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Sub-surface Geomodels development based on Elastic Dislocation theory for stresses and sub-seismic fractures corridors identification for carbonate reservoirs and its impact on the hydrocarbon productivity in fold & thrust belts of Pakistan.

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Summary

The basic objective of this research work was to develop a robust subsurface 3D-geomodel based on the elastic dislocation (ED) theory for an exploratory block, located in a complex compressional tectonic zone of Pakistan to identify the regional and in-situ stress state along with the natural fracture network for a fractured carbonate reservoir to address its impact on the reservoir behavior for petroleum productivity. The data sets utilized in the project were 3D-seismic data, well data (E-logs, cuttings, tops, core, etc.), and laboratory-standard mechanical properties of rocks. The rocks deposited in the sedimentary basins, deformed through co-seismic, inter-seismic, and post-seismic tectonic stresses operated in either direction. The stresses deformed the strata in a particular direction in compressional, extensional, and strike-slip tectonic deformation zones, but we have also analyzed through geological and geophysical methodologies that in a specific tectonic event some stresses at the same time operating in the opposite direction of the major stress direction. The stresses generate strain in the deformed strata in the form of folds, faults, and fractures (Seismic and sub-seismic scale). This variability and identification of sub-seismic deformation will be addressed through a geomechanical approach based on elastic dislocation (ED) theory apart from well data (E-logs, cores, lithologies) and 2D/3D seismic data attributes analysis. The basic purpose of the geomechanical modeling techniques is to forecast how rocks would survive the deformation following changes in stress, pressure, temperature, and other environmental factors. The geomechanical models play a significant role in the pre-drilling program generation, completion of the well, and production phases. Among the pertinent uses of geomechanical model results for the optimal production of a reservoir is the planning of a mud density program that guarantees wellbore stability during drilling, intervention in hydraulic fracturing programs, the measurement of stress transient changes, and the selection of casing point selection. Whether a resource extraction attempt is successful or fails depends on the precision of the mechanical variability prediction made at the pre-drilling stage by developed subsurface geo-models.

The structural geological and geomechanical modeling based on ED theory are the two types of techniques that exploration companies use today to forecast structural geometry validity and its deformational effects, especially in the form of seismic and sub-seismic scale faults and fractures to find its impacts on the reservoir behavior and hydrocarbon prospectivity. A key component for the geomechanical model build-up to precisely forecast the sub-seismic scale faults and fracture pathways and their properties (density, orientation, etc.) is the establishment of a validated, restored, and balanced 3D-structural geological model, which showed observed slips on the objective surface as a result of tectonic stresses.

The Upper Indus Basin (UIB) of Pakistan, is a complex fold and thrust belt zone located in the northwest corner of the Indian Plate (Fig. 01). The ED methodology was used to identify the strain and stresses in this complex tectonic zone, after building a valid 3D-structural framework with faults and fractures (Seismic and sub-seismic scale) corridors to address its deformational impact on the overall reservoir behavior and well productivity.

Theory / Method and Workflow

The theory of Elastic Dislocation (ED) (Geomechanical Modeling Approach, basically forward modeling techniques) is nowadays exercised by different researchers to find out the sub-surface deformation (strain) and the intensity of stresses and ultimately its impact on the reservoir behavior for petroleum productivity (S.J Dee et, al 2007, Maerten et al. 2002, Bourne & Willemse 2001, Bourne et al. 2001). The ED theory-based research work has found that the generation of small-scale faulting and fracturing depends on the intensity of strain development around larger faults (Dee et. al, 2007). The mapped major faults act as a dislocation in an elastic medium, for computing the strain around these large faults at different points of the rock volume, the boundary element or elastic dislocation methods (Thomas 1993) are applied (Dee et al. 2007). This geomechanical modeling approach based on elastic dislocation theory has successfully predicted the stress and strain in the area and the deformation nature and intensity. The mechanical properties (Elastic modulus, Poisson's ratio, rock strength, etc.) of rocks are used to convert strain into stresses and measure failure characteristics (density and orientation). The seismic data and well data give us an initial idea of sub-surface deformation intensity and its impact on reservoir potential, while the geomechanical approach portrays the hidden deformation.

The base for geomechanical modeling based on ED theory is the best seismic interpretation on 2D or 3D seismic data of any type of tectonic setting. The interpreted sections and models were subjected to structural validation, restoration, and balancing before building a valid 3D-Structural model. The geomechanical model was then developed after building a geometrically consistent 3D-structural framework model, a logical selection of mechanical properties, and a realistic estimation of regional background.

The ED theory (Solutions of Okada 1985, 1992) was used to test the created geomechanical model (Fig. 03). The orientation and distribution of fractures, as well as strain fields, were determined by the ED Model. The ED model, which displays the fracture density through Maximum Coulomb Shear Stress (MCSS) attribute (Color Coding in Fig. 04) and orientation represented by intermediate stress (S2-minimum horizontal stress (SHmin) represented by black tubes Fig. 02 (A, B, C), is subjected to the analysis for regional and local, stress and strain prediction of the area. For accuracy and validity, the results were analogized with FMI logs.

Results, Observations, and Conclusions

The geomodels model based on ED theory finds out that in this complex fold and thrust belt region of Pakistan (Fig. 01), which is developed due to the tectonic collision of Indian and Eurasian plates, the dominant stresses are from north-south (Fig. 02), but east-west tectonic stresses also present at different tectonic episodes. Due to this reason apart from east-west striking faults, the north-south striking faults and fracture sets (Sub-seismic) are also predicated through ED models. The study results also confirmed that in the area (Fig-01) the sub-seismic faults and fracture sets identified through three (03) drilled wells data (E-logs, core, lithology) (Fig. 03) validate the model results for stresses variation and as a result the sub-seismic faults and fractures characteristics (Density, orientation, strike, dip, etc.) variations. The ED model results show that Wells # 01 & 02 (Producing) have high fracture density and fracture sets are striking almost NW-SE / WNW-ESE direction apart from some variation, while well # 03 (Dry well) has lass fracture density and its fracture set strikes in NE-SW / ENE-WSW directions (Fig. 04). The Max stress direction in producing well #01 & 02 is N-S or NE-SW, while at well#03 it is transverse that is E-W or NW-SE. The FMI logs of the three (03) drilled wells correlate with the ED model results.

The developed models based on ED theory will accurately predict the sub-seismic faults and fracture sets and their characteristics (density and orientation) if developed after building a valid, and balanced 3D-structural geological model (Fig 03) based on good-quality 3D-seismic data.

Novel/Additive Information

The methodology adopted for stresses and strain identification in the sub-surface along with sub-seismic faults and fractures corridor in the case of carbonate reservoir, which is an indirect tool to find out the tectonic deformation intensity and its characteristics on a developed 3D-structural framework and ultimately its impact on the reservoir behavior for petroleum productivity in wildcat, exploratory or development blocks.

Acknowledgments

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References

Dee, S. J., Yielding, G., Freeman, B., Healy, D., Kusznir, N. J., Grant, N., & Ellis, P. (2007). Elastic dislocation Modeling for prediction of small-scale fault and fracture network characteristics. Geological Society, London, Special Publications, 270(1), 139-155.

G Yielding, JA Jackson, GCP King, H Sinvhal, C Vita-Finzi, R Muir Wood. Relations between surface deformation, fault geometry, seismicity, and rupture characteristics during the El Asnam (Algeria) earthquake of 10 October 1980. Earth and Planetary Science Letters, 56, 287-304.

OKADA, Y. 1985. Surface deformation due to shear and tensile faults in a half-space. Bulletin of the Seismological Society of America, 75, 1135–1154. OKADA, Y. 1992. Internal deformation due to shear and tensile faults in a half-space. Bulletin of the Seismological Society of America, 82, 1018– 1040.

OKADA, Y. 1992. Internal deformation due to shear and tensile faults in a half-space. Bulletin of the Seismological Society of America, 82, 1018-1040.

Figures;

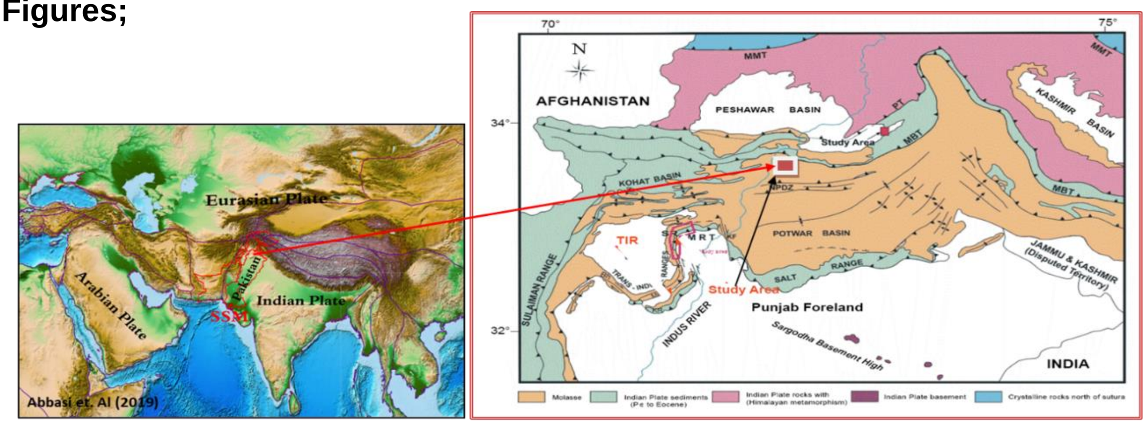

Fig. 01 - Map showing the Tectonic location of the model area. (UIB Pakistan)

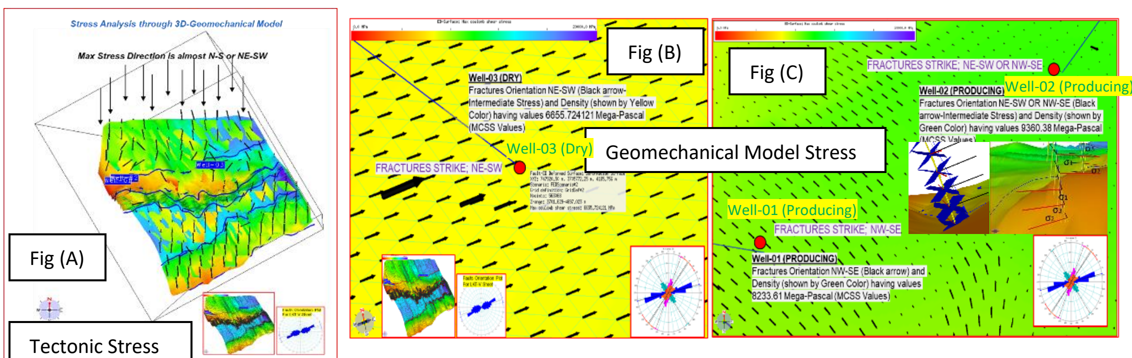

Fig. 02 (A, B, C) – Stress Analysis through Geomechanical Model (Max Stress (σ1) and Intermediate Stress (σ2) showing elastic medium deformation direction and sub-seismic fractures sets strike orientation). The Color Coding in Figures showing the fractures density (Maximum Coulomb Shear Stress (MCSS-Megapascal).

σ1 (Red Line-Max Stress-SHmax)
σ2 (Black Line-Intermediate Stress-SHmin)
σ3 (Yellow Line-Minimum Stress-Sv)

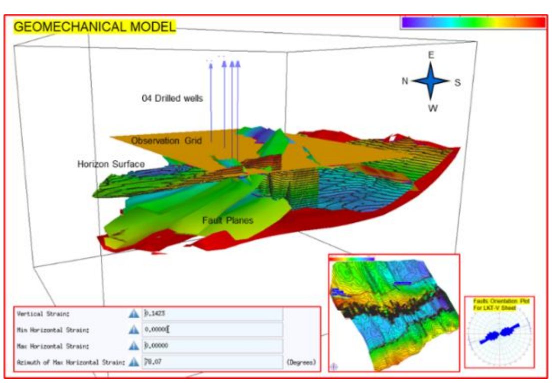

Fig. 03 ED Model for carbonate showing observation Grid, Horizon & Fault Planes. (3D-Structural Model for ED Modeling)

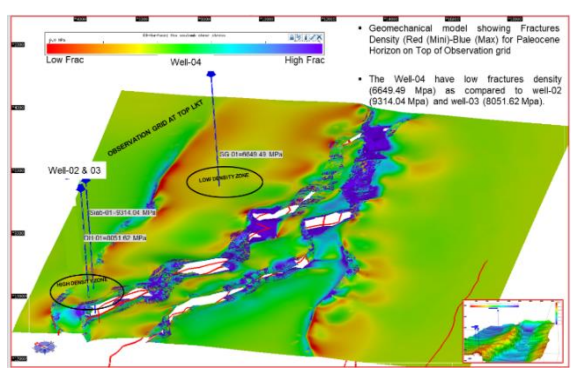

Fig. 04 ED Model showing fractures density on top of observation grid (Applied Max Coulomb Shear Stress-MCSS).