Field Study Of Shear Fractures – Its Tectonic Significance And Possible Application In Hydrocarbon Exploration – An Example From Vindhyan Basin

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Summary

Evaluation of the hydrocarbon potential of a sedimentary basin must take into consideration its tectonic evolution, which is a prime factor in the migration and accumulation of hydrocarbon. Tectonic control is imposed on the development of sedimentary basins preserving the resultant signatures. Since the structural framework of a sedimentary basin is inherently a part of, and consequently the result of the regional tectonic control, the study of the tectonic signatures assumes considerable importance for basin analysis. Sedimentary basin analysis, to a large extent depends on the physical examination of exposed rock section within the basin. It is axiomatic that the geologist aims for as full an understanding as possible of what he observes. The development of shear zones bears significant importance in establishing the petroleum system of a sedimentary basin. The effects of shearing are in general manifested in form of change in grain size, development of micro fractures, development of foliation, rearrangement of mineral distribution and shape (framework collapse) under geometrical weakening, permeability enhancement (dialatancy) etc. The associated structures observed in the field due to shearing include fault planes, shear fractures (at variety of scales), microfracturing, granulation, foliations (mica alignment), mylonites, slickensides, polished surfaces, grooves, striations, boudins, veins, stylolites etc. Manifestation of shearing needs to be observed in the field thoroughly before establishing tectonic history of a basin. The direction of movement on shear zones is important for reconstruction of the tectonic history of an area and the sense of displacement is of prime importance, which can be dextral or sinistral, normal or reverse. There are a large number of useful criteria for deduction of the sense of shear on a microscopic and macroscopic scale. Hence identification of the shear sense indicators in the field and collection of structural data from the shear zone manifestations holds immense importance for interpretation.

Proterozoic basins are on record, elsewhere in the world, to have produced oil and gas. Vindhyan basin being of Proterozoic age and due to the optimism generated by the gas shows encountered in the well Jabera#1, intensive exploration efforts in favourable locales in this basin is warranted. Vindhyan sediments have appreciable thickness and geologically belong to the same age group of Proterozoic basins of Siberia and Amedius basin in Australia, where these sediments are proved to have generated hydrocarbons. The study of shear zones helps in stress field analysis, timing of deformation and computation of strain rate. By deducing maximum and minimum stress direction, it becomes easy to interpret the compression and extension kinematics of the whole basin in a regional as well as local scale. Study of fracture pattern and stress field analysis would help in predicting fractured reservoirs and conduits for hydrocarbon migration in the Vindhyan basin.

In frontier basins like Cuddapah, Vindhyan and Satpura, study of shear zones can contribute to stress field analysis and as a result, areas of possible secondary porosity, in terms of fractures, could be located. Though shear zone manifestations are reported from frontier basins like Cuddapah, Vindhyan, Satpura and Himalayas, their field study and interpretation could help in exploring these basins further.

Introduction

When rocks are deformed, the distribution of deformation is not homogeneous, there are rather parts of high or low strain respectively. One of the most common patterns of this heterogeneous deformation is the concentration of deformation in planar zones that accommodate movement of relatively rigid wall-rock blocks. Deformation of such high-strain zones usually contains a rotation component, reflecting lateral displacement of wall rock segments with respect to each other, this type of high-strain zone is known as a shear zone. These zones may have long history and cut through large section of the crust. In general from upper to lower crust (Fig-1), the deformation sequence is in the order of brittle, brittle-ductile transition, ductile.

Since shear zones are easily reactivated, rocks in major shear zones commonly show evidence of several overprinting stages of activity at different metamorphic conditions. Result can be a wide variety of structures and overprinting relationships.

Effects of shearing

Several structural elements and processes operate to control hydrocarbon systems in complex terrains

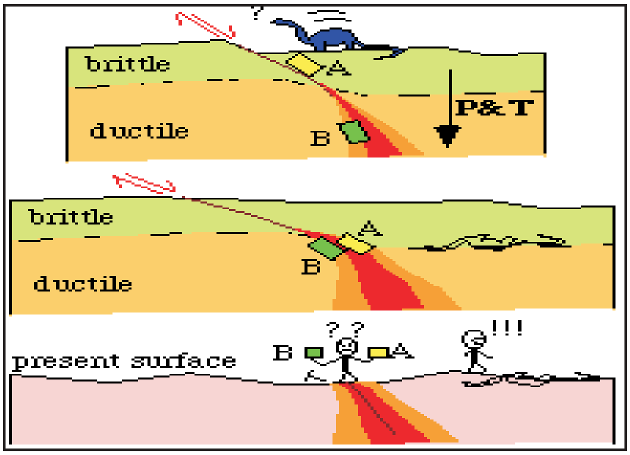

Fig.1- Deformational mechanism and localized behaviour with varied P&T along the crust (Ref. www.earth.monash.edu.au)

- ❋ Fabrics, fractures and small-scale faults
- ❋ The geometry of individual field-sized structures
- ❋ Families of structures within a given domain
- ❋ Regional considerations
- ❋ Mechanically induced kinematic controls.

These elements contribute to

- ❋ Hydrocarbon generation, migration and entrapment
- ❋ The maintenance and modification of traps
- ❋ Remigration following loss

The following could be effects of shearing, which is schematically shown in figure-2.

(a) Changes in grain size, with grain size sensitive deformation mechanism and development of foliation

(b) Influx of fluids

Enhanced permeability during deformation (dilatancy)

(c.1) Previous brittle faulting

(c.2) Ductile shear in extension of brittle fault zone

(d) Shear heating giving thermal weakening

(e) Transformation plasticity: metamorphic reaction enhances deformation and reaction softening where a new metamorphic mineral is softer or finer grained than the old one.

(f.1) Geometric weakening

(f.2) Development of grain shape foliation & domainal fabric

(f.3) Rearrangement of mineral distribution & shape (frame-work collapse)

(g) Recrystallisation

3. Shear Sense Indicators in the field

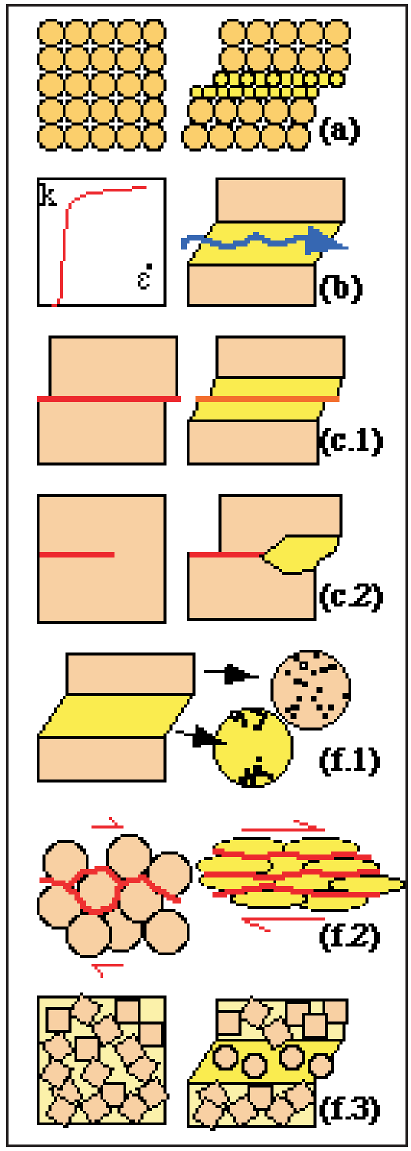

Fig.2-Effects of shearing (Ref. www.earth.monash.edu.au)

A shear sense indicator is a structure with a monoclinic symmetry that can be used to determine the sense of shear in a rock. The direction of movement on shear zones is important for reconstructions of the tectonical history in an area, but most important is the sense of displacement, which can be dextral or sinistral, normal or reverse. There are a large number of useful criteria for the deduction of the sense of shear on a microscopic and macroscopic scale. Porphyroclasts, mica fish and porphyroblasts are considered as main shear sense indicators. In use are porphyroclasts of relatively strong minerals with tails of dynamically recrystallized material known as mantled porphyroclasts. Different types of mantled porphyroclasts can be distinguished based on the geometry of the porphyroclast system.

Applications

4.1. Palaeostress determination

Assessing deformation and fault reactivation potential within the contemporary stress field is a valid approach for understanding the present day. At the time of hydrocarbon charge, uncertainly in the predicted reactivation potential is reduced if the palaeo-stress regime is known. Study of shear zone signatures in the field tells about the paleostress conditions. The hypothetical stress distribution pattern along the fault zone and application of stress differences to formation of sheared zones is shown in the figure 3 and 4.

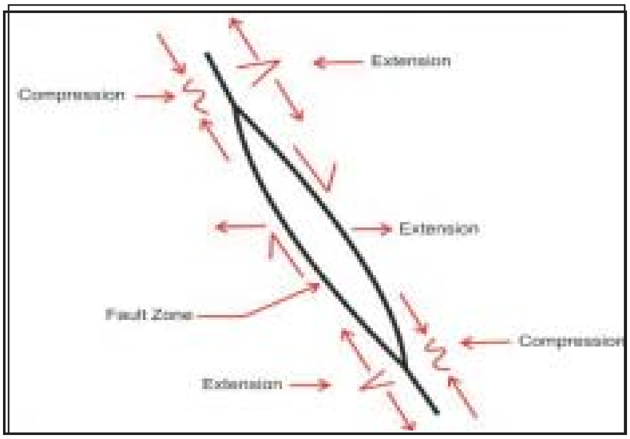

Fig.3 Hypothetical stress distribution pattern along the fault zone (After Barnett et.al. 1987, Knott, 1993)

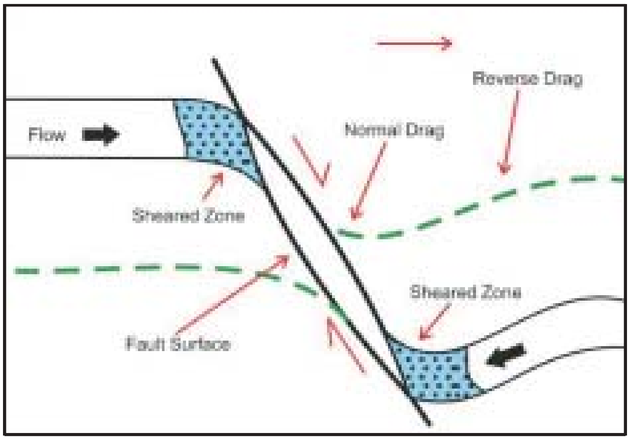

Fig.4 Application of stress differences to formation of sheared zones by ductile flow and normal drag (After Barnett et.al. 1987, Knott, 1993)

4.2. Geomechanical properties of reservoirs, faults and top seals

The potential for faults to act as seal and conduit is controlled by the regional stresses and the geometry of the fault. However, faults can also cause seal breaching through the process of reactivation. Shear reactivation as a consequence of reservoir production may aid hydrocarbon recovery by increasing fracture permeability. To calculate the effective stresses acting on a fault segment and assess the propensity of fault reactivation, geomechanical study requires knowledge of fault geometries, the stress tensor and the pore pressure profile.

4.3. Microstructural evaluation

Examination of fault rocks provide information on fault rock processes that can give insights on depth of faulting, timing and relationships between structural and diagenetic events as well as enhancing the understanding of petrophysical and geomechanical properties. Fault rock mechanical formation processes include grain boundary sliding, disaggregation, grain fracturing and clay smearing. Fault rocks formed by such processes include disaggregation zones, cataclasites, phyllosilicate framework fault rocks and cemented fault rocks. Fault textures can provide constraints on stress conditions at time of faulting (disaggregation = low stress; cataclasis = high stress). This can be combined with charge and burial histories to evaluate the risk associated with timing of fault movement with respect to charge.

4.4. Petrophysical properties of the rocks

Since the effect of faulting on both migration and entrapment depends on the rock properties of strata juxtaposed by the fault and on the structural attitudes of the juxtaposed blocks, the fault plane section analysis basically provides information regarding the trapping potential of the fault. For assessing mechanical and flow properties of top seals, fault rocks and reservoirs, velocity and density studies are being carried out. Which in turn helps in fault seal evaluation. Petrophysical properties can be altered by physical processes and diagenetic reactions, reducing permeability and increasing seal capacity.

4.5. Fault seal processes in layered sand-mudstone sequences

The development of normal faults in layered sand-mudstone sequences is described by field observations.

Special focus is put on the processes of clay smear and telescoping along parallel strands. A clay smear process by which unexpected amounts of clay can be added to the fault gouge is lateral clay injection.

5. Example: Vindhyan basin

The Vindhyan basin is one of the largest sedimentary basins of India covering 1,62,000sq.km. It has been divided into the Chambal sub basin lies west and north west of the Bundelkhand massif while the Son Valley sub basin is disposed in the area east, south east and south of the Bundelkhand massif. Proterozoic basins such as the Tunguska basin of Siberia and Amaedus basin of Australia have produced hydrocarbons. Drawing an analogy, Bhandari et. al (1983) classified the Vindhyan basin in category IV. ONGC's efforts in exploring for hydrocarbons bore fruit when the first well Jabera#1, drilled in this basin encountered a gas show. This attracted intensification of exploratory efforts and two more wells, Damoh # 1 and Kharkhari # 1 were drilled. With the knowledge acquired so far as regards reservoir rocks (Petres & Anand, 1982 and Pendkar & Peters, 2002), it is apparent that reservoirs in the Vindhyan basin could be fractured reservoirs.

The area of study (Fig-5) covers Damoh – Jabera - Katni block of the Upper Vindhyan Formation. Vindhyans are extensively faulted along the southern margin. In the Son valley area a large number of ENE –WSW and NW -SE trending faults have been mapped. There are a large number of rift and wrench faults in the Son valley that are geomorphologically expressed as offset in the ridges, depressions, straight drainage channels, termination of trends and shift in lithology. Many of these form boundaries of structures. The fault coincides with the trend of Son – Narmada fracture. Son- Narmada lineament is the oldest and yet the youngest, youngest due to neo tectonic reactivation. 130° – 310° trend is the second oldest trend in the area followed by 20° – 200° trend (Bhoj, R. 2001)

6. Field manifestation of shearing

Associated structures observed in the field are fault planes, shear fractures (at variety of scales), foliations (mica alignment, compositional, shear fractures), Polished surfaces, grooves, striations, veins, stylolites, slickensides. Among these manifestations the features, which were conspicuously observed in the field are described below.

6.1. Shear fractures — Fractures and faults are planes of tensile or shear failure at microscopic to regional scales in brittle rocks. Shear fractures are the most common type of geologic fracture and they develop because of the stress difference between $ó_1$ (maximum) and $ó_3$ (minimum). As $ó_2$ is an intermediate stress, it can be ignored and shear fracturing analyzed in two dimensions. Plane of failure is oriented about 30° from $ó_1$, 60° from $ó_2$, and parallel to $ó_3$.

The effect of shearing couple on a body is three fold {Riddel (1929), Closs (1937), Kanungo (1956)}:

- It tends to cause the body to rotate
- It produces compression at 45° to the direction of the applied couple
- It develops tension at right angle to the direction of compression

Anderson (1951) has suggested the relationship of faults to axis of principal stress:

Thrusts – Form when the greatest principal stress is horizontal and the least principal stress is vertical

Normal faults – Form when the greatest principal stress acts vertically and least principal stress is horizontal

Wrench faults – Form when the greatest and least principal stresses act in the horizontal plane and the intermediate stress acts vertically

Shear fractures are the results of differential movement of rock masses along a plane are of tectonic origin. Occasionally two interesting shear planes or sets of planes conjugate or complementary shears are encountered in the field. Similar to shear fractures a fault is a plane of fractures, which exhibits signs of differential movement of the rock mass on either side of the plane. Faults are therefore, planes of shear failure.

It is generally understood that fractures form in an orientation perpendicular to the minimum compressive principal stress direction Thus fracture orientation may be used to study paleo stress conditions at the time the fractures formed. It is assumed that fractures along large-displacement fault zones occur in preferred orientations and record the spatial and temporal variations in local stress states during fault initiation and growth. Thus, we can use the information for regional stress analysis.

Characterizing the structure of faults observed in the field furthers our understanding of the geometry, boundary conditions and mechanical behavior of the components of faulted crust. It is assumed that micro fractures along large-displacement fault zones occur in preferred orientations and record the spatial and temporal variations in local stress states during fault initiation and growth.

Typically the micro faults developed by shearing exhibit several distinct characteristics.

- They tend to form in conjugate sets with orientations parallel to the strike of local (extensional) faulting - leading to high connectivity in a plane perpendicular to strike,

Ø They cluster in space - leading to relatively high structure densities.

Ø They tend to anastomose along strike.

Slickensides

Slickensides are parallel striations, occur on fault surfaces and to a lesser extent joint and bedding surfaces where tectonic slipping has occurred on these surfaces. These slickensides are observed profoundly in the field (Fig.7,8) of the study area, which has got great importance in deriving the stress acted in local as well as regional scale. These movement directions on planes are usually assumed to occur in the plane of the $ó_1$ (maximum) and $ó_3$ (minimum) stress directions. Thus in the case of faults and joints that can be assumed to be created by the same stresses that caused the slickensides, the following statements are true:

- The $ó_2$ (intermediate stress) direction is normal to both the pole of the fault plane and the slicken line.
- A plane (great circle) plotted (Fig-6) through the pole to the fault line and the slickenline will contain both $ó_1$ and $ó_3$.
- If a second fault or joint set that represents a complementary failure direction can be plotted, then the $ó_1$ direction will bisect the acute angle and the $ó_3$ the obtuse angle.

If three sigma directions (axes or principal stress) are found then the plane normal to $ó_2$ will contain any slicken sides caused by this stress system.

Mylonites

"Mylonite" observed in the field (Fig-9), is a fine-grained, brecciated, well-laminated rock, which shows evidence for strong ductile deformation. The term is purely structural and conveys no indication of the mineralogy of the rock. The microfractures developed during mylonitisation are related to the stress state at the time of formation and which can be used to investigate the origin of the internal structure of fault zones. These may help in enhancing permeability in the rocks. In some cases, the granulation takes place during faulting creating sealing faults.

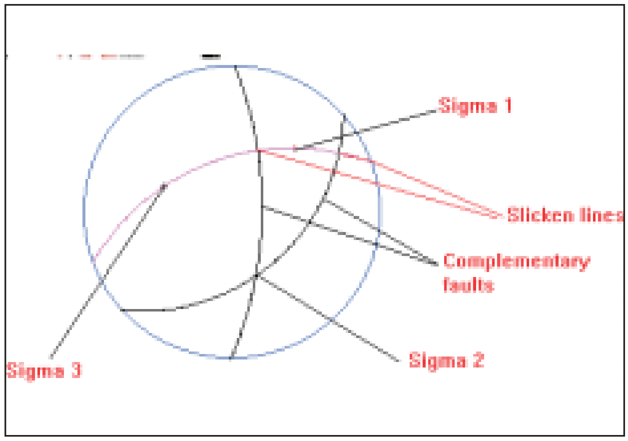

Fig.6: Complementary Faults, sigma directions and slicken lines (Ref. www.agt.net)

Fig.7 : Field photograph showing oblique slicken sides in Quartizite observerd in the study area.

Fig. 8 : Field photograph showing hhorizontal slicken sides observed in the study area.

Fig. 9: Field photograph showing brecciated rocks giving evidence of shearing observerd in the study area.

Polished surfaces

Along the slip plane in the field, polished surfaces are observed with striations (Fig-10). These striations on the polished surfaces tell about the direction of movement of the two displaced blocks.

Fig.10: Field photograph showing polished surface indicating action of shearing and displacement in the study area.

Fault gouge

Fault gouge is crushed and ground-up rock produced by friction between the two sides when a fault moves. The granulated rocks produced in this zone observed in the field helps in enhancing permeability and sealing for migration.

Boudins

The length of boudin fragments observed in the field may be used to estimate the differential stress. The geometry of structures makes it possible to determine sense of shear for a shear zone. Boudins are structures that can also give information about the deformation history, but they are not so useful or reliable as shear sense indicators

7. Study of fractures

In field the joint data were collected thoroughly as the joints are brittle fractures, which may develop either by tensile failure or by shear failure. The study of fractures from the image and field (Fig-11) revealed the following observations.

Fig. 11- Lineament map of the study area (After Samal et.al., 2005)

- Image interpretation of the lineaments shows that the ENE – WSW and NNW – SSE trending lineaments are present in the area, the latter is the dominating trend (Banerjee et.al. 2002). Most of them coincide with the surface faults, topographic breaks, and straight segments of the drainage
- The selective occurrence of highly fractured zones do not reveal any lithological control, as they are found to occur in varied rock types. Topography too appears to have played no role in the intensity of fracturing.
- The Son – Narmada lineament represents an ancient suture, which witnessed repeated rejuvenations in the geologic past and continues to do so even today.

7.1 Fracture Trends

The strike frequency of fractures (manifested in the form of joints, slip planes, fault plane etc.) is represented by rose diagram (Fig.12). The rose diagram gives an immediate visual impression of the strike frequency. The maximum stress direction (compressive stress) is deduced by the direction of acute bisectrix of two fracture trends and the other minimum stress direction (tensional stress) is derived from the obtuse bisectrix direction of the two major fracture trends. It is generally believed that under the action of uniformly oriented principal stresses, we get either a single set or a conjugate set of fractures. The orientation of fractures with reference to the directions of principal stresses depend on the absolute value of the principal stress differences and tensile strength of the rock. Fractures can develop at different stages of the tectonic cycles. Where we get two sets of fractures orthogonal to each other, they are regarded as extension fractures. The stress directions inferred from fracture trends are given in a tabular form as below (Table – 1)

Table1-Fracture trends of different Formations of study area and stress derivation

Formation	Maxima I	Maxima II	Angle	Inferred stress directions	
				σ_1	σ_3
Domar Khoka qtz	55 ±5	125±5	70	90°	00°
Upper Rewa SST	125±5	65±5	60	95°	05°
Ganurgarh Sh	85 ±5	165±5, 125±5	80	105 °	15°
Nagod lst	55 ±5	115±5	60	85°	355 °
Sirbu Sh	65±8	115±8	50	90°	00°
Maihar SST	55±5	135±5	80	95°	05°
Trap	115±5	55±3	60	85°	355 °
Alluvium	60±10	130±10	70	95°	05°

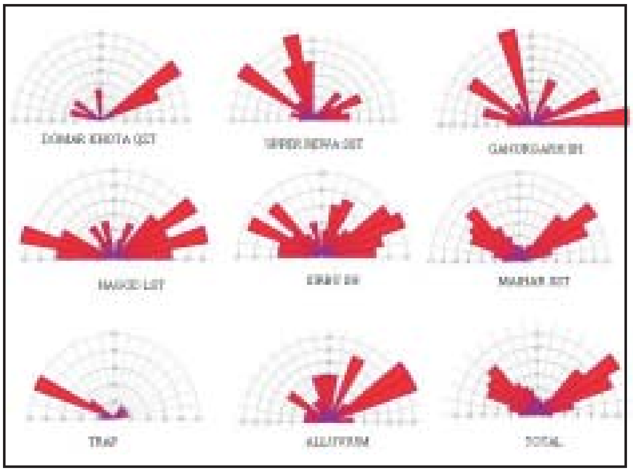

Fig. 12 : Rose diagram showing fracture trends in different Formations of Upper Vindhyan Group)

7.2. Observations from fracture trends

- There are almost two preferred joint orientations viz. 55°±5° and 125°±5° from Domarkhoka to Trap through all the Upper Vindhyan formations (Fig.12 and 13). Of the two trends 55° ±5° trend is more pronounced than the later.
- From Table 1, it is inferred that the compressive stress direction through all the formations was East – West direction and the tensional direction was N –S.
- Hence irrespective of formations, the fractures, which have been developed through ages, will act as a conduit for migration of hydrocarbon for entrapment in suitable traps. The principal stress reflects that the deformation, which these rocks have been subjected to, are influenced more by strike slip movements.
- From the Table-1 it is observed that major fractures trends are parallel to the oldest Son- Narmada Geo fracture.
- The geomorphic features river trend, stream and ridge offsets are directly related to strike slip movements and are well correlatable with the lineaments observed in the satellite imagery (Banerjee et.al. 2002).

8. Correlation with the Lower Vindhyan Formations

The data of earlier workers (Dutta et.al, 1997) of Lower Vindhyan adjacent to the Upper Vindhyan were taken into consideration for correlation of deformational history of the two Groups. When the trends of the joints of Lower Vindhyan are compared with the trends of Upper Vindhyan it is inferred that the trends in both the groups are almost same (Samal et.al, 2005). Though the Upper Vindhyan is tectonically more stable and less deformed than Lower Vindhyan, the fracture trends show that deformational activity with the same trends have continued from Lower to Upper Vindhyans.

Conclusions

In the study area of Upper Vindhyan Formations, from the study of fractures it has been inferred that there are almost two preferred orientations of fractures viz. 55°±5° and 125°±5° from Domarkhoka to trap. Of the two trends 55°±5° trend is more pronounced than the later

Crosscutting relationships between different types of fractures infer Son – lineament is the oldest and yet the youngest, youngest due to the neotectonic reactivation.

130° – 310° trend is the second oldest trend in the area followed by 20° – 200° trend.

The principal stress reflects that the deformation,which these rocks have been subjected to, are influenced more by strike slip movements.

It is inferred that the compressive stress direction through all the formations was East – West direction. And the tensional direction was N –S

Microfractures observed in the field are related to the stress state at the time of formation and which can be used to investigate the origin of the internal structure of fault zones. These microfractures developed in the shear zones may help in enhancing permeability in the rocks. In some cases, the granulation takes place during faulting creating sealing faults

Though the Upper Vindhyan is tectonically more stable and less deformed than Lower Vindhyan, the fracture trends show that deformational activity with the same trend has continued from lower to upper Vindhyan part. Hence irrespective of Formations, the fractures, which have been developed through ages, will act as a conduit for migration of hydrocarbon for entrapment in suitable traps.

In frontier basins like Vindhyan, Cuddapah and Satpura study of shear zones could help in envisaging stress field analysis and as a result of which, areas of possible secondary porosity, in terms of fractures, could be located.

Though shear zone manifestations are reported from frontier basins like Vindhyan, Cuddapah, Satpura and Himalayas, their field study and interpretation could help in exploring these basins further.

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References

Anderson, E.M. 1951. The dynamics of faulting and dyke formation with application to Britain, 2nd Ed. Edinbergh. Oliver Boyd.

Banerjee et.al. 2002, Report on Synergistic studies for hydrocarbon prospect evaluation in Vindhyan Basin

Barnett et.al., 1987, Displacement geometry in the volume containing a single normal fault, AAPG bulletin, V.71, p. 925-937

Bhandari,L.L, 1983. Petroliferous basins of India, Edited by-Bhandari.L.L, Venkatachala, B.S, Kumar Ruby, Swamy. S. Nanjunda, Pomila Garga, Srivastava. D.C., Petroleferous Asia Journal.

Bhoj Rajeev, 2001. Integrated Remote Sensing , Gravity, Magnetic, stress field analysis of Vindhyan sediments north east of hosangabad, Jabera dome and Aloni anticline. Unpub. Rep. KDMIPE, ONGC

Bhoj, R and Peters, James, 2002. Geology of Aloni – Kharkhari and contiguous area, Vindhyan Basin – a re look through integrated Remote sensing and field studies, Proceedings of the first conference of APG, Vol 1, pp.291-296

Cloos, E. 1937. 'The application of recent structural methods in the crystalline rocks of maryland'. Maryland Geol surv., V.13, Pt.1, pp.27.

Dutta et.al, 1997. Evaluation of Lower Vindhyan based on geological investigations of the nearest available outcrop analogous east of Jabera #1: Son valley, Vindhyan Basin, Field party report

Kanungo, D.N. 1956. 'The structural geology of the Torridonian, Lewisian and Moinian rocks of the area between Plockton and Kyle of Lochalsh in Wester Ross, Scotland'. Unpublished Ph.D. thesis, Imperial College of Science and technology (University of London)

Knott, S.D., 1993, fault seal analysis in the North Sea, AAPG Bulletin, V.74, p.778-792

Pendkar, N and Peters James, 2002. Characterization of Jardepahar porcellanite, Unconventional fractured reservoir in Vindhayan basin, Proceedings of the first conference of APG, Vol 2, pp.105-112

Riedel, W. 1929. 'Zur Muechaink geologischer brucherscheinungen' Eine Bitrog Zum Problem Der Fieder Spalton.d

Samal et.al. 2005. Fracture pattern and stress field analysis of katni-Damoh-jabera block, Vindhyan Basin on the basis of lineament studies and field attributes. Unpublished report.