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Role of Geophysics for Economic Exploration and Production: Oil and Gas, Base Metal and Coal

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Abstract

A few case studies are illustrated here to demonstrate how exploration and production cost or investment pain can be minimized in oil and mining industries with the use of modern geophysical techniques. Surface geophysics, particularly active seismology or seismic prospecting as well as borehole geophysics are the most common and popular techniques in oil and gas exploration. Passive seismology or modern micro-earthquake seismology, on the other hand, can play a vital role in oil and gas exploration in an inaccessible area. It has also an important role in Enhanced Oil Recovery (EOR) during production. In mineral or coal exploration, along with the surface geophysical surveys (say, gravity, magnetic, electrical etc.) borehole geophysical methods play a major role for mining planning and economic production. The micro-earthquake seismology also can be very useful for underground mining planning, particularly in rock burst or roof collapse problems, for hazard free production.

Keywords: *Active Seismology, Borehole Geophysics, Micro-earthquake Seismology, Passive Seismology, Surface Geophysics*

1.0 Introduction

Oil and gas, mineral and coal exploration or production are the basic needs for the growth of industries, and economic development of a country. In India, the first oil field was discovered on surface evidences of oil seepages in Digboi, Assam in 1886, and the first drill hole for oil production was made in 1890. Since1948 Geological Survey of India (GSI) initiated systematic geophysical surveys for oil and gas exploration. In 1956, the ONGC (Oil and Natural Gas Commission, now Corporation) came into being for this specialized exploration, and in 1973 the OIL (Oil India Ltd). At present many oil companies including several global companies are investing for oil and gas exploration in the country.

The history of minerals or mining in Indian sub-continent, however, took place during the Harappan era, starting around 800 BC. India is a mineral rich country with its own history for coal, copper, lead or Zinc, gold mining *etc*. Underground gold mining perhaps started some 2000 years ago, and commencement of coal mining dates back to the year 1774 (Soni[1]). All these historical mining were based on surface geological evidences. In the present era, we are, however, run out of exposure or evidences of oil or minerals on the surface. Technology is developed for exploration of the subsurface natural wealth, which requires judicious investment and planning, economic evaluation and production. Here we present a few field examples to illustrate how the modern technology in geophysics can be used, which may, however, fail at times, for economic planning and production of oil and gas, base metal and coal.

1.1 Oil and Gas

In oil and gas exploration, among various surface geophysical techniques, seismic reflection survey is the most popular and efficient method to identify subsurface favourable structures for oil or gas bearing formations (*e.g.* McQuillin *et al.*[2]). Before conducting this expensive seismic survey, the regional gravity or magnetic maps are examined for selection of sites. However, seismic reflection survey can only identify a favourable subsurface structure that may be oil or gas bearing. Based on this survey, drilling is recommended, but it is generally found that the

success rate is no more than 1: 5, *i.e.* out of five boreholes only one may hit success, four may go dry. Such success rate is also considered to be much economic compared to oil prices. After drilling, the borehole geophysics or well logging plays the most vital role to identify the oil bearing horizons or reservoirs at depths and to determine all required parameters to estimate the oil or gas reserve.

In an inaccessible area, say in dense forest or tea gardens, such active seismology or seismic survey by huge explosive blasting and recording the generated seismic waves along a long geophone array may not be possible. In such cases, if the study area is prone to natural earthquakes, exploration pain may be reduced by passive seismology technique, *i.e.* by recording seismic phases of micro-earthquakes (magnitude<3.0), which occur in hundreds and thousands during a short time period in any seismically active area, say in northeast India region of our country. Here a field example is illustrated where a dense micro-earthquake network in an inaccessible area is deployed (Figure 1). Some 70 or more seismic stations are closely installed to record the micro-earthquakes in a seismically active oil field. A large number of events (more than 2000) are recorded in a few months. The P and S phases of these events recorded by the digital seismic stations are precisely read and analyzed for the source zone locations as well as for imaging the velocity structure below the study area (Figure 1). These results are critically examined to identify the oil or gas zones below the area as exemplified.

In Enhanced Oil Recovery (EOR) operation the role of micro-earthquake seismology is also immense. A field example is given in Figure 2, which shows micro-seismicity caused by hydro-fracturing in the reservoir rock. The micro-seismicity is generated or induced by fluid or gas injection into the formation. The injection causes hydro-fracturing in the reservoir formation, and the induced micro-earthquakes are recorded. The micro-seismicity trends indicate lateral extent of hydro-fracturing along the existing fault (s) or newly developed transverse cracks. The cross-section of the events reflects the reservoir formation or horizon at a depth 1.0-1.5 km (Figure 2). These valuable information obtained by the micro-earthquake seismology technique, no doubt, are much useful for planning oil production.

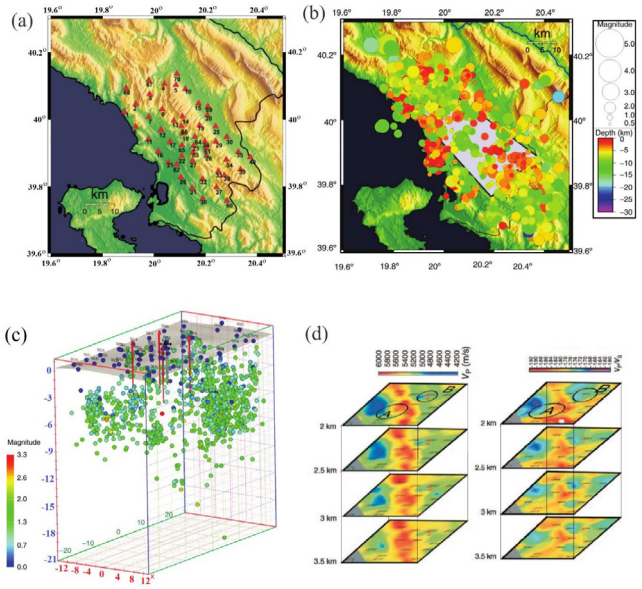


Figure 1. **(a)** A close spaced 70-station micro-earthquake network, **(b)** micro-seismicity map, **(c)** depth section of the events, and **(d)** Vp and Vp/Vs seismic images identifying A: Oil and B: Gas bearing formations, Albania oil field[3].

2.0 Base Metal

Detailed surface geological, geochemical and geophysical surveys are normally carried out for identifying subsurface mineralized sites for drilling (*e.g.* Bacon[5], Gupta *et al.*[6], Haldar[7], Moitra *et al.*[8]). Based on detailed surface geological and geochemical maps, potential sites are selected for geophysical exploration. The geophysical exploration techniques may include detailed gravity, magnetic and electrical methods. With modern technology in electrical methods, electrical tomography may be a very useful technique to image subsurface conductive zones for selecting drilling points. Normally, 90 per cent or more mineral boreholes go successful. After drilling, geophysical logging is carried out to define the mineralized zones at depths (Kayal[9]). The drilling cores or rock cuttings are critically examined along with the borehole geophysical logs to assess the mineralized zones at depths. Here an example of single electrode resistance and Self-Potential (S.P.) logs is shown for copper sulphide deposits in a borehole, Mayurbhanj district, Odisha (Figure 3). It is a simple single-electrode logging technique that not only clearly delineated the sulphide deposits at depths but also show a good correlation of the log responses with the Cu percent in the deposits. The borehole geophysical logs exhibit low resistance or resistivity and significant

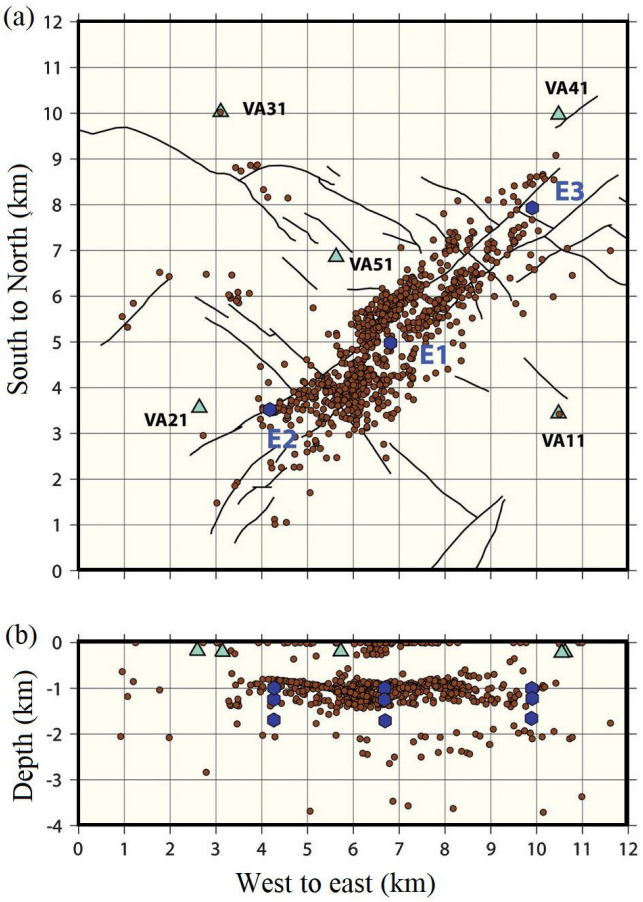


Figure 2. **(a)** Hydro-fracturing induced seismicity by fluid injection in EOR operation showing the lateral extent and trend of the fracture propagation, the triangles indicate the seismic stations, E1-E3 the existing faults, and **(b)** depth section of the events showing reservoir horizon at a depth 1.0-1.5 km, Oman oil field[4].

low self-potential responses with higher Cu percent mineralization. Such investigations are most important for economic evaluation and planning for mining activity.

Further, to investigate lateral extent of the mineral zones 'Mise-a-la-Masse' geophysical technique maybe employed. This method is useful if an ore body is exposed on the surface or discovered in a borehole during drilling. The ore body is charged with one electrode on the exposed ore body or in the borehole and one electrode on the surface at an infinite distance, the other two potential electrodes search the lateral extent of the conductive ore body in the vicinity. Successful results were reported by Gupta *et al.*[6], in mineral exploration in Rajasthan to recommend more boreholes for the target ore bodies.

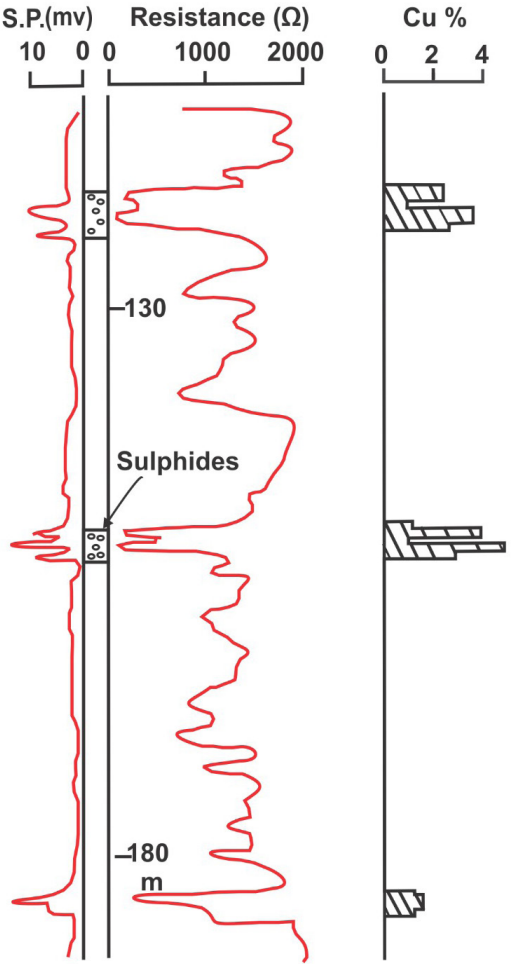


Figure 3. Single-electrode resistance and S.P. logs recorded in a borehole with sulphide deposits, and correlation with copper percent, Mayurbhanj, Odisha, India[9].

They recommended five drilling points, four hit the mineralised bodies.

3.0 Coal

In coal exploration, first a regional geological and surface geophysical mapping is conducted (*e.g.* Pant and Murty[10]). Drilling and borehole geophysical logging are, however, the most extensively used techniques to delineate coal beds at depths (*e.g.* Tixer and Alger[11], Reeves[12], Kayal[13]). The borehole geophysical logs, if properly recorded and analyzed, can play a major role in coal mining planning. The logs also help in evaluating the coal quality (*e.g.* Reeves[12], Borsaru *et al.*[14] Kayal and Christoffel[15]). An example of resistance, S P and Gamma-ray logs recorded for Tertiary coal in Assam is illustrated in Figure 4. The

logs show good correlations against coal seams and shale partings within it. The coal seams are characterized by high resistance, low SP and low gamma responses. Shale in coal bearing formations show higher gamma responses and sands lower responses, whereas coal beds show lowest gamma response (Kayal[13]). In this example, it may be noted that upper part of the borehole (from surface down to 72m) was cased due to caving problem in the borehole; the Resistance and S.P. logs could not be recorded, but the gamma log could be recorded in cased part of the borehole also. Shale line and sand line are drawn based on the gamma responses, and the log is diagnostic to delineate the coal seams (Figure 4). Based on multi-parameter borehole geophysical logs, (like, multi-electrode resistivity, Gamma-ray, Neutron, Density and Sonic logs) empirical formulas are developed by multiple regression analysis for coal quality estimation in terms of ash, moisture, fixed carbon and volatile matter content in Gondwana and Tertiary coals of India and New Zealand[15]. It is found that these precise borehole geophysical logs are not only useful for precise identification and coal quality evaluation, but also for coal mining, planning and production.

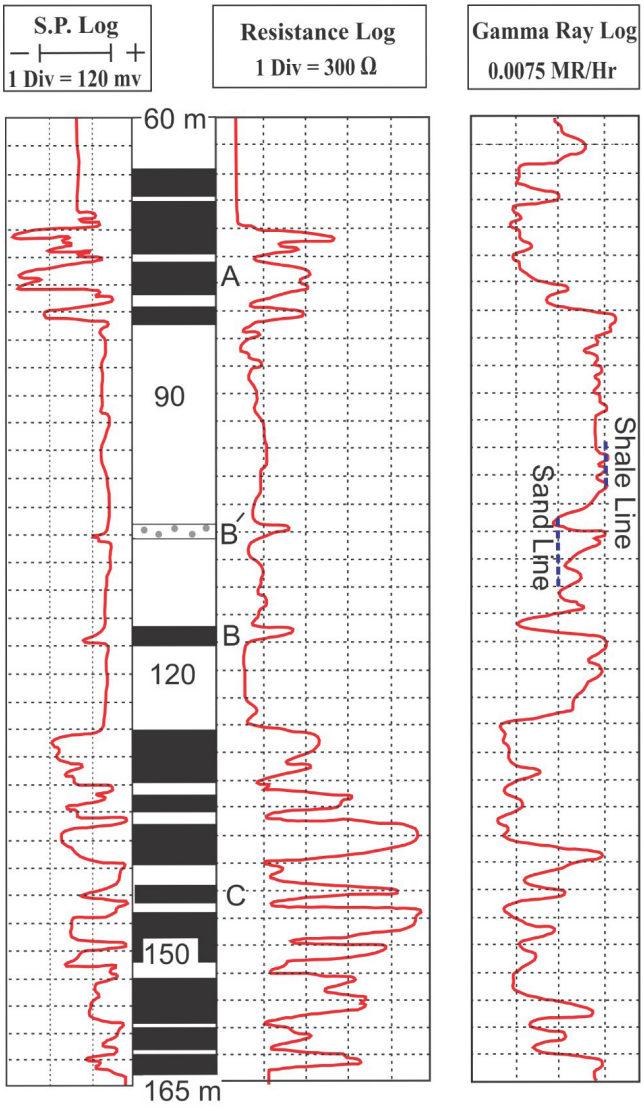


Figure 4. Single electrode resistance, S.P and natural Gamma-ray logs recorded in a coal borehole, Makum coalfield (Tertiary coal), Assam, India. The coal beds in the cased portion of the borehole is identified by the Gamma log only, as the electrical logs could not be recorded. The shale partings within the coal seams are well reflected in all the logs; the logs are well correlated[13].

Core-drilling in coal exploration is much expensive. The geophysical logging techniques can reduce the expensive core-drilling in detailed exploration. Once the geophysical logs are well recorded and calibrated in the regional exploratory core-drilled boreholes, no core-drilling is required for detailed exploration. In this phase of detailed exploration, non-core boreholes can be logged with the borehole geophysical techniques. These geophysical logs can not only define the coal beds, but the calibrated logs or the coal quality model evolved in regional exploration can be used to evaluate coal quality of

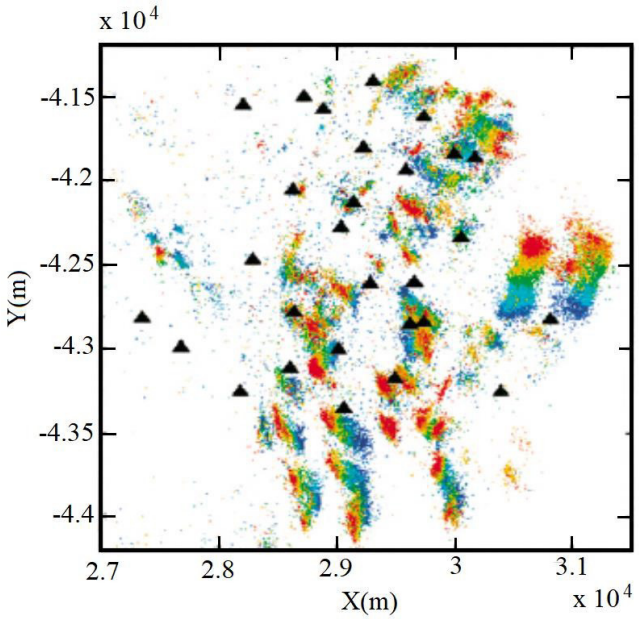


Figure 5. Mining Induced Seismicity (MIS) progresses (cool to hot colours) with the dynamic stresses due to mining advancement in a gold mine, South Africa (Sileny and Milev[16]). The black triangles show the seismic stations.

these non-core boreholes, thus reducing huge investment pain for coal mining planning[13,15].

Further, in various coal mining problems, like subsurface voids, water logging or subsidence, surface geophysical techniques are now a days widely used (Pant and Murty[10]). The geophysical methods like gravity and electrical tomography are most useful in identifying such problems to mitigate mining hazards. The micro-earthquake seismology is also a modern technology that is used for safe and hazard free production. An example is given here in Figure 5. It shows how a dense micro-earthquake network can monitor the Mining Induced Seismicity (MIS) as the mining operation advances. The seismicity pattern and its intensity of occurrence can define the vulnerability of roof collapse or any similar hazards in the mine.

4.0 Conclusions

Modern geophysical techniques can play a major role in oil and mining industries not only for exploration but also for planning economic and hazard-free production. Along with the conventional surface geophysical surveys, the borehole geophysical techniques record *in-situ* physical parameters of the oil or gas reservoir, mineral deposits or coal beds to evaluate their economic viability for production. In an inaccessible area, the micro-earthquake seismology may be useful for oil or gas exploration where the surface geophysical surveys particularly seismic prospecting by huge blasting cannot be carried out. In production stage, micro-earthquake network may be effectively used for enhanced oil recovery.

The borehole geophysical logging techniques, which are extensively used in oil exploration, if properly used in coal exploration, it can drastically reduce the huge cost of core-drilling in mining industry also. Similarly, in mineral exploration judicious use of surface and borehole geophysical techniques can be useful for planning and economic production of minerals. Micro-earthquake seismology and other surface geophysical techniques may be used for safe and hazard free coal mining or production. A few case studies are exemplified here to show how the modern state-of-art geophysical techniques are useful in economic planning for exploration and production both in the oil and mining industries.

In India, we are yet to implement micro-earthquake seismology technique in oil or coal industries. The borehole geophysical logging though extensively used in non-core borehole in oil industry for exploration as well as for economic evaluation, it is yet to be implemented for detailed exploration in the coal industry. For regional exploration of coal, geophysical logs can be well calibrated with respect to coal quality, and in detailed exploration geophysical logs in non-core boreholes may be used for coal bed identification as well as for coal quality evaluation. Such use of the geophysical techniques not only reduce the huge investment cost, but provide a sound scientific base for economic evaluation and planning for production.

5.0 Acknowledgement

I sincerely thank the Editor-in-Chief for inviting this article to share my practical experiences in exploration and production in oil and mining industries. To make it a concise article, I simply exemplified a few case studies without describing the referred text book methodologies, hopping the readers are benefitted with my practical experiences and suggestions.

6.0 References

1. Soni A K. History of mining in India. Indian J Hist Sci. 2020; 55(3):218-234. https://doi.org/10.16943/ijhs/2020/v55i3/156955
2. McQuillin R, Bacon M, Barclay W. An introduction to seismic interpretation - Reflection seismics in petroleum exploration. Graham and Trotman. USA, 1984.
3. Tselentis GA, Martakis N, Paraskevopoulos P, Lois A. High-resolution Passive Seismic Tomography (PST) for 3D velocity, Poisson's ratio and P-wave quality QP in the Delvina hydrocarbon field, Southern Albania. Geophysics. 2011; 76(6). https://doi.org/ 10.1190/1.3560016.
4. Li J, Kuleli SH, Zhang H, Toksoz MN. Focal mechanism determination of induced microearthquakes in an oil field using full waveforms from shallow and deep seismic networks. Geophysics. 2011; 76(6). https://doi.org/10.1190/geo2011-0030.
5. Bacon LO. Induced polarisation in the search for native copper. Geophys. 1965; 30. https://doi.org/10.1190/1.1439564.
6. Gupta D, Radhe S, Agarwal AK, Bhattacharya BB, Banerjee B. Principles of Mise-a-la- Masse method and its application to polymetallic sulphide deposits

of Rajasthan. JGSI. 1999; 53:49-57. https://doi.org/10.17491/jgsi/1999/530106.
7. Haldar SK. Mineral exploration: Principles and applications. Elsevier Inc. 2nd Edition. 2018.
8. Moitra AK, Bhattacharya J, Kayal JR, Mukerji B, Das AK. Innovative exploration methods for minerals, oil, gas and groundwater for sustainable development. Elsevier Inc. 2022. https://doi.org/10.1016/c2020-0-00590-6
9. Kayal, J R.. Borehole geophysical logging for coal and mineral exploration in GSI: A new perspective. Indian Minerals, Geol. Surv. India. 2002; 56(3):259-270.
10. Pant PR, Murty BV. Geophysical exploration for coal, the Indian scenario. Geol Soc India. 2004; pp310
11. Tixier MP, Alger RP. Evaluations of non-metallic mineral deposits. Geophysics. 1970; 35:124- 142.
12. Reeves DR. *Insitu* analysis of coal by borehole logging techniques. CIM Transaction. 1971: pp. 61-69.
13. Kayal J R. Electrical and gamma ray logging in Gondwana and tertiary coalfields of India. Geoexploration. 1979; 17:243-258. https://doi.org/10.1016/0016-7142(79)90019-x.
14. Borsaru M, Charbucinski J, Elser PL. Youi SF. Determination of ash content in coal by borehole logging in dry boreholes using gamma-gamma methods. Geoexploration. 1985; 23:503-517. https://doi.org/10.1016/0016-7142(v) 85)90077-8.v
15. Kayal JR, Christoffell DA. Coal quality from geophysical logs: Southland lignite region. New Zealand. The Log Analyst. 1989; 30(5):343-352.
16. Sileny J, Milev A. Source mechanism of mining induced seismic events - Resolution of double couple and non-double couple models. Tectonophysics. 2008; 456:3-15. https://doi.org/10.1016/j.tecto.2006.09.021