100 years of seismic prospecting: the geophysical journey of Oil India Limited

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Abstract

Geophysics plays a vital role in the realm of hydrocarbon exploration, especially Exploration and Production (E&P) of hydrocarbons globally in the petroleum industry. The geophysical journey of Oil India Limited (OIL), the second-largest National Oil Company (NOC) in India's upstream sector, is indeed exceptional. OIL has discovered several productive fields in the northeastern region of India through geophysical methods. For a century, seismic data acquisition has been the backbone for pinpointing probable hydrocarbon-bearing prospects and streamlining drilling operations for their discoveries. Geophysical applications tailored to geological objectives yielded the discovery of OIL's initial fields, including Naharkatiya, Moran, Jorajan, and Kusijan. However, the venerable Digboi Field was a noteworthy exception. In 1889, it was stumbled upon by curious observers who noticed oil stains on an elephant's feet, and the rest is history.

As the technology advances and new concepts for hydrocarbon prospecting develop, OIL has increased exploration activities across multiple sectors, with the seismic serving as the key geophysical tool. Exploration continues in the face of depleting hydrocarbon reservoirs, which demands careful interpretation of geophysical data to comprehend the underlying subsurface geological complexities. Seismic surveys and their in-depth studies are critical to exploration success. A study of seismic prospecting history indicates a dedication to improve and innovate in increasing survey acreage has led to the discovery of new fields. However, the contribution of gravity, including airborne and gravity gradiometry, magnetic and magneto-telluric surveys, and the other principal geophysical technologies used by OIL cannot be ignored. Incidentally, the first stage of hydrocarbon exploration was carried out by way of gravity surveys using torsion balances, which at a later stage evolved into commonly used "2D/3D" seismic technologies. OIL presently uses cutting-edge seismic technology and has accumulated vast experience, particularly in India's northeast.

Keywords: seismic prospecting, geophysical exploration, evolution of geophysical technology, wireless seismic

1920-1960: Early years and colonial era

In 1887, the British colonial administration established the Assam Railway and Trading Company Limited (ARTC), which was the predecessor of OIL. The oldest Digboi oilfield's discovery brought up new opportunities for hydrocarbon development in several sedimentary basins. As time went on, geologists all across the world began to see that there may be oil and gas deposits beneath the alluvium near the surface and various geological layers. In the early 1900s, a new science called "exploration geophysics" came up to locate these subsurface reservoirs.

Although seismic technology currently dominates geophysics, particularly petroleum geophysics, this was not the case in the early stages of oil exploration. The seismic reflection survey was developed a few years later Lorand van Eotvos invented gravity survey with torsion balance in Hungary in 1915, and over time, it gradually replaced other methods for looking for oil and natural gas. In 1923, ARTC made its first oil discovery in Assam, marking the beginning of oil exploration in the region. This discovery was a significant milestone in the

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development of India's oil industry and played a crucial role in the country's economic growth after independence.

A remarkable occasion in global seismic exploration history was the submission of a patent application for the seismic reflection technique in 1920, with John Evans and Bevan Whitney creating the foundation. A significant finding was made when an oil field was located beneath the Nash salt dome in Texas four years later, in 1924. By then, the first gravity survey employing a torsion balance was conducted on the plains of Upper Assam in 1925.

Meanwhile, during the early 1930s, there was some advancement in other geophysical exploration techniques, particularly related to seismic. Reflection seismic quickly became the primary technology for hydrocarbon prospecting during this time. The first analog filters were introduced in 1932, which initiated the processing of seismic data as it progressed. The first seismic survey in the Gulf of Mexico began in 1937, broadening the scope of investigation. The Government of India received a proposal in 1937 from Burmah Oil Company, British Petroleum (formerly Anglo Iranian Oil Co.), and Shell for conducting geophysical studies in the plains of Upper Assam. A new license for geophysical surveys was then introduced considering the region's need for substantial geophysical surveys. The license, which had a validity for five years, was intended for geophysical surveys covering a 5320 square mile region.

(Seismic survey being shot in Upper Assam, 1930)

In order to plan seismic surveys just in the selective areas of interest, gravity surveys were carried out with the goal of identifying and defining the prospective locations. After that, starting in December 1937, a single-fold seismic reflection survey was conducted by M/s Petty Geophysical Engineering Company, based in the USA, and it is possibly India's first reflection seismic survey. The survey found a structural high close to Naharkatiya, not far from the gravity high discovered by a torsion balance gravimeter survey in 1925–1926. Due to the onset of the Second World War, the seismic and gravity survey programs were then abandoned.

With the start of maritime seismic surveys in 1944, a major milestone was finally reached by the industry, opening the door for further developments in seismic prospecting. India gained independence from British colonial rule in 1947. In the years that followed, the Indian government took steps to nationalize key industries, including the oil industry. The Naharkatiya oil field was discovered in 1954 because of these geophysical survey programs. In 1959, the government acquired the majority stake in ARTC and renamed it Oil India Limited.

Exploratory activities increased in vigour and excitement following the finding of oil in Naharkatiya. Geophysical exploration was restarted with new dynamism. Magnetic and gravity surveys quickly covered the whole basin. These surveys were unable to identify the drilling locations for the prospects confidently. Detailed single-fold reflection seismic survey was conducted in several regions of the basin, to help drilling of the prospects, and this practice persisted until 1957.

Period between 1960-1980

During this period, the field of geophysics witnessed an extraordinary expansion in all its dimensions. It was an era in which OIL could not afford to lag in the wake of such monumental progress. Numerous geophysical campaigns of substantial magnitude were meticulously executed in the pristine landscapes of Arunachal Pradesh and the elevated terrains of Upper Assam.

The seismic data were acquired for exploring areas in onland and offshore as well. The invention of the airgun seismic source in 1965 completely changed the way offshore seismic data was gathered by providing a faster and better technique in the oil industry. The quality of the data was improved by streamer depth control, which was introduced to seismic surveys just six years later, in 1971. With the development of bright spot technology in 1972, which gave important new insights into hydrocarbon reserves, there was a huge advancement. The first 3D seismic acquisition, which revolutionized reservoir characterisation, and the first mainstreamer acquisition, which increased the capabilities of seismic exploration, were both accomplished in 1976. The seismic sector has been significantly changed by these significant developments, allowing for more thorough and precise subsurface imaging for the benefit of oil and gas exploration across the globe.

The seismic survey endeavours in OIL, which had temporarily ceased, were reignited during the years 1964–1965. In this instance, the esteemed geophysical service provider, M/s Seismograph Services Ltd., introduced a groundbreaking innovation: the adoption of cutting-edge equipment capable of capturing data in digital format. During this phase of seismic studies, remote and previously unexplored areas within the Arunachal Pradesh concessions were subjected to intensive examination, marking a significant milestone in the annals of hydrocarbon exploration.

It is imperative to underscore here that the data, regardless of its initial format, whether captured on paper or in analog magnetic recorders, seismic data acquisition underwent a transformation into digital form. Subsequently, the data was subjected to meticulous processing within ONGCL's state-of-the-art data processing facilities, facilitating the interpretation of the vast basin's geological nuances. Seismic campaigns persisted, and with the aid of ONGC's services, seismic data was meticulously collected within the basin on an annual basis between 1969 and 1974. The adoption of the CDP (Common Depth Point) technique significantly enhanced data quality, culminating in the discovery of fields in Jorajan and various other locations.

Furthermore, during the winter seasons spanning 1972 to 1974, ONGC personnel conducted comprehensive seismic surveys across the entire basin. Simultaneously, a dedicated gravity party from ONGC embarked on gravity surveys in the hills of Arunachal Pradesh's Lohit district and the nearby Manabhum area.

As time progressed, maintaining an optimal level of hydrocarbon output became increasingly imperative for OIL. This necessitated extensive research efforts. In response, the company took the strategic decision to host its proprietary seismic event. On February 7, 1977, OIL's inaugural seismic crew utilized the then cutting-edge DFS-V equipment, representing India's pioneering implementation of the system. This 24-channel system would eventually undergo expansion. In the same year, 1978, OIL embarked on its maiden offshore seismic data acquisition program with M/s Delta Exploration, USA, in the Mahanadi offshore area.

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OIL INDIA LAUNCH SEISMIC OPERATION WITH SOPHISTICATED EQUIPMENT

At 9 a. m. on Monday, the 7th February, 1977, Oil India's seismic crew operating in the Kathaljuri area took the first seismic shot with the newly acquired digital seismic equipment, DFS V. This simple act climaxed months of hard work to acquire and commission a sophisticated piece of equipment and to be self-reliant in its maintenance and operation.

The seismic survey field system called DFSV (abbreviation for digital field system V) purchased by Oil India Limited, from the renowned American firm—Texas Instruments Inc., Houston—is the most advanced seismic survey equipment used so far in India and is considered to be one of the finest in the world to-day. The system makes use of highly intricate TTL, CMOS integrated circuits and other electronic devices and incorporates the latest innovations in electronic design and instrumentation for high fidelity recording of small seismic signals reflected from different strata below the surface of earth. In seismic surveys these signals are generated by blasting a dynamite in a 'shot hole' about 10-20 metres deep at a certain distance away from the recording station.

In the older analogue mode of recording seismic data, only the 'character' of the reflected seismic pulses were recorded, not their strength'. The modern digital form of recording seismic data on magnetic tapes permits, by virtue of its large dynamic range, recording of the relative reflection strengths of the seismic pulses with a great deal of accuracy. A knowledge of this signal strength is considered essential for mapping minor structural features or stratigraphic traps that may contain significant accumulations of oil and natural gas.

The cost of conducting seismic surveys by a foreign contractor equipped with a DFS V type of equipment is extremely high. By conducting surveys with its own crew and equipment, Oil India Limited will not only be saving valuable foreign exchange but such a sophisticated equipment, backed by its (Oil India Limited's) own expertise in seismic surveys accumulating over the years, will be an invaluable tool in our search for additional reserves of oil and gas.

Building up a seismic team from scratch is a painstaking affair as it requires training of personnel in various aspects of seismic surveys like layout of cables, loading and shooting of dynamite, supervision of shot-hole drilling and such other jobs. Besides, a full-fledged seismic team will require mobilization of a large labour force, arranging transport for movement of men and materials to various parts of the survey area, arranging workshop facilities for repairs and maintenance of the recording equipment, cables, etc.

The seismic data collected by this equipment will be both on paper record as well as on magnetic tapes. The tapes will then be processed in a high-speed digital computer for obtaining the so-called time section which is analogous to a geological section.

EMPLOYEES' VEGETABLE GARDEN COMPETITION

As in the previous years, a vegetable garden competition was organised amongst our employees who live in the Housing area. The gardens were judged on the basis of cleanliness, layout and output, by a committee of judges appointed by the Labour Superintendent, in January.

In 'B' & 'C' type area, Shri Tileswar Roy of Drilling Department and Shri J. B. Bhattacharjee of Production Department were adjudged the best and the 2nd best gardeners respectively.

Shri Bir Bahadur of Transport Department and Shri Samsul Hussain of Engineering Department became the best and 2nd best gardeners in 'A' type.

In Naharkatiya South Bank, Shri Krishnamurty of Production Department won first prize and Shri Adi Narayan, also of Production Department, 2nd prize.

At a simple function held in the Labour Bureau, Shri B. K. Chaudhuri, Labour Superintendent

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The acquired digital seismic data necessitated prompt processing. Hitherto, seismic data from all corners of the company had been primarily managed at ONGC's headquarters in Dehradun. However, with the Mahanadi offshore seismic data, a processing centre at Digicon in Singapore was deployed. Recognizing the need for self-sufficiency in this crucial area, OIL procured an exceedingly sophisticated computer system, the Megaseis, which was successfully commissioned at Duliajan in the early months of 1980. This formidable instrument empowered the company to achieve self-sufficiency across the entire spectrum of seismic prospecting.

Period between 1980 – 2000

Significant turning points in seismic processing and interpretation technology development have pushed the discipline into new spheres of accuracy and reliability. The first Amplitude-Versus-Offset (AVO) study was introduced in 1984 (Ostrander, 1984), and it paved the way for improved reservoir characterisation and exploration tactics. By 1989, the industry was able to track changes in reservoir parameters during production over a period of time thanks to the development of 4D, time-lapse seismic monitoring, which provided important information for reservoir management. The development of DGPS (Differential Global Positioning System) and acoustic ranging during the 1990s resulted in widespread innovation and made precise location and navigation during seismic surveys possible. Concurrently, 3D seismic data acquisition proliferated during this time, providing more thorough subsurface imaging. The first 4C Ocean Bottom Cable (OBC) acquisition in the Gulf of Mexico in 1995 (Dondurur, 2018) was a substantial advance and provided novel insights into challenging offshore environments. Finally, the deployment of 14 streamers in 2000 (Dondurur, 2018) helped seismic acquisition reach new heights and increased the industry's capacity to gather precise subsurface data. The technological development that happened worldwide demonstrated seismic technology's extraordinary progress in the direction of improved precision, effectiveness, and comprehension in the field of subsurface

investigation. This was expected to have an impact on hydrocarbon exploration in India in the upcoming period.

Meanwhile, OIL began expanding into new areas outside of the northeastern part of India. It acquired new Petroleum Exploration Licenses (PELs) in Rajasthan, Saurashtra, and the Ganga Valley. These programmes included a variety of geophysical activities. Vibroseis surveys were conducted in Rajasthan and the Ganga Valley. M/s CGG conducted the Vibroseis survey in Rajasthan between 1984 and 1987. A computer centre was also set up to process the seismic data instantly. OIL acquired seismic data in offshore Saurashtra. Seismic data was also acquired in both the onland and offshore parts of the Mahanadi basin and North East Coast (NEC) basin as part of OIL's Bay Exploration Project. Geophysical Services Inc. conducted an extensive seismic survey at Mahanadi Onshore in 1981-82.

There was a push in Assam and Arunachal Pradesh during this time to seismically scan the entire basin. Between 1983 and 1987, OIL purchased three (3) more DFS V systems and one SN 358 system and deployed five (5) crews equipped with state-of-the-art technologies to explore the entire Upper Assam Basin seismically. With the help of all five (5) in-house seismic crews, the basin was seismically explored throughout the course of the following 15 years. This helped OIL to discover new plays at greater depth, i.e., at the Eocene levels.

OIL has consistently embraced cutting-edge technology. 3D seismic surveys gained popularity in the 1980s. M/s Western Geophysical conducted 3D seismic work off the NEC in 1987–1988. This was the first 3D offshore survey by OIL. After that, a 3D seismic study was conducted in Rajasthan's Jaisalmer Basin in 1991 and 1992. This was the first 3D seismic survey conducted by OIL on land. Then, in 1992–1993, 3D seismic was adopted in Assam, and the 3D seismic survey became an integral part of the exploration efforts in Upper Assam. Different areas were covered by a 3D seismic survey employing an SN 368-line telemetry system thanks to OIL's own competence in this field. The need for 2D seismic surveys rapidly decreased as 3D seismic began to gain popularity in the mid-1990s.

New processing systems were also set up as seismic volume grew. The GeoMASTER processing system, based on the Cyber 830, was put into operation in 1992. After that, a PROMAX processing system based on SGI Hardware was installed and put into operation in 1996 to handle 3D seismic data by internal efforts. In addition to PROMAX, software packages for seismic modelling and reservoir characterization, among others, brought up fresh possibilities in seismic data processing and reservoir analysis.

The interpretation of the data needed to be accelerated due to the growing volume of data being acquired. Five (5) stand-alone interpretation workstations were acquired in the late 1980s and early 1990s. This made it possible to understand and analyse the massive amount of seismic data quickly.

OIL was able to interpret seismic data independently from Assam and Arunachal Pradesh as well as from other areas where the company was operating. In 2000, OIL received recognition for its work in gathering seismic data linking two wells on the north and south banks of the powerful Brahmaputra River, and the group was given a special mention by the National Petroleum Management Programme (NPMP) for its originality and inventiveness.

Period beyond 2000

The paradigm of exploration has evolved across the nation during the New Exploration Licensing Policy (NELP) era. OIL actively participated in this new liberalisation age. It acquired blocks not just within the nation but

also overseas, where OIL is the operator, such as Libya and Gabon. With the development of computing power, the requirements for geophysics gradually altered. In 2000, the GeoFrame system was included as an enhancement to the interpretation system and new hardware was added in 2004. FOCUS and GEODEPTH, two newly released processing and depth-imaging software, were released in 2005. To have a complete suite for successful reservoir characterization, additional software products from M/s Hampson Russell were purchased in the intended manner.

Three (3) new seismic data acquisition systems were added in 2001 and 2002 with the goal of having more channels for deployment in logistically challenging and environmentally sensitive places and the adoption of the latest technology. In 2001, the first radio telemetry RSR system of its sort was deployed for seismic data acquisition in India. This technology was discovered to be incredibly ideal for logistically challenging and environmentally delicate places, such as the Brahmaputra River bed, among others. The other two equipment were line telemetry systems, both made by Sercel, and they were put into service in 2001 and 2002, respectively.

Two (2) new equipment, SN 428, were once more purchased in 2009. These devices have several channels, and the internal seismic crews are now able to collect seismic data with even more channels. Additionally, this allowed the acquisition of seismic data with better subsurface images. The acquisition of these equipment introduced new technology to OIL. It was also the time to start multi-component data acquisition. During this period, OIL started regular reservoir geophysics studies to carry out advanced seismic studies, viz. AVO and Inversion studies, complex attributes, etc., that aid in the planning of exploration, development, and drilling activities of the company. These are part of a quantitative interpretation (QI) study, which gives valuable inputs beyond structural interpretation, which helps to find out the extension of reservoir sand with possible hydrocarbon. Thus, it can mitigate the exploration and development risk to a great extent. Pore-pressure prediction and geomechanics, etc., are also being carried out regularly, which has immense significance and influence on well construction and well planning.

OIL used the services of reputable geophysical service providers to conduct massive 3D surveys in only its typical areas and 2D surveys in logistically challenging locations. Modern imaging techniques like Common Reflection Surface (CRS) were used to image the logistically challenging areas, and an integrated interpretation of seismic, gravity-magnetic, and magneto telluric data helped to provide some insight into the intricate subsurface of places like Manabum.

New acreages were acquired through NELP bidding rounds and international bidding procedures. The atmosphere, logistics, and other factors varied from place to place. With all the aforementioned factors taken into account, thorough geophysical surveys, including 2D and 3D seismic and aero-magnetic, were conducted.

With the partnerships of academic institutions, OIL has also made a lot of effort in the field of geophysics. A novel method called Unified Imaging was created through a collaborative study with Rice University in the United States for imaging the subsurface in geologically complicated places. The pursuit of perfection in geophysics has reached a new level with this.

(Seismic survey in Assam. Top Left: Preparing for the shot. Top Right: A shot being taken using an explosive source. Bottom: Truck with wireless recording capabilities.)

Recent times

The cableless seismic data acquisition system was assimilated by OIL in the year 2017. In the fiscal year 2020-21, the company conducted seismic surveys covering a total of 13,103 line kilometres of 2D data and 2,104.08 square kilometres of 3D data in its designated acreages and Open Acreage Licensing Policy (OALP) blocks. Notably, the company achieved the distinction of being the pioneering operator to commence exploration activities in OALP blocks in the nation by initiating both 2D and 3D seismic acquisition within Rajasthan's OALP blocks. Additionally, the company initiated the seismic data acquisition campaign within a month following the award of PEL for the OALP block, which was secured through the OALP-V round. It's noteworthy

that the exploration block is situated in the Biswanath district of Assam and poses logistical challenges due to its riverine terrain and susceptibility to flooding.

The High-Performance Computing Centre (HPCC) —Bhudristhi— was commissioned on 30 May 2015 at OIL's field headquarters in Duliajan (Assam), wherein the vintage processing system was upgraded to the cluster-based computational hardware and the latest seismic data Imaging, AVO, inversion and geomechanics software suites. Since its inception, the centre has consistently matured itself into a high-end and self-sufficient setup to provide geophysical support for achieving the exploration and development objectives of the company. This has been achieved by handling an increased quantum of 2D and 3D datasets with varying complexities and achieving better imaging and detailed specialised studies. Currently, this centre caters to time and depth domain Imaging of 2D & 3D seismic datasets, pre-stack/post-stack seismic data merging, AVO/seismic inversion, and pore pressure studies from MPA, NELP, OALP regimes as well as overseas projects.

Passive seismic tomography emerges as an exceptionally potent and specialized tool to help enhance the quality of subsurface imaging, particularly in situations where the existing seismic data is scarce or compromised due to surface and sub-surface complexities. This technique is also anticipated to furnish a comprehensive structural configuration in cases where seismic data is lacking or minimal. OIL has additionally executed PST (Passive Seismic Tomography) surveys in its operational areas, which form a part of the Thrust Belt Area.

Oil India possesses extensive expertise in successfully addressing the challenges associated with subsurface mapping in the logistically complex regions of Upper Assam. OIL carried out an Airborne Gravity Gradiometry (AGG) along with gravity, magnetic, and LiDAR survey in the year 2020–21 with the objective of mapping subsurface information, including basement configuration, deeply buried structures, and sub-thrust structural information. To attain the desired objectives, a multi-disciplinary approach was adopted. AGG and gravity-magnetic data were interpreted in conjunction with available geoscientific data, viz., seismic, well log data, geological information, etc. Modelling was carried out along a few identified profiles with inputs from other available geoscientific information to constrain the results. The outcomes of the survey further helped in understanding the subsurface better.

In an era defined by exponential growth in data volumes, OIL's seismic data management stands as a testament to managing huge volumes of datasets. As data acquisition technologies continue to advance, OIL has met the challenge of seamlessly integrating cutting-edge solutions into its data management practices. With the implementation of state-of-the-art data storage facilities, OIL ensures that every piece of geophysical information, no matter how vast or complex, is not just stored but also harnessed for various studies. Our commitment to data-driven innovation is evident since all the datasets are digitalized and migrated from physical storage to 500 TB digital storage, embarking on a transformative journey for integrating seismic data management with GIS, AI, ML, and Big Data, sparking a digitalization revolution.

Way forward

OIL is diligently broadening its knowledge base through ongoing assessment of various technologies for potential adoption. Promising technologies such as Full-Waveform Inversion (FWI), Distributed Acoustic Sensing (DAS), quantum seismic sensing, virtual source seismic imaging, big data analytics and machine learning in seismic data are currently under consideration. Furthermore, virtual reality and augmented reality

visualization have already made their debut in OIL's interpretation centre. It is anticipated that the utilization of seismic data for geothermal energy exploration and carbon capture and storage will be realized soon. *G*

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All the authors who have contributed to this article belong to the Department of Geophysics, Oil India Ltd. The department has expanded its geophysical activities from gravity surveys using torsion balance to onland, shallow and deep offshore seismic (2D, 3D, HD, broadband, multi-component and cable-less), passive seismic tomography and airborne gravity gradiometry. In recent times, the department has also acquired bathymetry, side scan sonar, sub-bottom profiler, and geo-technical surveys for offshore site investigation, including met ocean and shallow hazard studies. The department is also equipped with a high-performance processing centre (HPCC), which routinely undertakes depth imaging, inversion, pore pressure and geo-mechanical studies. The infallible achievements, unparalleled growth, and development through decades have brought the geophysics department to the pinnacle of exploration activity and placed Oil India Limited on the global picture with a distinct identity. This department is an emblem of specific distinction and depicts the decades of affirmative transformation and the glorious journey that it has gone through in quest of hydrocarbon resources.