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Ontology based warehouse modeling of fractured reservoir ecosystems – for an effective borehole and petroleum production management

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***Abstract*— Exploration business deals with structure and reservoir data. The carbonate reservoirs, (especially of Jurassic age), establish its hydrocarbon potential and production on commercial scale in Middle Eastern onshore petroleum systems. There is an immense scope of exploration and production from the fractured horizons and their associated reservoirs. Most of the fractures are networked or interconnected through fluid media. The wells drilled in carbonate reservoir areas, have been under an unbalanced-stress system that exhibits commonly two types of borehole failures, shear and tensile failure, where the rocks drilled, are replaced with drilling mud. Rocks undergo hoop and radial stresses that occur by drilling and also natural fracturing. A robust methodology is needed to address issues of integrating multiple fracture systems. Issues relevant to borehole management are addressed through ontology modeling of networked fractures. Authors propose data warehousing approach supported by ontology that can integrate data attributes associated with fractures of multiple horizons from several wells, geographically (distantly) located within a producing basin. Authors attempt to make connectivity between structure and reservoir data attributes. Integration is done by mapping and modeling conceptually (more logically) interpreted relationships among multidimensional inter-dependent data structures and attributes through their data property instances that are described from different fracture systems. Data mining can separate out these stresses, so that driller or well planner knows in advance the fracture systems that are being drilled. The proposed methodology is robust and can resolve issues relevant to deviation and smart drilling in the fractured reservoir systems. This approach integrates and makes connectivity among varying common and conceptualized attributes associated with structure and reservoir. If the proposed methodology is successful, it can be applied any fractured shales and tight-gas reservoir systems worldwide.**

***Index Terms*—ontology, warehouse modeling, fractured reservoirs, borehole planning and production management**

I. INTRODUCTION

Placement of wells and managing the production from the unconventional reservoirs [5], are based upon judicious well planning, such as vertical and or horizontal well locations. Precisely, the well placement is done where dense fractures are interpreted. The magnitude and direction of fractures and the subsequent causative effects (in the form of stress/strain) on reservoir rocks are also significant and these are most popularly explored by seismic and or drilling methods.

The rocks withstand both compressive and shear stresses but the fluid filling the borehole bears only compressive stress and not shear stress. Consequently, concentration of stresses takes place around the well borehole in the form of hoop stress or tangential stress. When the mud weight is too low (radial stress = mud weight minus pore pressure), the maximum hoop stress becomes much higher than the radial stress. Consequently, a shear failure of rocks exposed to the borehole takes place, which is exhibited in the form of borehole elongation. On the contrary, when the mud weight is too high the radial stress increases and the hoop stress decreases. Consequently, rock around the borehole comes under tension; the fractures thus created are called induced fractures.

Generally, in vertical wells and those with smaller deviation, the orientation of borehole elongation is aligned with the trend of minimum horizontal stress. Similarly, the strike of drilling induced is aligned with the trend of maximum horizontal stress. However, it may not be the case with the deviated wells and particularly those wells that are not aligned with either of the two horizontal stresses. In such wells, orientations of borehole breakouts and drilled induced fractures may not represent true orientation of the two horizontal stresses. It is because of the fact that all three principal stresses (vertical and two horizontal) act oblique to the borehole. Fracture dimensions are critical in well bore planning and production management.

Three types of fractures occur in shale. They are regional, tectonic and expulsion. All fractures are *lithology* dependent; differ in degree and type of fracturing. Mineralization on fracture surfaces is absent. Natural fractures are differentiated from induced fractures based on pore size (usually a micro-porous surface). Micro-porous surface does not occur on freshly broken bedding planes or on induced fractures. Regional fractures form an orthogonal pattern over a wide area and are open in a direction parallel to the maximum horizontal stress. In order to determine direction of horizontal stress, cores are subjected to differential strain analysis. Caliper (four-arm) data also provide sufficient clues of direction of break-outs. At times, regional fractures are responsible, providing most significant transmissibility element for fluids, in which case, north-south horizontal drilling direction is preferred.

In case of expulsion fractures, fracture widths vary from 10 to 20 microns. Length varies from one-half inch (one cm), in which case, fractures are usually horizontal. They may have resulted because of pressure release. Both vertical and horizontal macro expulsion fractures may exist, however, distinguishing between small scale regional fractures, small tectonic fractures and possible bedding plane breaks, is difficult.

Pressure and production data suggest the character of the natural fractures. High fluid pressures and the lack of propping material within fractures also create a usual drive mechanism. In most reservoirs with only rock-compressibility and solution-gas drives, rock compressibility is a dominant drive mechanism only above the bubble point. It is normally ineffective, resulting in a sharp early decline. Once the bubble point is reached, decline becomes more moderate as solution-gas drive becomes dominant.

II. OBJECTIVES AND PROBLEM DEFINITION

A. Objectives and problem issues

1. Distinguish fracture data patterns and their impacts on pressure and production
2. Reservoir uncertainties and risk minimization.
3. The data acquisition plans, addressing the development strategies for each field.
4. Static field model development
5. The review of wells (associated with fracture patterns) and their completion requirements and facilities.
6. Economic analysis

First three issues are the present scope of the study and analysis. The static reservoir model consists of a structural framework that is populated with matrix and fracture properties. It is constructed by integrating all the available geological, geophysical, petro-physical and engineering data.

B. Characterization of the Fracture Systems

The main objective of the present study was to characterize fracture system at the borehole scale so that in conjunction with other measurements, like 3D seismic and well tests, the information could be used to build a comprehensive fracture model. In addition to fractures, structural dip, fault analysis and in-situ stress analysis are carried out and used to design and map different data structures. It is important to understand the fracture characterization to build conceptual data models. Basic criteria for identifying the fractures are given in the following sections.

C. Criteria of fracture identification

Data instances of fracture dimensions are acquired. For this purpose, fractures and patterns need to be identified and documented. Fractures are planar features with no apparent displacement of blocks along their planes. Generally, they possess steep dips in tensional and wrench regimes. In compressional regimes, they may have, high to low angle dips. Their apertures may be open, tight (closed) or filled with minerals such as, clays, calcite, anhydrite, pyrite etc.

Fractures tend to occur as linear features that generally have steeper dip attributes, compared to the structural dip. Open fractures and fractures with apertures filled with resistive material, like calcite and anhydrite may have same resistive appearance, because open fractures are invaded with oil-base mud, have the same resistive appearance as the one filled with resistive minerals like calcite and anhydrite. Such closed fractures can be differentiated from the open fractures using amplitude attributes. The amplitude of the acoustic pulse decreases in front of open fractures filled with oil-base mud, thus open fractures appear as darker linear features. The calcite and or anhydrite filled fractures do not affect the amplitude image, because the rock matrix and fracture filling have more or less same amplitude range. However, there could be amplitude contrasts between rock matrix and fracture filling material. Clay/shale filled fractures have conductive appearance due to no invasion of oil-base mud along the planes. Categories of fractures and dimensions of each category are continuous open fractures, discontinuous open fractures, induced fractures, borehole breakouts, horizon bedding dips, large open fractures, partially open fractures and styloites. In each category, several dimensions, based on scales and attitude attributes, can hierarchically be classified as depth, fracture type, dip-magnitude, dip-azimuth, strike-azimuth, borehole coverage, confidence level, and average aperture. Here strike and dip are key data attributes, when considering the fracture types and orientations.

III. METHODOLOGY & DATA MODELLING FRAMEWORK

Domain ontologies ([4], [8], [9]) are used to conceptualize relationships among different types of datasets. Local geometry and flow capacity dimensions of the natural fracture network are captured in the static fracture model framework for reservoir development. Fracture orientation and intensity (density) dimensions are attributed to the measured and also interpreted data. Flow capacities of fracture systems are compared among production rates of the wells from different geological age dimension attributes. Besides these data attributes and dimensions, authors attempt to build relationships among rock properties, fracture types and strengths.

A. Building rock stress-strain domain ontologies

The sub-surface of the continental crust rarely remains at a stable hydrostatic stress condition - the stress state under which all points in the crust are subjected from all directions to equal stresses. However, such stress conditions are rarely met in the earth's subsurface as many structural movements keep taking place in it. The larger portion of the disturbance in the equilibrium in the stress state is controlled by plate movements that ultimately result in the formation of regional stress system for the area bounded by them. However, sometimes the regional stress is completely overprinted due to stresses localized to a certain area. The source of local stress system may be associated with faults, folds, diapirism [5]. The orientation of stresses may be changed abruptly over short distances in any area. The wells drilled in areas may have been subjected to some kind of unbalanced stress system (especially in carbonate reservoir systems) often exhibit two types of borehole failures, shear and tensile failure, when the rocks drilled by them, are replaced with the drilling mud.

Integrated interpretation of fractures is done from image logs with core data and subsequently calibrated into seismic data. Interpreted layers (horizons) are linked through vertical fracture connectivity among different stratigraphic unit dimensions. Next step is to predict the spatial variations in the orientation and intensity of each fracture set. This is done by comparison ontology and again integrating magnitude and direction dimension components along with attributes of seismic and well data (gamma, density, sonic) with the intensity variations among producing wells. The fracture geometry dimension is evaluated with parametric dimensions of structural and reservoir attributes, so that consistent geological implication and validation are achieved.

Though qualitative fracture geometries are established, the flow and storage capacities still need to be established in terms of quantifying through fracture hydraulic data attributes. Permeability, aperture and compressibility attributes are connected and assigned among each and every fracture set. Aperture information is interpreted from fracture image logs.

B. Building structure and reservoir domain ontologies (through fracture systems)

Establishing connectivity between structure and reservoir is a significant issue in planning and management of boreholes. In fractured carbonate reservoir systems, it is required to prove this phenomenon through orientations and density of fractures if they pass though structural highs. Three types of fractures [5] in terms of their orientation, relative to the principal horizontal compressive stress direction are: extensional; longitudinal; and shear. Extensional fractures have dips ranging 70 to 90 degrees and strike direction ranging +ve or -ve 150 degrees to the fold axis. Longitudinal fractures have dips that are variable but are often normal to bedding and oriented sub-parallel to the fold axis. Shear fractures cut the other fractures at an angle and occur as conjugate pairs, with the development of one of the pair dominating over the other.

Fractures are also grouped according to their order of frequency for each well, with first order fractures having highest frequency, 2nd, 3rd, and 4th order fractures having lesser frequencies. All the wells have one dominant set of fractures (first order) with 2nd and 3rd order fractures occurring at comparative frequency ratios of 2:1-25:1. No one fracture type dominates in the order of development and the development appears to be random across the structure. Extensional fractures are common to all the wells, whereas the longitudinal and shear fractures are not. Extensional fractures probably provide a mechanism for connecting other fractures that have developed at all scales, from the microscopic to mega-scopic. The result is that extensional fractures may be responsible for draining the reservoir.

Production in fractured reservoirs is largely controlled by fractures. Fracture orientations and their occurrences (frequencies) and possible relationship to lithology and systematic orientation of fracture sets as a response to regional compressive stresses. Fracture orientations and number of fractures, are key criteria. A fracture set is any set of systematic joints that are planar and parallel, and continuous in orientation from stratum to another. The recognition of fracture sets and their orientations can visually be seen from contour maps of geological structures.

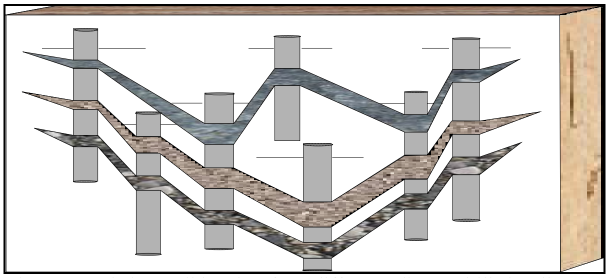

Fig. 1: Correlation well log data from different adjacent drilled wells; connecting and interpreting the fracture patterns (as interpreted on their respective core data)

As shown in Fig.1, log signatures of different geological units from nearby wells, are correlated in order to establish the structural position of each geological horizon and its associated reservoir (porosity attributes) character. These structure and reservoir attributes are made interconnected through domain ontologies and also establish the fracture network among these wells. This network in well-log domain is further integrated with seismic markers and their network.

C. Building Fracture Frequency and Lithology Domain Ontologies

The relationship of fracture frequency with lithology and to bed thicknesses is an interesting property and attribute. Fracture intensity is directly related to the silica content of the rock and to the diagenetic grade. It is reported that the order of decreasing fracturability and increasing fracture spacing to be the first in chert, then porcelanite, mudstone and dolostone. Fracture density increases with increasing silica content of the rock and decreasing bed thicknesses. Upper calcareous-siliceous is fractured most and intervals with lower silica contents are not heavily fractured. Thinner siliceous beds have a higher fracture frequency than the mudstone and many fractures are confined to individual beds and are normal to bedding planes.

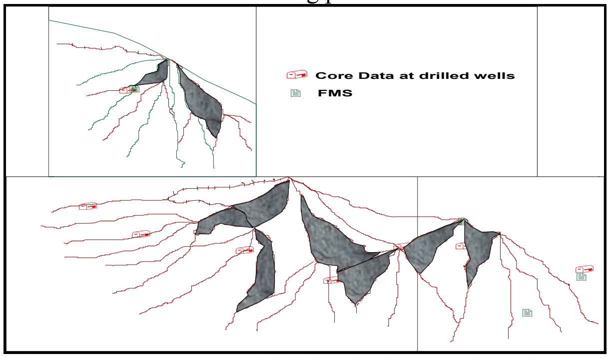

Fig. 2: Fracture patterns around drilled wells – heterogeneity and connectivity of fractures and their orientations

As demonstrated in Fig. 2, fracture orientations are controlled by regional stress patterns. The most common sets are roughly parallel and perpendicular to the strike of the bedding. Fracture sets are classified according to their orientation relative to the axis of anticline structure. Fractures are extensional, longitudinal or shear. Most extensional fractures are nearly vertical and oriented normal to the local axial trace of the structure or normal to bedding strike. These are common to all wells drilled. Longitudinal fractures have dips that are variable but are often normal to bedding and have strikes sub-parallel to the fold axis or bedding strike. Shear fractures cross other fractures at an angle. Dips are variable, ranging from 40 degrees to vertical. Shear fractures in some wells indicates their occurrence as conjugate pairs with the development of one of the pair dominating over the other.

The following tasks are put in the data schema framework, as narrated in Figs. 3 and 4. Fracture data facts are being connected to the fracture data dimensions, by one-to-many and also many-to-many relationships. There are already known relationships among these data facts and instances of fracture data dimensions. Some of the relationships, unknown may be conceptualized by ontology modeling, so that the type of fractures based on their size and behaviour (properties) are appropriately connected to the respective conceptualized data instances of the rock properties and hydrocarbon drive mechanisms (Figs. 3 and 4). Conceptualized dimensions are evolved after data integration process, using data instances of hydrocarbon pressure and production data dimensions. For building conceptualized relationships, domain ontologies are integrated as described in the following sections.

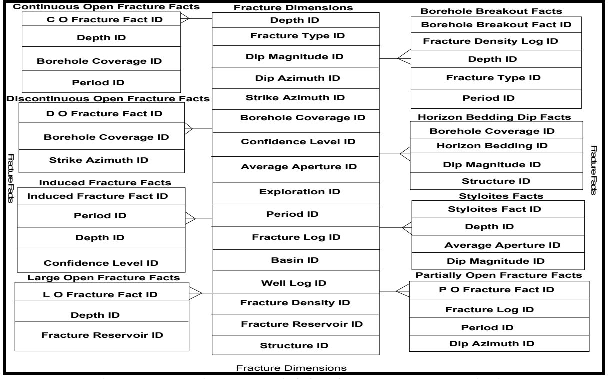

Fig. 3: Star schema model for fracture systems design

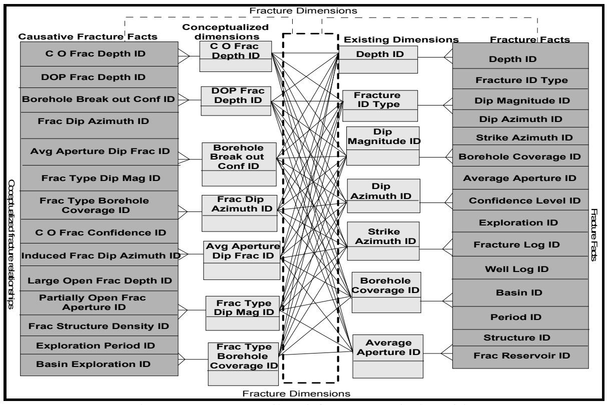

Fig. 4: Conceptualized fracture relationships

Not all the fracture sets are developed with the same frequency (occurrence) in the same well. One fracture set is generally developed at a greater frequency than others by ratios of 2:1 to 25:1. Based on this, fracture sets are classified by their order of frequency for each well. First order fractures have the highest frequency, with 2nd, 3rd, and 4th order fractures having lesser frequencies. The type of first order fractures, varies from well to well and can be extensional, longitudinal, or shear. Fracture distribution, though, is more dependent on lithology, but structural position has a role. Extensional fractures are common to all wells, whereas longitudinal and shear fractures are not. Shear fractures orient variably from one well to other and probably do not provide significant source of directional permeability. Extensional fractures are consistent in their orientations and since they are common to all wells, probably contribute to the directional permeability in the field.

As shown in Fig. 5, an integrated framework ([4], [8], [9]) is designed for combining different domain ontologies not only from different fracture systems, but also from diverse datasets, such as log and seismic data. In the process of integration, it is important linking the fracture systems interpreted on the log data, and are appropriately calibrated on the seismic data. Calibrated fractures are correlated and propagated in the entire seismic data to establish the vertical, horizontal and lateral fractures connectivity through conceptualizing and integrating ontology domains. Relational, hierarchical and networking data structuring methodologies are followed and the one that describes the hierarchical structuring of fractured data is shown in Fig. 6.

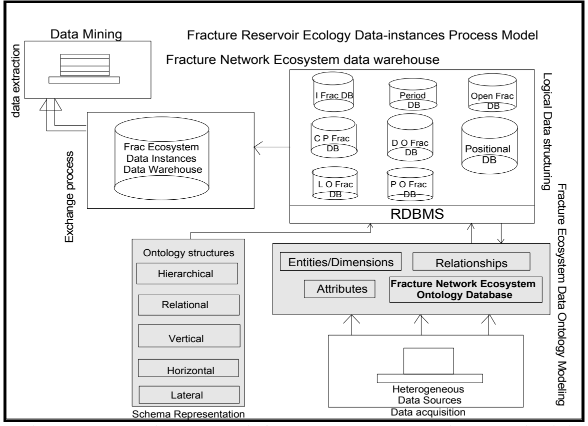

Fig. 5: Integrated Framework for Fracture Data Warehouse and Mining

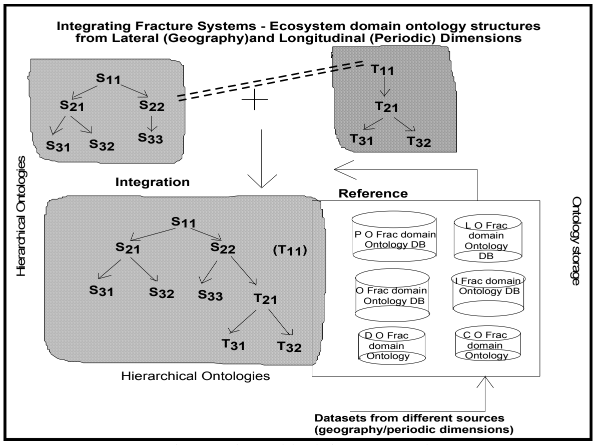

Fig. 6: Hierarchical data structuring

IV. DATA MINING OF FRACTURED RESERVOIR DATA

A. Classifying multiple dimensions for rule mining

Discovery of association mining rules ([1], [2], [3], [6]) is solely dependent on discovery of frequent occurrence of multidimensional data attributes. Oil/Gas businesses are often interested in Yes or No response, such as reservoir engineers wanting to know whether a reservoir is productive or not; and explorers seeking to establish if the petroleum system is productive or not with existing secondary porosity fracture system. These are classification issues, in which data attributes and their instances with finite number of classes, are explicitly described.

The classifying attributes may be related to many other attributes, which may have been conceptualized among other classifications. For example, structure and reservoir attributes among several horizons have similarity and scalable property instances. Among reservoir subsets, there may be fracture attributes, both relationally and hierarchically interconnected among multiple horizons. Classifying the intensity and frequency of fractures in different orientations is an interesting data mining issue. Each fracture is characterized by its physical properties such as surface area and shape, and each has specific fluid flow properties—of permeability, compressibility, and aperture. It integrates the information from a wide range of sources including 2D and 3D seismic, maps, outcrops, reservoir geo-mechanics, well logs, well tests, and flow logs, as well as structural or depositional conceptual models. Several data views are extracted from the fractured reservoir data warehouse. Several dimensions are chosen for mining the data views and interpreting them for significant fractured reservoirs from integrated data warehouse model. Some such data views are deduced and interpreted in terms of multidimensional decision tree mining model, views from data cubes and cluster mining through bubble plot analysis among multiple dimensions and are given in the following sections.

B. Design of multidimensional decision trees

Which horizon has a greater number of fractures, indicating the strength of porosity? The answer can assist in planning for borehole placement. A decision tree is a classification scheme which generates a tree type model and with a set of rules, representing the model of different classes from a given data set. Two disjoint subsets are made, which are 'training set" and "test set". The former is used for delivering the classifier while the latter is used to measure the classifier accuracy.

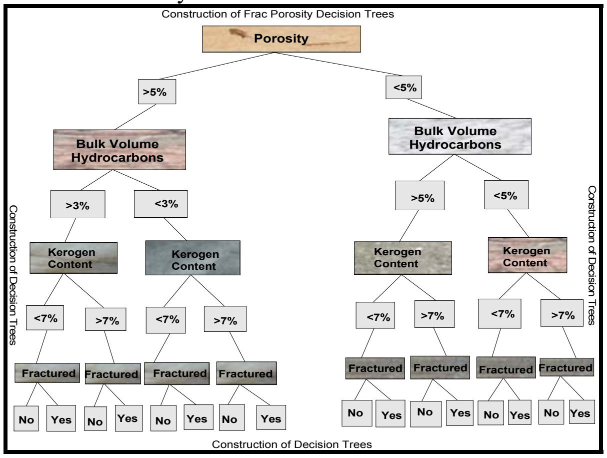

Fig. 7: Multidimensional decision tree structure.

The accuracy of classifier is determined by the percentage of the test examples correctly classified. In our case, attributes are two different types - one is porosity, and the other is kerogen content. Attributes whose domain is numerical are called numerical attributes and non-numerical attributes are called categorical. Fig. 7 shows a construct of decision tree mining model, in which various rules associated with porosity and kerogen instances and their cut-offs are described. Favourable data instances of porosity and kerogen content of rocks contribute to various fractures and their categorizations. Interpreters make use of this information model, a decision making tool for ascertaining which type of rocks and kerogen content contribute to the hydrocarbon accumulations with favourable porosities. Major strengths of decision tree are, generating more logical and understandable mining rules, handling of both numerical and categorical attributes, and also providing clear clues of which fields are significant for prediction and classification.

C. Dimension modeling and data cube

The dimension provides much semantic information [7, 10], especially about the hierarchical relationships between its elements. It is important to note that dimension modeling is a special technique for structuring data around fracture systems. Dimension modeling structures the numeric measures and the dimensions. The dimension schema (Fig. 3) represents the details of the dimension modeling; in which period is key dimension that enables analysis of historical datasets. The dimension hierarchy helps viewing multidimensional fractured data in several data cube representations. Data views will be finer to access, if fine-grained structuring [10] is done, while designing the domain ontologies.

A popular conceptual model that influences data warehouse architecture is a multidimensional view of the data, as shown in Fig. 8. This model views data in the form of a data cube (more precisely, hypercube). It has multiple dimensions, each dimension again is subdivided. In this multidimensional model, there are sets of numerical measures that are the main theme or subject of the analysis. Each fracture type, such as open fracture, has different dimensional attributes, such as dip, azimuth, and density. There is more than one numeric measure. Each numeric measure depends on a set of dimensions, which provide the context for the measure. All the dimensions together are assumed to uniquely determine the measure; the multidimensional data views a measure as a value placed in a cell in the multidimensional space. Each dimension, is in turn, is described by set of attributes. The attributes of a dimension may be related via a hierarchy of relationships (Fig. 6) or by a lattice [10]. As an example, in Fig. 8, drawn from the "frac data cube" is during 1998, under depth category, open fracture system has 5% fracture density (porosity) with a specific count of 76 and during 2002, under structure category, fracture density is 8% (porosity) with counting rate 100.

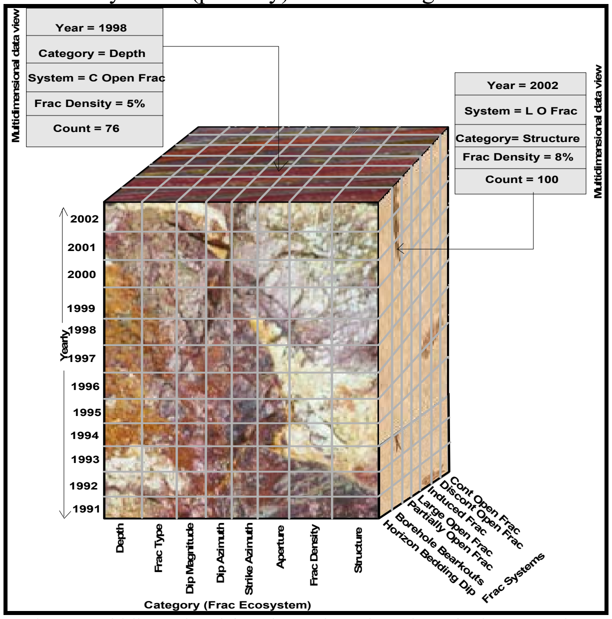

Fig. 8: Multidimensional frac data cube – data views for interpretation

D. Multidimensional cluster mining

Clustering discovers data patterns (Figs. 9-12) and distributions from large number of multidimensional attributes, organized in a warehouse environment. Identifying the dense and sparse regions of dataset are significant and the real goal of multidimensional clustering. Number of attributes is multidimensional, in large size datasets. Horizons having more and similar type of fracture patterns belong to a particular cluster. Data instances that consist of large numerical data may be categorized into two groups in which partition and hierarchical types are popular. Most of the algorithms existing today can handle multidimensional data, but they differ in their ability to handle different types of attributes, numerical, categorical, and accuracy of clustering.

Measuring the distances or similarity metric among partitioned or hierarchical clusters is also a significant concept. Knowledge of which horizon has a greater number of fractures occurring in particular groups or types of fracture patterns, is helpful in planning for new borehole placement.

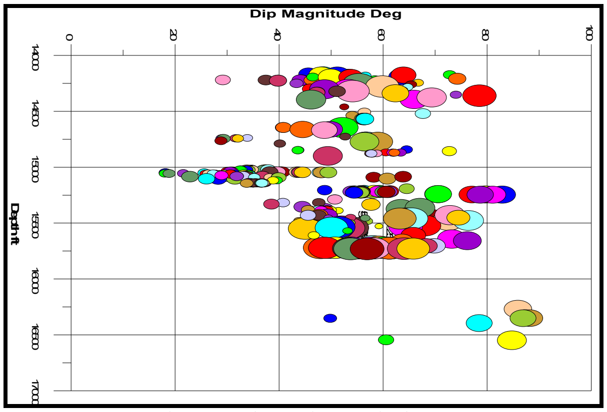

Fig. 9: Depth vs. Dip Magnitude Deg

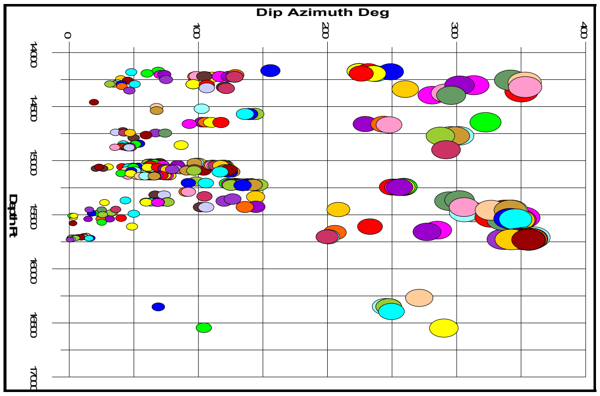

Fig. 10: Depth vs. Dip Azimuth Deg

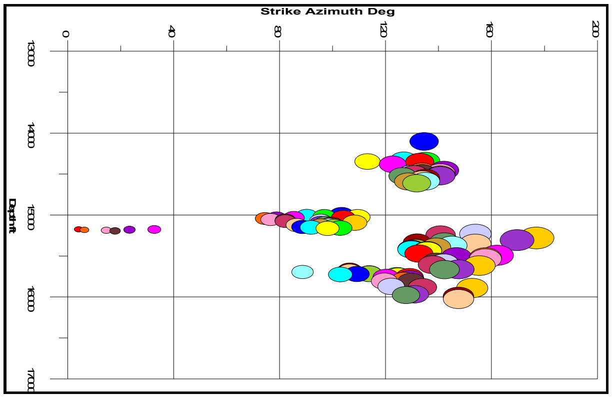

Fig. 11: Depth vs. Strike Azimuth Deg (borehole breakouts)

V. RESULTS AND DISCUSSIONS

Fractured reservoirs, especially carbonates, hold significant oil and gas reserves, besides it is challenging to predict these reserves under complex and heterogeneous conditions. Most carbonate reservoirs are naturally fractured and due to brittleness and size of fracture may vary from isolated microscopic fissures to kilometres-wide. At geological times and places, these fractures create complex paths for fluid movement, which impact reservoir characterization and ultimately production performance and total recovery.

Operating companies in the Middle East have been exploring and developing the fractured reservoirs [5], especially when they are associated with particular geological age attributes. Low porosity carbonates with high kerogen (geochemical property) contents of the horizons also act source rock attribute. Certain reservoirs are entirely dependent on natural fractures for their productivities. Hydrocarbon pore volumes in reservoirs cannot be produced commercially unless there is connectivity among natural fracture systems. In order to plan and select drillable exploratory and development targets, it is necessary to optimally design the trajectories and completions and develop sustainable field development plans, improving the understanding of the natural fracture system. The scope of the current study is to assess the application of directional/horizontal drilling (in new wells or side track of existing wells) and hydraulic fracturing, develop better understanding of reservoir fracture/matrix architectures (fracture storativity, connectivity, replenishment, flow capacity, intensity), and finally develop a fracture network model with predictive capabilities.

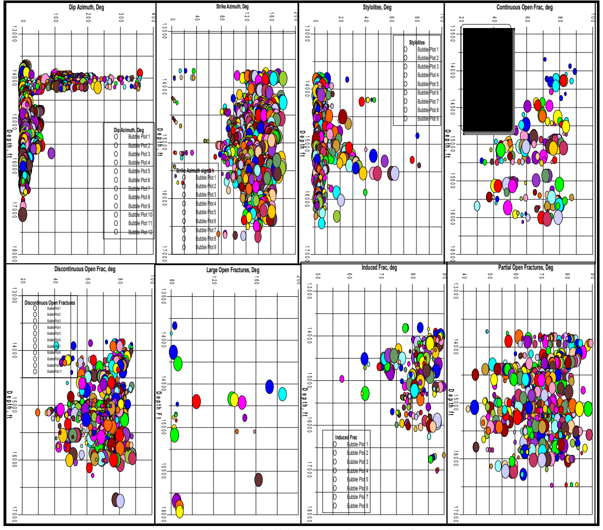

Fig. 12: Comparison of different domain fracture systems

Spectral amplitude and velocity anisotropy from 3D seismic datasets with known drilled well information are used in assessing the fracture reservoirs. Fracture image logs and core data are integrated with interpreted fracture systems from 3D seismic data cubes. Borehole breakouts are also considered in terms of their measured depths and orientations. Logs and 3D seismic data suggest wide-spread fracture porosity and permeability distributions in the study areas. Production rates are dependent on the quality and distribution of fractures and their densities, which also significantly provide decline rates (because of reduced porosities and permeability of interpreted lithologies). Depth surfaces, gridded with faulted structures are attributable to interpret the compressional and extensional structure dimensions of the fracture reservoir systems. Reactivation attributes interpreted based on the geological age, are integrated with structure attributes, which ultimately made through ontology connectivity to fracture reservoir systems. For example, Late Jurassic, Late Cretaceous and Tertiary aged structures and reservoirs are well connected through ontology based data warehousing and data mining approaches.

A. Fracture Analysis

Fractures identified on borehole wells are classified as natural and induced fractures. Natural fractures cut across the entire borehole, are traced as sine waves on borehole images. These fractures appear as darker than the surrounding rocks and contain drilling mud. Drilling induced fractures appear as dark (low amplitude) thin vertical lines and 180 degrees apart on images and as echelon chatter fractures at places. These fractures are produced during drilling.

Low amplitude fractures: these appear as dark sine waves on the image since they absorb more acoustic energy than the surrounding rock matrix. When the filling material is drilling mud, these fractures are open, but fractures sealed with clay can have the same signatures if the acoustic contrast between clay/formation is sufficient. Small size bubble clusters are noticed.

High amplitude fractures: these appear as bright sine waves since they absorb less acoustic energy than the surrounding rocks. In this case, the filling material is necessarily a material which is tighter than the matrix, usually quartz and or carbonate cements. Depending upon their density, sealed fractures can act as strong permeable barriers in the direction perpendicular to their strike. So based on the filling material, fractures appear to represent separate bubble clusters and their sizes.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. Domain ontology is a solution organizing different fracture systems. Warehouse modeling integrates domain ontologies.
2. Exploration data are heterogeneous and multidimensional. These are compatible for building data warehouse models.
3. Data mining such as designing rule mining, decision trees and cluster model are significant in representing data views in interpretable form.
4. Data views of dip and strike azimuths indicate abrupt change in bedding dip attitude, either magnitude or azimuth, across the fault plane; fault identification & characterization
5. Sudden change in borehole drift or deviation azimuth
6. Faults visualized along strike and dip attributes, especially at their intersections, since fractures often occur, where EW and NS faults juxtaposed with each other. Occurrence of fractures around the fault intersection
7. Abrupt changes in bubble size response across the feature interpreted as a fault.
8. Abrupt change in size of bubble, density and their orientation indicate change in formation pressure in case, the fault is sealing
9. High dips; change in the fault direction
10. The amplitude of the acoustic pulse documented by logs, decreases in front of open fractures filled (as in the case larger bubble sizes) with oil-base mud, thus open fractures appear as darker linear features on the amplitude images due to lower acoustic amplitude. However, in some cases such filled fractures can be seen on the acoustic amplitude images when there is enough amplitude contrast between the rock matrix and the fracture filling material.
11. On the borehole images, fractures tend to occur as linear features that generally have a dip steeper than the structural dip. The criteria to differentiate between open and closed fractures are different for oil-base mud imaging tools than the water-base mud imaging tools. Fracture aperture defines how wide the open part/section of an open fracture is. It is measured perpendicular to the fracture plane along its open part.
12. Faulting is observed in the bubble plots, represented as separation of bubble clusters.
13. Structural dip is low in most wells mostly following structural contours at all well locations. Wells with higher structural dip can easily be identified from bubble plots via their magnitudes and spacing.

VII. FUTURE SCOPE OF STUDY

Design of an integrated workflow is in progress with seismic and borehole data that enable an understanding of the fracture properties, especially their densities and orientations. Fluid distributions affected by these fracture types and properties have definite role to play in ascertaining the hydrocarbon holding capacity (porosity) in fractured reservoirs. This will facilitate the well planning and subsequent production management.

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