State-of-the-art Seismic Tools for Subsurface Imaging

Due to the advent of high-resolution digital data acquisition and high performance computers, there has been phenomenal growth in advanced processing and modeling/inversion of surface seismic data for subsurface imaging. Applications of some ‘state-of-the-art’ seismic tools such as the 2D traveltime tomography, 1D and 2D full waveform inversion (FWI), prestack depth migration (PSDM), common reflection surface (CRS) stack, seismic meta-attributes based on Machine Learning (ML) technique to both vintage and new controlled source seismic (CSS) data have led to the delineation of subsurface structural features that were not evident earlier.

Background

During the last few decades, there has been tremendous development in seismic image enhancement starting from the PSDM through the reverse time migration (RTM) to present-day broadband FWI. The CSS experiment, where artificial sources are used and near-vertical reflections, refractions and wide-angle reflections are recorded at the surface, has been very powerful for delineating both shallow and deep structures and subsurface features. Shallow structures of sedimentary basins are useful for the exploration of conventional hydrocarbons and understanding geological history, whereas deep crustal structures provide useful inputs for geotectonic implications, insight on mineralized prospects and evolutionary processes of various regions. High-resolution seismic data are essential for delineation of near-surface structure for the exploration of unconventional gas-hydrates, coal bed methane and shale gas/oil. All these have been possible due to technological advancement in high performance computation, state-of-the-art data acquisition, and advanced processing, modelling and inversion of data. The main question lies ‘how thin a thin layer can be resolved’. Thin layer is a relative terminology and it all depends on the frequency content into the data. The oil industry uses typical frequency band of 10-100 Hz for shallow investigation. The deep travelling seismic waves in crustal seismology mainly contain 8-25 Hz frequencies. In near-surface high-resolution seismic survey, the data with frequency up to 200 Hz can be acquired. Definitely, the resolution of CSS study is much higher than that of earthquake seismology in which signal having maximum frequency up to 5 Hz can be extracted. The seismic waves lose their higher frequency components as they propagate deeper and travel longer distances. Thus, what can be resolved at shallow level or near source cannot be resolved at deeper level or far away from source.

Since 1972, more than 6000 line-kilometers of CSS data have been acquired by CSIR-NGRI, Hyderabad. Conspicuous structural and evolutionary signatures, which have been brought out during the last three decades of the 20th century, are available in review literatures (Kaila and Sain, 1997; Sain, 2008). Details of other advancements that have taken place in seismic data acquisition, processing and modeling during the last two decades, are also available in a recent review article (Sain, 2019).

Some of the advanced tools and their application to the CSS data for deriving near-surface, shallow and deep structures of the earth with special references to the exploration of both conventional and unconventional hydrocarbons, imaging sedimentary formations over the basement in understanding the geological processes, and delineating crustal structures to provide geotectonic implications are described next.

State-of-the-art Seismic Tools

The state-of-the-art seismic tools have been employed to the vintage and new CSS data that have provided improved subsurface images and advanced interpretations. Significant results derived from the modern tools over the Indian landmass are briefly described below.

Common Reflection Surface (CRS) Stack

The CRS stack has been applied to the vintage crustal seismic data across the Delhi-Aravalli-fold-belt (DAFB) in NW India (Mandal et al., 2014). This has brought out Moho below the Marwar basin and Sandmata complex, prominent upper to mid-crustal reflectors and extension of crustal-scale Jahazpur thrust becoming listric at lower crust / Moho below the Sandmata complex (Fig.1). The study indicates that the CRS stack is more appropriate than conventional stack (Prasad and Rao, 2006) for imaging in the complex region.

The CRS stack of deep travelling multi-channel seismic (MCS) data in the Central Indian Tectonic Zone (CITZ) has revealed subsurface features (Mandal et al., 2013) that were either poorly imaged or entirely absent in earlier conventional section (Mall et al., 2008). The result has brought out Moho throughout the seismic line, existence of crustal blocks with distinct dipping reflection fabrics on northern and southern sides of the central Indian suture (CIS), 8 km Moho offset beneath the CIS, and high amplitude reflectivity representing the CIS.

The CRS stack of MCS data along the 165 km long Chandli-Bundi-Kota-Kunjer profile in Chambal-valley, shows a gently dipping structure with 7.5 km thick Proterozoic Vindhyan sediments and 1.5 km volcanic sequence over the granitic-basement (Mandal et al., 2018). The seismic images of compression on one-side and extension on other-side along with differences in the Moho characteristics, strong lateral discontinuity and strike-slip features are observed.

2D Traveltime Tomography

Traveltime tomography of wide-angle seismic data along a 240-km Hirapur-Mandla CSS profile in central India has delineated shallow
structure that depicts a horst feature in which high-velocity (6.5 km/s) lower crustal materials have risen up to a depth of less than 2 km below the Narmada lineament. North of this horst feature has received ~1.5 km thick Upper Vindhyan (4.5 km/s) and ~4.5 km thick Lower Vindhyan (5.3 km/s) sediments (Zelt et al., 2003) (Fig.2). The tomographic model also provided the model bounds and lateral resolution that are required for assessing a model. Traveltime tomography of wide-angle seismic data has been an effective tool for imaging Mesozoic (Sain et al., 2002a) and Gondwana (Sain et al., 2002b) sediments below the volcanic rocks, imaging of which has been rather difficult by conventional approaches.

**Full Waveform Inversion (FWI)**

It is the state-of-the-art seismic FWI that has the ability to estimating accurate seismic velocities and delineating fine-scale structures by exploiting all components (traveltimes, amplitudes, frequencies, phases) of seismic data (Sain et al., 2004). The application of FWI to MCS data has delineated 1D fine-scale velocity structure of gas-hydrates bearing sediments in the Makran accretionary prism (Sain et al., 2000), and 2D velocity-structure in the KG basin (Ojha et al., 2016). For the first time in India, the FWI has been employed to the wide-angle ocean bottom seismic (OBS) data in the Kerala-Konkan (KK) offshore that has delineated 105 m limestone formation below 950 m volcanic rocks (Sain et al., 2018), which could not be delineated by traveltime tomography due to inherent limitations. The result matches reasonably with the available log data.

**Prestack Depth Migration (PSDM)**

The PSDM of seismic refraction data has revealed crustal-scale hidden faults beneath the 2001 Bhuj epicentral region and highly reflective 45 km thick crust compared to shallow (35 km) crust in the coastal region (Sarkar et al., 2007). The data were originally acquired for the delineation of basement configuration and overlying formations. This observation contradicts the seismic activity in the Bhuj/Kutch region due to thin rifted crust as was found along the East African rift (Moneey and Christensen, 1994). The crustal thickening could be due to the compressive regime of the past 55 my or may be attributed to magmatic intrusions during the Mesozoic rifting connected to the Gondwanaland breakup.

The PSDM to high-resolution MCS data in the Mahanadi offshore has brought out the finer details including the faults that act as migration paths for fluids to help understand the genesis of gas hydrates (Sain et al., 2012). The PSDM of MCS data in the KK offshore using the tomographic velocity model has further improved the subsurface images, and boosted oil industries for pursuing similar studies using wide-angle seismic data in the Kutch, Saurashtra and Cauvery offshore. The oil industries have also developed interest for imaging Proterozoic Vindhyan sediments below the volcanic rocks and exploration of hydrocarbons in thrust-fold belt regions of the sub-Himalaya.

**Seismic Meta-Attributes**

When seismic attributes are combined and trained over an interpreter’s acquaintances or past knowledge through artificial intelligence (AI) or ML technique, a new attribute, called the meta-attribute can be generated. Several new work-flows have been designed and meta-attributes have been computed from available 3D seismic data, which show how the subsurface images can be improved for the interpretation of several geologic features (Singh et al., 2016; Kumar and Sain, 2018; Kumar et al., 2019a, b).

A case study in the Kora prospect, off New Zealand, is presented. The objective is to generate an Intrusion Cube (IC) meta-attribute from 3D seismic data for the interpretation of submarine buried volcanic system. Since the buried volcanic system is accompanied with the igneous and sedimentary processes, the study is very important to understand the petroleum system (maturity of source rocks; migration pathways for hydrocarbons; sealing and trapping mechanism; geothermal history of the basin; etc). The complexity sometimes changes the porosity and permeability of the reservoirs and may thus pose risks to exploitation. Hence, such complex geological system should be examined critically and investigated thoroughly. Submarine buried volcanoes have a tendency to pierce vertically through the host sedimentary succession. Internally they are associated with distorted and chaotic reflections and dissimilar seismic events. Over the crater and along the flanks they are associated with high amplitudes due to larger impedance contrasts with the surrounding sedimentary rocks.

Sills and dykes generally act as conducive pathways for the movement of magma into the overlying sedimentary units. Sills are concordant intrusive bodies, commonly sub-horizontal with a gentle inclination cross-cutting the subsurface stratigraphy and exhibits major impact on basin history and petroleum system. These appear as saucer shaped, gently inclined, distinct high amplitude and discontinuous event on seismic section. However, dykes vertically intrude into the overlying younger strata and exhibit steep dips. Thus, the seismic attributes such as the reflection strength, dip angle variance, energy gradient, azimuth, similarity etc., when combined and trained over interpreter’s knowledge to capture the extension and distribution of such complex plumbing system, a new attribute defined as the IC meta-attribute can be generated. Kumar et al. (2019a) make a first documentation of such a meta-attribute that has brought out a realistic image of the plumbing system (consisting of buried volcano, sill networks, dyke swarms, magmatic ascent) from seismic data. Fig.3 shows the IC meta-attribute co-rendered over a conventional seismic section. The approach can be extended to any basin for subsurface image enhancement to aid interpretation of 3D seismic data.

**Future Work with Social Relevance**

As requisite expertise in state-of-the-art seismic data acquisition, advanced processing, inversion/modelling have been developed, reprocessing/remodelling of vintage data using modern tools as well as acquisition, processing/modelling of new data can be taken up to build improved images of the subsurface in following areas:

- The long-offset MCS and wide-angle OBS data, acquired by CSIR-NGRI, need to be analysed based on tomographic modelling followed by CRS stack or PSDM to delineate plate geometries, dip angles, extent of asperity zone, fault-systems for understanding seismicity of the Andaman subduction zone.

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**Fig.2.** Shallow velocity model derived from traveltime tomography using CSS data along the Hirapur-Mndla profile across the NSL in Central India. Open circles at the top show the shot locations (after Zelt et al., 2003).
The MCS and wide-angle seismic data, acquired by CSIR-NGRI, can be reprocessed by advanced tools for delineating crustal fabrics including the subsurface disposition of faults (known and hidden) to shed light on seismotectonics of the Kutch peninsula.

Seismic tomography followed by CRS stack can be attempted to CSS data for imaging Achankovil Shear Zone in Southern Granulite Terrain (SGT) (Rao et al., 2006) to better understand the geotectonics of the region.

The CRS stack or PSDM of CSS data in the sub-Himalayan fold-thrust belt, acquired under the HIMPROBE Project (Prasad et al., 2011), can be pursued for delineating the geometry of decollement (sites for large/major earthquakes) that detaches/separates deformed rocks above from undeformed or differently deformed rocks below.

Wide-angle and MCS data need to be acquired along suitable profiles in the Himalaya using state-of-the-art wireless nodes to provide information on the nature of decollement, thrust geometry, splay faults, role of fluids in rupturing, effect of crustal thickness and rheology on locking, changes in physical properties as precursors for future events, etc. All these may provide clues to the fundamental question of the Himalayan seismogenic zones if they have the potential for great earthquakes.

As finding oil/natural gas at ease is almost over, concerted efforts can be made for the exploration of hydrocarbons in the Mesozoic or Proterozoic Vindhyan or Gondwana sediments covered by the volcanic rocks in both onland and offshore of India by wide-angle seismic experiments. Similar studies can be taken up in the fold-thrust belt of the sub-Himalaya in Himachal Pradesh near Jawalamukhi or in Assam-Arakan fold belt.

The MCS and OBS data, acquired by CSIR-NGRI in KG and Mahanadi offshore, can be modelled by FWI followed by PSDM or CRS stack for understanding the genesis of gas-hydrates. The data can also be utilized for estimating critical parameters such as the porosity, permeability, pore pressure and geotechnical properties that provide useful input for developing viable production technology.

Since both margins of India have many petroliferous basins such as the Bengal, Mahanadi, KG and Cauvery basins in the eastern margin, and Kutch, Saurashtra and KK basins in the western margin, it would be appropriate to reanalyse/remodel the MCS data, acquired under the Commission on Legal Continental Shelf (CLCS) program of MoES. This may lead to the exploration of hydrocarbons or delineation of gas hydrates bearing structures.

The Himalayan tectonics and regional climates are achieved into the sedimentary piles of the Indus Fan, Indo-Gangetic Plains and Bengal Fan, where high-quality MCS data are available with the industries (ONGC, Reliance Co.). Application of FWI followed by PSDM or CRS stack or RTM to such data and correlating the sections with available litho-stratigraphy may provide sediment thickness map of different geological periods leading to deriving sedimentation rate, spatial-temporal distribution of lithology etc. This will help to shed light in understanding the Himalayan geodynamics and paleoclimates.

The concept of combining several other seismic attributes into a meta-attribute by designing a new workflow based on AI any other ML technique can be subjected to industry-standard 3D seismic data for cutting-edge interpretation of subsurface.

Concluding Remarks
Applications of modern tools such as the 2D traveltime tomography, 1D and 2D FWI, PSDM, CRS stack, meta-attributes based on ML approach to the new and vintage CSS data have shown significant improvement over the conventional images, and hence help in providing better interpretation of subsurface features at near-surface, shallow depth and deep crustal levels. The main results of CSS experiments over the Indian subcontinent are imaging of (i) crustal-scale Jahazpur thrust that becomes listric at the lower crust/
Moho below the Sandmata Complex in Delhi-Aravalli fold belt; (ii) crustal blocks with distinct dipping reflection fabrics in the northern and southern sides of CITZ, characterized by high amplitude reflectivity with 8 km Moho offset; (iii) crustal-scale hidden faults and thickened crust beneath the 2001 Bhuj epicentral region; (iv) crustal-structure beneath the Kangra fold-thrust belt that places Himalayan decollement at 6-8 km depth above a thin but reflective Mesozoic to Neo-Proterozoic Vindhyan strata; and (v) different crustal structures to the west and east of the Chambal-valley Vindhyan basin indicating a tectonic boundary that has separated the compression events to the west from the extensional activity to the east.

As oil industry shows a lot of interest for the exploration of sub-volcanic Mesozoic sediments for commercial gain, 2D traveltime tomography of wide-angle seismic data has been employed for delineating Mesozoic sediments below the Deccan volcanic rocks in the Saurashtra and Kutch peninsula, Tapti graben, and KK offshore. The Gondwana sediments masked by the Rajmahal Traps have also been delineated in the Mahanadi delta and West Bengal sedimentary basins. The basement configuration and overlying sedimentary formations have been delineated in the Vindhyan and Marwar basins from CSS data and their tectonic/geological implications have been provided.

Several innovative approaches have been proposed for the delineation, characterization and assessment of gas-hydrates using seismic data (Sain and Gupta, 2012). Prospective zones of gas-hydrates have been identified in KG, Mahanadi and Andaman regions from where gas-hydrates were later recovered by drilling & coring of Indian National Gas Hydrates Program. The test productions provide great hopes for a plausible exploitation of this gigantic energy reserves (Sain, 2017).

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