Distinguished Instructor Short Course (DISC-2017)

and

Workshop on Applications of Geophysical Electromagnetics

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Content

Distinguished Instructor Short Course (DISC-2017)

Instructor: Douglas W. Oldenburg

Geophysical Inversion Facility, UBC, Canada

The course is being held during Feb.27-28, 2017 at CSIR-National Geophysical Research Institute, Hyderabad, India by Prof. Doug Oldenburg under the Aegis of Society of Exploration Geophysicists (SEG). He is a professor of Geophysics, Director of the Geophysical Inversion Facility (GIF) and world leader in geophysical inversions.

The aim of this course is to provide a fundamental understanding about EM geophysics so that practitioners can decide if an EM technique can help solve their problem, select which type of survey to employ, and set realistic expectations for what information can be gleaned. First day of DISC2017 is devoted to lectures by the expert and second day is a DISC Lab day (attendance optional) in which the expert will work with a smaller group of geoscientists to capture their problems, discuss them, and perhaps provide tutorials on EM computation and inversion.

About the DISC2017 Instructor:

Doug Oldenburg's forty-year research career has focused upon the development of inversion methodologies and their application to solving applied problems. He, with students and colleagues at the University of British Columbia Geophysical Inversion Facility (UBC-GIF), have developed forward modelling and inversion algorithms for seismic, gravity, magnetic and electromagnetic data. The inversion techniques and software are widely used in resource exploration problems. In recognition for his work building collaborative interactions between industry and academia, he was awarded the NSERC Leo Derikx and the AMEBC Special Tribute awards as well as the J. Tuzo Wilson medal. Doug's current research activities include: inversion of EM data and their application to a wide range of problems, development of practical methodologies for combined inversion of geophysical and geological data, development of software for unexploded ordnance discrimination, and the use of self-potentials for dam safety investigations.

“All charged up": Advances and applications for induced polarization surveys

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Induced polarization (IP) surveys have been an important for mineral exploration and are continuing to find new applications in permafrost, ground water studies, and some environmental contaminant problems. In a traditional IP survey a DC current is input to the ground and voltages, measured during an off-time, indicate chargeability. This talk focuses on two advancements that have arisen over the last decade that allow us to extract more information about the chargeable earth. The first is the ability to sample the voltage waveform at a high sampling rate. Voltages at early times after shut-off are generally heavily affected with EM induction signals and these are traditionally thrown away. However, we show how these early time data can be inverted to yield information about the background conductivity. In a subsequent process, at later times where chargeability is important, we use this conductivity to remove the contaminating EM induction effects. This enhances the time range over which IP signals are available and thereby makes them more useful in detection and discrimination problems.

A second advance is the application of IP surveys that use inductive transmitters. Although the same physical principles apply as in the traditional grounded DC/IP survey, the charging process is never allowed to achieve a steady state. This complicates the analysis. We outline a general procedure to overcome the hurdles and apply the technique to an airborne time domain EM survey over a kimberlite pipe in Canada. The same analysis has applications for permafrost studies and near-surface geologic mapping.

Role of Airborne Electromagnetic Surveys in Uranium Exploration in India

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Airborne electromagnetic (AEM) surveys have become increasingly popular in the exploration industry for both direct and indirect detection of mineralization. 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 identifying hidden mineral potential. Both active and passive (natural field) EM methods have increasingly been used for exploration of uranium, base metal and precious metals like gold diamond.

Electromagnetic methods essentially have a transmitter that carries a current that varies in magnitude as a function of time. This current has an associated (primary) magnetic field that has similar time dependence. According to Faraday's law of induction, this time varying field induces currents in conductive features in the ground. These currents have an associated (secondary) magnetic field that can be detected by an electromagnetic receiver. There is no need for the transmitter or the receiver to be placed on the ground, so electromagnetic systems can be mounted on aircraft and used to cover large areas quickly and efficiently. Of late the use of natural field (passive) EM methods are continued to increase, with new or improved systems becoming available for both airborne and ground surveys.

Most of the uranium in the world is associated with Proterozoic Basins as their depositional environment is suitable for uranium mineralization (Gandhi, 1995). For instance the Athabasca Basin (Canada) accounts for 30% of high grade uranium production in the world. In the Athabasca Basin, hydrothermal alteration in combination with conductive graphitic zones in the basement is a strong indicator of the presence of economic amounts of uranium. TEM surveys in Athabasca Basin clearly mapped the steeply dipping basement conductor and also the flat-lying conductor (paleo-regolith) close to the basement/basin unconformity up to a depth of 700 m. Therefore, the most favourable targets for uranium exploration in India, as elsewhere in the world, are Proterozoic Basins. In India, there are as many as 16 Proterozoic Basins

(Banerjee, 2005). While these basins have been explored to some extent for uranium, it was confined to subsurface to near surface deposits mostly along the margins of the basins. In view of the increasing criticality of the resource, now there is an urgent need to locate and establish concealed sizable medium to large tonnage deposits at greater depths.

Uranium exploration is a multi-stage and multi-disciplinary approach ranging from regional investigations to establishing of a uranium deposit. Recent advancement in geophysical methods and instrumentation has led to resurgence of uranium exploration activity in both Greenfield and Brownfield exploration areas. New technologies development such as development of GPS and software for rapid data processing, modelling and data inversion encourages new strategies and approaches in the field of uranium exploration. High resolution Airborne Electromagnetic (AEM), magnetic and radiometric surveys are valuable tools in geological mapping and are being increasingly used in India for delineation of target areas for uranium exploration.

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 uranium exploration program. AMD successfully acquired the heliborne high resolution magnetic, gamma ray spectrometric and time domain electromagnetic geophysical data over different important geological domains viz., Cuddapah Basin, North Delhi Fold Belt, Aravalli Fold Belt, Singhbhum Shear Zone, Chhattisgarh Basin, Bijawar Basin, Shillong Basin etc. for its uranium exploration program. Several target areas have been identified based on integrated interpretation of these data sets. Few interpreted results of the acquired high resolution heliborne time domain EM data utilized in our uranium exploration programme are discussed in the present paper.

Geothermal Scenario in India – India Centric Geothermal Technology Development

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For the last few decades, both Geological Survey of India and National Geophysical Research Institute (CSIR-NGRI) have made sincere effort to develop geothermal energy in India. Geological, Geochemical and Geophysical investigations have been carried out on all geothermal provinces, namely Himalayan geothermal province, Konkan Geothermal province, Narmada-Son geothermal province etc.

Most of the geothermal fields in India is of hydrothermal type. Surface water temperature ranges from 40-90 C. Estimated subsurface temperature is about 120 and goes to even 250 C at few places. Identification of such locations is one of the important tasks and geophysics can play a vital role in this direction. Among the various geophysical methods, Magnetotellurics can play a vital role in geothermal fields. This is mainly due to existence of conductive regions in geothermal fields as compared to its background. Conductive regions can easily be mapped through magnetotelluric technique. General depth range of subsurface conductive regions is about 1-5 km. Magnetotellurics with the observation of natural electric and magnetic field variations can easily scan the Earth from shallow to as deep as few tens of kilometres.

EM investigation of geothermal fields by NGRI was first initiated using Telluric field measurements probing northern part of west coast geothermal region covering, Ganeshpuri, Koknere, Sativili etc. hot spring areas in Maharashtra state and also Tatapani hot spring area in Surguja district, Chattisgarh. Tatapani hot spring area falls within Narmada-Son geothermal province with a surface water temperature of about 95 C. This area further probed using magnetotellurics. Results have identified a large conductive body related to hot geothermal fluids. Another important geothermal field namely, Puga region, Ladakh district in Jammu and Kashmir located at an altitude of about 4 km above mean sea level is also investigated by magentotellurics. This study has delineated a large conductive body at a depth of about 1.5 km. Estimated temperature is about 200 C.

Earlier, the geothermal requirement for power generation is to locate high temperature regions, of the order greater than 150-200 C. Due to technology development, if the difference in temperature between hot and cold fluids is 60 C, one can generate power. This is being promoted by many industries and such technology is more suitable to India. There are about 3 to 5 locations are high temperature (150-200 C) fields, 20-25 locations are medium (100-150) fields and more than 100 locations with low temperature (<100C). Accordingly, with innovation we need to plan our geothermal energy utilization in a big way. In my talk I will be discussing all the above aspects and also provide details of GERMI-PDPU geothermal project completed in Gujarat.

Large Scale Mapping of groundwater is feasible and cost-effective through applications of Heli-borne Transient EM investigations

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Country's economic growth and prosperity, knowledge of various natural resources like water, minerals and energy are vital. Setting up of heavy engineering structures, sky scrapers, subsurface waste disposal, construction of dams and river-linking projects, etc.; require reliable information of the subsurface geology.

CSIR-National Geophysical Research Institute (NGRI) has recently completed successfully pilot project in six areas covering major hydrogeological setup the country where advanced geophysical investigations employing the modern state of the art technology of helicopter borne geophysical investigations were carried out that have provided a high-resolution 3D image of the sub-surface geology up to a depth of 200 to 300 meters below the ground. This scanning is **extremely** cost-effective given its tremendous applications in the present time as well as in future to prepare a basic and essential knowledge base for all research in earth sciences in the shallow sub-surface.

For the prosperity and water security of the country that is also related to many aspects such as food security, poverty alleviation, cleanliness, disaster management and so on and the impact of Climate Change being witnessed, **intelligent assessment and management of surface and groundwater resources** are of paramount importance. The management greatly needs subsurface conservation of rainwater (as groundwater). To locate such recharge zones a complete and precise knowledge of the sub-surface is crucial. The Pilot project on aquifer mapping has covered almost all types of geological formation where potential aquifers are found in the world and established the specific methodologies with important findings to upscale the same on a larger scale.

The CSIR-NGRI has prepared a road map to upscale in selected water scarce and contaminated regions of the country for high resolution geophysical mapping of the to generate a 3D geoscientific knowledge base that will provide detailed information at meter scale precision from very shallow (2 to 5 m depth) to deeper regions (400 to 500 m depths). This knowledge will be finally translated into aquifer geometry that will be used for groundwater flow and transport modelling as well as developing decision support tool for effective groundwater management plan. This knowledge base will play the most vital role in planning various developmental programs not only today but for decades to come.

Current Channeling Phenomena in Electromagnetic Methods of Prospecting

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A systematically conducted electromagnetic model work, using moving coplanar horizontal loop transmitter-receiver system, found that the presence of a conducting host rock may substantially enhance the observed EM anomaly if the introduction of the target in the host rock alters the geometry of induced current paths (Guptasarma and Maru, 1971). A numerical model study for TURAM method to determine the 3D electromagnetic fields in the vicinity of a finite, thin, conductive plate buried in a horizontally stratified, conductive environment. The study concluded that a current gathering or current channeling effect may vary from negligible to enormous as its amplitude and phase depend strongly on the conductivity of the host rock Lajoie and West (1976). The problem has been studied from the circuit theory approach (Bhattacharya et al., 1983). The study showed that the real and imaginary components of the response of a conductor with leakage are enhanced when both the “leakage factor” and “leakage parameter” are positive. The circuit theory analysis provides insight into the leakage mechanism that actually takes place.

The effect of current channeling phenomena in audio magnetotelluric (AMT) has not been studied in any detail though it is used in the exploration of shallow conducting ore bodies. Anomalous tipper responses (tipper magnitude of more than 1.0) over Northern Singhbhum Mobile Belt located at the northern margin of Singhbhum Craton (Maurya et al, 2017, communicated). Synthetic data set indicate that tipper more than 1.0 is only possible in extreme resistivity contrast situation and can be through current channeling phenomenon. Current channeling might have occurred in two ways: i) near surface conducting heterogeneities, underlying over a resistive formation, over the highly conducting formations, affecting tipper for the shorter periods for MT/AMT sites, and ii) the conducting formations embedded in moderately resistive host rocks surrounded by resistive formations, influencing tipper for longer periods of MT sites in such a region. Such tipper magnitudes may be carefully interpreted for the possible detection and delineation of metallogeny over the cratonic margins and or mobile belts.

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Efficacy of Airborne and Ground TEM Methods in Delineating Paleochannels in India

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Under a pilot program to test the efficacy of heliborne geophysical surveys for 3D delineation of aquifers, surveys were carried out during the field season 2013 -14 in six diverse geo-hydrological regions in India. The results of these surveys were complemented and validated by ground geophysics and borewell data. During these surveys, palaeochannels were mapped in Rajasthan, Bihar and Tamil Nadu. In Rajasthan the surveys were conducted in the districts Jaisalmer and Dausa and at both places signatures of palaeochannels were picked up. In Jaisalmer, the survey successfully mapped a branch of the mythological river Saraswati, while in Dausa, the ancient river course of the River Banganga was traced. Near Patna in Bihar, the ancient course of the Son River was delineated along with clear signature of Patna fault. These results are particularly important in view of the Arsenic contamination in shallow aquifers in the region. In Tamil Nadu, a palaeochannel was mapped between Cuddalore and Neyveli. This palaeochannel clearly revealed the extent of ancient delta region and how the river course shifted in time from nearly N-S orientation to the present E-W direction due to neo-tectonic activity. The results highlight the significance of mapping palaeochannels and their interesting implications to archaeology, tectonics, controlling geo-genic contamination, quaternary tectonics and global warming.

In northern part of the Jaisalmer District, paleo-channels ascribed to the ancient river Saraswati have been proposed in the Ranau - Tanot and Tanot - Longewala region (Singh, 1994; Soni et al., 1996; Gupta and Sharma, 1999; Valdiya, 2002; Sharma, et al., 2006). The CGWB carried out vertical electrical sounding (VES) surveys in the region (Chandra, et al., 1999) and a status report was brought out by the CGWB (2001, Western Region). Since the VES needs good electrical contacts of current and potential electrodes with the earth, in desert environment it gets time consuming needing additional logistics. An alternative method is to employ ground time domain electromagentic (EM) method, that does not require any ground contact, to map the subsurface electrical structure. For this purpose we used the Zonge TEM system with a transmitter loop of 40m X 40m with a small receiver coil placed in the center. The transmitter energized the earth through trapezoidal alternating current pulses in the loop. The transient decay behaviour of the eddy currents induced in the earth were measured by the receiver coil. At each location the transient decay fields were recorded for 5 pulse repetition frequencies at 32, 16, 8, 4, 2 and 1 Hz. The signals were stacked to further improve the signal to noise ratio. The recorded data were of very good quality as the ambient EM noise was low.

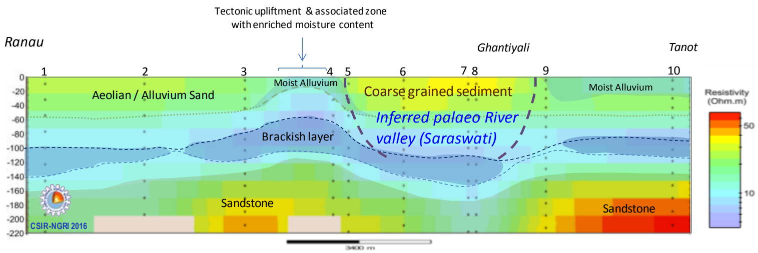

Figure 1: Subsurface electrical section derived from the ground TEM survey conducted along the Ranau - Tanot profile (After Verma et al., 2016).

The electrical section along the Ranau - Tanot profile surveyed by the Zonge TEM system is depicted in Figure 1. Our studies reveal a palaeo-channel located between stations 5 and 9, below and south of Ghantiyali. This channel appears to be flanked by steep structures that controlled the flow of the palaeo river. Also, coarse grained sediments (resistivity ~30 ohm.m) are observed along the inferred river course. In general, a river flows under a valley structure and follows the least resistance path cross cutting the relatively soft structures over different geological formations. The heavy particles get settled down under the gravity along the river course. There are strong structural controls mostly dealing with tectonics and geomorphology in the case of rivers passing through hard rocks. Whereas in alluvium, the river cuts layering structure composed of sand, clay, silt, etc., that provide structural controls. Mitra and Bhandu (2012) have established that the course of paleo River Saraswati is controlled by the fault structure at most of the places. Thus, there are two key parameters in mapping palaeo river channels: (a) structural controls, and (b) coarse grained sediments along the river course.

The shallow moist alluvium over the uplifted structure (pts. 3 to 5) and beyond points 9 & 10 provide good targets for satellite imagery that maps shallow (top few centimeters) soil moisture. The dimension of these shallow moist patches may vary with season as well as over the years. These soil moisture patches have been used by the satellite imagery to reconstruct the course of palaeo river channels (Gupta and Sharma, 1999; Sharma et al., 2006).

Our results clearly establish the efficacy of the TEM survey in mapping the palaeo-channels in desert environment. The results clearly brought out the palaeo river course along with the associated structural controls. Also the coarse sediments along the river channel are demarcated. In comparison to the VES logistics, the TEM survey was found to be very fast as the complete profile from Ranau to Tanot was completed in a single day with base camp located in Jaisalmer (120 km away). However, one should keep in mind a general limitation that most of the ground geophysical surveys in desert can be carried out only along the road side. This can be overcome if the survey is conducted from air. Our experience with the recently concluded AQUIM Project (Ahmed et al., 2015 and Ahmed et al., 2016) has established that conducting helicopter borne geophysical surveys employing TEM and magnetic measurements provide the best tool to delineate subsurface 3D structures with high resolution in fastest and most economical manner, particularly in mapping palaeo-river channels/aquifers in desert. In this context it is worth mentioning that successful mapping of the palaeo river channels in the Thar desert in Pakistan was done in 1992 emloying helicopter borne EM surveys (Ploethner, 1992).

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Very Low Frequency electromagnetic measurements: Theory and applications for mineral exploration

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The Very Low Frequency (VLF) electromagnetic method is a popular plane wave electromagnetic (EM) method to map the shallow geological conductors in large scale due to its low cost and fast survey speed. The VLF method uses high powered and long vertical transmitters as a source of primary field. These transmitters are located around coastal areas worldwide and used for long distance marine communication as well as communication with submarines. Accordingly these transmitters operate on the lower frequency band (15-30 kHz) in comparison to the high and very high frequencies (several hundred kHz to GHz range) used in radio, television and mobile signals. Signals transmitted from these transmitters travel a long distance and can be detected several thousand km away. At sufficiently long distance these signals acts like plane electromagnetic waves. Due to low frequency these signals diffuses into the Earth's subsurface and electromagnetic induction takes place in subsurface conductors. On the Earth surface amplitude and phases of two orthogonal magnetic field components as well as one electric field component are measured and transformed into real, imaginary components, apparent resistivity and phase anomaly. To interpret the VLF electromagnetic data two types of interpretation procedure has been developed namely qualitative, and quantitative. Qualitative approaches are faster than quantitative techniques and provide the apparent/ equivalent current density distribution of the earth subsurface whereas quantitative approaches will provide the true resistivity distribution of the subsurface. The approach is used for mineral, groundwater and other shallow depth investigation. The presentation will focus on theory and applications of VLF method for various mineral deposits. Specific studies related with deposits such as uranium, thorium, chromite, gold, graphite will be emphasized in the presentation.

Ground Penetration Radar: imaging shallow subsurface as intervention to urban problems

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The shallow subsurface of the earth constitute the potential zone for exploitation and is locus of anthropogenic activity. The growth in resource exploitation and urban infrastructure development involve the active interaction of shallow subsurface with the natural/anthropogenic processes. Poorly planned activity in this zone often poses challenge for harnessing resource and the Ground Penetration Radar (GPR) provide one such non-disruptive technological intervention in mapping shallow subsurface. The technique is based on radio EM wave scattered and/or reflected by changes in impedance from an interface of varying dielectric material property thereby characterizing the geometry and location of dielectric contrast in shallow subsurface.

We present results of GPR survey involving shallow subsurface imaging and interpretations from natural environment and civic utility. The shallow subsurface geological setups have implication on natural hazard and health of civic infrastructure. The results of the GPR survey provide reasonable confidence in mapping and managing the civic infrastructure and natural environments without involving disruptive technological intervention.

Geomagnetic studies in India

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Geomagnetic observations commenced in India and rest of the world almost concurrently. The first magnetic observations in India were started at Madras in 1822, followed by the recordings at Simla (1841), Trivandrum (1841) and Colaba (1846). Among these, only Colaba observatory continued uninterrupted since 1841. The combined observations at Colaba and Alibag provide the longest series of magnetic field data. Important scientific observations were recorded by Brown and Moose using Indian data in the nineteenth century. Their findings include dependence of magnetic field variations on the time of day, season, solar cycle and lunar phase. In past six decades, the geomagnetic studies in India has enormously advanced covering wide spectrum from space physics to solid earth geophysics. The presentation will provide a brief overview of the progress made in the field of geomagnetism.

Geomagnetic observations atthe Multiparametric Geophysical Observatories in Kachchh, Gujarat

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The Institute of Seismological Research has established three Multiparametric Geophysical Observatories (MPGOs) at Badargadh, Vamka and Desalparin the seismically active Kachchh region of northwest India, which is host to the devastating Mw 7.6 2001 Bhuj earthquake. These observatories functional since March 2009 are aimed at integrated earthquake precursory investigations in an intraplate setting. Here, we report the magnetic field perturbations due to magnetic storms and moderate local earthquakes. We used the data of one Digital Fluxgate Magnetometer which was deployed in 2009 and three Over hauser and three ULF Magnetometers (LEMI-30), which were installed in December 2012.

We observed a clear variability in the polarization ratio and a marginal increase in fractal dimensions of the ULF magnetic data recorded at Desalpar for the earthquake of 20th June 2012 (M 5.0). The polarization ratio exhibited an apparent increase, as a precursor to this moderate earthquake in Kachchh. We also studied the geomagnetic variations during eleven small magnitude earthquakes (3.8-4.5), during 2011-16. We noticed small anomalies before two earthquakes (29th Sept 2014, M 3.8; 29th July 2013, M 4.5). Similarly, we found anomalous changes in the Total Geomagnetic field before six small magnitude earthquakes. The difference between the total magnetic field data of the two MPGOs (Badargadh and Desalpar), which removes the secular trend of the geomagnetic field, showed an increase prior to these events. We also applied improved polarization ratio (Ida et al, 2008) method to the magnetic data of four years, recorded at Desalpar. The number of peaks in PR data is found to be considerably smaller compared to that obtained by applying the standard method. In order to discriminate the effect of geomagnetic storm activity, the planetary index Kp and Dst were also analyzed in the corresponding period.

The magnetic storm is a worldwide disturbance of the Earth's magnetic field when the plasma bursts emitted from solar flares cause the solar wind to behave erratically. When the plasma comes in contact with the geomagnetic field, it raises the field intensity on the surface of the Earth. This phenomenon was detected for three severe magnetic storms (18 Mar 2015; 23 June 2015 and 07 Mar 2016) by H,D components data of DFM with 1 s sampling rate at Desalpar and TMF data of OHMat Badargadh/Desalpar.This data was analyzed during the storm periods to investigate the characteristics of the local magnetic field components dH, dD and dZ during the events. All the three phases i.e. initial, main and recovery, are clearly visible in the H-Comp during these three storms. The most intense magnetic storm was observed on 21June 2015, with a Dst value of - 205 and KP value of 9. During this storm, the sudden commencement (SC) in the form of a sharp increase of the H-component occurred during the initial phase at 16:45 UT. Then, the main phase occurred when the H-component decreased for a long period of duration. Finally, the recovery phase lasted for 8 days after the storm until 29 June 2015.

Schumann resonances are obtained from ULF/ELF magnetic field emissions recorded by a set of 3-component search coil magnetometer (LEMI 30). Schumann resonances (SchR) are the electromagnetic eigen modes in the almost concentric spherical cavity formed by the Earth's surface and the lower ionosphere layers (at an altitude of approx. 50-60 km). The corresponding eigen frequencies lie in the ELF range (the first one about 7.8 Hz, then approx. 14, 20, 26 Hz and higher). Our analysis of spectrograms of the Induction coil magnetometer and their diurnal behavior for winter, summer seasons, reveals clear appearance of the first three bands of Schumann resonance over two magnetically disturbed days. The effect of summer high solar glint has clearly been seen on 07th Mar 2016. During the afternoon period, the resonance band has depleted with the high temperature. A similar phenomenon has not been observed in the winter season of the magnetically storm regime (1st Feb 2016).

Geomagnetic Precursors: scope in the Indian context

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Over the last few decades significant advances have been made in determination of tectonomagnetic and tectonoelectric effects from minute changes in magnetic and electric fields from high precision measurements using arrays of magnetometers and electric field monitors. The detection thresholds of variations of the magnetic field associated with crustal processes, which are controlled by parameters like sensitivity of the magnetometers, distance from source region and local noise characteristics of the observation site, have vastly improved with modern instrumentation and software capability. Laboratory experiments, mid 1900 onwards have shown that magnetic properties of rocks are influenced by the state of applied stress; strain dependence of electrical resistivity of rocks has also been demonstrated.

Evidences for travelling ionospheric disturbances (TID)s have been recorded for some earthquakes by workers, which are generated by acousto-gravity waves after a moderate or large seismic event. At present, anomalous signatures of TEC variations are the standard tools to investigate ionospheric disturbances before, during and after an earthquake. There is also accumulation of evidences that ULF geomagnetic phenomena may provide reliable evidences of seismic and volcanic events, which are waiting to happen. It is theorised that such changes occur due to emissions from the crust in the source region or electrical structure changes in the subsurface. Rigorous studies are being carried out in Russia, Japan, US, China and Taiwan.

India has an earthquake belt in the north along the front of the Himalayan collision zone and another one to the east along the Andaman-Sumatra subduction zone and is a very appropriate place to study the nature of geomagnetic precursors. A network of geomagnetic observatories provides the required control for identifying signatures not related to seismic/volcanic sources. Several studies have been taken up, showing promising results. A summary of these efforts in the context of global research scenario will be presented.

Regularization of inverse diffusive geophysical problems

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All geophysical problems are ill-posed or ill-conditioned as we have always few numbers of observations, which are always noisy, than the number of parameters needed for quantifying realistic geophysical knowledge. Main problem arises from realization that even if the bounds in error in the observations, data, may be small, but the differences in the exact and approximate solution with noisy data could become large. Since sixties geophysical knowledge has become more definitive after extensive use of inverse methods where the observations are used to localize the solution in a likely solution function space. Tikhonov's regularization has played a great role in this endeavor getting solution based on noisy data and using possible physical based constraints and this theory continues to develop in several new directions. Singular value decomposition (SVD) of matrices is of great help in both theoretical and practical applications in regularization method. Changes in deterministic or stochastic internal electrical and thermal transport properties and sources show up in the observations of diffusive fields at the earth surface. All such inverse problems can be categorized as inverse problems of properties or boundary conditions or initial condition or sources. We shall illustrate applications of Tikhonov regularization to these categories with few selected examples. We shall also present history of use of regularization concept by A Tikhonov and his interest in inverse geophysical problems.

Remote Reference Measurements in Magnetotelluric Methods

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Magnetotelluric (MT) method records times series of horizontal, orthogonal components of time-varying electric field and all the three orthogonal components of the magnetic field are recorded as time series. These time series are typically filtered and fast Fourier transformed (FFT) to estimate the impedance (Z), which relates the observed electric field **E** to the magnetic field **H** as

$$\mathbf{E}=Z\mathbf{H}. \quad (1)$$

The information about the Earth resistivity structure is encoded in the impedance tensor as a function of frequency. Typically, Z is estimated by post multiplying both sides of equation (1) by the conjugate of electric or magnetic fields. The products $\langle E_x E_x^* \rangle$ and $\langle H_y E_x^* \rangle$ are called autopowers and cross powers, respectively. The presence of noise in the magnetic field (Hx), for example, can bias the autopower $\langle H_x E_x^* \rangle$i resulting in upward or downward biased estimates of Z [Sims et al., 1971 and others].

Gamble et al. [1979a, 1979b] showed that employing cross powers incorporating a remote referenced (RR) magnetic field educes the bias effect present in the impedance estimate. In such cases, it is necessary to assume that noise at the RR site is uncorrelated with that of the local site and that the signals are correlated. So the impedance estimates in such cases are effectively unbiased.

However, relatively little information has been available about the maximum distance up to which the far RR has been found to be effective. The initial work of Gamble et al. [1979a] was for a separation of 4.8 km only. Goubau et al. [1984, p. 432] states that ‘‘sources of noise are not well understood, but general experience has indicated that a separation of several kilometres between the base and reference stations is sufficient to ensure that the data are unbiased.’’ Jones et al. [1989] suggested that to minimize the bias errors, RR should be undertaken. They have reported RR measurements with 135 km separation between stations for MT measurements over 5-day intervals. Chave and Smith [1994] suggest that greater attention be given to galvanic distortion of magnetic fields during MT surveys. In Japan, Tarakura et al. [1994, p. 24] find that ‘‘the separation between a measurement site and a reference site is usually at most 20 km.’’ However, they carried out a field experiment in Higosi-Kubiki area, Niligata prefecture, where the noise could be removed sufficiently only when the reference site was 147 km away from the measurement site. Larsen et al. [1996] used a relatively clean MT site in central California ~100 km from the local site to test their code. Egbert [1997] used a remote site at a distance of 100 km from the local site while using his robust processing approach based on multivariate statistical methods. Shalivahan and Bhattacharya (2002) carried out a study to find the farthest distance of a far remote site for crustal study which maintains the effectiveness of the RR technique. From theoretical studies the conditions for valid RR estimates have been obtained. The study shows that the remote site can be kept at a considerably large distance from the local site. In a field experiment a fixed local site and several remote sites have been selected at distances of 80, 115, and 215 km away in the frequency range of 30 Hz to 0.00055 Hz at midlatitudes where the wavelengths of the source magnetic fields are long compared to the site separation. The remote sites are distributed over diverse geological settings. All the data of the fixed local site have been remote reference processed with the corresponding remote sites. The study reveals that using a remote site located at as large a distance as 215 km results in unbiased observations and remains effective in improving the MT data quality for all frequency ranges.

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Processing of Magnetotelluric Data by Continuous Wavelet Transformation

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Current practice of use of Fourier transform (FT) for Magnetotelluric (MT) data processing has been proved to be helpful for estimation of the MT transfer function. However, as well known, the MT data have always been severely affected by natural source noise, such as MT dead-band noise at 0.1 Hz – 10 Hz and at audio-MT frequencies, 1 KHz – 5 KHz. As a result, the estimated MT transfer function was always biased. Fourier transform has been found to be of little usein minimizing the effect of these noises on the estimated impedance. This is the limitation of FT. Therefore, novel signal analysis tools must be applied to improve the MT response function. Wavelet analysis, because of its ability to provide the best time-frequency localization of signals, is one of the novel signal analysis techniques that can be effectively used to enhance the signal-to-noise ratio of MT signals. Wavelet analysis facilitates to easily identify the transients in the data noise in the time-frequency plane, and by choosing the corresponding wavelet coefficients, an unbiased MT response function can be estimated. In the present study, we discuss the use of continuous wavelet transformation (CWT) to determine the unbiased MT response functions. We present the preliminary results of CWT analysis of MT data recorded at Kachchh region, Gujarat, India. We compare and discuss the CWT results obtained by using Morlet and complex Gaussian wavelets.

Directionality in the EM signal

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The concept of electromagnetic (EM) signal decomposition into the two modes is based on the directionality criteria and is a proven useful tool. Of course, this is because of the gained mathematical simplicity and better accessibility to a conductive structure. Fundamentally, there are two physical ways for generating an EM signal. The first by the magnetic field (i.e. Faradays law) and the second by the electric field (i.e. Ampere-Maxwell Law). Both, electric and magnetic fields, always act together for reinforcing the existence of each other in the space. Directional criteria is when imposed, two EM modes can be constructed. In the one construction, when electric field E_{ψ}, and in the other, when magnetic field B_{ψ}, is tangential to the surface z_{ψ}, = constant, the modes are respectively called tangential electric (TE) and tangential magnetic (TM) mode. Responses in two modes are dissimilar even for an identical structure because of the difference in the current system. The TM mode carries magnetic field in the strike (horizontal) direction and current encloses it in the perpendicular plane. On the other hand, in the TE mode, an electric current flows in the strike direction and magnetic field encloses it in the perpendicular plane. In short, the TM mode has vertical while TE has horizontal electric current system. Creation of charges is interesting characteristic in the TM mode. TE mode is an inductive mode.

Some EM methods use the directional characteristics during the data processing and acquisition. However, some uses in the instrumentation like the VLF (very low frequency, 5-25 KHz) method. Here, two magnetic sensors are used for self referencing. One having the vertical orientation and the other either in line with the transmitting antenna or tangential to this direction.

Usually, the EM field direction is given by the Pointing Vector (E x H), which demands the knowledge of both electric and magnetic vector. It rates the total power flow per unit area. However, often one has only the electric or magnetic field data. Then, finding the direction is complicated. We suggest a simplified approach as spectral-directionalogram (SD-gram). This maps the spectral line direction of a vector field with respect to the time. Method allows an easy investigation of the spectral direction. Simulations are done for evaluating the limitations and advantages of the method. Finally, using a marine controlled source electromagnetic data, we will demonstrate an application of the method.

In short, primarily we will discuss the necessity and use of the directionality in the EM investigations.

3D forward Modelling and Inversion of Controlled-Source Electromagnetic data

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The controlled-source electromagnetic (CSEM) method is an important tool for subsurface conductivity imaging. Forward modelling and inversion algorithms are essential for analyzing and interpreting the observed data. Accurate interpretation necessitates accounting of three dimensional (3D) variation of subsurface conductivity. Here, I shall present the salient features of the algorithm developed by us for 3D forward modelling and inversion of CSEM data.

In 3D forward modeling algorithm for CSEM data, the Finite Difference Method (FDM) is used for solving the governing (Helmholtz) equation. A staggered grid is employed for accurate simulation of nodal fields. The source singularity is overcome using the primary/secondary field approach. A preconditioned iterative solver is used for solving the matrix equation for secondary field. It is efficient both in terms of memory and computation time. The convergence of iterative solver is improved further by applying the static divergence correction.

The Gauss-Newton optimization technique has been used for solving 3D CSEM inverse problem. The storage of Jacobian matrix requires huge memory, hence, the formation of Jacobian matrix is generally avoided. It is achieved by using the conjugate gradient (CG) solver where only matrix-vector multiplication is needed to solve the system of equations. The adjoint field approach has been used for efficient computations which make the CG iterations independent of the number of forward/adjoint solver calls. For insightful demonstration, the matrix operations for CG iteration are presented through block matrices. The parallel computing platform OpenMP has been used for efficient computation. Finally, I shall present the inversion results of synthetic and Troll field data to discuss the versatility and efficiency features of the developed algorithm.

Electrical Resistivity Imaging of Frontal Himalaya: Implications on Seismogenesis and Seismotectonics

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Imaging of internal structures and physical state of rocks in the Himalayan collision belt continues to be challenging as it holds key to understand the process of Seismogenesis and Seismotectonics. Given the sensitivity of the electrical resistivity of rocks to fluids and temperature, extensive magnetotelluric measurements in the Himalaya have begun to complement the active and passive seismic imaging programs. The imaged resistivity cross-section is dominated by a low-angle north-east dipping intra-crustal high conducting layer (IC-HCL). At transition from the Lesser Himalaya to the Higher Himalaya, the IC-HCL is marked by a ramp structure across which its top jumps from a depth of 8 km to 13 km. The high conductivity of the layer, immediately above the positive seismic interface can be attributed to the impoundment of upward propagating metamorphic fluids trapped by tectonically induced neutral buoyancy. Modulation of frictional coupling and mechanical weakening by high-pore pressure fluids counteract the arc-normal stresses creating conditions for failure and nucleation of the large earthquakes, e.g. 1991 Uttarkashi and 1999 Chamoli earthquakes on linear plane viewed as top of the IC-HCL. In this tectonic setting, the high conductance ramp symbolizes a block of low shear strength and high strain, which under the deviatoric stresses release accentuated stresses into the brittle crust, thereby generating small but more frequent earthquakes in the narrow Himalayan Seismic Belt. Such a seismotectonic model is fully corroborated by the 2015 Mw7.8 Gorkha earthquake which was rooted in the high conductivity zone. Examination of spatio-temporal patterns in aftershock activity of this earthquake favours that main shock-induced stress fields facilitated upward injection of high pore-pressure fluid fluxes into the hidden out-of-sequence thrust, creating conditions to trigger Mw7.3 aftershock.

Magnetotelluric Experiments in NW Himalaya

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Electrical resistivity, sensitive to rheological properties, is an important parameter to understand geodynamic evolution of Himalaya, particularly understanding of the seismogenesis of earthquakes. Magnetotelluric (MT) investigations in order to derive subsurface electrical resistivity variations are now routinely being employed in Himalaya. Although, few profiles across different sector of Himalaya has been covered but most of them are delimited with the inaccessibility factors in this mountain terrain. Therefore most of profiles do not reflect image of all the tectonic units accessible in Indian region. We have attempted a profile of Broadband MT from Bijnaur to Mallari covering right from the Indo-Gangetic plains to Southern Tibetan detachment (STD). Electrical resistivity cross-section across this profile in Garhwal Himalaya is dominated by low-angle north-east dipping intra-crustal high conducting layer (IC-HCL) with a ramp at the transition from the Lesser to Higher Himalaya. We interpret the low resistivity of IC-HCL layer in a depth range of 10-15 km is caused by the fluid reservoirs formed by stalling of upward propagating metamorphic fluids and/or tectonically induced neutral buoyancy. The effect of fluids counteracts the fault-normal stresses, facilitating brittle failure at lower threshold and therefore explained clustering of hypocentres of great earthquakes on a surface defining the seismically active detachment beneath the Sub and Lesser Himalaya. Ramp symbolizes block of low shear strength and high degree of strain, which under the deviatoric stresses releases accentuated stresses into the brittle crust to generate small but more frequent earthquakes in the narrow Himalayan Seismic Belt. In the compressional regime of the Himalaya, the upward propagation of fluid fluxes through the over pressured zones allows to see mega thrust and shear zone as locales of concentrated seismicity. Integrating the resistivity cross section of Darcha-Mallari profile, which complement the Bijnaur- Mallari profile from STD, with this section shows continuation of mid crustal conductor toward north side, indicating the role of channel flow model in Himalayan tectonics. In this paper brief details of completed few magnetotelluric profiles along different sector of Himalaya with emphasis on Bijnaur-Mallari profile will be discussed.

Imaging of deep crustal fluids in the Kachchh region – Implications for seismogenesis in an intraplate environment

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The Kachchh rift basin in the northwestern part of the stable Indian shield has experienced several moderate and large magnitude earthquakes like those in 1819 (Mw7.8) and 2001 (Mw7.7). Magnetotelluric (MT) investigations along two profiles in the eastern Kachchh region reveal an assemblage of resistive and conductive features down to upper mantle. The electrical structure reflects the major tectonic features, namely faults, fracture zones and magmatic intrusives. A very high conductive zone (< 10 ohm.m) revealed by the 2-D geoelectric model suggests presence of a fluid reservoir at depths of 35-40 km. The near vertical north dipping mantle reaching South Wagad Fault (SWF) and the south dipping north Wagad Fault imaged in the model seem to serve as feeders for the fluid flow from the reservoir to the epicentral depths. Further, we interpret that the migration of fluids from the reservoir and the injection into the fractured regions of the crust or the fracturing of the region due to the fluid injection could explain the aftershock activity in the region. We also hypothesize trapping of fluids at the shallow brittle-ductile boundary and devolvement of a creeping segment over the Gedi fault zone. The interconnection of the different parts of the region through the fluid pathways seen in the geoelectric model indicates that the Kachchh basin had undergone considerable deformation during its tectonic history. The present study clearly demonstrates the role of fluids in seismogenic processes in an intraplate region.

EM induction studies by IIG in Andaman Islands, NE Indian Ocean

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Electromagnetic (EM) fields are widely used to study the geodynamic processes of the Earth due to their deeper penetration into the Earth and ability to resolve the parameter (in terms of electrical conductivity) of complex geological structures. The electrical conductivity (apart from being determined by chemical constituents) is sensitive to most of the thermodynamic processes in the Earth, such as partial melting, phase transition, fluid content etc. Therefore, measurement of electrical conductivity can provide knowledge of the present state and temperature of the Earth's crust and upper mantle.

To determine the electrical conductivity distribution beneath Andaman-Nicobar region (outer arc region), Geomagnetic Depth sounding (GDS), Magnetotelluric (MT) and long period Magnetotelluric (LMT) surveys were conducted. Regional Geomagnetic depth sounding carried out in Andaman-Nicobar region brings out conductivity anomalies associated with (a) the Cretaceous–Tertiary sediments filling the Andaman–Nicobar sedimentary basin whose depth and conductivity increases towards SE of Car-Nicobar, (2) the Invisible bank is due to partial melts/volatiles that have intruded into the eastern margin of the fore-arc basin through the west Andaman fault (WAF) and (3) the highly conducting sediments filling the southern part of Mergui basin along with mafic intrusions within the basin.

Local EM conductivity anomalies along the eastern margin of Andaman Islands have been reflected in MT/GDS studies that can be attributed to expelled free water due to compaction of subducted sediments and collapse of porosity in the upper oceanic crust. This has been reflected as highly conducting obducted sediments that are scrapped off the subducting plate to form an accretionary wedge or prism extending to a depth of about 10-15 km along the eastern margin of Andaman Islands.

The same is observed in pilot long period Magnetotelluric (LMT) soundings that were carried out in the south Andaman Islands to understand the Geoelectrical structure of the outer arc region and nature of the subducting Indian plate in Andaman Sea. 2D inversion that best fits the observed data also brings out a deep seated conductivity anomaly at a depth of about 100-

120 km that could be related to partial melts related to the ongoing tectonics of the region. IIG is planning to carry out more detailed surveys in the Andaman Islands.

In addition, ocean bottom magnetometer studies across the volcanic arc region (Barren Island) brings out a high conducting zone at a depth of about 17–27 km. The enhanced conductivity at a shallow depth is due to the concentration of magma chambers that may have been produced by an upwelling of the mantle material). Most probably, a partial melting of this magma chamber may have given rise to the volcanic activity that is taking place at Barren Island.

Electrical signature of Narmada Son Lineament region from 3D magnetotellurics

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As a part of integrated geophysical approach for sub-basalt Mesozoic imaging in the Narmada Son Lineament region, large scale magnetotelluric (MT) data was acquired at 500 stations in a grid fashion with an inter site spacing of 7-8 km during the year 2000-2003. The study area is mainly covered by Deccan Traps and the Tertiary sediments are exposed at few segments such as to the west, northwest and centre of the study region (20.95 ^{o} to 21.89 ^{o} N and 72.75 ^{o} to 75.31 ^{o} E). Considering the computational constrains and the data quality a part of the data (i.e 153 MT stations) was considered for 3D modeling. Four impedances were inverted using WSINV3DMT in the frequency range 0.03 to 100 s. The modeling results brought out several major crustal conductors with different geometrical configurations, distributed at different depth levels. This evidently points out to a more complex structure and a prominent heterogeneity of the crustal column suggestive of an intense crust mantle interaction. These conductive features are inferred to be mafic-ultramafic bodies intruded into the crust from mantle and represent the intrusive component of the Large Igneous Province of the Deccan volcanic province. We propose that the disposition and geometry of the conductive bodies, which must have served as magma chambers for the Deccan volcanic activity, is closely associated to the plumbing geometry of the Deccan Volcanic Igneous province.

3D Imaging of Lithospheric structure beneath NW Indian shield: An MT perspective

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The NW shield region of India comprises of four major terrains, namely the Marwar, Aravalli-Delhi fold belt, Mewar and Bundelkhand. The region presents a wide range of geological formations of different ages, ranging from oldest crustal segments (>3.5 Ga) to the Tertiary basins like Jaisalmer and Barmer. The magnetotelluric (MT) method, which make use of the natural electromagnetic fields on the earth surface, has been widely utilized to distinguish between old (high resistive) and young (low resistive) lithospheric blocks of contrasting age. Here, long period (30-30,000 s) MT data has been acquired in a grid fashion, with an average station interval of ~55 km, in different parts of Rajasthan and adjacent regions in Madhya Pradesh and Gujarat states covering an approximately 500 x 500 km^2 area of NW part of the Indian subcontinent. 3D inversions of the full MT impedance tensor from 120 locations, on a quasi-regular grid, were performed using the WSINV3DMT algorithm. The 3D resistivity depth sections revealed extensive areas of high conductivity in the lower crust and shallow upper mantle regions to the west of the Delhi-Aravalli Mobile Belt (DAMB). A reduced resistivity feature following the western edge of the SW-NE oriented Proterozoic DAMB is imaged from mid-crustal level to upper mantle depths, indicating the Paleo-suture between Marwar and Bundelkhand cratons. A crescent shaped high resistive (>10^3 Ωm) zone delineated at lower crustal depths in the eastern side of DAMB represents the southwestward extension of the Bundelkhand terrain up to DAMB. The geoelectrical model also shows a prominent and narrow (~100 km wide) lithospheric scale linear conductive (<200 Ωm) feature extending from Jaisalmer in the NW to Ujjain in the SE. This can be attributed to a pre-outburst trace (70-65 Ma) of the Reunion mantle plume erupted in the form of Deccan traps at ~65 Ma. In general, shallow asthenosphere is imaged towards northern and southeastern parts of the studied region.

VLF anomalies associated with gold mineralization near Lawa village, North Singhbhum Mobile Belt, India: A Preliminary study

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North Singhbhum Mobile Belt (NSMB) which is almost 200 km long and comprises the Dhanjori, Chaibasa, Dhalbhum, Dalma and the Chandil Formations and has a complex history of lithology, structure, metamorphism and tectonic setting which closely mirrors other gold producing orogenic metamorphic mobile belts. Lawa village which is located in Patamda Tehsil of Purbi Singhbhum district in Jharkhand, India is a part of North Singhbhum Mobile Belt. A detailed Very Low-Frequency Electromagnetic (VLF-EM) study has been carried out around Lawa village to investigate the lateral extension and depth extent of the subsurface structures associated with gold mineralization. The VLF-EM data in the study area was contaminated by non-stationary and nonlinear noises where the noises could not be removed by conventional filtering methods. Therefore, to recover signals with considerable geologic information is must. For this purpose present work used empirical mode decomposition (EMD) technique. Further, the apparent current density pseudo-sections were obtained by using Karous and Hjelt (K-H) filtering technique. The preliminary results show the good correlation between each VLF profile and a steeply dipping conductor with E–W strikes was identified. The results obtained from VLF data were also compared with other geophysical methods like self potential and direct current method.

Geologic separation using fuzzy constrained resistivity tomography

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Most of the geologic units often have distinct range of resistivity values. Statistically similar resistivity values can be grouped into one unit or cluster by using any clustering algorithm. In the present study with the assistance of fuzzy c means clustering procedure of resistivity distribution and geologic separation were accomplished. The highest membership value which is a direct outcome from the fuzzy constrained resistivity tomography corresponds to a geology separation result during iterative minimization. Synthetic electromagnetic data examples showed the efficacy of presented fuzzy constrained resistivity tomography to improve the resistivity image and it is also a reliable tool to separate two geologic units within the inversion. We have also noted that if resistivity values of the geologic units will be close to each other it will not be able to fit distinguish between them however inversion can fit the observed data equally well.

As a case study, we have used fuzzy constrained resistivity tomography to identify the extension of uranium bearing target rock around Beldih open cast mine. Presented FCRT is good way to differentiate between target rock (kaolinite and quartz–magnetite–apatite rocks) with ultramafic rock ultramafic rocks (host rock), and Quartzite/Alkaline granite. However it has some limitation like it not able to differentiate between kaolinite rock and quartz–magnetite–apatite rocks. This is the limitation of the present study.

Key words: plane wave electromagnetics, electrical resistivity; inversion, geologic separation, fuzzy c-means clustering.

EM imaging of Saurashtra region

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EM techniques have been used to map the geoelectrical structure of Saurashtra region. Geomagnetic deep sounding (GDS) involves in recording the geomagnetic field variations by an array of magnetometers that are widely spread in Saurashtra region. Induction arrows are computed showing the relationship between vertical and horizontal magnetic field components that serves as a diagnostic tool for lateral electrical conductivity variations. From the spatial distribution of these arrows, it is inferred that the sediments filling the offshore basins are more conducting than the basins in Saurashtra region. Z/H pseudo sections suggests anomalous conductivity anomaly in the eastern part of Saurashtra region that decreases with periodicity.

2D inversion of GDS responses (related to the ratio of vertical magnetic field (Hz) to the horizontal fields (Hx and Hy)) brings out conductivity anomalies associated with sediments and beneath the basins. Most probably, upward migration of CO_2-bearing volatiles through fault zones during the emplacement of basalts is the likely source of the enhanced conductivity.

1D Occam inversion of long period Magnetotelluric (LMT) data in northern part of Saurashtra brings out a high resistivity layer in the eastern part of Saurashtra region that is extending up to mantle depths.Another high resistivity block is observed in the western part of Saurashtra that extends up to 50 km. These high resistivity blocks may have formed due to the ascent of magma through the lithosphere due to the partial melting of the mantle. Later, cooling and solidification of magma may have given rise to resistive blocks. High resistive block underlies Jasdan basin/plateau.

Study of Lithospheric structure across north Cambay rift basin using Magnetotelluric study

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To study the impact of reunion mantle plume on continental lithosphere and Geodynamics of Western Continental margin of India, we have acquired 109 stations Magnetotelluric data containing both long period (LMT) and Broad Band Magnetotelluric data (BBMT) along four profiles of E-W direction. The data has been processed and resulting responses were subjected to decomposition approach using multi-site, multifrequency analysis code of MacNeice and Jones. This has brought out two major strike directions of Cambay basin (N5^{0}E and N12^{0}W) and Precambrian trends (N50^{0}E and N59^{0}E). The tensor decomposed TE and TM modes are inverted using the 2D algorithm, as implemented in WinGLink (Schlumberger). The preliminary 2D inversion models of the four profiles indicate a very high conductive Tertiary and Quaternary/Eocene) sedimentary deposits with resistivity 5-15 ohm. The thickness of the sedimentary deposits vary from 1-5 km, shallow in Kutch basin and is thickest in Cambay rift basin. At mid to lower crustal depths a low resistivity layer of 20-40 ohm-m is delineated outside the Cambay basin due to presence of fluids. A high conductive layer on the eastern edge of the Cambay rift basin is delineated at 50 km depth interpreted as due to an elevated thermal anomaly in the rift basin. Lithosphere-Asthenosphere boundary (LAB) is delineated at depth of 180-200 km outside the rift basin and whereas within the eastern edge of rift basin the LAB is raised up to 150 km interpreted as modified mantle due to the Deccan plume.

Key words: Cambay Rift, Lithosphere, Magnetotellurics, Reunion plume.

Depth of Investigation of Magnetotellruic method from phase

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Being an electromagnetic (EM) technique, magnetotelluric (MT) is associated with phase lag between the inducing (H-Field) and induced (E-field) fields. In the present study this phase lag along with the instantaneous phases of H-field and E-field fields are taken to calculate the depth of investigation (DOI) of MT method. To apply the earlier concept on DOI, one has to do the 1D inversion and then calculate different parameters for DOI estimation. But our study has proposed a simple and direct method for computing the DOI of MT method which is based on the observed data only. So, for that a relation between the phase lag and depth is derived from Maxwell's equation. After that, the derived relation is applied on synthetic and real data. While comparing the DOI by the new approach with the DOI calculated by the approach of Spies (1989), the outcome seems to be satisfactory.

Magnetotellurics data analysis with Mohr circle approach

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Mohr circle represent graphically stress on given geology structure, are used to quantify the strength of materials in under given stress. For magnetotellurics (MT) data, Mohr circle takes real and imaginary components of MT tensor individually to understand the MT impedance information. Mohr circle represent graphically 1, 2 and 3-dimensionality, skew and anisotropy or strong 3-D distortion over the response of MT tensor. We examined the MT data from Rewa-Shahdol region with Mohr circle for individual frequency and compared these results with polar diagram and skew.

Shallow subsurface imaging of the Wagad active normal faults system (Kachchh, northwestern India) by time domain electromagnetic studies

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The Kachchh region in north western Indian shield is one of the most seismically active intraplate regions of the world. The Wagad region in the eastern Kachchh basin lies in between the south Wagad Fault (SWF) and Gedi Fault (GF), is an elevated terrain comprises couple of other active faults and believes to be reactivated after the 2001 Bhuj earthquake. The surficial expression of the faults in some places of the Wagad region are concealed by recent Holocene deposits and difficult to image using conventional DC electrical imaging studies. The Time domain electromagnetic method (TDEM) has proven to be effective tool in mapping these concealed geological structures and can image the transposition of the various litho units in terms of resistivity contrast. Further, unveiling the nature of the shallow basin infill mainly from alluvium fan filling is very important in evaluating the role played by the active faults in its depositional evolution. Here we present the results of TDEM investigations carried out across the Wagad highland which display significant details of the fault structures and geometry of shallow basin infill down to 200 m. The obtained resistivity section including topographic variations shows significant resistivity contrast across the fault zones. The shallow layer of the basin infill across the Chitrod normal fault (a branch fault of the SWF) has a Wedge shape made of unconsolidated deposits with thickness of ~15-20m might be due to syn-tectonic growth of the alluvial fan filling the accommodation space provided by the hanging wall subsidence. The resistivity model indicates a minimal ∼110–120 m estimate of the cumulative throw of the CF in the investigated section. A throw of 45-50m in across the NWF is estimated. Interestingly, between the CF and the NWF, displacement of two blocks is seen with an estimated throw of 50-55m. Across the GF, the derived resistivity section indicates least block displacements (less than 40 m) which might either due to dominate strike-slip nature of faulting in addition to normal or more activeness of NWF compared to GF during the recent geological past. The study highlights the efficacy of the TDEM studies in structural geology and morphotectonic studies in the active intraplate region.

Variations of Total Magnetic Field before two small magnitude Earthquakes in Kachchh, Gujarat, India

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In this study, variations of Total Magnetic field recorded in overhauser magnetometer at Multi Parametric Geophysical Observatories (MPGO) of Badargadh and Desalpar are analysed to correspond with small magnitude earthquakes occurred in 2014 in Kachchh, Gujarat employing different techniques such as power spectral density, fractal dimensions and principal component analysis. To reduce the effects of manmade and atmospheric perturbations magnetic data of mid night (i.e., 18-21 UTC) times were considered. Two small magnitude earthquakes occurred on 9^{th} March 2014 (Mw 4.1, R=58 km) and 29^{th} April 2014 (Mw 3.8, R=43 km) within the preparatory zone were studied in this analysis. In order to discriminate the effect of geomagnetic storm activity, the planetary index Kp and Dst were also analyzed in the corresponding period. These parameters are found to be normal during 9th March event and high during 29th April event. Total Magnetic field however, recorded considerable enhancement (10 nT for 9^{th} March event and 30 nT for 29^{th} April event) three days prior to these events. These enhancements persisted during the event and latter decreased exponentially. The difference between the total magnetic field data of the two MPGO Observatories (Badargadh and Desalpar), which removes the secular trend of the geomagnetic field showed exponential increase prior to these events. We here by conclude that the observed magnetic anomaly prior to 9^{th} March earthquake might be related to seismogenic origin while we cannot attribute the variations before 29^{th} April with local earthquake activity as there was a record of global geomagnetic effects during this period.

Key Words: Total magnetic field, Principal Component analysis, Fractal dimension, PSD, earthquake

Geo electromagnetic induction vectors along Northern Indian Ocean

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Significant results of induction arrows from magnetometer deployed along northern Indian Ocean are analysed for evidence of electrical conductivity structures in the region. Here we are using short period geomagnetic variations (minute mean data) contains information about the crust and upper mantle depth.

The Andaman-Nicobar subduction zone is the one of the most seismically active regions of the world, which is also characterised by several factors like oblique subduction, arc volcanism, and Andaman spreading ridge in the Andaman Sea. EM studies are used to derive lithosphere conductivity structure, which provide constraints on the dynamics of the Andaman-Nicobar subduction zone.

To investigate the conductivity structure of the crust and upper mantle, electromagnetic variation data over a period of two years was acquired at six sites along Northern Indian ocean. Induction vectors were estimated at the six sites NBG (Nabagram) & PBR (Portblair) in Andaman , KTC (Katchal) & CBY (Campbell Bay) in Nicobar, VEN (Vencode) in Kanyakumari and MNC(Minicoy) in Lakshadweep using 1minute magnetic variation data over the periods 4-140 minutes. On the whole the amplitudes of the real and imaginary components approximately vary between -0.5 to 1 and -0.5 to 0.5 respectively. The directions of the real vectors are mostly eastward, however there is significant variation at the sites from north to south and also at different seasons at Andaman-Nicobar Islands. Impedance tensors calculated at each site was used to generate 1D conductivity models of the subsurface. It is possible to infer that the conductivity structure differs significantly over the 800km length of Andaman-Nicobar subduction zone and along northern Indian ocean.

Keywords: Andaman-Nicobar subduction zone, Induction vectors, Conductivity structure.