primary and secondary fields. Upon normalization by the input source or by the received primary field, either the secondary or the total (primary plus secondary) field response is interpreted to yield the significant resistivity information of the subsurface. Electromagnetic response, usually expressed as the secondary field or the mutual impedance between the transmitter and receiver, depending on the frequency, the conductivity of the structure, and the geometric coupling between the transmitter and receiver (Swift, 1988).

Time Domain Electromagnetic Methods (TDEM) involves generating periodic magnetic field pulses penetrating below the Earth surface. Turning off this magnetic field at the end of each pulse causes an appearance of eddy currents in geological space. These currents then gradually decay and change their disposition and direction depending on electrical resistivity and geometry of geological bodies. The electromagnetic fields of these eddy currents (also called transient or secondary fields) are then measured above the earth surface and used for mapping and future geological interpretation in a manner that is known (Nabighian and Macnae, 1988).

The frequency range of TDEM systems has extended higher and more attention is being paid to the on-time and early time data. On the other hand, exploration for highly conductive or deeply buried mineral targets has resulted in TDEM configurations with lower base frequencies (25 Hz), larger transmitter moments (1600 000 Am2) and longer pulse widths (4–6ms). TDEM receivers can now measure three-component data, rather than the standard X-component. The Z-component improves the response and resolution for flat-lying conductors; dip determination and depth of penetration, whereas the Y-component improves determination of the strike and location of discrete conductors (Smith and Keating, 1996). The three-component measurements also increase the signal-to-noise ratio, and facilitate the detection of conductors laterally offset from the survey line. Sampling of the TDEM waveform now reaches 256 channels, which provides possibilities for more sophisticated processing, modelling and imaging techniques (Reeves et al, 1997).

Atomic Mineral Directorate for Exploration and Research (AMD) of Department of Atomic Energy is one of the earliest adopters of the airborne geophysical survey technology for its exploration program. National Geophysical Research Institute (NGRI), Geological Survey of India (GSI), and National Remote Sensing Centre (NRSC) are other government organizations that took active part in airborne geophysical surveys over different parts of the country. In the recent past, with the opening of exploration activity to Multi-National companies, high resolution multi-parameter airborne geophysical surveys were conducted over parts of Rajasthan, Orissa, and Karnataka for Hindusthan Zinc Limited (HZL), AMD, Oil and Natural Gas Corporation (ONGC) and Oil India Limited (OIL). AMD and NGRI successfully acquired the heliborne high resolution magnetic, gamma ray spectrometric and time domain electromagnetic geophysical data over different parts of the country with advancedsystems like time domain electromagnetic (VTEM& HeliTEM), magnetic and gamma ray spectrometer. Further, AMD has planned to take up Airborne Gravity (AG), Airborne Gravity Gradient (AGG), Full Tensor Gravity (FTG) and Heliborne natural source EM surveys in targeting the deep seated uranium deposits. NGRI in association with Arhus University, Denmark has taken up an ‘Aquifer India Mapping Project’ (AQUIM) funded by World Bank to map deep and shallow aquifers in five States using Heliborne Time Domain Electromagnetic system-SkyTEM.

Airborne TEM systems

In the case of airborne TEM surveys fixed wing and heliborne electromagnetic methods are well known. However, heliborne time domain techniques are more popular than the fixed wingtime domain techniques because of greater depth of investigation and the speed with which ground that can be covered at low altitude in geological surveying(Thomson et al, 2007). There are good numbers of service providers in the market with advanced TDEM systems like high dipole moment, low noise, low base frequency, greater depth of investigation. Some of the advanced systems are, VTEM Max, VTEM Plus, VTEM, SkyTEM, HeliTEM, HeliGEOTEM, AeroTEM, GPRTEM etc. For resolving the shallower geological conductive units, SkyTEM introduced the dual moment systems whereas, CGG introduced the Multipulse systems and both the systems demonstrated with good case histories. Typical heliborne time domain EM system (sketch) is shown in Figure 1.

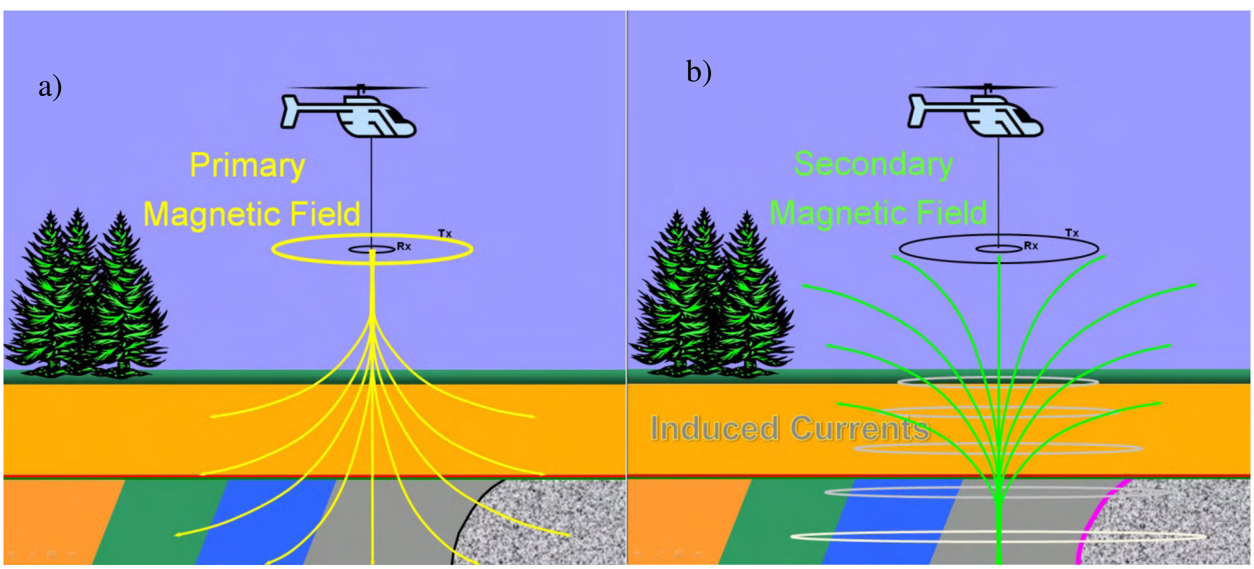


Figure 1. Typical heliborne time domain EM system (Sketch) a) primary magnetic field due to alternating current in the transmitter loop (Tx) b) Secondary magnetic field received in the receiver loop (Rx) due to subsurface conducting geology.

Navigation

Geophysical exploration, as with other spatial information sciences, is reliant upon accurate positioning. The availability of the Global Positioning System (GPS) by the early 1990's tremendously improved the location accuracy. The high resolution was achieved primarily by tightening by line spacing and lowering the flight altitude. To perform the survey, a helicopter is fitted with geophysical instruments. The survey area is then covered by a series of parallel flight-lines, commonly spaced 50-1000m apart. Heliborne surveys are flown close to the ground, often with a clearance of only 50-150m. This maximises the measured signal which attenuates rapidly with increasing survey height (Chaturvedi, 2008). A typical survey plan on Google earth for airborne surveys is shown in Figure 2.

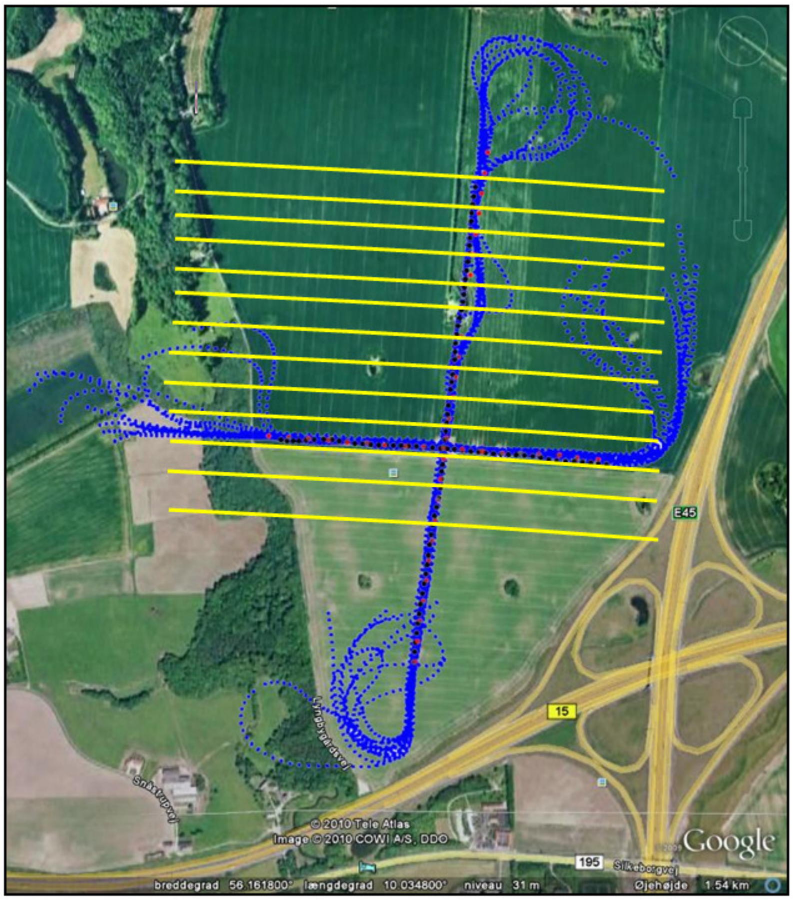


Figure 2. Typical survey plan highlighting the flight paths in yellow and blue shown on Google earth for airborne surveys.

Processing and Interpretation

Airborne Electromagnetic (AEM) data are collected by the computer based data acquisition system fitted in the aircraft/helicopter. The acquired data are subsequently processed into an array of channel amplitudes. These channel amplitudes are most sensibly interpreted after conversion into depth-related conductivities and displayed as depth sections. All checks and adjustments viz., system noise, primary filed compensations and calibration are to be performed on the acquired raw data which forms the part of quality control. Processed data are displayed as profiles and images in the field. Minimal levelling is required if the receiver data is normalized during the acquisition time. Micro-leveling is generally applied to adjust the minor decorrugation effects (Chaturvedi, 2008).

Interpretation of electromagnetic data requires presentations that are geologically intuitive. Images of half-space apparent resistivity or decay constant τ (tau) have proven to be effective geological mapping tools, although they oversimplify the information inherent in the data. For qualitative and quantitative purposes, the color images of decay constants for a number of decay windows ranging from early to late time can be useful to identify conductive domains associated with known geology, mapped magnetic/radiometric structures /domains and obviously new domains with no known correlation. It is also relatively easy to distinguish spatially between weak, intermediate and good EM conductors.

Conductivity Depth Imaging (CDI) also called Conductivity depth transform (Tau domain) is routinely used to obtain cross-sectional images showing the distribution of conductivities with depth along the every survey line/profile. Conductivity depth transforms are not quantitative inversion techniques, hence they can only provide a general image about the distribution of conductivities verses depth that are not easily quantified in terms of depth and thickness. However, since all Conductivity depth transform algorithms are based on the assumption of either Layer earth models or half spaces, they usually provide reliable enough results in cases of layered earth geology, but not in case of steeply dipping conductors. In other words CDI's gives better approximation in simulating the layered Earth models (Stolz and Macnae, 1998).

Modeling

Forward modeling refers to the computation of theoretical anomalies for assumed geometry and shape parameters. On the other hand, modeling and inversion refers to the assumption of geophysical models and parameters based on known geology or characteristic curves and modified in an iterative approach such that the observed anomalies and theoretical anomalies fit closely. All the inversion schemes are iterative and utilize one or the other form of optimization techniques. Quantitative interpretation refers to drawing geologic conclusions from the inverted models. In inversion, a model is parameterized to describe either source geometry or the distribution of a physical property such as conductivity. There are several commerciallyavailable software packages in the market for 1D, 2D, 2.5D and 3D for modeling of EM data.

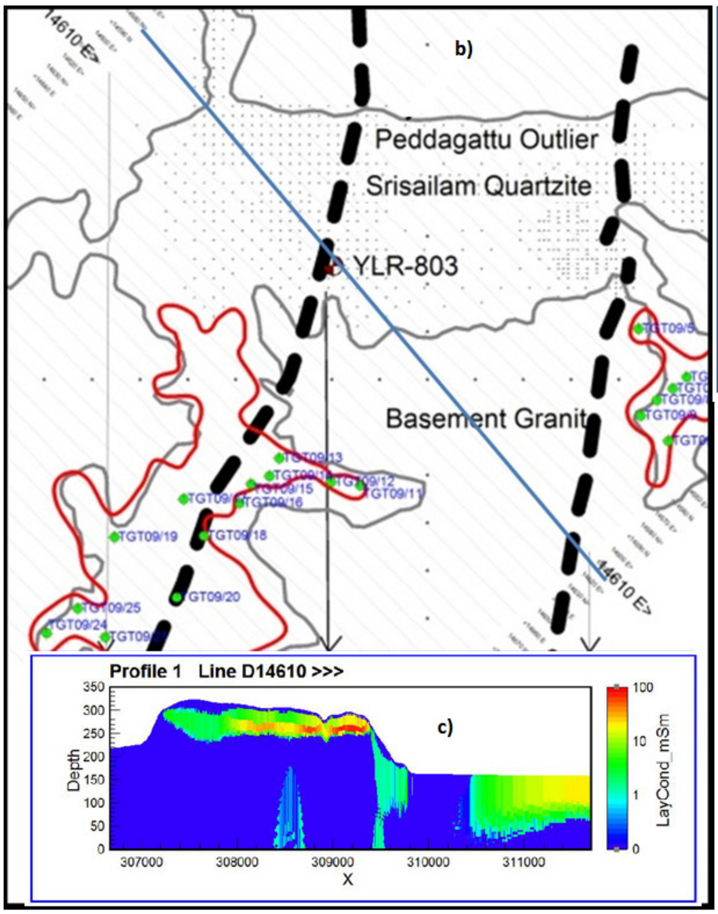
Since last decade, high resolution magnetic, radiometric and VTEM surveys conducted in different parts of the country for various exploration programs has given encouraging results (Chaturvedi et al., 2008, 2010, 2011 and 2013; Ramesh Bau et al., 2011; Patra et al., 2013; Markandeyulu et al., 2013). Many targets have been identified based on the integrated interpretation of these high resolution heliborne geophysical datasets. A few of them are tested by ground geophysical surveys followed by drilling confirm interpreted results. Present paper discusses the interesting results of these findings.

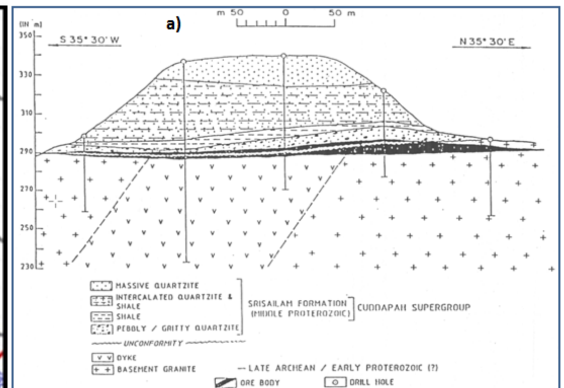
Cuddapah Basin, Andhra Pradesh

High resolution Heliborne geophysical surveys were conducted over northern parts of the Cuddapah Basin to identify unconformity type uranium deposits employing Versatile Time Domain Electromagnetic (VTEM) system along with magnetometer and Gamma Ray

Spectrometer mounted on B3 Squirrel Helicopter. Unconformity related uranium deposits associated with or without faulting and/or shearing, intruded by N-S to NNE-SSW trending basic dykes within the basement granite overlain by the sediments is a well established geological model in Peddagattu, and Lambapur (Figure 3a) areas along northern margin of Cuddapah Basin.

Conductivity Depth Images (CDI) generated from the VTEM data acquired over the ***Peddagattu outlier*** along the northern margins of the Cuddapah Basin has indicated unconformity response distinctly and is shown in Figure 3c. Borehole lithology pertaining to YLR-803 is given in Table 1. Shale quartzite intercalation along with the chunks of pyrites and altered granite occurring along the unconformity is very well reflected in the CDI as conducting lithology (Figures 3b&c).





From	To	Lithology
0	4	Fe-quartzite (weathered)
4	23	Fine grained quartzite with minor shale
23	45	Siltstone/shale with minor quartzite
45	48	Black shale/quartzite
48	58	Black quartzite with shale intercalation/ Chunks of pyrite
~~Unconformity ~~~~~~~		
58	65	Altered greenish granite
65	81	Fresh grey granite

Table 1. showing the Borehole lithology for YLR-803

Figure 3. a) Geological cross section across Lambapur outlier b) Geological map of Peddagattu outlier c) CDI along the flight line 14610 (part) highlighting the unconformity.

Thearea shown in Figure 4is located 24 km SSE of Chitrial in the deeper part of the Srisailam sub-basin, Cuddapah basin (Block-II).The area exposes sediments of Srisailam Formation represented by quartz arenite/shale/ferruginous feldspathic arenite. Ferrruginous feldspathic arenite is characterized by relatively high radio-elemental concentration. No significant AGRS anomalies are picked in the area. VTEM early to late channel profile indicates NS trending single peak response representing the flat (horizontal) conductor (Figure 4b). Decay constant pertaining to the area (tau) less than 1 ms may be representing weak to moderate conducting lithology (Figure 4a). Response of dBz/dt and its Conductivity depth image along the line L11480 represents a flat conductor response at a depth less than 100 m (Figure 4c). Layered earth 1D model simulated using Airbeo algorithm on Maxwell platform for the selected transient along the line represents a conducting layer at depth of 25 m with an approximate thickness of 20 m (Figure 4d). This is interpreted in terms of shale intercalation within Srisailam quartzite based on the existing borehole data. The high resistive basement can be seen at a depth of 100 m. In view of the structures and conducting formation such as shale/altered granite along the unconformity forms the favorable location for uranium mineralization.

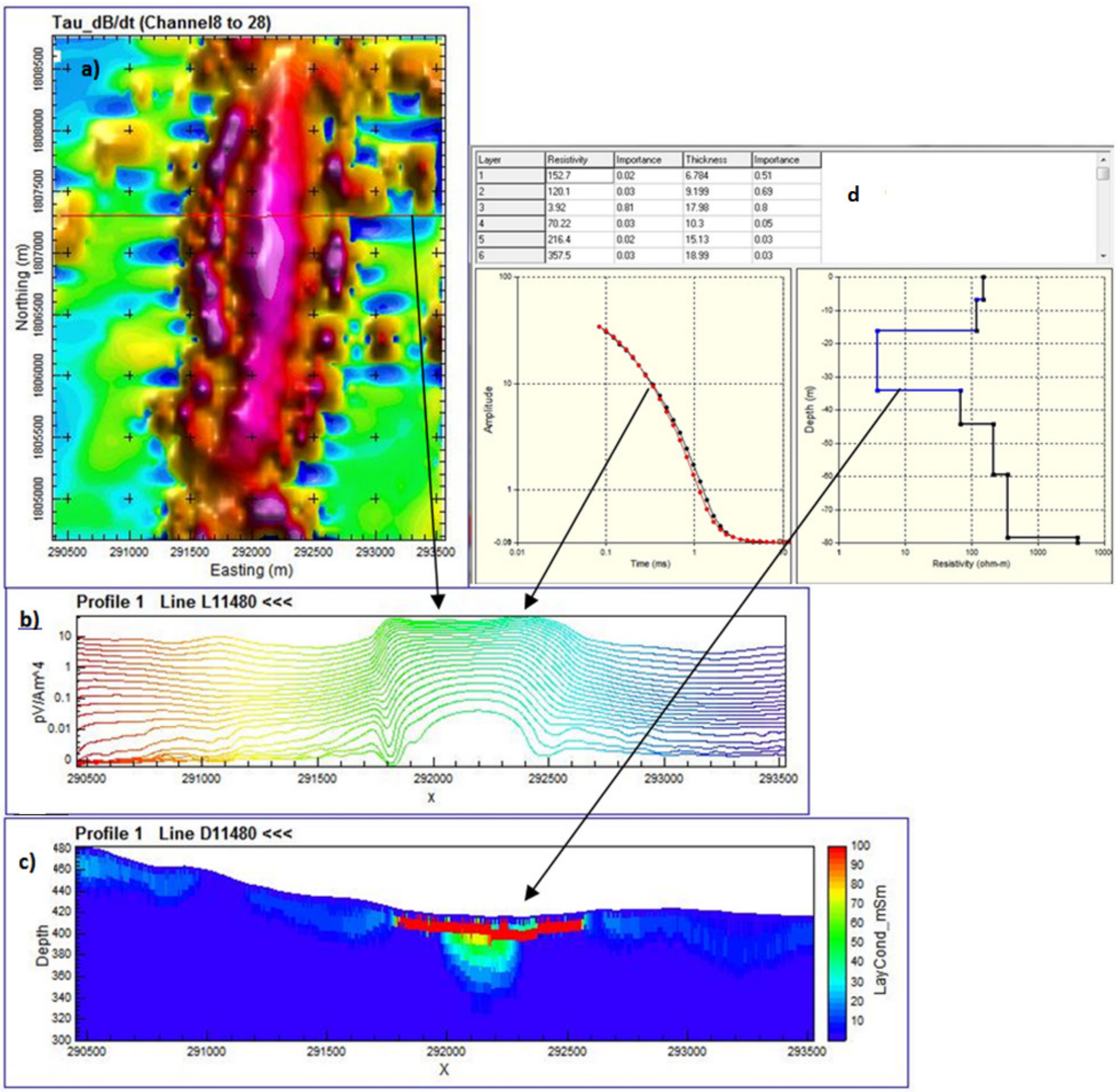


Figure 4 a) Tau image for the target area b) dBz/dt profiles along the line L11480 c) CDI along the line L11480 and d) Layered modeled response for the transient indicates a low resistivity layer at a depth of 25 m with a thickness of 20 m.

Geological map of the Block-III, Cuddapah basin covered by heliborne surveys are shown in Figure 5. To visualize the 3 dimensional distributions of the conductivity, 3D voxel models (Figure 5b) are generated utilizing the 2D Conductivity Depth Images for the three areas of interest.Contact of Srisailam Formation with Nallamalai's and Nallamalai's with Kurnools and their depth extension can be visualized from the combinations of CDI, voxel and chair clip models from the Cuddapah basin Block-III (Figure 5b i, ii and iii). This exercise helped in delineating the geological contacts favorable for uranium mineralization.

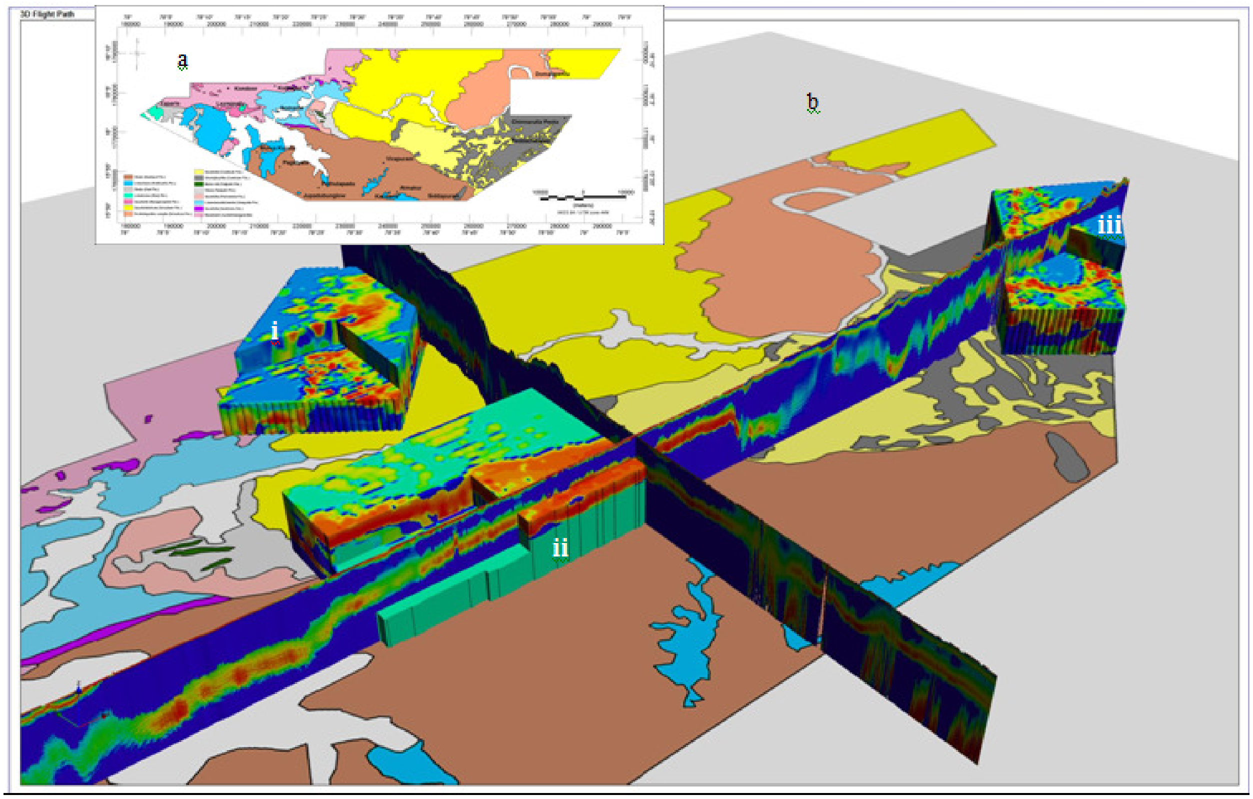


Figure 5. a) Geological map of northern part of the Cuddapah basin (Block-III) b) CDIs along the tie line T90150 and flight line L13500 in a 3D perspective view similar to fence diagram viewing from SE highlighting the conducting layer below the Kurnool group of rocks. Also, 3D voxel chair clip models generated for the three selected areas i) in parts of Srisailam sub-basin, ii) Kurnool sub-basin and iii) Nallamalai sub-basin highlighting the conductivity structure in the area.

NSSZ, Jharkhand West Bengal

North Singhbhum Shear Zone (NSSZ) also called as South Purulia Shear Zone (SPSZ) is the northern margin of North Singbhum Mobile Belt (NSMB), which makes the contact between Singhbhum Group of rocks and Chhotanagpur Granite Gneissic Complex (CGGC). It is a curvilinear tectonic belt with strike length of 150 Km from west of Arki and passes through Tamar, Malti, Beldih, Kutni and Porapahar and varies in width from 4 to 10 km. It is characterized by widespread brecciated zone associated with quartz – apatite magnetite rock, emplacement of alkali granite and alkaline carbonatite bodies along structurally weak planes / fractures. It is known to host different types of mineralization viz. Apatite – magnetite, Niobium (Nb), Base metals and Rare Earth Elements (REE). In addition to these, uranium occurrences have been located at places like Chirugora, Kutni, Meditarn, Beldih, Sushina, Tamkhun, Maskapahar and Porapahar. The study area comprises tuffaceous phyllite/schists of Singhbhum

Group of rocks, quartz-apatite-magnetite rock in the proximity of North Singhbhum Shear zone and younger intrusive Biramdih granite.

High resolution heliborne TDEM surveys conducted in NSSZ helped in delineating the conducting sulphides/carbonaceous phyllites in a non-conducting volcano meta sediments like phyllite/tuffaceous phyllites/quartzite host rock. Uranium mineralization in the area is closely associated with conducting sulphides/carbonaceous phyllites and magnetite. Geological map of the Malti area, Purulia district, West Bengal is shown in Figure 6a along with geophysical interpretation. Figure 6b shows the 3D voxel model highlighting the conductor with 150 mS/m iso-surface.

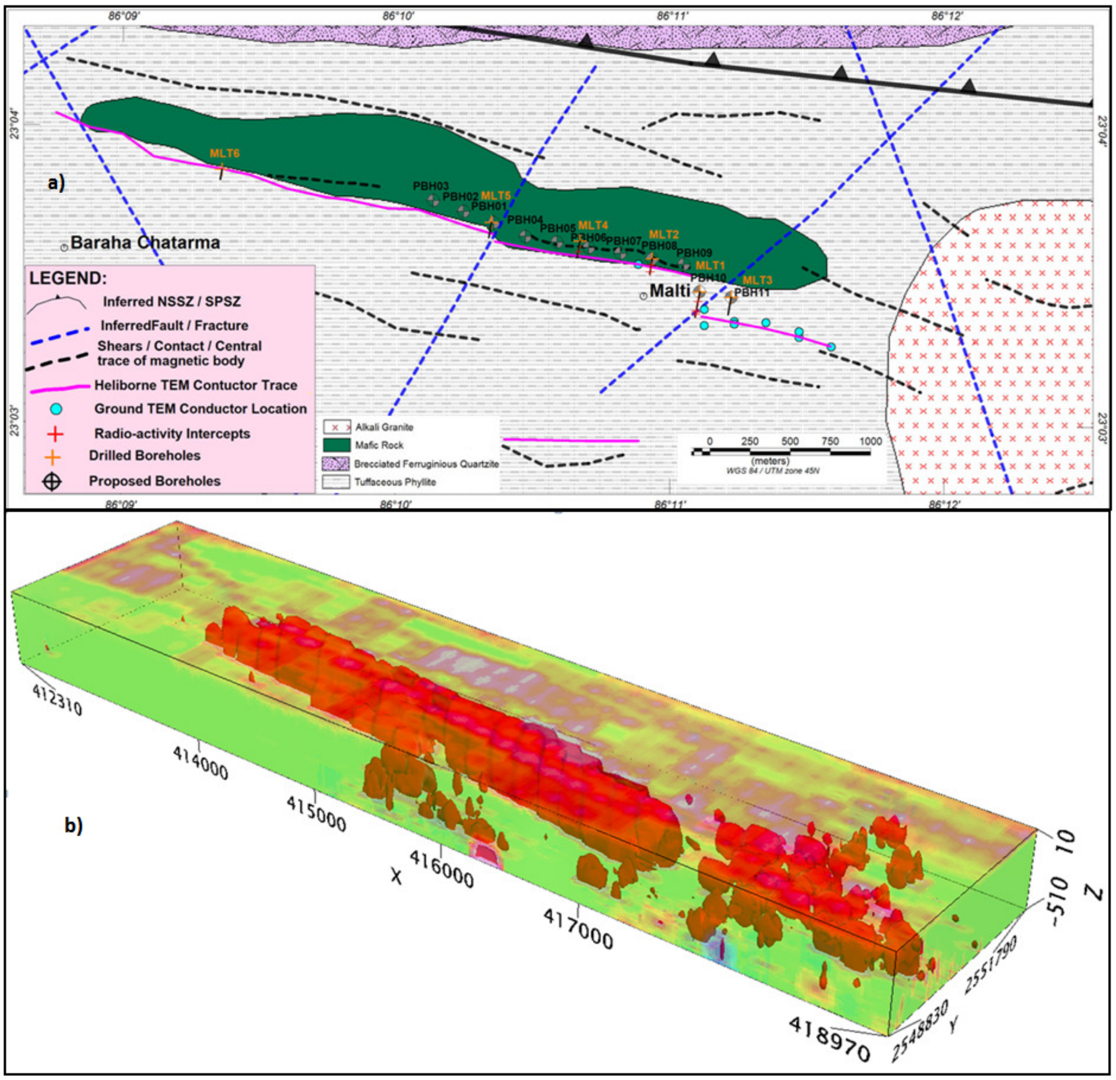


Figure 6 a) Geological map of the Malti area, Purulia district, West Bengal highlighting WNW-ESE conductor b) 3D voxel model with a 150 mS/m iso-surfcae representing the conducting sulphides/carbonaceous phyllite.

Conclusions

Mineral exploration in our country till today was mostly limited to areas around mineral shows and old workings in relatively accessible areas. So far airborne geophysical surveys with limited depth of investigation were used for mineral exploration mostly over similar terrains and hard rock areas. The trend of increasing the number of geophysical sensors on survey helicopter is continued since last decade. With the advent of new technology and advanced data processing techniques, the search for concealed deeper mineral deposits requires to be emphasized. Case histories presented in the present paper demonstrated that the new heliborne systems are capable of locating concealed and buried mineral deposits at greater depths.

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