Artificial Intelligence for automatic interpretation of subsurface geologic features from surface data:

Effective identification and mapping of subsurface geologic features from surface seismic data are very important for characterizing surface and subsurface processes in understanding geotectonics, basin evolution, earthquakes processes, resource evaluation, landslide studies etc. For these, acquisition of seismic data keeps on growing, making the processing jobs computationally intensive and interpretation tasks tedious. Thanks to the high performance computing systems that have made processing of such voluminous data within a reasonable time, but human analysts struggle for manual interpretation, particularly when the area is geologically complex and data volume is so big. There is a strong need to automate the process of interpretation.

We have developed neural-based practical approaches for accelerating the interpretation of subsurface geologic features from 3D surface seismic data, first of its kind, by computing new attributes, called the meta-attributes, from a set of other seismic attributes (Kumar and Sain, 2018; Kumar et al., 2019a, 2019b, 2019c, 2020; Sain and Kumar, 2019, 2020; Kumar and Sain, 2020a, 2020b). This semi-automatic approach has successfully delimited subsurface geometries or architectures of several geologic features from huge volume of 3D seismic data at a fast rate. Here are some examples with full references for readers to follow.

(i) Magma transport through saucer sills in Waka prospect of Canterbury Basin:

The sill complexes significantly contribute to the transport and storage of hot magma, and doming of overburden. This acts as plausible structural traps for hydrocarbon accumulations in sedimentary basin. The petroliferous Canterbury basin off New Zealand is a classic example, where saucer-shaped magmatic sills are emplaced within the Cretaceous to Eocene succession resulting into forced folds and hydrothermal vents above the sill terminations. We have captured this scenario by designing workflows and computing Sill Cube (SC) and Fluid Cube (FC) meta-attributes. The outcome has prominently brought out the structural architecture of sill complexes and fluxed-out magmatic fluids within the Cretaceous to Eocene strata in the Waka prospect of Canterbury Basin (Fig.1). [P. C. Kumar & **K. Sain**, 2020. Interpretation of magma transport through saucer sills in shallow sedimentary strata: An automated machine learning approach, **Tectonophysics**, 789 (228541), 1-16.]

(ii) Mass Transport Deposit in Karewa prospect of Taranaki Basin:

The mass transport deposits (MTD) are wide-spread in the Karewa prospect of Taranaki Basin off New Zealand. Individual attributes, corresponding to the MTD geologic feature, are extracted from 3D seismic volume, and then amalgamated into MTD Cube meta-attribute through a supervised learning system. This has resulted into delimitation of internal structure and distribution of MTD (Fig.2) distinctly within the Karewa prospect, and therefore accelerating the process of interpretation with a much reduced human intervention. [P. C. Kumar & **K. Sain**, 2020. A machine learning tool for interpretation of Mass Transport Deposits from seismic data, **Scientific Reports**, 10:14134, 1-10.]

(iii) Forced folds in magmatic province of Taranaki basin off NZ

The intrusion of magmatic sills often results into the upward displacement of strata to generate forced folds. This work uses high-resolution 3D seismic volume in the Taranaki Basin to investigate Late Cretaceous-Paleocene successions in a magmatic province of New Zealand where forced folds have been identified, which were generated due to the intrusion of saucer-shaped magmatic sills into the relatively shallow strata. The two forced folds (Fig.3) resemble domal structures and show a structural relief of 250-350 m over total area of 35 km^2 and 45 km^2 respectively. Out of 18 interpreted sills, two sills (S1 and S4) contributed most to the generation of the forced folds of interest. The sill-fold relationship proves that sills with larger length-to-intrusion ratios deform the adjacent strata in greater magnitudes. Importantly, deformation within the interpreted strata led to the development of structures that are well defined viable traps for hydrocarbon and geothermal energy resources. [P. C. Kumar, T. Alves & **K. Sain**, 2020. Forced folding in the Kora volcvanic complex, New Zealand: A vase study with relevance to the production of hydrocarbons and geothermal energy, ***Geothermics, online published on 18th September, 2020***].

(iv) Lithology Prediction from downhole log data using ANN:

The neural method has been employed for lithology prediction from downhole density, neutron porosity, gamma ray, resistivity and sonic logs, which were acquired at three sites (10A, 03A and 04A) in KG basin during the Expedition-01 of Indian National Gas Hydrates Program in 2006. First of all, we apply unsupervised classification method to assess the data dimensionality and number of litho-units, which are further refined by supervised network. This has resulted into four types of litho-units, dominated by clay (~64%) with some amount of silty clay, silt and minor sand (Fig.4). Very low permeability (<0.1 mD) at these three sites indicate clay-dominated lithology in gas hydrates bearing sediments. The effects of gas-hydrates have been removed while predicting the lithology. The lithologies (Fig.4) correlate reasonably with the seismic section crossing the wells. [Amrita Singh, M. Ojha & **K. Sain**, 2020. Predicting lithology using neural network from downhole data of a gas hydrate reservoir in Krishna-Godavari basin, eastern Indian offshore, **Geophys. Jour. Internat.**, 220 (3), 1813-1837.]

(v) Submarine Buried Volcanic System in the Kora Field of Taranaki Basin:

The Kora field in northern Taranaki basin off NZ is well known for hydrocarbon prospects within the volcanogenic deposits. The buried volcano and enclosing older sedimentary strata have been structurally modulated that has led to the structural and stratigraphic traps for hydrocarbon accumulation. The best possible image of complex geological system consisting of several structural elements such as the sill networks, dyke swarms, forced folds, drag folds, jacked up strata and pinch-outs has been captured in the host sedimentary successions along with delimitation of volcanic edifice through the computation of Intrusion Cube (IC) meta-attribute (Fig.5).[P.C. Kumar, **K. Sain** and A. Mandal, 2019. Delineation of a buried volcanic system in Kora prospect off New Zealand using artificial neural networks and its implications. **Journal of Applied Geophysics**, 161, 56-75.]

(vi) Fluid Leakage along Hard-linked Faults in Taranaki basin off NZ

Increasing displacement and strain accumulation in normal faults can result into hard-linked structures that are preferred loci for fluid leakage. We have applied the ANN-based automatic approach to 3D seismic data in the Taranaki basin off NZ by designing two different meta-attributes – Thinned Fault Cube (TFC) and Fluid Cube (FC) that have captured detailed geometry of hard-linked fault zones and fluid-flow through these structures. The result shows the Miocene geological units that were structurally deformed to form several hard-linked fault zones. Fluid migrations are observed through these breached zones into younger strata (Fig.6). The strikes of the faults are oriented into the NE direction with different geometries, e.g. forming curved shapes (F1 & F2), sigmoid shapes (F3), and Y shapes (F4). [P.C. Kumar, K.O. Omosanya, T. Alves and **K. Sain**, 2019. A neural network approach elucidating fluid leakage along hard-linked normal faults. **Journal of Marine and Petroleum Geology**, 110, 518-538].

(vii) Sill Complexes in Kora prospect off NZ and Voring basin off Norway

We present an automated approach for advanced interpretation of seismic data by computing a hybrid attribute, called as the Sill Cube (SC) meta-attribute. The approach has delivered enhanced image of magmatic sills in three frontier areas: (i) Kora prospect in Taranaki basin off NZ, (ii) Utgard, and (iii) Tulipan prospects in the Vøring basin off Norway. The image has brought out saucer-shaped geometry of most of the sills along with different structural elements (Fig.7A and Fig.7B). Such an interpretational approach does not only honour the interpreter's knowledge on sills' network but also adds values in understanding tectonics of an area. [P.C. Kumar, K.O. Omosanya and **K. Sain**, 2019. Sill Cube: An automated approach for interpretation of magmatic sill complexes in reflection seismic data. **Jour. of Marine and Petroleum Geology**, 100, 60-84].

(viii) Thinned Faults in Waitara prospect off NZ

After having conditioned the time migrated seismic data (acquired over the Waitara 3D prospect in Taranaki basin off NZ), a set of individual attributes was extracted to compute the meta-attribute, defined as the thinned fault cube (TFC), by amalgamating the attributes using a fully connected multilayer perceptron (MLP) based on ANN. The TFC meta-attribute has brought out thinned and sharpened images of subsurface faults (Fig.8), which have augmented the interpretation of seismic data, which act entrapment for hydrocarbons. [P.C. Kumar and **K. Sain**,. 2018. Attribute amalgamation-aiding interpretation of faults from seismic data: An example from Waitara 3D prospect in Taranaki basin off New Zealand. **Jour. of Applied Geophysics**, 159, 52-68].

(ix) Gas Clouds in Maari prospect off NZ

The new approach has been applied to the time migrated 3D seismic data in Maari prospect of highly structured and deformed Taranaki basin off NZ. By combining energy, similarity, dip variance, frequency washout, simple chimney attributes into a single attribute, defined as the chimney probability cube, the study shows clear picture of subsurface gas clouds, discriminated from geologic features, in which the gas originates from the Late Cretaceous source rocks (Pakawau Group) and migrates into the Eocene (Kapuni Group) and Miocene (Mahakatini Group) formations (Fig.9). The study shows that gas has seeped through the overlying Pliocene to recent formations, imprints of which are observed as pockmarks on the seabed. The fault intersection or weak zones are the main causes for high probability of gas chimneys. [D. Singh, P. C. Kumar & **K. Sain**, 2016. Interpretation of gas chimney from seismic data using artificial neural network: A study from the Maari 3D prospect of Taranaki basin, New Zealand, **Jour. of Natural Gas Science & Engineering**, 36, 339-357].

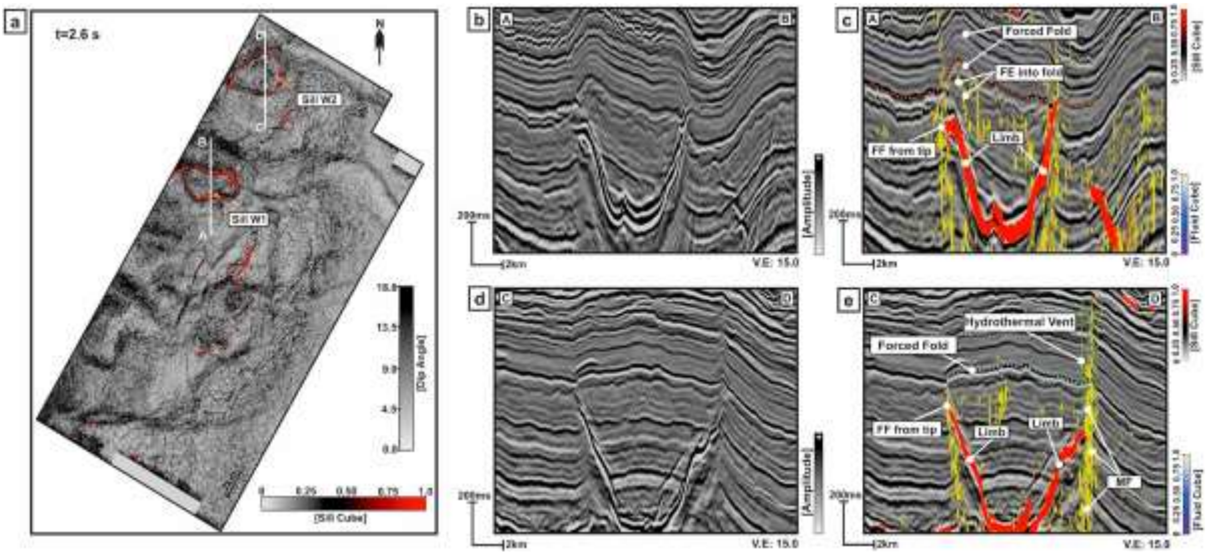

Fig. 1: (a) Time slice at *t* =2.60 s, displayed using co-rendered volumes of dip magnitude attribute and SC meta-attribute, clearly shows the magmatic sill complexes namely Sill W1 and Sill W2 in the NW part of the prospect. Their presence is confirmed on randomly taken seismic lines (AB and CD) that are perpendicular to the trend of sills; (b) Random seismic line (AB) demonstrating the presence of Sill W1 which is characterized by concave upward geometry with concordant base and discordant limbs. Vertical transport of magmatic fluids through the limbs has resulted into forced folded structures; (c) Interpreted section as explained in (b); (d) Random seismic line (CD) showing the presence of Sill W2 characterized by concave upward geometry. Magmatic fluid vertically rises through the hydrothermal vent thereby doming the overlying strata; (e) Interpreted section as explained in (d). FF: Forced Fold; FE: Fluid Emplacement; MF: Magmatic Fluid.

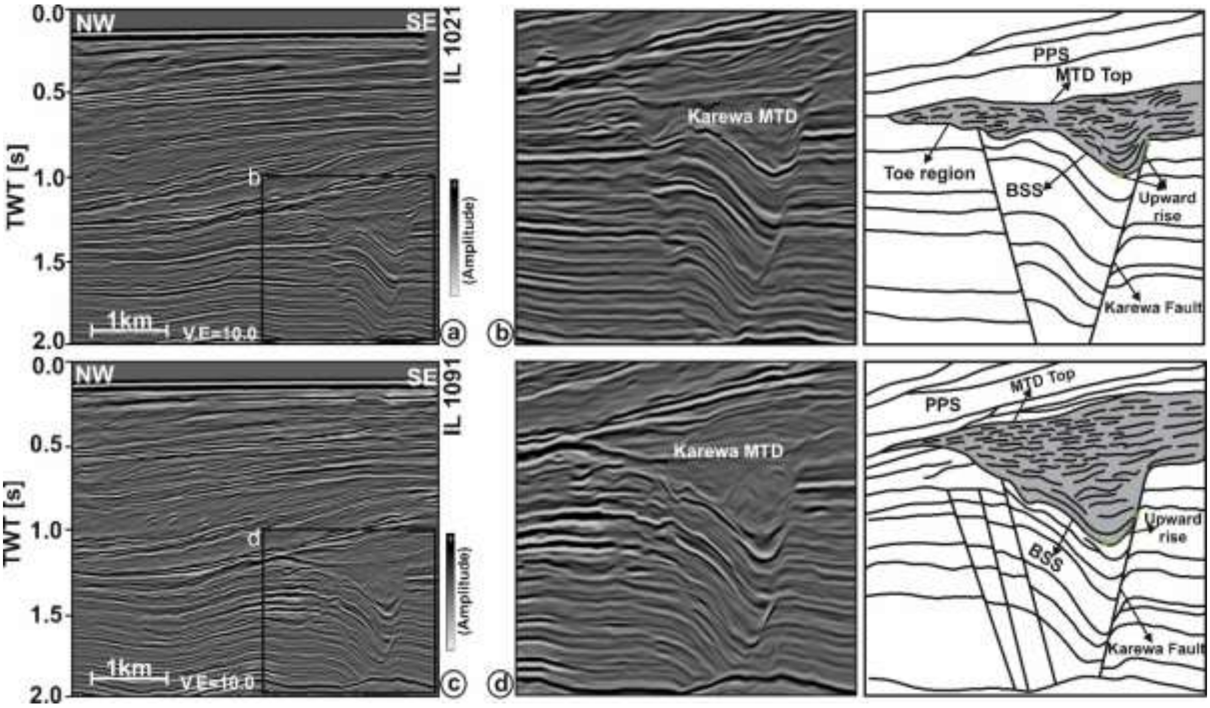

Fig.2: (a) Original and (b) improved section along the line IL 1021; (c) original and (d) improved section along the line IL1091 within the Karewa prospect. Right panel shows schematic interpretation along the seismic lines. The Karewa MTD is fault bounded both on the head wall and toe domain. The BSS of the MTD rises upward along the Karewa fault towards the eastern part of the survey. The top of the MTD runs more or less parallel to the overlying Plio-Plestiocene Sequence (PPS).

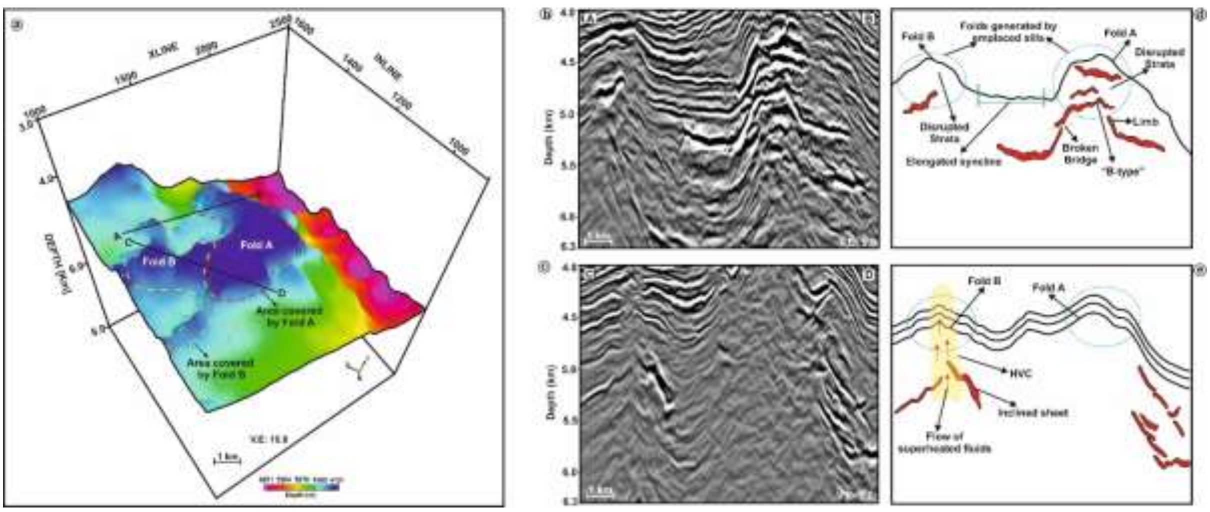

Fig. 3: (a) TWT structure map that shows two major forced folds named Fold A (marked by red dotted polygon) and Fold B (marked by yellow dotted polygon). (b-c) Seismic sections along A-B and C-D lines and their corresponding (d-e) sketches. Fold A occupying the central part of seismic profile and Fold B lying towards NW are semicircular in nature. The intrusion of magmatic sills vertically displace the strata and generate the forced folds. A hydrothermal vent complex (HVC) is observed below the Fold B suggesting for flow of superheated fluids through these structures.

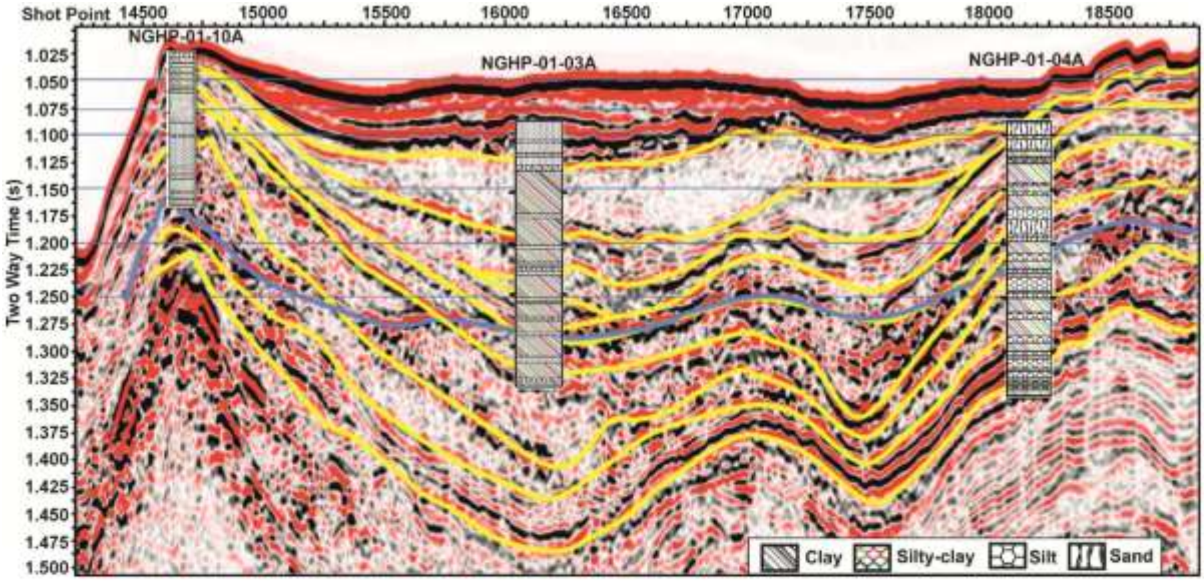

Fig.4: Correlation of predicted lithology with seismic litho-facies. Blue line denotes the BSR, where yellow lines are indicating various boundaries of sedimentary layers.

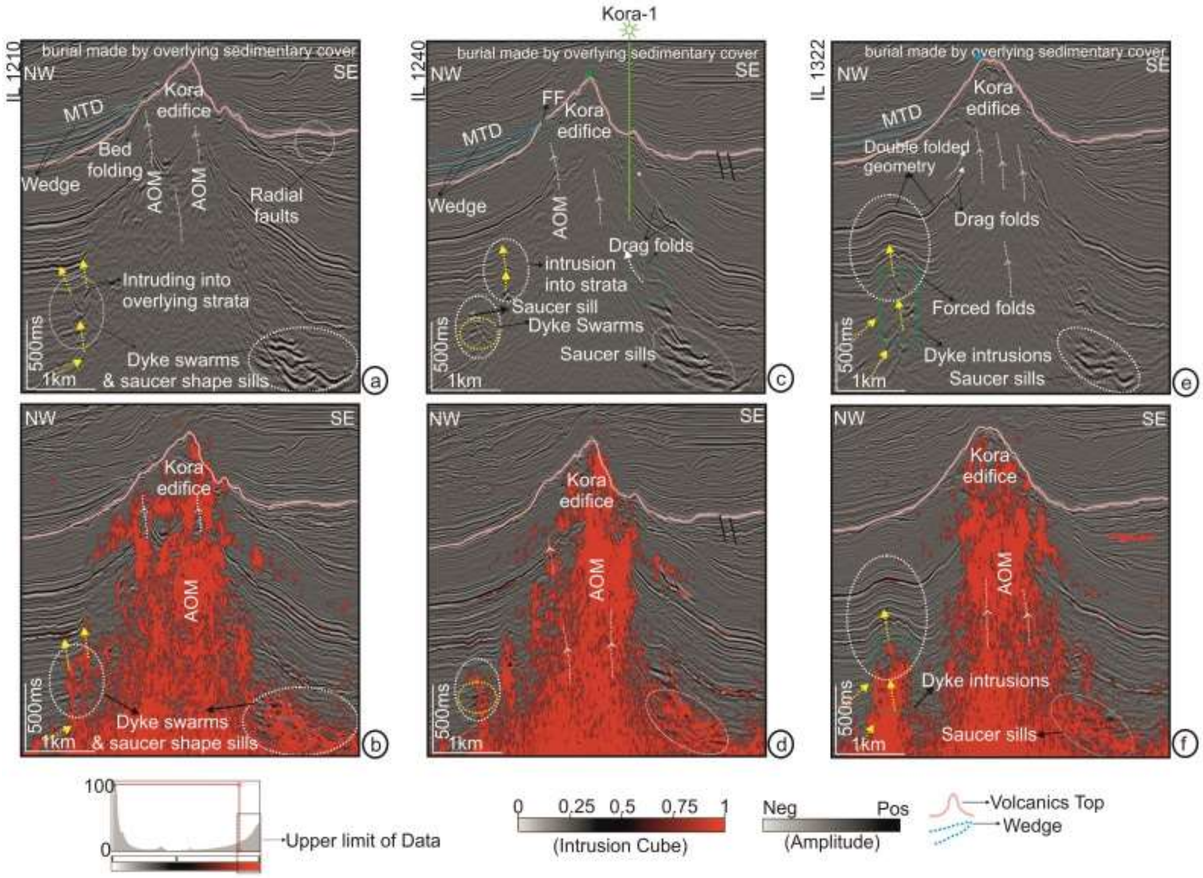

Fig.5: Interpretation using IC meta-attribute over different profiles of 3D seismic volume in the Kora prospect.

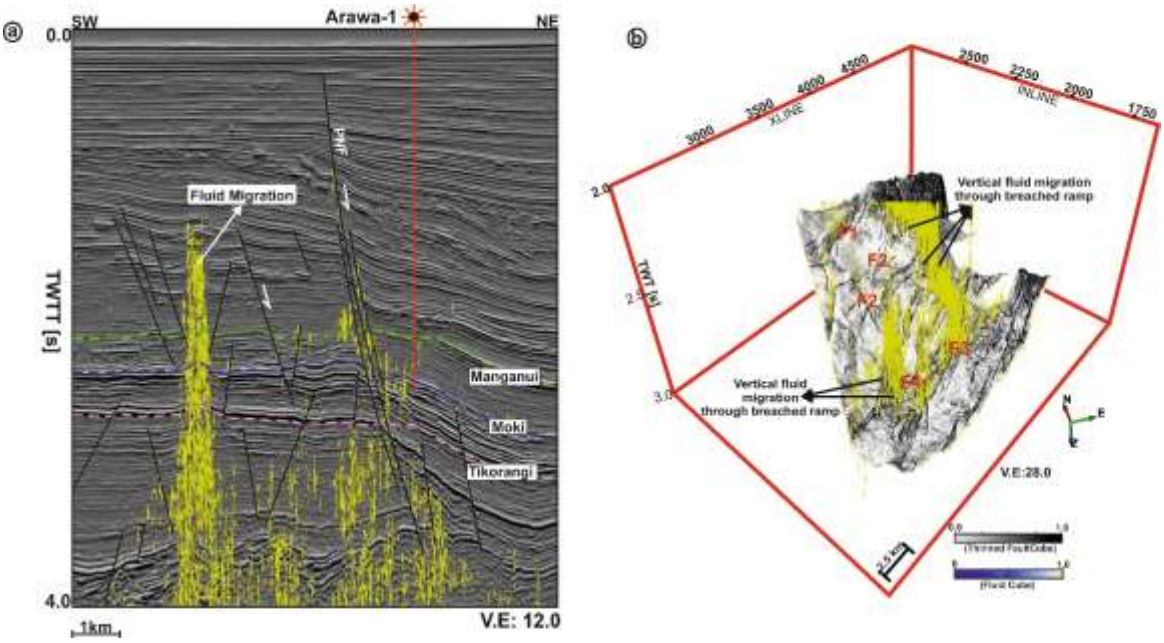

Fig.6: (a) Fluid Cube meta-attribute revealing fluid migration through hard-linked normal faults. (b) 3D view of breached ramp between faults F1-F2 and F3-F4.

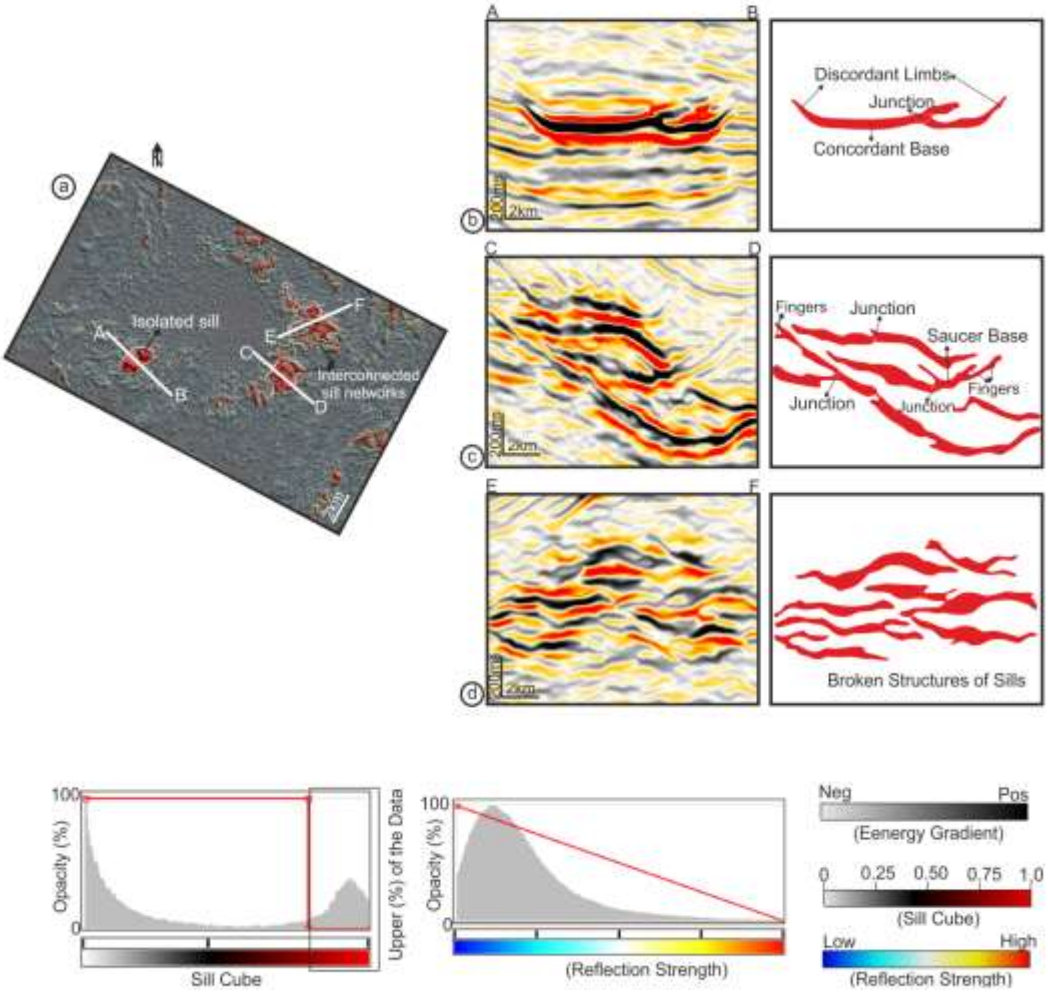

Fig.7A: (a) Time slice at t=4.06 sec, co-rendered volume of energy gradient, SC meta-attribute and reflection strength attributes, shows clear picture of magmatic sill complexes. Their presence was further confirmed on seismic lines (AB, CD & EF) randomly taken perpendicular to the trend of sills; (b) Seismic section along random line AB showing isolated saucer shape sill in the SW part of the Kora prospect. The sill with concave upward geometry along with concordant base and discordant limb is connected to a nearby sill through junction; (c) Seismic section along random line CD showing saucer shape geometries of the sill networks in the SE part of the prospect. The sills are interconnected through junctions;(d) Seismic section along random line EF showing broken structures of sill networks clustered in the NE part of the prospect.

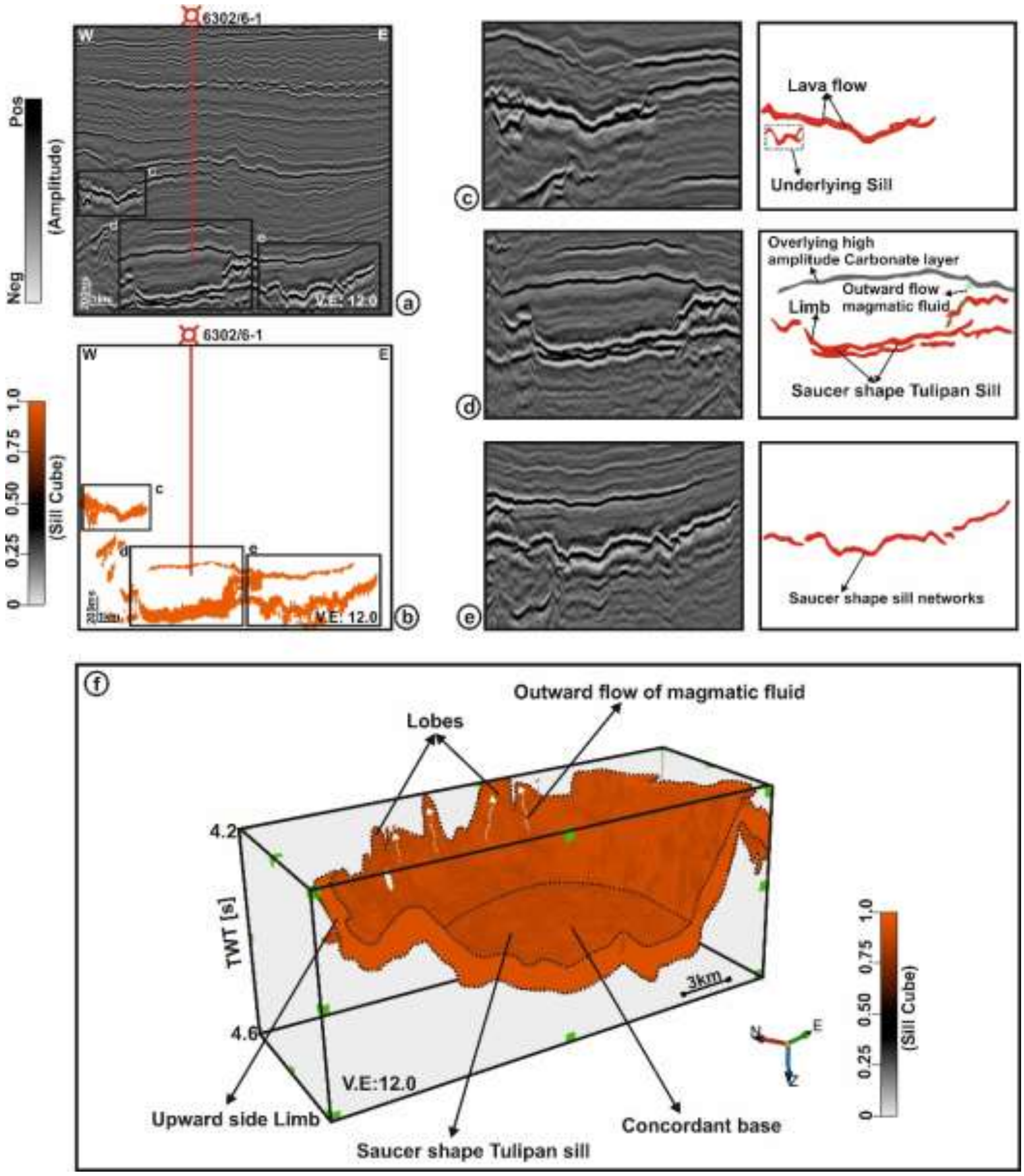

Fig.7B: (a-e) Amplitude section and the SC meta-attribute revealing the Tulipan sill and associated magmatic emplacements from the Tulipan prospect, Vøring Basin, off Norway; (f) 3D structural geometry of Tulipan sill, delimited using SC meta-attribute.

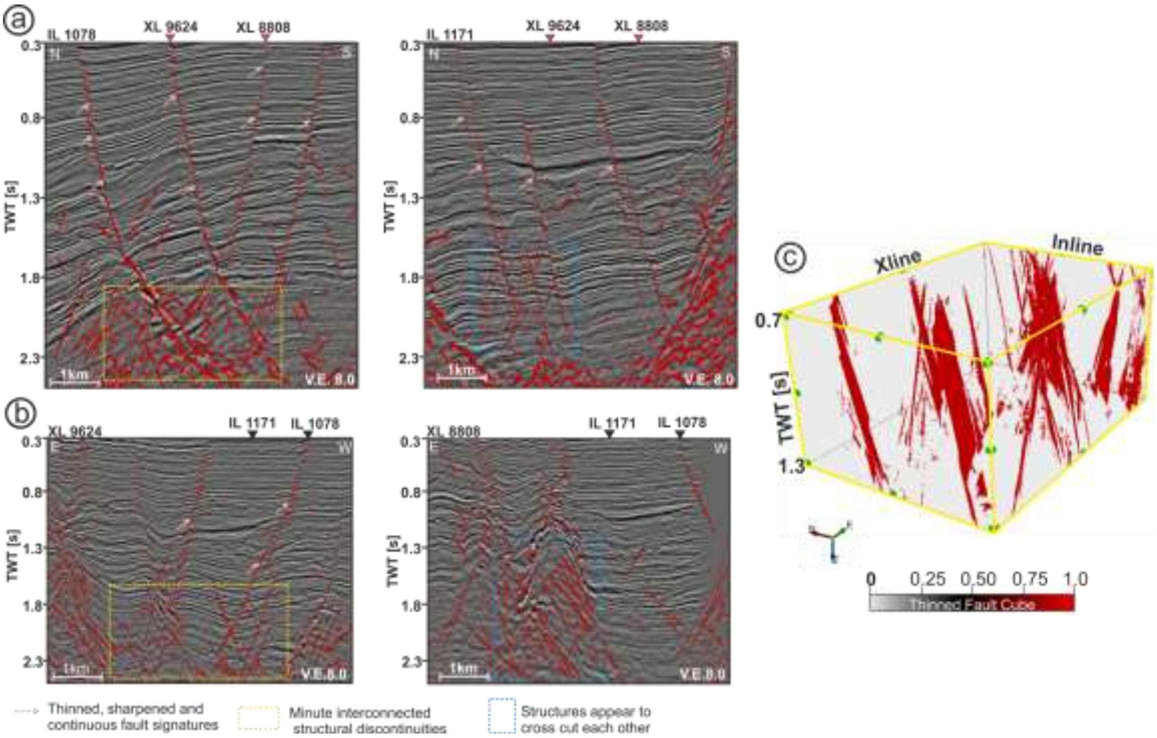

Fig.8: (a) TFC meta-attribute co-rendered with amplitude data for inlines IL 1078 & 1171 showing distinctly the thinned faults; (b) TFC meta-attribute co-rendered with amplitude data for xlines XL 9624 & 8808; (c) 3-D view of the TFC meta-attribute.

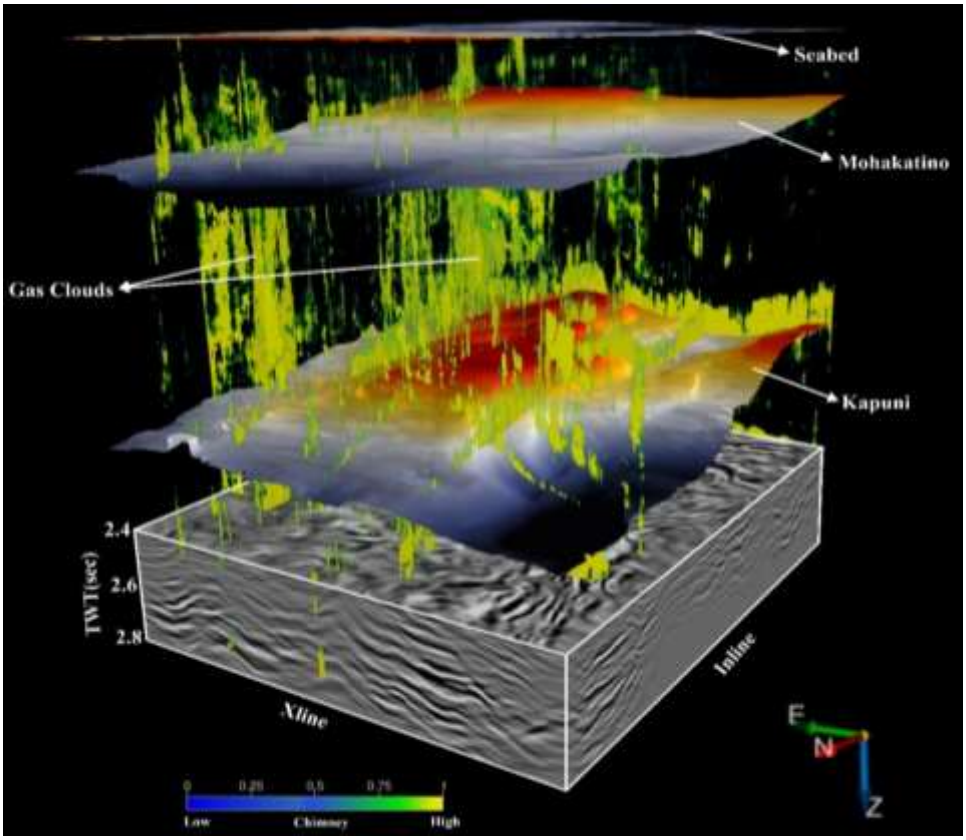

Fig.9: 3D visualization of gas clouds, delineated by computing chimney probability cube, rising from thermally matured source rock and propagating through Eocene and Miocene sandstone reservoirs to the seabed.