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Impact of Stress and Mineralization on Flow-Controlling Fractures: A Pan-India Comparison

Abstract:

Comparisons of stress directions and orientations of flow-controlling fractures show that open fractures in the subsurface are not necessarily parallel to maximum compressive stress (SHmax) and that fractures perpendicular to this direction may be open. Moreover, sealed fractures parallel to SHmax are numerous. Parallelism of SHmax and open fractures is not good evidence, by itself, that modem-day stress controls the orientation of open fractures. A determining factor for fluid flow is the degree of mineral cement within fractures, which is a function of fracture size and the rock's diagenetic history. In most subsurface opening-mode fracture systems, fractures are partly filled with cement deposited at the time of fracturing. This cement forms strong mineral bridges that prop the fracture open. The remaining part of the fracture may be open or filled with cements precipitated after fractures ceased opening. For the many reservoirs in which opening-mode fractures are the key flow pathways, cement patterns rather than stress data may provide the insight needed to determine which fractures are open to fluid flow. The present study tried to examine the validity of the contemporary stress/open fracture paradigm and its implications for exploration risk and reservoir management in Assam-Arakan, Cauvery and Mumbai offshore basins of India

Introduction:

Understanding the distribution of permeable fracture set can resolve many exploration and development challenges in fractured reservoir. A widely held belief in the petroleum industry is that modem state of stress determines which natural fractures are important for fluid flow at the reservoir scale. Fractures that strike parallel to present-day maximum horizontal compression (SHmax) and perpendicular to the horizontal direction of current minimum compression (Shmin) are inferred to have a greater likelihood of being open (e.g. Queen& Rizer1990, Parks & Gale 1999). But this concept of parallelism of SHmax and open fractures does not hold true always, that modem-day stress controls the orientation of open fractures. A determining factor for fluid flow is the degree of mineral cement within fractures, which is a function of fracture size and the rock's diagenetic, metasomatic or metamorphic history. It is only through identification of most productive fracture orientation, proper horizontal well can be planned to enhanced HC recovery. Hence, fracture characterization based on the hereditarily relationship with the earth stress heterogeneity can be very helpful in reducing exploration and development uncertainties.

Methodology:

In a fractured reservoir fractures are the sole contributor to the reservoir porosity and permeability. They serve as the conduits for fluid movement. So their openness categorization is the basic step towards the reservoir characterization. Commonly the most fracture dependent reservoir is basement rocks which are otherwise absolutely non-porous and impermeable.

It has been the widely accepted concept that fluid migration path through Fractures is controlled primarily by the regional extension of Fractures and the openness or aperture thickness of the

Fracture. The Regional Extension of the Fracture is controlled by Paleo-stress Heterogeneity or distribution (Sigma 1, Sigma 2 and Sigma 3) (**Figure-1**) and The openness or aperture thickness of the Fracture is controlled by Present-day Stress Distribution (**Figure-2**) .

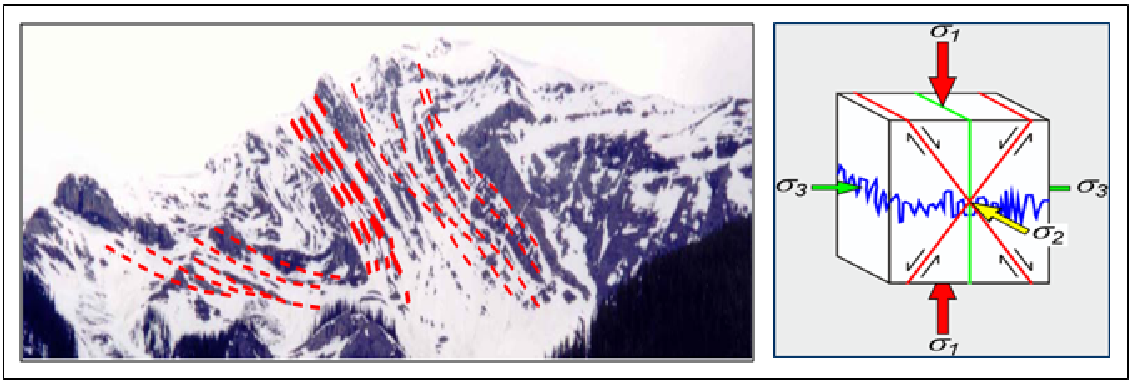


Figure 1: Paleo stress distribution mainly guides the regional extension of Fracture

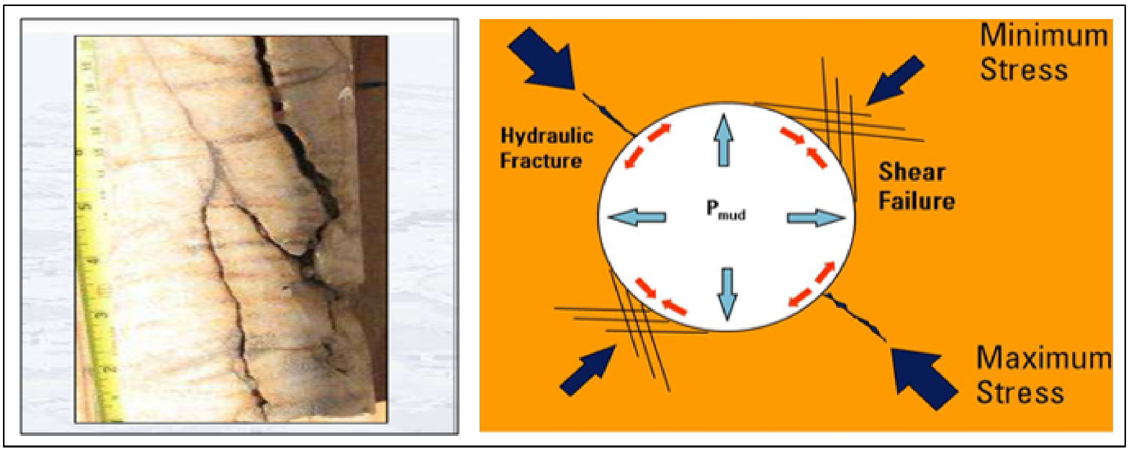


Figure 2: The aperture thickness of fracture is controlled by present–day stress distribution

Moreover, critically stressed fractures, as it is believed that they tend to slide and dilate **(Figure-3)**, often serve as highly efficient pathways for fluid migration, and hence the stress regime acting in a reservoir and the orientations of any fracture sets in relation to these stresses is a major control on the productivities of the fractured reservoirs.

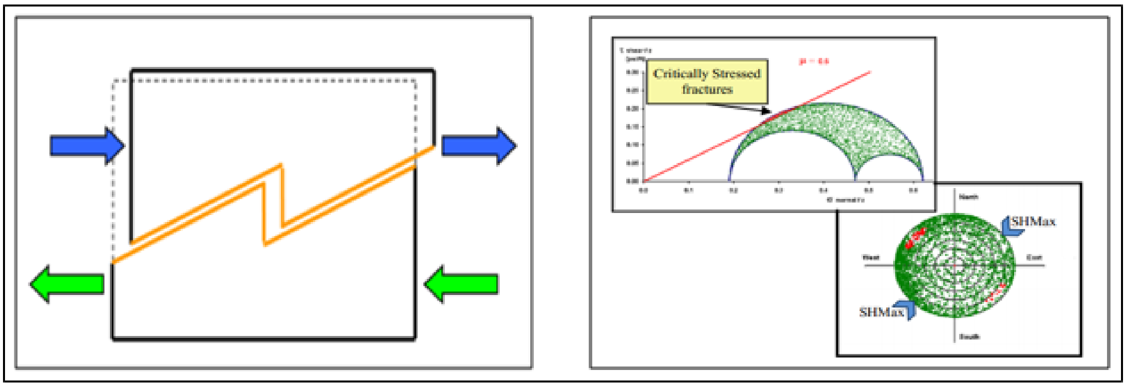


Figure 3: Critically stressed fractures (they tend to slide and dilate (and open) and be hydraulically conductive). Classification of open natural fractures based on their proximity to Mohr-Coulomb failure envelope.

However, in contrast to this concept a close study of these basement rock revels that the comparison of stress directions and orientations of flow-controlling fracture not always produce the expected results. Open fractures in the subsurface is not necessarily parallel to maximum compressive stress (SHmax) and that fractures perpendicular to this direction may be open. Moreover, sealed fractures parallel to SHmax are numerous. Considering the importance of natural fracture systems in this era of deep directional drilling and challenging fracture targeting, the present study tried to examine the validity of the contemporary stress/open fracture paradigm and its implications for exploration risk and reservoir management in Assam-Arakan, Cauvery and Mumbai offshore basins of India. The observations reveal that each basin has its own characters like stress, mineralization, cementation and sometimes recrystallization which place to place govern the openness of the fractures.

Examples:

The stress distribution, fracture orientation and production data from fractured reservoirs of Assam-Arakan basin (NE, India), Western Offshore basin, & Cauvery basin of India are reviewed. These examples illustrate a range of relationships between SHmax orientation, Shear stress component, mineralization and open, producing fractures. In these settings, borehole breakouts and other indicators provide quite reliability stress-direction information. The strike of open fractures in such reservoirs is commonly defined by lower reliability data, but for our examples, image log, core & other high-end well log data allow reliable specification of fracture orientation. Open fractures in image & core have apertures of as much as several millimeters and this openness can't be attributed solely to stress orientation but to possible mineralization leading to prominent partial cement fill or mineral bridges. At certain basins like Assam-Arakan basin and Cauvery basin it is observed that fracture openness is primarily guided by SHmax orientation (**Figure: 4**) and associated shear stress component. Where as in certain part of the Mumbai Offshore a determining factor for fluid flow is the degree of mineral cement within fractures, which is a function of fracture size and the rock's diagenetic history.

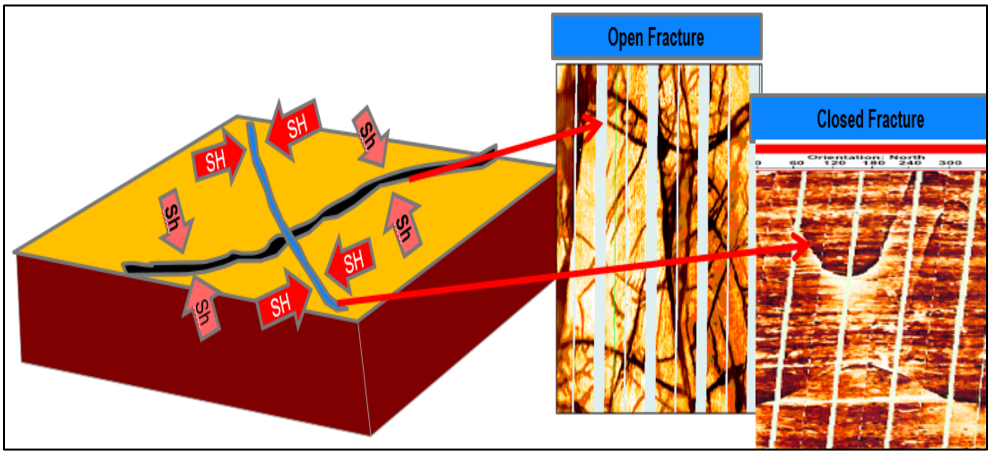


Figure 4: Impact of present day stress orientation on fracture aperture

Case Study 1: Assam-Arakan Basin (NE) - In this still active basin, the fractures' openness corroborates mostly with the present day stress orientation and the fluid path can be well related to the regional stress regime. The structural trend of Assam –Arakan basin is observed to be NE-SW (**Figure: 5**) and out of the different type of fold related fracture patterns developed in this regime, the tensile longitudinal fractures are happened to be regionally extensive in nature as it dominantly follows the regional trend (**Figure: 6**) and should contribute profusely to the flow potential of reservoir. But a close observation reveals that the fractures trending parallel to present day maximum compressive stress (SHmax) are having larger apertures and hence most likely falling into the category of potentially permeable. So, the fractured reservoirs of Assam-Arakar basin (NE, India) at most instances favors the contemporary stress/open fracture paradigm, where open fractures trend parallel to maximum compressive stress (SHmax).

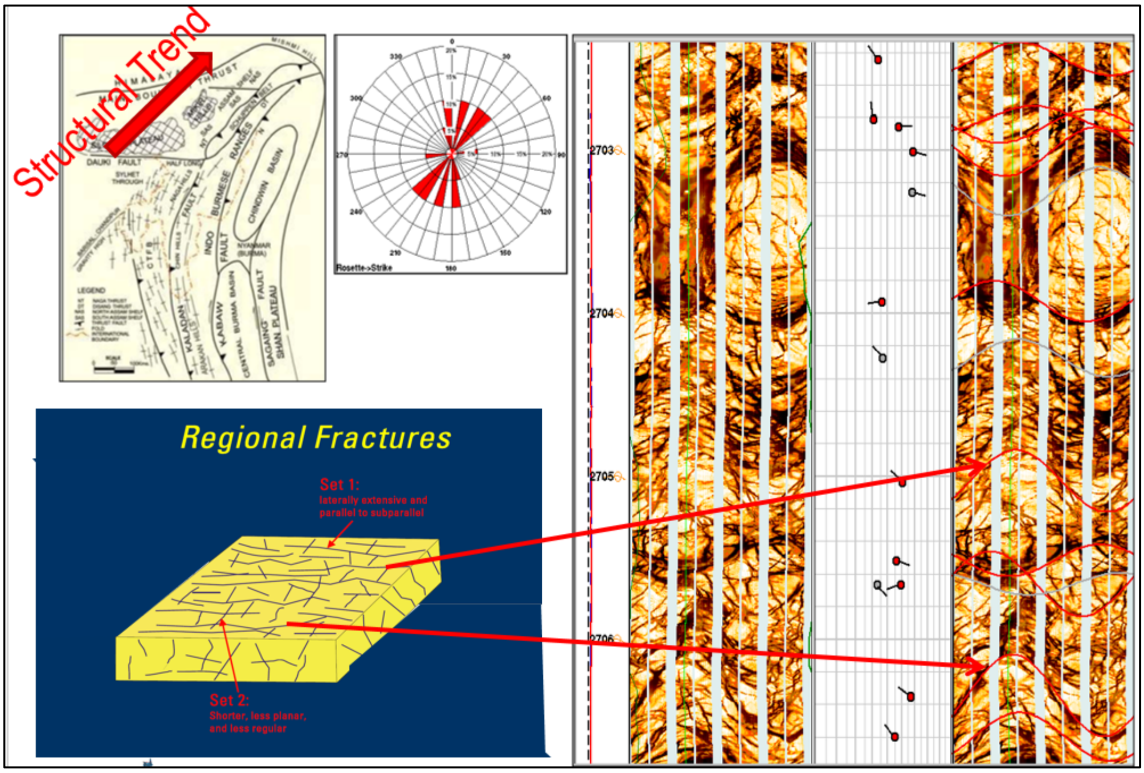


Figure 5: Structural trend of Assam-Arakan basin and alignment of major fracture pattern

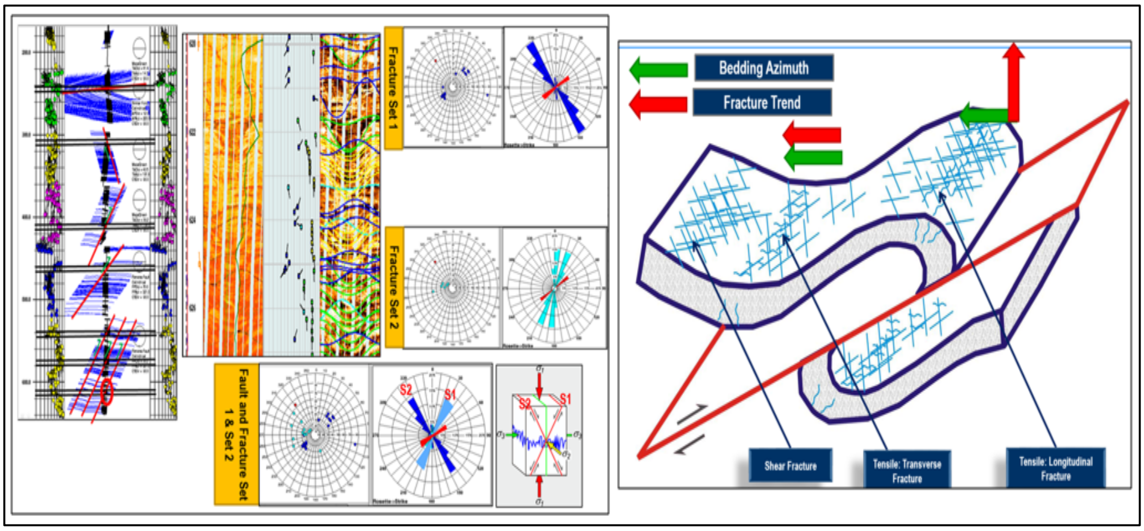


Figure 6: Different type of fracture generation associated to fault and the trend of tensile longitudinal fractures (Striking NE)

Case Study 2: Cambay Basin – Contrary to conventional wisdom, here a special study has been conducted using fracture orientation from image logs, openness from stonely and critical stress analysis that reveals the component of shear failure as one of the important contributor to the openness of the fractures and their tendency to slip. The present work has suggested that those fractures that are orientated such that they experience a high ratio of shear to normal stress are most likely to flow. These critically stressed fractures are in a state of stress that is close to failure, allowing them to undergo a degree of shear. Even small shear displacements can cause significant dilation along a fracture surface as the two surfaces un-mate during sliding. This dilation results in a significant increase in fracture permeability, resulting in an increase in flow from these features. The Mohr diagram is utilized to identify and visualize both critically and non-critically stressed fractures. Additionally, the categorized fractures may be represented in dip and strike stereo-nets.

In the quest to find the production ambiguities between wells, it is observed that a good number of critically stressed fractures or fractures close to critical stress state (Represented by red dots on stereo-net plot) are present in well-A (**Figure: 7**) that subsequently decides a better production profile for the well. Whereas a very few critically stressed fractures are present in well-B, thus contributing less to the production **(Figure: 8).**

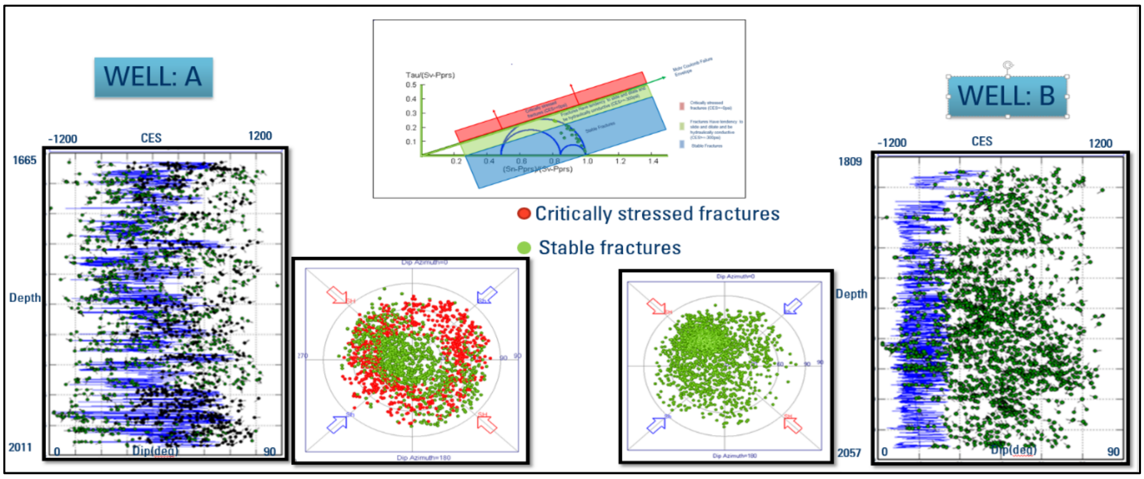
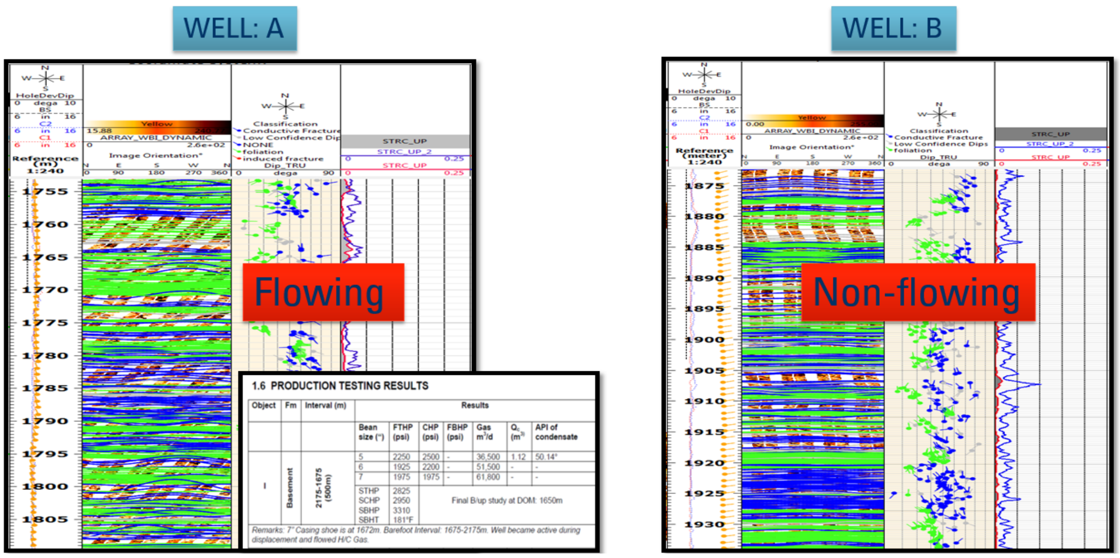


Figure 7: Results of Stress State on Fractures in Well-A and Well-B



Case Study 3: Bombay offshore- The theory of parallelism doesn’t really hold true in all places of basaltic traps & gneissic complex of Bombay basin (**Figure: 9**). Multistage influx of basaltic layers and hydrothermal activities helped in post-deformation mineralization in former basaltic traps & gneissic basements. Due to metasomatic activity though geological time, the then open fractures got sealed by late stage mineral deposits in those veins and at times the same mineralization helped in forming strong mineral bridges that prop the fracture open.

Despite near parallelism of open fractures and SHmax, a causal relationship is doubtful. Several lines of evidence suggest that fractures formed before Cretaceous volcanism, and fractures thus predate current loading conditions. Rather, the coincidence of orientation is a reflection of a long-lived stress regime in which SHmax had approximately the same orientation at the time of fracture formation in the Late Cretaceous and early Tertiary as it has at present. Open fractures could parallel SHmax in many settings where principal stress directions have remained constant from fracture formation to present. Regardless of the stress orientations, however, the history of fracture mineralization is key to whether the fractures are open under present-day producing conditions. Interestingly, not all fractures parallel to SHmax in the Mumbai Offshore Basin are open. Influx of post kinematic cementing fluids in some parts of the formation exerts a strong control over which fractures retain porosity. It is only those fractures with partial (not complete) mineral filling that maintain significant permeability. Core data from the Bombay High Field demonstrate that sealed and open fractures having identical strike are interspersed over vertical distances that range from a few meters or less to decimeters within individual reservoir and lateral distances of field and regional scale. Successful reservoir exploitation requires finding the zones having a preponderance of open fractures, which requires understanding of the diagenetic history of the formation, layer by layer (**Figure: 10**) and should not bank solely into stress/open fracture paradigm.

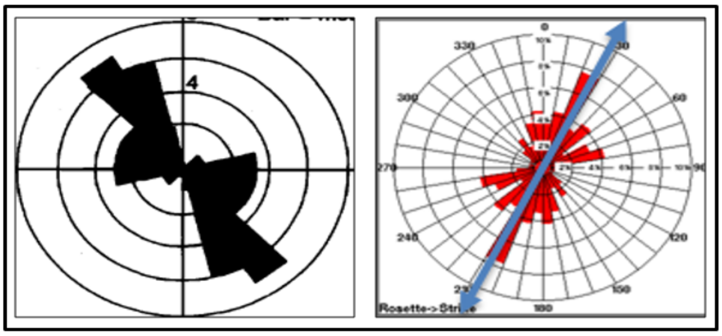


Figure 9: Rose Diagram of SHmax direction and open fracture strike in Well: X, contradicts the parallelism theory in Mumbai Offshore Basin

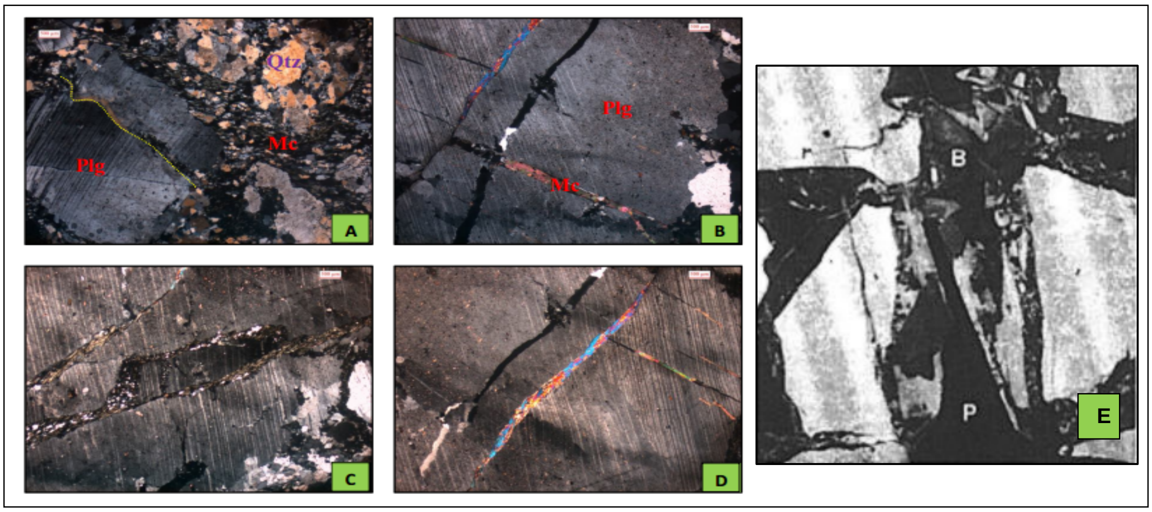


Figure 10: Photomicrographs of sample S11. TTG of Bombay High. (A). Large plagioclase grain surrounded by smaller grains of quartz and mica. Plagioclase grain is fractured (along yellow dotted line) (B). Mica along the fractures in plagioclase (C). Fractured plagioclase and along the fractures fine grains of mica and quartz are recrystallized (D). Mica along the fractures and kinking in bands of plagioclase (E). P indicates open fracture. B indicates quartz mineral bridge

Discussion:

In India, amongst the three basins, the Assam-Arakan basin strongly supports the idea of stress monopoly in openness identification. Whereas the Cambay basin study adds on the shear component and slippage factor to this. The Bombay basin is aberrant to the idea of present day stress parallelism with the fracture openness. These fractured traps' openness is mostly dependent on the metasomatic and hydrothermal events those took place at the late-post stage of Deccan trap formation. This portrays the reasons of fracture openness are multifold.

A survey of operators and industry structural geologists overwhelmingly rated present-day SHmax as the factor dictating strike of open fractures (AAPG Reservoir Deformation Group, 1999 pers. comm.). In seismic shear-wave analysis a basic assumption is that open fractures are preferentially oriented by the current stress field acting on the rock mass (Crampin 1987). In production analysis engineers frequently assume that fractures are the most compliant part of the rock mass and are susceptible to closure with increasing effective normal stress (Warpinski et al. 1991). A wide spectrum of rock-mechanics observations and model studies demonstrate compliant fractured rock masses and individual joints (non-mineralized fractures) (Barton et al. 1985). An opening-mode fracture is expected to close when pore pressure falls below the minimum stress, unless there is some mismatch or propping of the fracture. However, these contemporary views derive in part from influential studies that show that critically stressed faults in crystalline rock are the locus of fluid flow (Barton et al. 1995). The contrary view (e.g. Dyke 1995) that natural-fracture aperture and permeability are not highly sensitive to changes in effective normal stress has largely been neglected.

Conclusion:

Although opening-mode fractures most likely align with contemporaneous paleo-maximum horizontal compressive stress, open, flow-controlling fractures are not necessarily parallel to current maximum horizontal compressive stress (SHmax). In many petroleum reservoirs, fractures in any direction may be fluid conduits. Divergence between open fractures contributing to fluid flow and SHmax in examples from reservoirs of the Westerns Offshore, India ranges from a few degrees to 90^0. Moreover, fractures parallel to SHmax may be sealed. Parallelism with SHmax is not a reliable predictor of the strike of open fractures. Fortuitous alignments of open fractures and current SHmax may occur where paleo stress orientation matches the present-day stress orientation. Parallelism of modem-day stress directions and open fractures is not good evidence, by itself, that the current stress field controls the open fractures. In the absence of reliable measurements of both fracture strike and SHmax, these features should not be presumed to be parallel.

Examples in this paper show that SHmax and orientation of open fractures can differ. Fractures in the representative examples we describe have abundant, intact mineral bridges. Examples of stress control over fracture openness are found in tectonic settings where faults are critically stressed (Barton et al. 1995), yet in many reservoirs where flow is dominated by opening-mode fractures, the orientation of SHmax is a poor predictor of flow controlling fractures. Consequently, despite the technical challenges, the orientation of open, conductive fractures should be measured independently of principal stress direction.

Reference

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