Data geo-Science Approach for Modelling Unconventional Petroleum Ecosystems and their Visual Analytics

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SUMMARY

Storage, integration and interoperability are critical challenges in the unconventional exploration data management. With a quest to explore unconventional hydrocarbons, in particular, shale gas from fractured-shales, we aim at investigating new petroleum data geo-science approaches. The data geo-science describes the integration of geoscience-domain expertise, collaborating mathematical concepts, computing algorithms, machine-learning tools, including data and business analytics. Further, to strengthen data-science services among producing companies, we propose an integrated multidimensional repository system, for which factual instances are acquired on gas shales, to store, process and deliver fractured-data views in new knowledge domains.

Data dimensions are categorized to examine their suitability in the integrated prototype articulations that use fracture-networks and attribute dimension model descriptions. The factual instances are typically from seismic attributes, seismically interpreted geological structures and reservoirs, well log, including production data entities. For designing and developing multidimensional repository systems, we create various artefacts, describing conceptual, logical and physical models. For exploring the connectivity between seismic and geology entities, multidimensional ontology models are construed using fracture network attribute dimensions and their instances. Different data warehousing and mining are added support to the management of ontologies that can bring the data instances of fractured shales, to unify and explore the associativity between high-dense fractured shales and their orientations.

The models depicting collaboration of geology, geophysics, reservoir engineering and geo-mechanics entities and their dimensions can substantially reduce the risk and uncertainty involved in modelling and interpreting shale- and tight-gas reservoirs, including traps associated with Coal Bed Methane (CBM). Anisotropy, Poisson's ratio and Young's modulus properties corroborate the interpretation of stress images from the 3D acoustic characterization of shale reservoirs. The statistical analysis of data-views, their correlations and patterns further facilitate us to visualize and interpret geoscientific metadata meticulously. Data geo-science guided integrated methodology can be applied in any basin, including frontier basins.

Key words: geo-science; Unconventional Petroleum Ecosystems; Visual Analytics.

INTRODUCTION

The authors explore the applicability and feasibility of digital petroleum ecosystems in managing the data sources from sedimentary basins (Figure 1). We believe that both conventional and unconventional petroleum system elements and processes exist within a single digital ecosystem (reference). Establishing the connectivity between multiple unconventional petroleum ecosystems and interpreting the congruence for prospect locales are challenging (Durham, 2013). The phenomenon motivates us to explore holistic modelling methodology through an ontology-based data warehousing and mining approach. However, an entire digital ecosystem with multidimensional data structures can be managed within a single repository. In addition, an integrated warehouse approach can facilitate the connectivity between multiple petroleum systems. We propose to design and develop fine-grained data schemas for unconventional petroleum systems, easing the digital ecosystem connectivity and its complexity (Nimmagadda, 2015).

The authors in ecosystem contexts bring the attention of the data integration process that can fuse instances of different dimensions of exploration, drilling, production, including navigational entities. Relationships constructed in conceptual modelling are ontologically analysed (Nimmagadda, 2015). An integrated framework is a basis for generating metadata and extracting data views for visualization and interpretation. Preparation of a data warehouse with data mining (DM) is called Knowledge Discovery in Databases (KDD). It is the process of automatically searching large volumes of data for patterns and deriving association rules (Nimmagadda and Rudra, 2016).

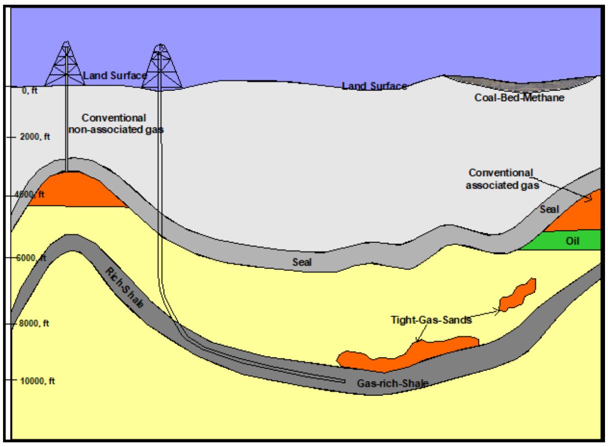

Figure 1. Ecosystem interpretation with the existence of conventional and unconventional petroleum systems

Due to the explosive growth of data and information, the exploration- production manager and petroleum data analyst examine the volumes of data sources, their data entities and dimensions. Data are primarily heterogeneous, multidimensional and unstructured; unifying them in a single repository and implementing them in integrated interactive workstations are additional challenges. We simulate a Big Data guided digital petroleum ecosystem approach as an unconventional digital oil field solution. Multidimensional star schemas are prepared for interconnecting various elements and processes of unconventional petroleum systems to accommodate them in an integrated framework that led us to design and develop a unified data warehousing and mining approach. We further examine the risk of exploratory drilling campaigns and how the integrated framework can be designed to visualise and interpret data views drawn from warehoused metadata structures. The approach can holistically support the delivery of high-quality unconventional data products and services in the investigating areas (Nimmagadda et al. 2021). Bonter and Trice (2019) demonstrate commercial gas production from fractured shales. Shales are part of the source-cum-reservoir element in unconventional reservoirs. The significance of fracture networks has motivated us to explore their connectivity through ecosystem phenomena and an integrated framework.

METHOD AND RESULTS

We propose a robust data warehousing and mining approach supported by ontology descriptions (Nimmagadda, 2015). The method can integrate data attributes of associative-fractures of multiple (dimensions) horizons from different types (geological and production regimes) of drilled-wells and fields. The attributes are periodical with longitudinal and geographical dimensions, located within a producing basin and extended groups of basins. The authors attempt to connect structure, reservoir and production data dimensions and their attributes through their common data instances. In other words, data integration is done by mapping and modelling logically interpreted relationships among multidimensional inter-dependent data instances of structures (including reservoirs). The attributes may possess similar data property instances (and or dissimilar) described in different fracture systems. For example, data mining measures can forecast and separate the rock-stress data patterns of shale-prone environments. The driller explores fractured shales to identify and appraise the types of fracture systems. Ontology-based multidimensional data warehousing and mining can integrate and make connectivity among conceptualized relationships associated with structure, reservoir and production data that exhibit their complexity in shale-gas environments.

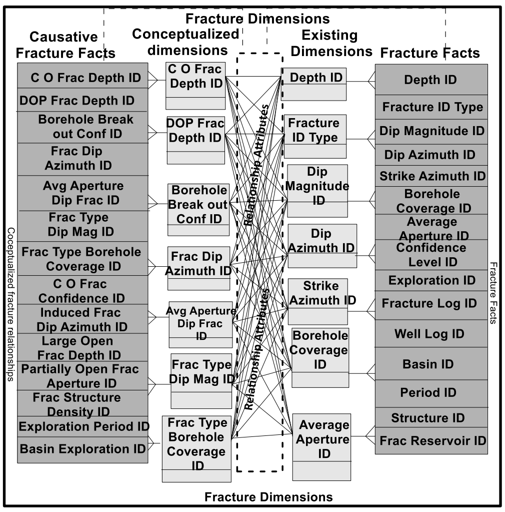

Figure 2. A conceptual model linking various fracture network attributes

Dimension modelling and data cube: The dimension modelling provides semantic information (Matsuzawa and Fukuda, 2000), especially about the hierarchical relationships between its elements of fracture networks. We outline dimension modelling as a special technique for structuring data around fracture systems. Besides, dimension modelling arranges the numeric measures and units of fractures. The dimension schemas represent the dimensions modelling details; period is an essential dimension that enables analysis of historical datasets (Figures 2 and 3). The dimension hierarchy helps to view multidimensional fractured data in several data cube representations. Knowledge-based fine-grained structuring is done for building the domain ontologies (Nimmagadda, 2015). So, the data views are made for adequate fracture interpretation.

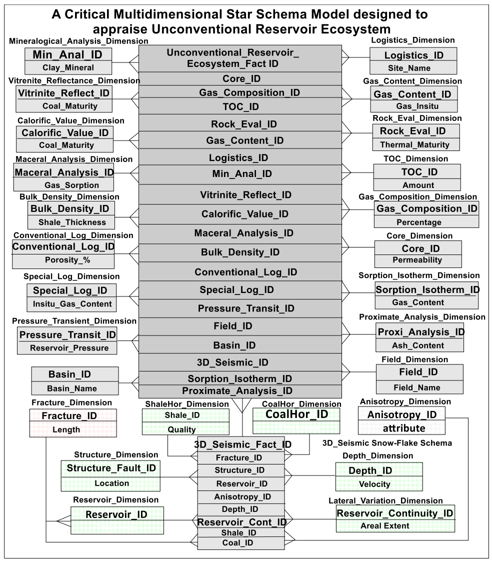

Figure 3. A schematic star schema model, connecting various fractured attributes

Conceptual models that influence data warehouse architecture are schematics multidimensional views of the data, as shown in Figures 2-3. These are star schema models built for analyzing the fracture networks. It has multiple dimensions; each dimension again is subdivided. In this multidimensional model, there are sets of numerical measures that are the central theme or subject of the analysis. Each fracture type, such as open fracture, has different dimensional attributes, such as dip, azimuth, and density. Models are representable in data cubes (more precisely, hypercube), as shown in Figure 4.

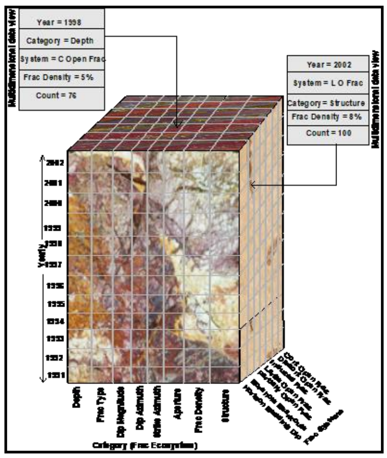

Figure 4. Multidimensional frac data cube – data views for interpretation

All the dimensions together are assumed to determine the measures and units uniquely. The dimensional data view the measure as a value placed in a cell in the multidimensional space. Each dimension, in turn, is described by a set of attributes. The dimension attributes may be related via a hierarchy of relationships or a lattice (Coronel et al. 2016). As an example, from the "frac data cube" slices are drawn during 1998, under depth category, open fracture system has 5% fracture density (porosity) with a specific count of 76, and during 2002, in the structure category, fracture density is 8% (porosity) with counting rate 100.

Multidimensional cluster mining: Cluster mining can discern data patterns (Nimmagadda, 2015) and dissemination of a large number of multidimensional attribute instances interpreted in a warehouse environment. Identification of density and sparse regions of datasets has significance, and it is the real goal of multidimensional clustering. Several attributes are interpretable with large size multidimensional datasets. Multiple horizons exhibit similar and or dissimilar characteristics of fracture patterns, representing multiple clusters. Data instances that consist of extensive numerical data are categorized into two groups, in which partition and hierarchical types are prevalent. Most of the existing algorithms can handle multidimensional data, but they differ in managing different attributes, numerical and categorical, with clustering accuracy. The presence of discontinuities in rock bodies is interpreted as fractures, which may result from the stress applied to overcome the strength of the host rocks. Dip, strike and azimuth are key multidimensional attributes used in bubble plots shown in Figures 5-7. In a bubble plot, the bubble's diameter varies in size, providing a way to represent additional data dimensions.

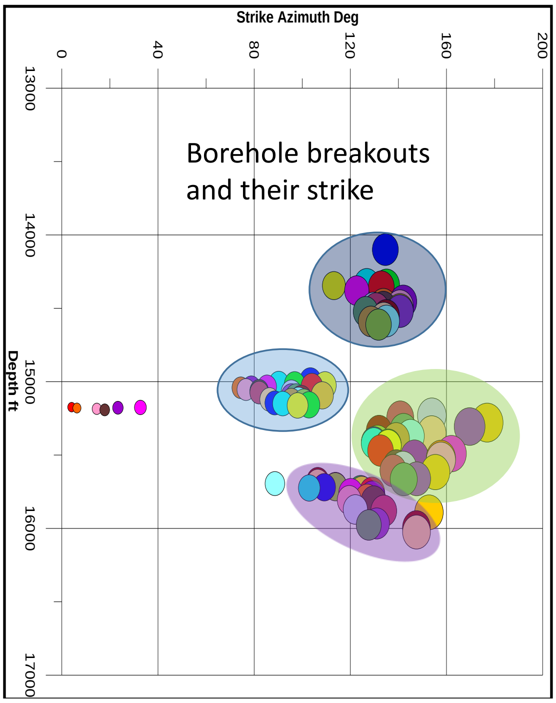

Figure 5. Depth vs. Strike Azimuth

Measuring the distances or similarity metric among partitioned or hierarchical clusters is also a significant concept. Knowledge of which horizon has many fractures occurring in particular groups or types of fracture patterns help plan for new borehole placement. As described in Figures 5-7, based on strike and dip attributes and their magnitudes, different bubble sizes, densities and orientations are interpreted, suggesting dip attribute magnitudes play roles in fracture orientations. In addition, geo-mechanical attributes, such as stress and strain attributes and their relationships on rock properties, all can describe the direction attributes. The fractures are interpreted in dip and strike features in and around the drilling wellbore (Figures 5-7).

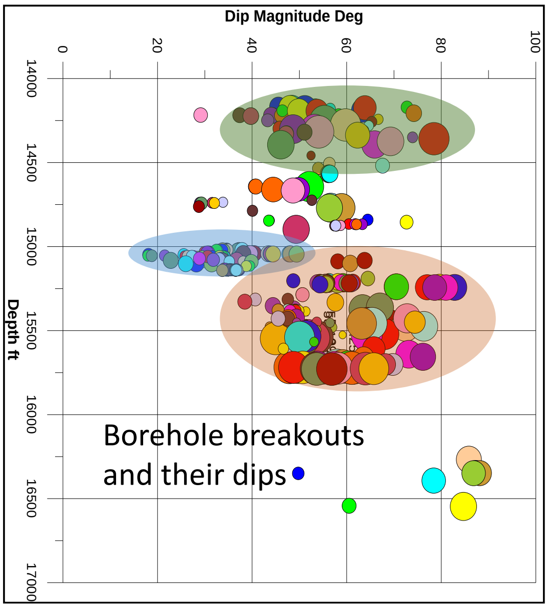

Figure 6. Depth vs. dip magnitude (degrees)

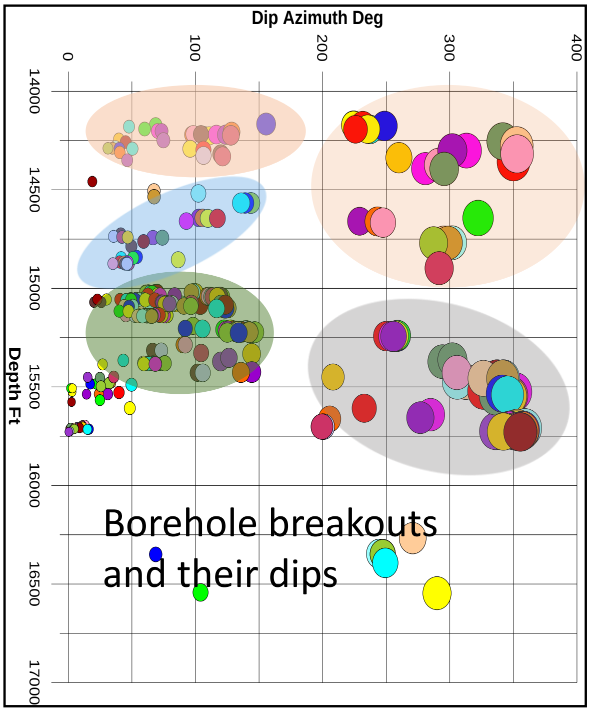

Figure 7. Depth vs. dip azimuth (degrees)

Analysis of Unconventional Petroleum Digital Ecosystems: The petroleum ecosystem is simulated in a data warehouse environment, a system designed for archiving and analysing historical data, such as oil and gas exploration and production data, drilling data, or other information, such as day-to-day operations. Data integration is a crucial issue, combining data residing at different sources and providing the user with a unified view of metadata. Data integration is an emerging process in various situations, both commercial (when two similar companies need to merge their databases) and scientific.

Bonter and Trice (2019) demonstrate commercial gas production from fractured shales. Shales are part of the source-cum-reservoir element in unconventional reservoirs. The importance of fractures and their connectivity are explored through ecosystem phenomena and an integrated framework. Implementation of the data models and framework is a major challenge for any producing (upstream) company. Several major challenges and implementation issues are discussed in Nimmagadda et al. (2019). The multidimensional data are fine-grained, and all the heterogeneous data are in denormalized form. Knowledge building analysis, including interpretation of data views from massive data structures, is a challenging task. With increased volumes of periodic data, perceiving and retrieving knowledge from heterogeneous historical data is now relatively easy. Many E & P applications need data integration for which volumes of multi-disciplinary data are shared among interconnected workstations. However, without prior knowledge of unconventional petroleum-play entities and their business contexts, data processing and interpretation are futile Nimmagadda et al. (2019).

Improved data management in time – and depth – domains has become influential in the data mining of multidimensional metadata. The data created from heterogeneous sources, at times, are difficult to interpret because of the volume and complexity of information and bounded (embedded) patterns. The visualization techniques facilitate the uncovering of the hidden patterns in the data we presented and interpreted. Different data views are extractable from an integrated ontology framework (Nimmagadda, 2015) for interpretation and knowledge extraction. In all the shale-gas projects, the reservoir ecosystems data, integrated into a warehouse modelling environment, underwent a domain ontology modelling process. Finally, the applicability and feasibility of data warehousing, supported by ontology, combined with data mining and visualization, have a tremendous impact on business-data based knowledge discovery systems that can change the economics of exploiting unconventional oil and gas in massive geological structures. As described in Carvajal et al. (2017) and Nimmagadda (2015), online analytic processing (OLAP) models are extracted in the form of map views from explored metadata. The seismic and well-domain data dimensions are representative of an integrated metadata structural model. This structural model is the basis for working on an unconventional resources project, and it is further refined based on geological and geophysical inputs provided in the framework.

Analysis of shale gas ontology: Analysis of shale gas ontology: Fractures and existing fracture networks link with shales to be fracked or defracked. Ontology descriptions are used to make interconnections and explore the effectiveness of fractured shales. As interpreted in Nimmagadda et al. (2019), several fractured networked signatures are used for modelling reservoir capabilities, responsible for holding massive hydrocarbon accumulations and thus for reserve calculations. However, classifications, decision trees and other mining rules are used while interpreting such fracture anomalies, but our focus is on multidimensional data cube and its feasibility and applicability, how the slicing and dicing can bring out interpretable fracture data views (Figures 8 and 9). Low porosity carbonates with high kerogen (geochemical property) contents of the horizons also act as source rock attribute. Certain reservoirs are entirely dependent on natural fractures for their productivities. Fractured reservoirs, especially carbonates, hold significant oil and gas reserves; besides, it is challenging to predict these reservoirs under complex anisotropic and heterogeneous conditions.

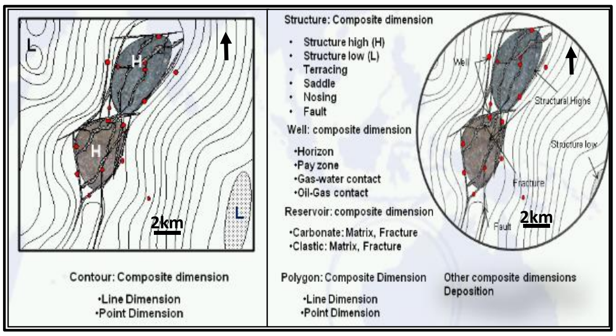

Figure 8. Building fracture networks from ontology-based multidimensional metadata

Most carbonate reservoirs are naturally fractured, and due to brittleness and size of fracture may vary from isolated microscopic fissures to kilometres-wide. These fractures create complex paths for fluid movement based on geological ages and geography, impacting reservoir characterization and, ultimately, production performance and total recovery.

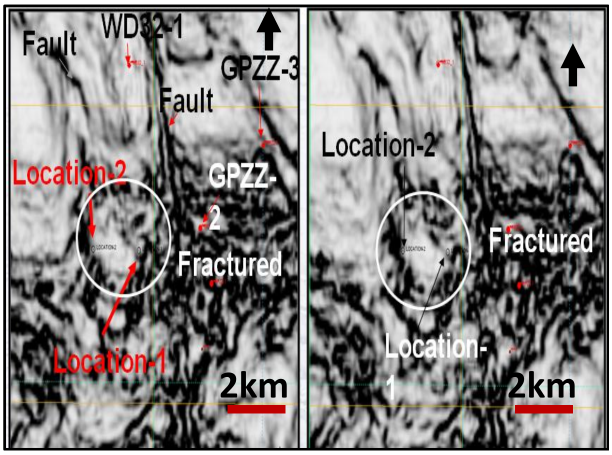

Figure 9. Fractures signatures, based on the connections interpreted from multidimensional metadata

Hydrocarbon pore volumes cannot be commercial in unconventional reservoirs unless there is connectivity among natural fracture systems (Castaneda et al. 2012), especially dense systems around the drilled wellbore. In order to plan and select drillable exploratory and development targets, it is necessary to optimally design the trajectories, completions and develop sustainable field development plans with an improved understanding of the natural fracture systems. The current study assesses the application of directional/horizontal drilling (in new wells or sidetrack of existing wells) and hydraulic fracturing. We develop a better understanding of reservoir fracture/matrix architectures (fracture storativity, connectivity, replenishment, flow capacity, intensity), and finally develop a fracture network model with predictive capabilities.

For assessing the fracture reservoirs, spectral amplitude and velocity anisotropy attributes (from 3D seismic datasets) are corroborated with known drilled well information (Brown, 2013). Fracture image logs and core data are integrated with interpreted fracture systems from 3D seismic data cubes. For measuring depth and orientation attributes, borehole breakouts are considered in the study. Logs and 3D seismic data suggest widespread fracture porosity and permeability distributions in the study areas. Oil and gas 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).

We interpret the depth surfaces, gridded with faulted structures. We integrate with the compressional and extensional structure dimensions of the fracture reservoir systems. Reactivation attributes, interpreted based on the geological age, are unified with structure attributes. It has been possible through ontology connectivity to make up fracture reservoir systems. For example, Late Jurassic, Late Cretaceous and Tertiary aged structures and reservoirs are connectable through ontology-based data warehousing and data mining approaches.

Fracture (reservoir) 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. The fractures appear 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 have produced commercial hydrocarbons during drilling.

Low amplitude fractures: The fractures 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: They 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 that is tighter than the matrix, usually quartz and or carbonate cement. Depending upon their density, sealed fractures can act as 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.

CONCLUSIONS

Data structuring discussed in the unconventional petroleum research approach is holistic and robust in sustaining models with various fracture networks attributes. Building relationships between varieties of fracture network attributes are crucial for interpreting knowledge-based prospective locales. The methodology is practical and can resolve issues relevant to deviation and smart drilling in fractured reservoir systems. However, data qualities in the fractured shales have slowed down our interpretation, for which more efforts on data processing are needed. Despite these challenges, the proposed drillable locales are successful in the investigating areas. The methodology will be successful if applied cautiously in any basin, not only conventional reservoir ecosystems but also fractured networks, including tight-gas and gas-hydrate systems worldwide.

REFERENCES

Bonter, D. A. and Trice, 2019, An integrated approach for fractured basement characterization: the Lancaster Field, a case study in the UK, Petroleum Geoscience, https://doi.org/10.1144/petgeo2018-152 | Vol. 25 | 2019.

Brown, D., 2013, Looking Deeper into Fracture Impacts, AAPG Explorer, March Archive, USA (2013).

Carvajal, G., Maucec, M., Cullick, S., 2017, Intelligent Digital Oil and Gas Fields, 1st edn. Gulf Professional Publishing, Elsevier, 374 p. (2017).

Coronel, C., Morris, S. 2016, Database Systems: Design, Implementation, & Management. Cengage Learning US, Edition 12, 784 p. (2016).

Castaneda, G.O.J., Nimmagadda, S.L., Cardona, M., Lobo, A., Darke, K., 2012, On integrated quantitative interpretative workflows for interpreting structural and combinational traps for risk minimizing the exploratory and field development. In: Bolivarian Geophysical Symposium Proceedings, held in Cartagena, Colombia (2012)

Durham, S.L., 2013, An Unconventional Idea, Open to Interpretation. AAPG Explorer, March Series, USA (2013).

Matsuzawa H., Fukuda T., 2000, Mining Structured Association Patterns from Databases. In: Terano T., Liu H., Chen A.L.P. (eds) Knowledge Discovery and Data Mining. Current Issues and New Applications. PAKDD 2000. Lecture Notes in Computer Science, vol 1805. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-45571-X_30

Nimmagadda, Shastri; Reiners, Torsten; Wood, Lincoln; and Dengya, Zhu, 2019, "On Big Data guided Unconventional Digital Ecosystems and their Knowledge Management" (2019). *PACIS 2019 Proceedings*. 7. https://aisel.aisnet.org/pacis2019/7.

Nimmagadda, S.L, and Dreher, H., 2012. On new emerging concepts of Petroleum Digital Ecosystem (PDE). Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery. 2. 457–475. https://doi.org/10.1002/widm.1070.

Nimmagadda, S. L., Mani, N., Reiners, T. and Wood, L. C. 2021, Big Data Guided Unconventional Digital Reservoir Energy Ecosystem and its Knowledge Management. Pacific Asia Journal of the Association for Information Systems, 13 (1), 1-35. https://doi.org/10.17705/1pais.13101

Nimmagadda, S.L., Rudra, A., 2016, Big data information systems for managing embedded digital ecosystems (EDE), a book chapter in a book entitled. In: Big Data and Learning Analytics in Higher Education: Current Theory and Practice. Springer, The Netherlands (2016). https://doi.org/10.1007/978-3-319-06520-5, ISBN 978-3-319-06519-9.

Nimmagadda, S.L., 2015, Data Warehousing for Mining of Heterogeneous and Multidimensional Data Sources, Verlag Publisher, Scholar Press, OmniScriptum GMBH & CO. KG, Germany, pp. 1–657 (2015).