

## Subsurface Fracture Analysis In Carbonate Reservoirs: Kohat/potwar Plateau, North Pakistan

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### ABSTRACT

Carbonate reservoirs in Northern Pakistan are characterized by tight limestone. In these reservoirs, fractures are important for production and reservoir modeling. This paper addresses problems related to subsurface fracture analysis based mainly on image Logs.

Natural fractures occur as systematic and unsystematic sets of definite and random orientation respectively. The subsurface analysis of fractures uses electrical and acoustic image logs to characterize fractures as either natural or induced features. They are classified as conductive or resistive features, representing possibly open or closed (mineralized) fractures, respectively. Using image logs, natural fractures are interpreted and classified descriptively to be continuous or discontinuous features representing systematic fractures or classified as chicken-wire (micro fractures) fractures representing unsystematic sets. Statistical analysis of fractures is used to classify them into geometrical and genetic sets as longitudinal (extensional), transverse (tensional), and oblique (shear) to the structure. Transverse fractures are known generally to exist as open. They develop parallel to the maximum horizontal in-situ stress and extend deep into the structure. Longitudinal fractures, those parallel to the fold axes, are observed to produce hydrocarbons in several fields in Northern Pakistan. Fracture density impacts production and reserves calculations. However, fracture density is strongly influenced by the lithology and layer thickness. Widely spaced fractures are observed in massive carbonate reservoirs, and closely spaced fractures of narrower aperture are observed in laminated strata. Thus, individual fractures in massive carbonates require to be identified for their impact on production. Fractures are observed to occur as discontinuous features of right- or left-stepping geometry and as en echelon features of significantly wider aperture in shear bands. These features together with vugs and leached features may provide zones of higher porosity, permeability, and storage capacity with isolated distribution in tight carbonates. Therefore, knowledge about fracture occurrence and distribution is important to predict sweet spots for drilling and field development.

### INTRODUCTION

Tight carbonate reservoirs in Northern Pakistan have been targets of hydrocarbon exploration for about 100

years. Figure 1 shows the tectonic map and location of fields (Sercombe, et al., 1998) and Figure 2 shows the generalized stratigraphic column of the Kohat/Potwar plateau. The carbonate reservoirs, in this region, produce mainly from fractures. Therefore, knowledge of the fracture origin, fracture type, and fracture network distribution are important for hydrocarbon exploration. Because fractures provide high permeability and are known to have limited porosity; there are questions related to the dynamic behavior of fractures, production estimates, and storage of hydrocarbons in fractured carbonate reservoirs. As a result, exploration and drilling with uncertainty posed by fractures at greater depth-of-target (35 km) reservoirs in Northern Pakistan is a costly business. Realizing all these challenges, we have made an attempt to discuss subsurface fracture analysis with integrated surface (outcrop, thin-sections) and subsurface data (cores, borehole image, acoustic, reservoir, and seismic) following earlier work on fractures in Northern Pakistan (Jadoon, et al., 2002; Shami and Baig, 2002; and Jadoon, et al., 2003).

### FRACTURED CARBONATE RESERVOIRS

Fractured carbonate reservoirs have challenged Geoscientists due to their complexity and unpredictable nature (Nelson, 1998). They are categorized into four main types based on fractures, porosity, permeability and production:

- 1) where fractures provide the essential porosity and permeability (these are most common in Northern Pakistan, such as Sakesar).
- 2) where fractures provide the essential permeability.
- 3) where fractures provide the permeability assistance to already producing Reservoirs.
- 4) where fractures provide the permeability barriers in otherwise producible reservoirs (Nelson, 1992).

Fractures facilitate flow of fluids and increase effective permeability. Earlier studies (Belhaj, et al., 2002a) show that fracture aperture is the main factor responsible for changes in permeability (Figure 3). High permeability of 3388 md is reported with a fracture of 1.25 mm width (Belhaj, et al., 2002a). Permeability in carbonate reservoirs may drastically increase with fractures and faults (Antonellini and Mollema, 2000), therefore, awareness about the distribution of these features is crucial to predict sweet spots and zones of higher and lower permeability across a field.

In tight carbonate reservoirs, fracture porosity is not as important as permeability. However, an estimate of secondary porosity related to fractures and leaching is required for reserves estimates. Carbonate reservoirs in the Potwar plateau are reported to have approximately 3.5% secondary porosity in Eocene Chorgali/Sakesar limestone and approximately 2% in the Paleocene Lockhart limestone (Jadoon, et al., 2002; Shami and Baig, 2002). Outcrop analogs of tight carbonates show that fracture

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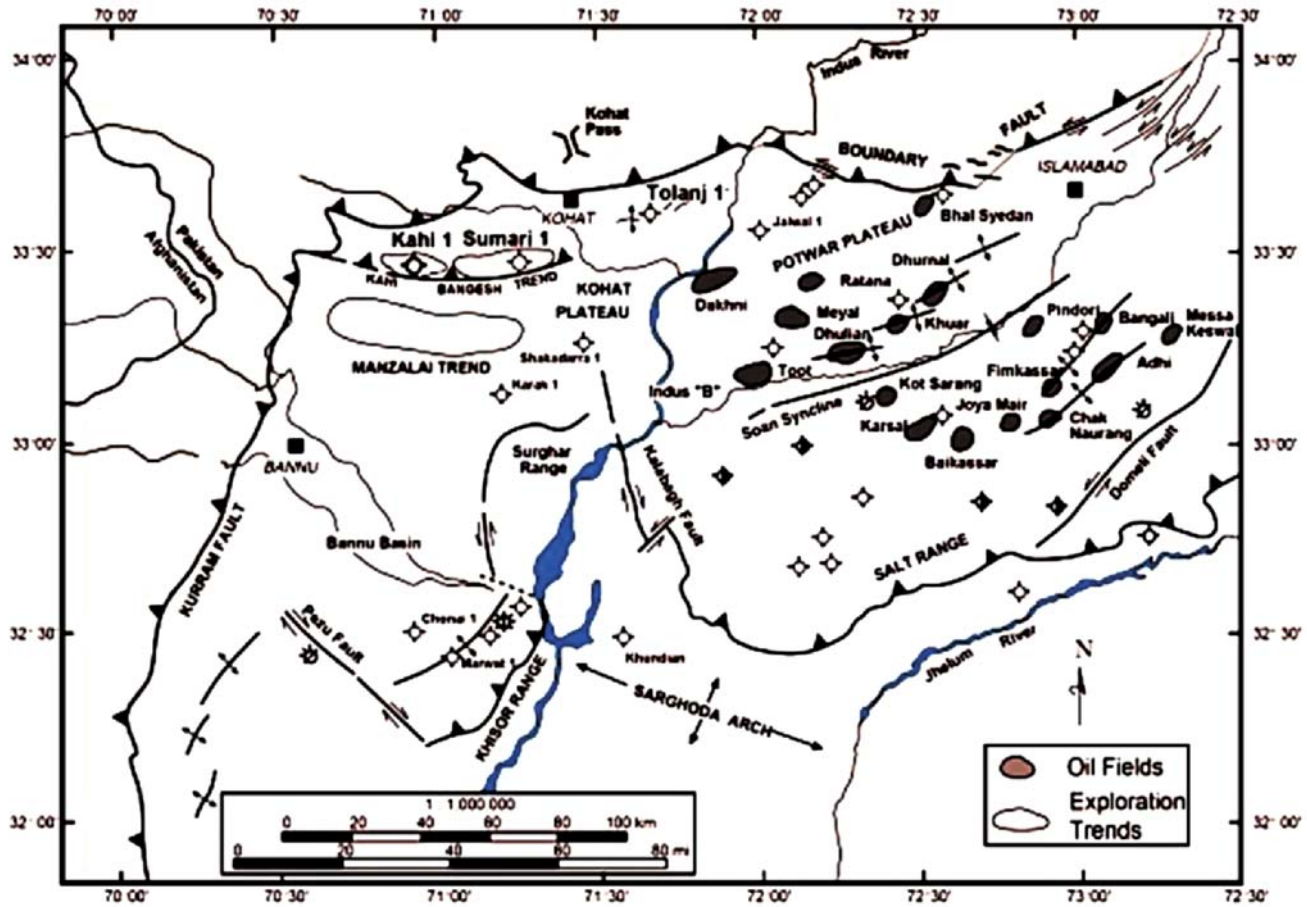


Figure 1-Tectonic map of Kohat/Potwar Plateau in North Pakistan ((Sercombe et al., 1998).

porosity may vary from less than 1% to 10 % in areas near faults and shear zones (Antonellini and Mallema, 2000).

### FRACTURE TYPES AND CLASSIFICATION

One of the biggest challenges in subsurface exploration of fractures is their detection and classification. Presently, cores and image logs are routinely used for subsurface fracture analyses. Image logs can be conveniently used for efficient fracture characterization and to provide directional trends of these features. Image tools make an image of the borehole based on resistivity variations of the strata and acoustic (amplitude/transient time) variations of an ultrasonic waveform. As a result, geological features are represented with an impression similar to that seen in the outcrops.

Outcrop studies allow fracture characterization as systematic and unsystematic sets (Suppe, 1985). Systematic fractures have predictable trends over relatively long distances; whereas, unsystematic fractures are generally small-scale features of random orientation owing to their origin related to diagenesis, contractional forces, and cataclasis (Figure 4). They are often termed

desiccation fractures (mud cracks) and syneresis or chicken-wire (polygonal) fractures (Nelson, 1979), hereafter collectively referred to as chicken-wire fractures. Chicken-wire fracture are observed to significantly enhance production of hydrocarbons from carbonate reservoirs of the Middle East and Northern Pakistan. Their detection during subsurface fracture analysis is therefore as important as the detection of systematic sets.

Mechanically induced fractures and borehole breakouts develop due to over-balanced (when mud-weight is higher than formation pressure) and under-balanced (when mud weight is lower than formation pressure) drilling respectively. They are required to be distinguished from natural fractures. The induced features appear as conductive, linear, discontinuous, or en echelon features on the two sides of the borehole wall, 180 degrees apart from each other. Thus, during subsurface analysis of fractures, our first goal is to distinguish between natural and induced fractures, followed by natural fracture characterization (Figure 5). Systematic fractures show definite trends. Unsystematic fractures (Chicken-wire) lack definite trends (Suppe, 1985). They develop due to brecciation and diagenesis

| AGE                   | FORMATION                                    | LITHOLOGY | OIL |
|-----------------------|--|-----------|-----|
| PLEISTOCENE - MIOCENE | ~3000 m of Fluvial Clastics (Siwaliks Group) |           | ●   |
| EOCENE                | Kohat  |           | ●   |
|                       | Kuldana                                      |           | ●   |
|                       | Chorgali / Sakesar / Nammal                  |           | ●   |
| PALEOCENE             | Patala                                       |           | ●   |
|                       | Lockhart                                     |           | ●   |
| PERMIAN               | Amb  |           | ●   |
|                       | Sardhai                                      |           | ●   |
|                       | Warcha                                       |           | ●   |
|                       | Dandot                                       |           | ●   |
|                       | Tobra  |           | ●   |
| CAMBRIAN              | Bhaganwala                                   |           | ●   |
|                       | Jutana                                       |           | ●   |
|                       | Kussak                                       |           | ●   |
|                       | Khewra                                       |           | ●   |
| PRECAMBRIAN CAMBRIAN  | Salt Range Formation                         |           | ●   |
| PRECAMBRIAN           | Indian Shield Basement                       |           | ●   |

Figure 2 - Generalized stratigraphic column of the Salt Range and Potwar Plateau.

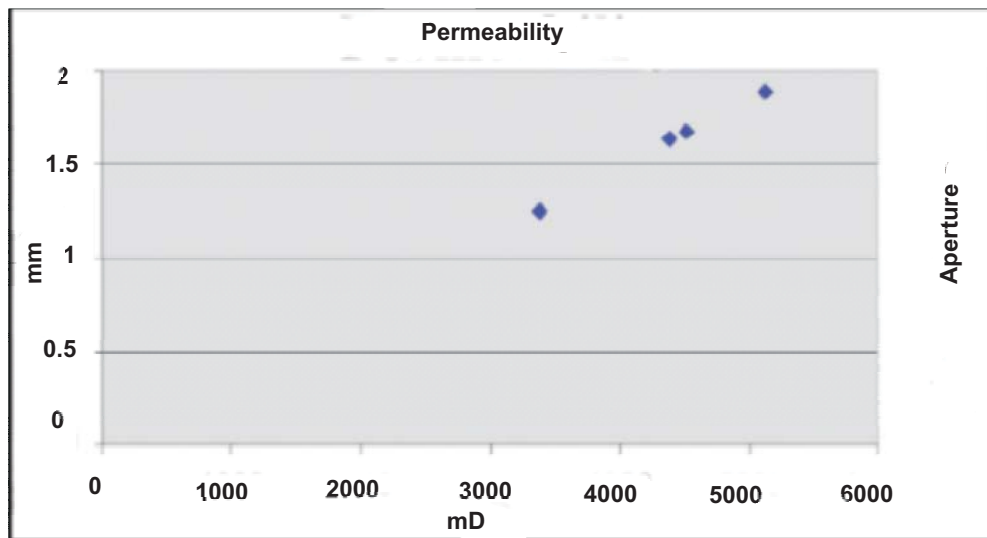


Figure 3 - Permeability as a function of fracture width (Belhaj et al., 2002a)



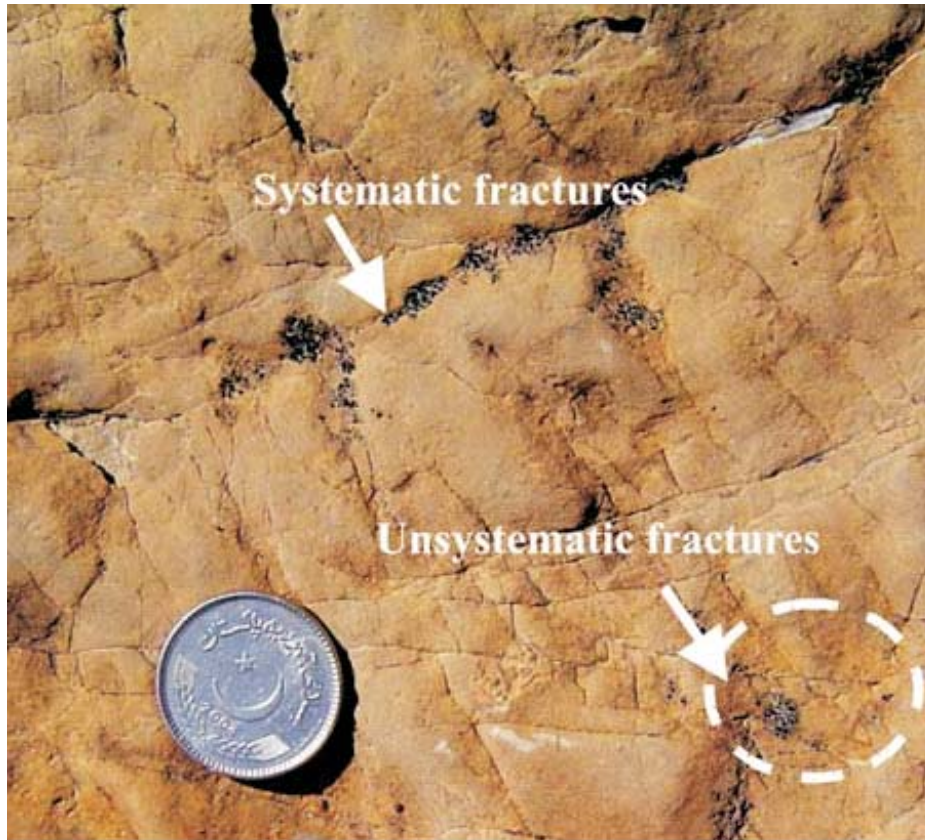


Figure 4 - Systematic and unsystematic sets of natural fractures.

### Natural Fracture Types

Natural fractures occur both as open and closed (mineralized) features, similar to as shown in outcrop and image examples of fractures in (Figure 6). Open fractures facilitate fluid flow. Whereas, closed fractures provide hindrance to fluid flow due to in filling or chemical precipitation of dissolved minerals such as calcite, quartz, or anhydrite. In outcrop examples, open fractures have a darker linear appearance due to open space (Figure 6a). A fracture filled with clay may be closed, with still a darker appearance.

Closed/mineralized fractures generally have a lighter appearance due to calcite/anhydrite or quartz filling (Figure 6b).

On resistivity image logs, resistivity variations are caused by lithologic changes and changes in porosity and hydrocarbon presence. Image data is acquired in water-base mud. Here, voids in porous strata have a darker (conductive) image impression. Whereas, dense rocks appear lighter (resistive) on the image logs. As a result, open or closed fractures have a conductive (dark) or a resistive (light) appearance, respectively, on the resistivity images (Figure 6c and d). The conductive nature of fracture traces is generally attributed to the

conductive drilling mud that fills the open fracture aperture. However, even shale- and pyrite-filled fractures also give a similar conductive response. Similarly, the resistive signature of fractures could be due to calcite or anhydrite filling their aperture. Therefore natural fractures on image logs may be classified as conductive and resistive and their impact on hydrocarbon production can be considered (Figure 6).

### Classification of Natural Fractures

Fractures can be classified based on their physical appearance, geometrical distribution, and genetic development across a structure (Nelson,1979; Muecke and Charlesworth,1966; Stearns, 1968; Stearns and Friedman, 1972; McQuillan,1973; McQuillan,1974). Three main classifications of natural fractures exist: Descriptive, Geometric, and Genetic.

**Descriptive Classification:** Descriptive classification is based on the physical appearance of fractures with surface and subsurface analysis; descriptive terms used include systematic and unsystematic, open (conductive) or mineralized (resistive), continuous or discontinuous. Discontinuity of fractures is related either to their

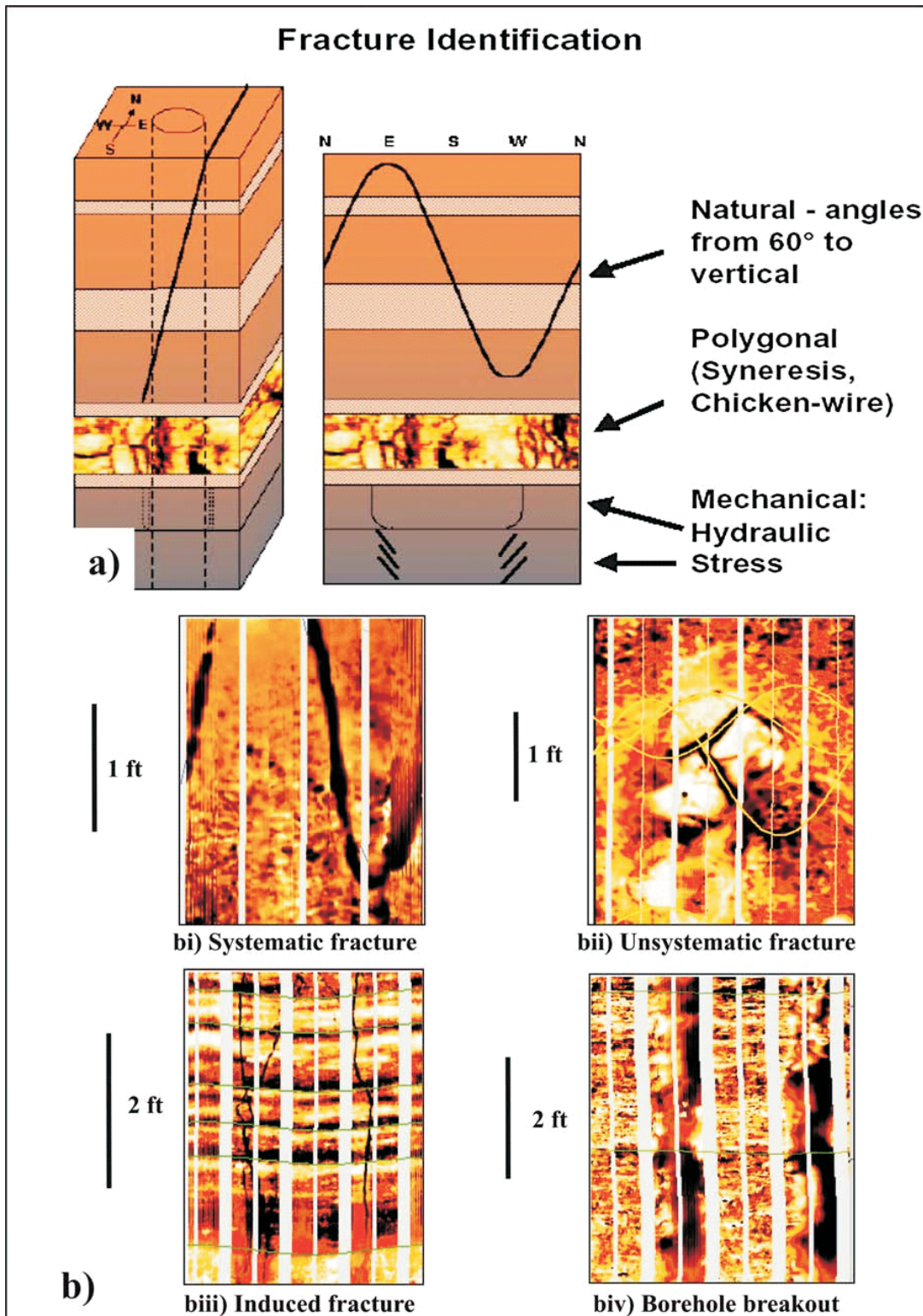
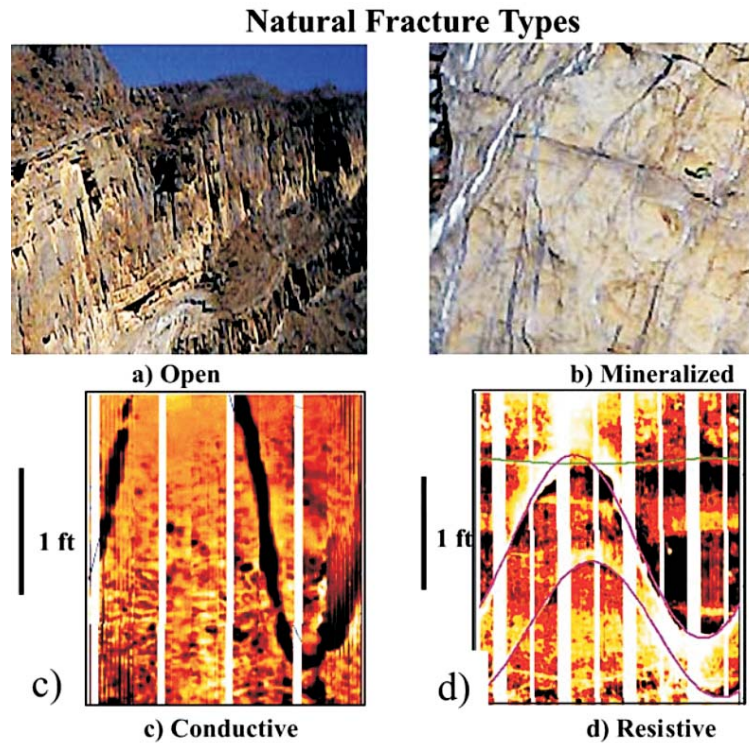


Figure 5 - a) Borehole representation of natural and induced fractures (with courtesy of Schlumberger), b) borehole electrical image examples of systematic and unsystematic natural and mechanically induced features.





**Figure 6 - Outcrop (a-b) and images (c-d) examples of natural open (conductive) and mineralized fractures.**

development as steps and en-echelon features controlled by causative stresses or by their dependency on the lithology and layer thickness. In laminated strata, fractures commonly about across layers of variable thickness and ductility. Based on the appearance and nature of fractures, a subsurface descriptive classification of fractures is introduced in Table 1, with image examples in (Figure 7). Although, image interpretation is routinely performed, a standard descriptive classification of fractures with symbols and assigned color codes is lacking. With this proposed classification, we can achieve consistency in presentation and systematic interpretation of fractures during subsurface image analysis (Figure 7).

**Geometric Classification:** Fractures are observed to be systematically distributed across a structure. The geometrical distribution of fractures in folded strata has been studied by several workers (Suppe, 1985; Nelson, 1979; Muecke and Charlesworth, 1966; Stearns, 1968; Stearns and Friedman, 1972; McQuillan, 1974; Akbar, et al., 1995). Based on distribution across a fold, fractures can be classified as transverse, longitudinal, or oblique sets when observed to be oriented, perpendicular, parallel, or oblique to the structure, respectively. Image logs can be used to achieve a similar classification of fractures during data analysis and multi well studies.









**Genetic Classification:** Open fractures are generally considered to develop parallel to the maximum horizontal in-situ stress orientation. However, experimental data shows development of open fractures oriented both

parallel and oblique to the maximum horizontal in-situ stress (Figure 8). Thus, open fractures may have more than one orientation, as seen in image logs and validated by outcrops data.

A genetic classification divides fractures into Type I and Type II (Stearns, 1968). Type I fractures are composed of a tensional set oriented perpendicular to the fold axis with an associated conjugate shear set whose acute bisector coincides with the orientation of tensional fractures. Type II fractures are composed of an extensional set oriented parallel to the fold axis with an associated conjugate shear set whose acute bisector coincides with the orientation of extensional fractures. Consequently, open fractures are classified as tensional, extensional, or shear sets (Figure 9) with orientation perpendicular, parallel, or oblique to the structural axis (Nelson, 1979; and Stearns, 1968;). Another category of fractures is added to this classification as contractional fractures to represent most of the unsystematic set of chicken-wire fractures (Nelson, 1979). The process (contractional fracturing) involves volume reduction and development of fractures due to dolomitization with additional porosity development of up to 13%. Systematic set of fractures are reported across folded structures in the Rocky Mountains of Alberta and British Columbia (Price, 1967; Norris, 1971) and in the Oman Mountains near Al-Ain in the United Arab Emirates (Akbar, et al., 1995). They are also observed in outcrops of folded Tertiary and Mesozoic strata in Hill Ranges in the Northern Pakistan (Figure 9).

Based on the fracture analysis, we have found that the descriptive classification of fractures is the most

**Table 1 - Descriptive classification of fractures**

| Fracture Type                  | Brief Description  | Symbol  | Color      |
|--------------------------------|--|---|------------|
| Continuous conductive          | Conductive feature, usually steeply dipping, discordant to bedding where latter visible, present mostly on 6–8 images.   |    | Blue       |
| Discontinuous conductive       | Conductive feature, usually steeply dipping, discordant to bedding where latter visible, present mostly on 2–6 images  |    | Light blue |
| Stylo-Fracture                 | Conductive short features, subvertical to vertical, controlled by stylolites, present mostly on 1–4 images   |    | Blue       |
| Chicken-wire (micro) fractures | Conductive, short features, subhorizontal to vertical, controlled by diagenesis, compaction, or cataclasis, present mostly on 1–4 images   |    | Yellow     |
| Possible open                  | Conductive feature, usually steeply dipping, discordant to bedding where latter visible, present mostly on 1–4 images  |    | Cyan       |
| Mineralized or Closed          | Resistive, high angle features, discordant to bedding, present mostly on 2–6 images  |    | Magenta    |
| Borehole breakouts             | Conductive, discontinuous, subvertical to vertical features, generally appear 180 degrees apart from each other and 90 degrees apart from drilling-induced fractures on the images |  | Black      |
| Drilling-induced Fracturees    | Conductive, discontinuous, subvertical to vertical, generally appear 180 degrees apart on the images   |  | Black      |

useful for single- and multiple-well image analysis. Subsequently, this data can further be used for geometric and genetic classification of fractures to define fracture network distribution, detect sweet spots, and to learn if a particular set of fractures is more productive for field development. Tensional fractures are generally considered to be more uniformly distributed and Productive (Antonellini and Mollema, 2000 and Nelson, 1979). However, several wells in Kohat/Potwar plateau in North Pakistan are observed to produce from extensional fractures in Eocene/Paleocene carbonate reservoirs.

#### FRACTURE ATTRIBUTES AND ANALYSES

Once fractures are detected in a subsurface reservoir, it is extremely important to understand their distribution, postulate their origin, and learn about their density and other petrophysical aspects such as fracture width, porosity, permeability, and saturation (Nelson, 1992). This can be done through cores, thin-sections, and a number of image tools and testing results. Presently, electrical image logs are most commonly used for the detecting and defining the distribution of fractures. Formation

resistivity imaging tools now have a high-resolution of 5.0 mm (0.2 inch) and are capable of detecting features as small as 5.0 mm (0.2 inch) and addressing petrophysical aspects of fractured reservoirs.

The fracture attributes that can be computed directly from the analysis of electrical images include (Cheung and Hiliot, 1990) fracture density (apparent and corrected for borehole deviation), fracture aperture in inches or millimeters, fracture porosity in percent or in fraction, and the cumulative fracture aperture profile (Figure 10).

#### Fracture Density

Layer thickness, mechanical properties of rocks (brittleness), and strain are among the most important factors controlling density and spacing of fractures. Both, field examples and image logs show that laminated strata exhibit a higher density of fractures compared to massive strata (Figure 11 and 12). A linear relationship between thickness and fracture spacing is documented in the literature (Narr, 1990; Narr and Suppe, 1991; Bai and Pollard, 2000). A first-order relationship between mean spacing of fractures and bed thickness is observed based on

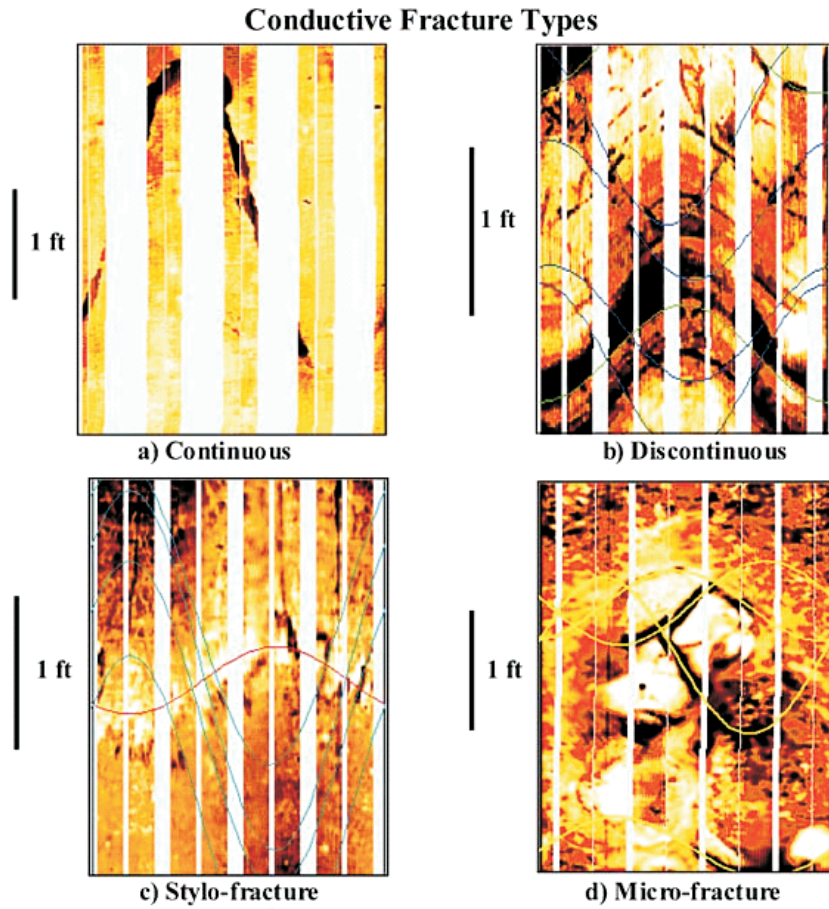


Figure 7 - Borehole electrical image examples of conductive fracture types.

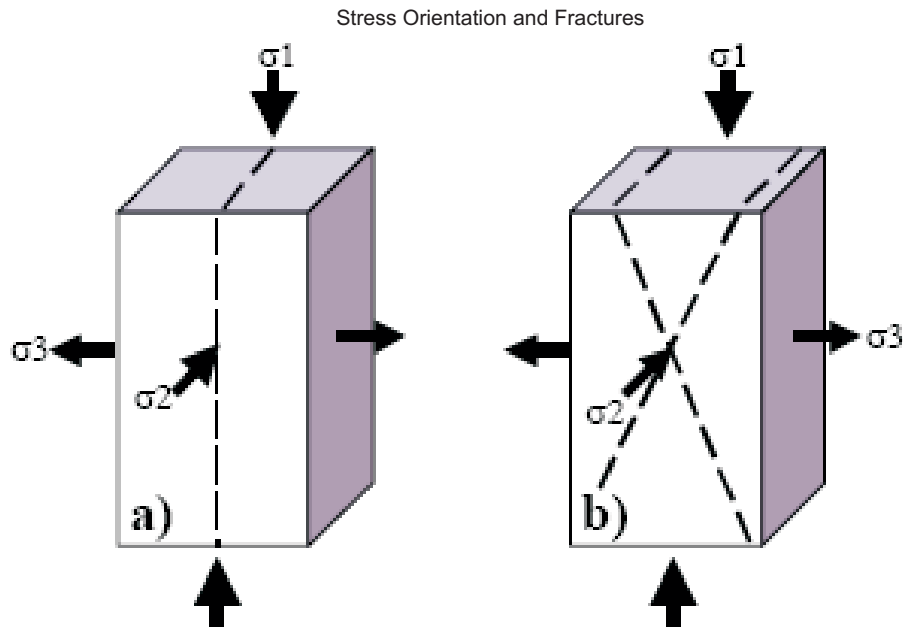
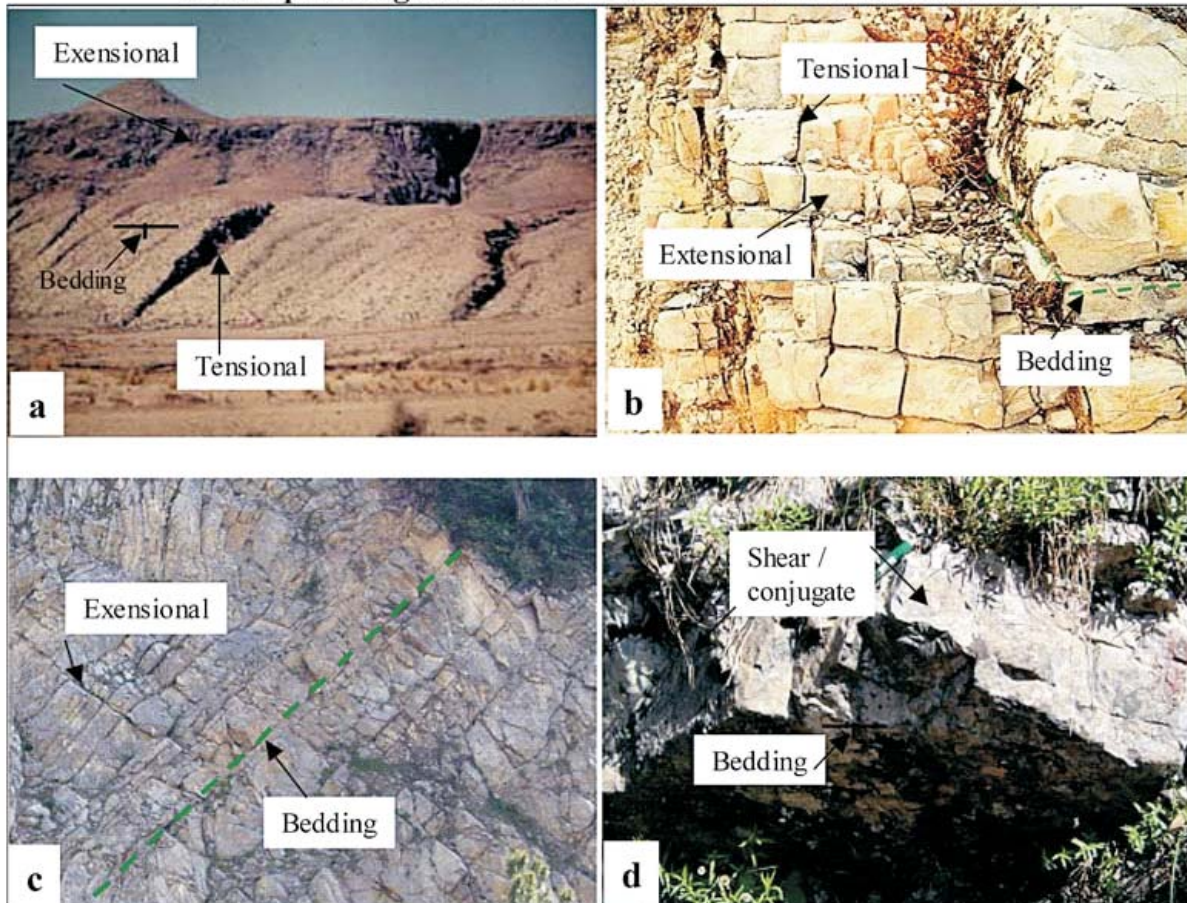


Figure 8 - Principal stresses and fractures:  $\sigma_1 > \sigma_2 > \sigma_3$  (a),  $\sigma_1 > \sigma_2 = \sigma_3$  (b).



### Outcrop Analogs of Natural Fractures From North Pakistan



**Figure 9 - Outcrop examples of open fracture types: a = Jandran anticline (Sulaman fold belt), b) Chorgali (Potwar plateau), c&d) Kawagarh limestone( Hill Range in Pakistan).**

outcrop studies where mean spacing of small faults and fractures is of the same order of magnitude as that of bed thickness (Florez-Nino, et al., 2005).

During image analysis, apparent fracture density (number of fractures along the borehole is corrected for the amount of well deviation at that particular depth. The corrected fracture density on the image logs represents the true fracture density perpendicular to the fracture plane. Good comparison of fracture occurrence in similar zones in widely spaced wells is observed based on the image log interpretation with deviations explained by variation in lithology and strain across the field.

#### Fracture Aperture, Porosity, and Permeability

One of the questions related to fractured carbonate reservoirs is the effect of fracture width on porosity. Because fractures provide both permeability and storage in low-porosity and nonporous carbonates, an estimate of fracture porosity is vital for the calculation of reserves. Published porosity values (Jadoon, et al., 2002 and Shami and Baig, 2002) of carbonate reservoirs (Chorgali and Sakesar) from the Potwar plateau range from 124% with an

average value of 4%. Porosity values of 6.5% and 1.8% are considered suitable for Chorgali and Sakesar reservoirs based on core analysis in Finkaser field (Jadoon et al., 2002). Their permeability ranges from 50 md with an average of 5 md (Jadoon, et al., 2002 ; Shami and Baig, 2002).

Generally, a low fracture width of 0.01 to 0.3 mm (Nelson, 1985) and a porosity value of 0.08 to 3% are recorded in carbonate reservoirs (Jadoon, et al., 2002). However, open fractures provide conduits for the flow of fluids due to high permeability. Image logs can now be used for the calculation of fracture aperture and porosity. Unlike cores and thin-sections, image logs provide a continuous curve characterizing fracture attributes (density, trace length, aperture, and porosity) along the borehole (Figure 10). Despite low fracture porosity, some tight carbonate reservoirs are known to produce for long durations (due to unknown reasons) such as the Ellen burger limestone in the Texas Permian Basin. Thus, the question related to the storage of hydrocarbons in tight carbonate reservoirs remains important. To address this question, we have looked at the image logs, outcrops, and thin-sections from carbonate units in Northern Pakistan (Figure 13, 14 and 15). Image-log and core-derived fracture-

Subsurface Fracture Analysis In Carbonate Reservoirs

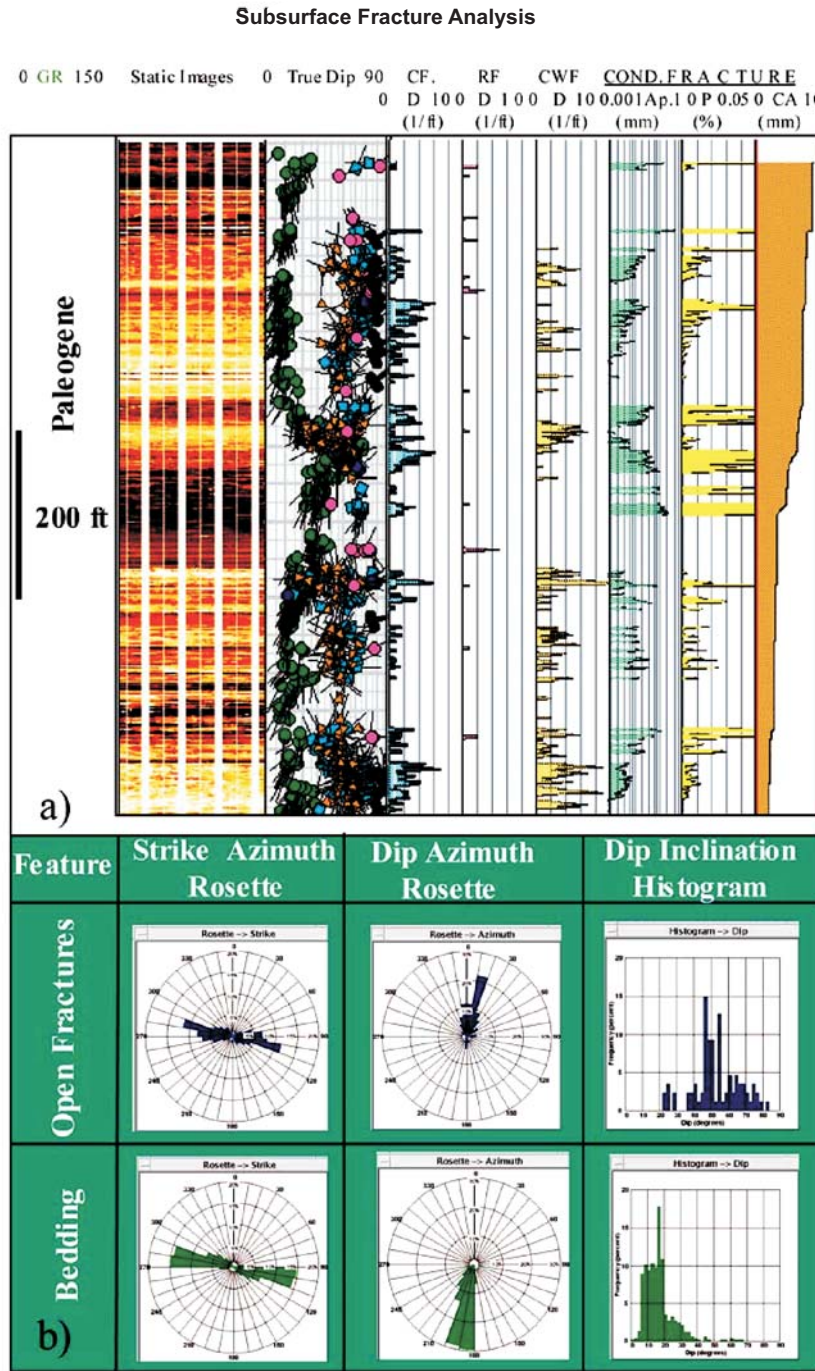
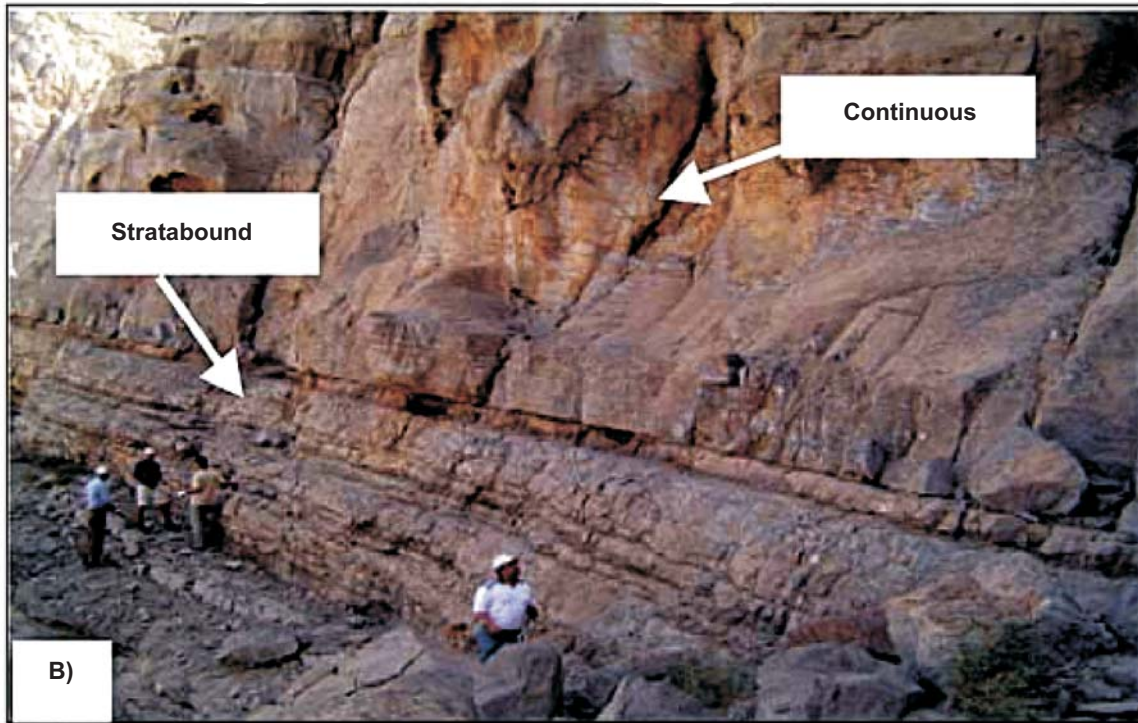


Figure 10 - A summary plot of subsurface fracture analysis based on borehole image interpretation to show fracture types, orientation, and attributes (a), and statistical plots of conductive fractures and bedding (b). Notice that the conductive fractures and bedding in this case have similar strike with opposite dip azimuth. Abbreviations: A = Aperture, CA = Cumulative aperture, CF = Conductive fracture, CWF = Chicken-wire fracture, D = Density, P = Porosity, RF = Resistive fracture.



### Lithology and Bed Thickness vs Fracture Density, Spacing and Extent



**Figure 11 - Outcrop example of fracture density and spacing in massive and laminated Cretaceous Thamama Carbonate reservoirs in Oman Mountains, United Arab Emirates.**

width (< 1 mm) and porosity (<1%) estimates are generally low but are similar to earlier estimates discussed above (Nelson, 1985). However, thin-sections of Chorgali and Sakesar reservoirs (Figure 13) from the Potwar plateau show a significant amount of secondary moulding and Inter crystalline porosity in addition to fractures (Jurgan, et al., 1988 and Mujtaba, 2001). Outcrop examples of carbonate reservoirs from the Hill ranges of Northern Pakistan have excessive porosity developed along en echelon shear bands with fracture widths ranging up to 8 mm along 13-cm long fractures and brecciated fault zones (Figure 14). Thus, higher porosity values in the Chorgali (28%) and Sakesar (~6.5%) Formations (Jadoon et al., 2002; Shami and Baig 2002) may largely represent secondary diagenetic and fracture porosity in the Potwar Plateau (Jurgan, et al., 1988 and Mujtaba, 2001).

Similarly, outcrop analogs of fractured carbonate reservoirs show sporadically higher fracture porosity along deformed zones, as in the study of the Triassic dolomite from Northern Italy (Antomellini and Mollema, 2000). Higher fracture porosity of about 2.4% and permeability of 3000 md occurs next to large offset faults (1200 m) and about 10 % porosity occurs in a brecciated zone with 110-m offset

faults. The porosity is observed to decrease to <1% in brecciate zones of large offset (10200 m). Maximum horizontal permeability ranges between 16 md (for a fracture of 0.005-mm aperture) and 1800 md (for a fracture of 0.0125-mm aperture). Permeability range of 0.01 to 2000 md for fractured dolomite reservoirs is estimated (Aguilera, 1995).

Our observations and literature review of the fractures described above suggests that the faults, fractures, and leached features may lead to excessive amounts of localized secondary porosity in tight carbonate reservoirs. Generally, these are subseismic-resolution features. Therefore, cores and image logs would be more suitable to learn about the small-scale variation of porosity distribution in tight carbonate reservoirs for field-scale structural models to recognize sweet spots for drilling.

#### NORTHERN PAKISTAN: CASE STUDIES

In this section, we review the drilling history of some wells for case examples of fractures and production in Northern Pakistan.



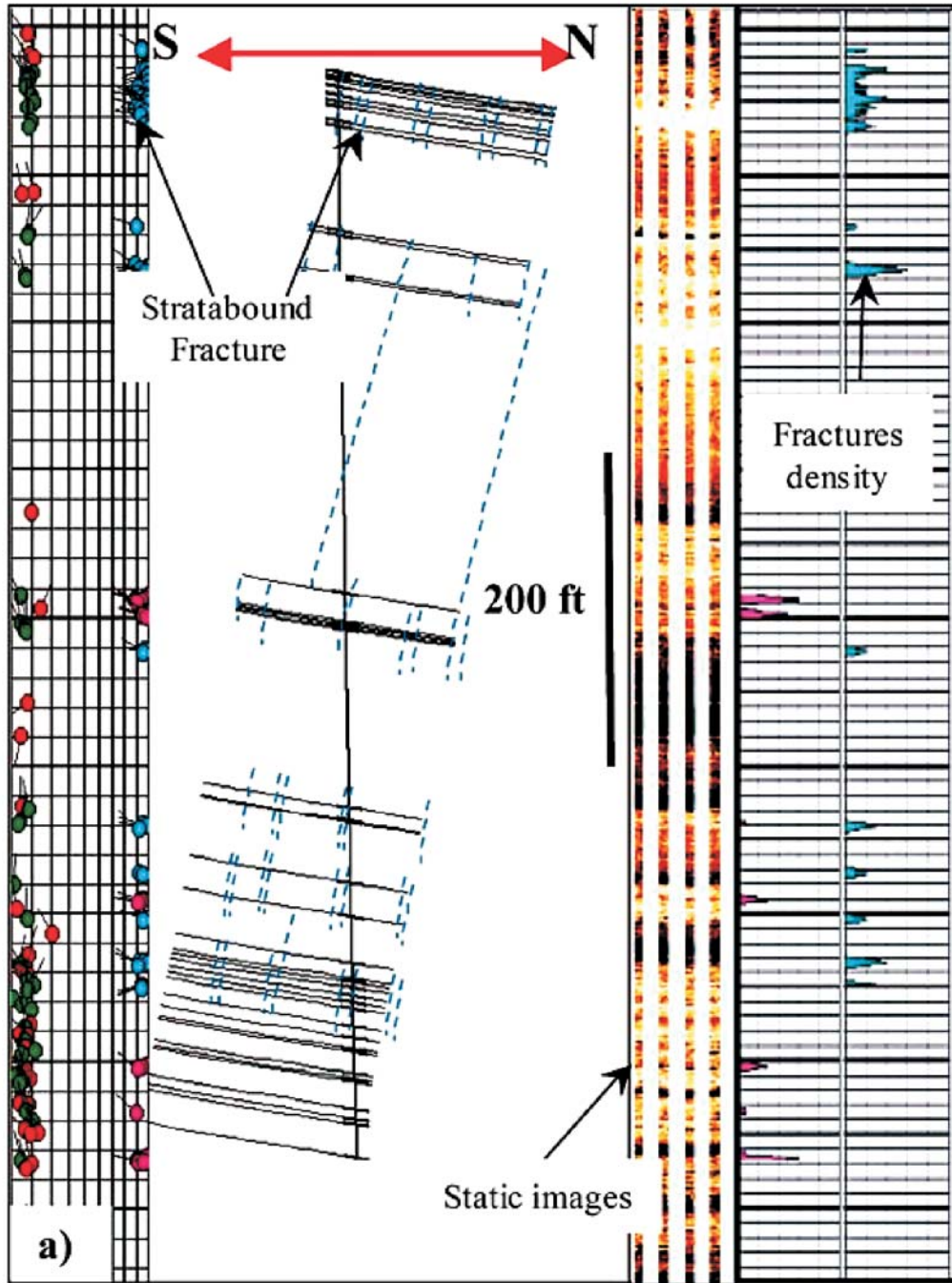


Figure 12 - A structural cross-section of bedding and fracture density based on image log interpretation.

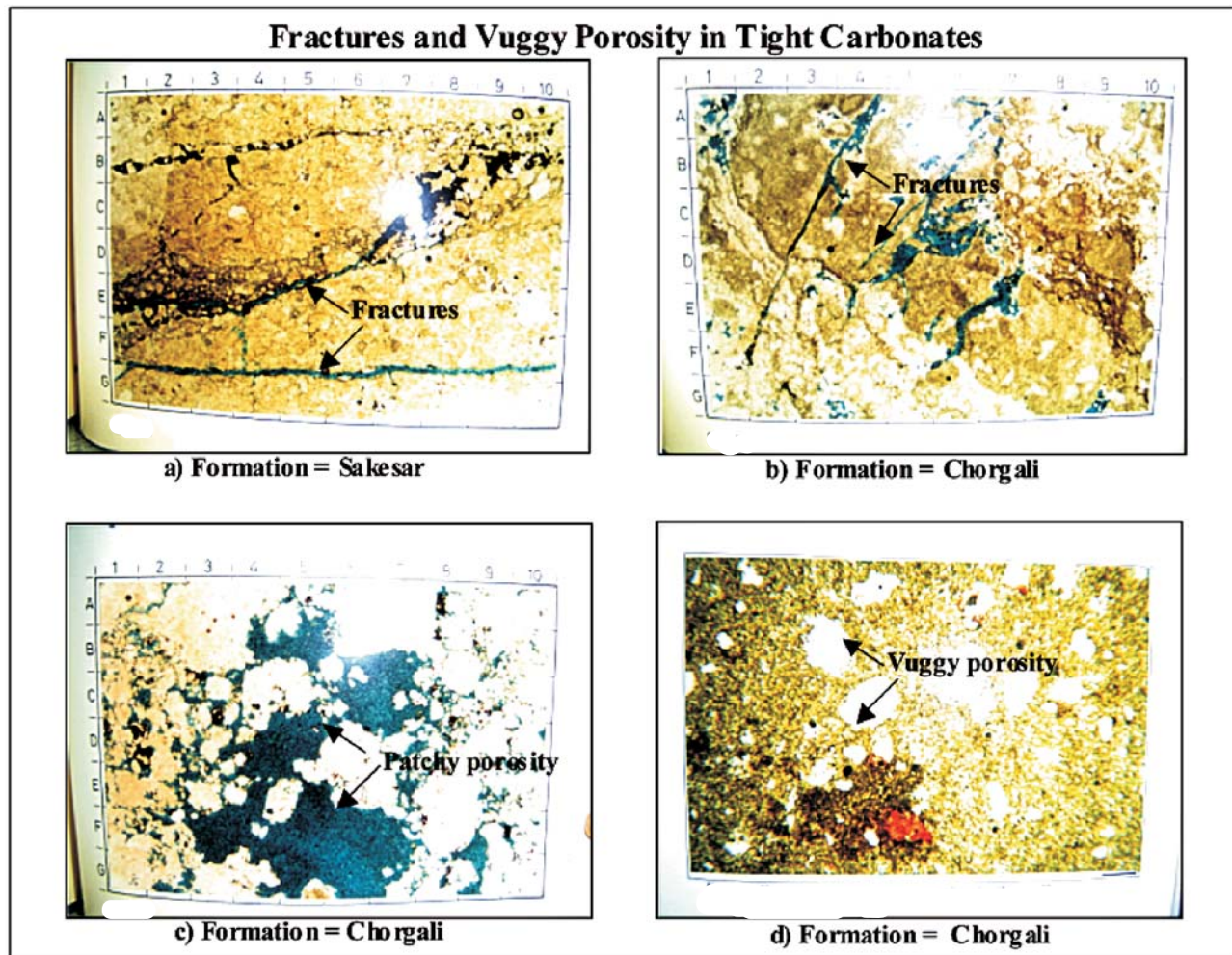


Figure 13 - Thin-sections of Chorgali and Sakesar carbonates with fracture (a, b) and vuggy/mouldic porosity (c, d) in Potwar Plateau [25, 26]. Open space in 'a, b' and 'c' is filled with blue colored resin. Whereas, pore space in 'd' it is represented by white patches. Magnification: 1 ~ 25.



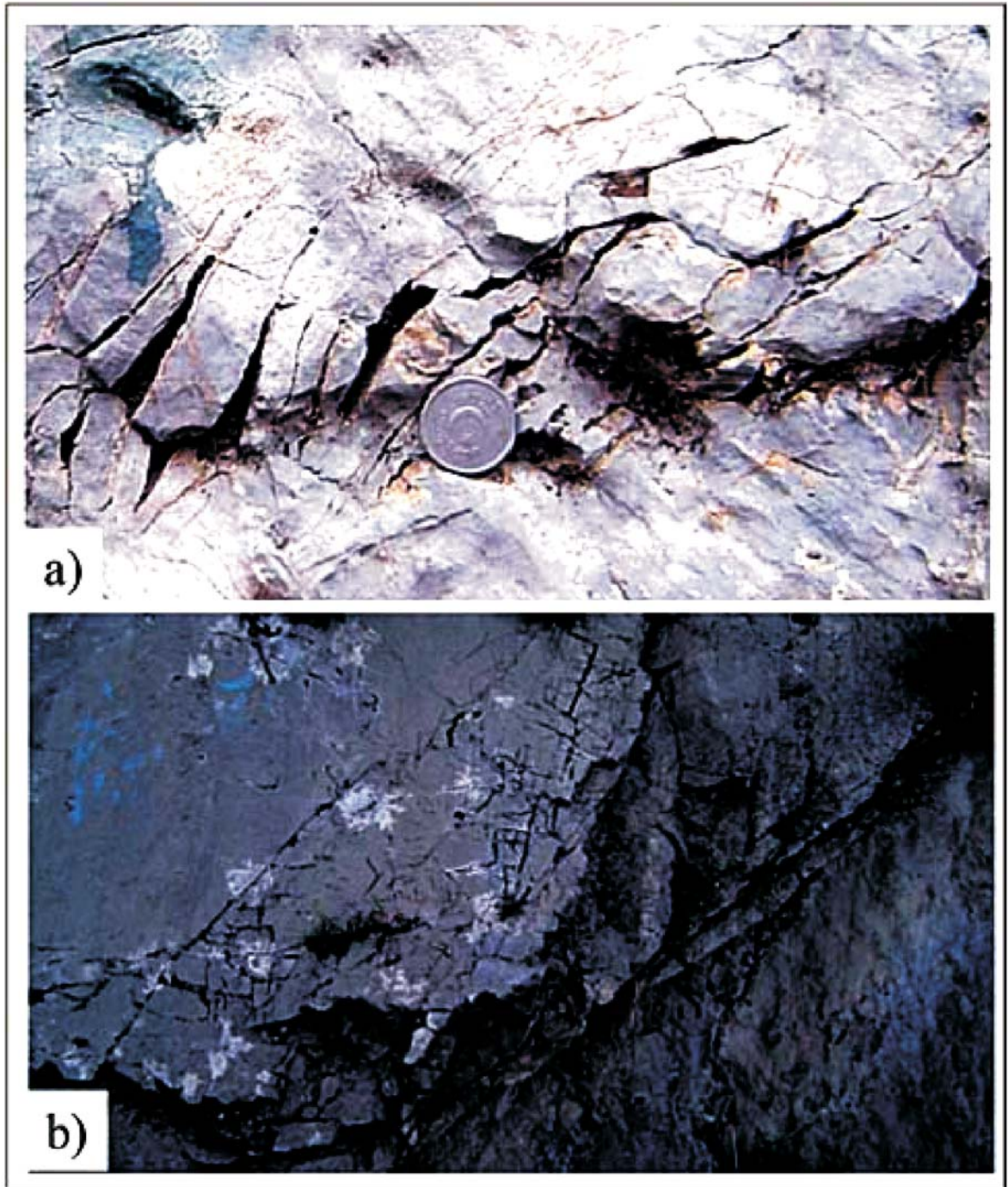


Figure 14 - Fractures in a shear band and a fault zone in tight carbonate reservoirs, North Pakistan. Snapshot 'a' represents one component of a conjugate shear band with an echelon fractures of excessive porosity and storage capability, and 'b' represents a brecciated zone with abundance of open fractures and excessive porosity along a minor fault.



### Case Study 1

In this example, both systematic and unsystematic (chicken-wire) fractures were detected across the reservoir zones. Subsequently, the zones with strong sets of systematic fractures were tested for hydrocarbons but with poor results. Barite mud was used for drilling this well. It was likely that damage to natural fractures was caused by the heavy barite mud. Therefore, an acid job was done. As a result production was enhanced to more than three times at some locations in Paleogene carbonate reservoirs. An acid job was also carried-out across a clastic reservoir where it was not successful. Fractures in this case were interpreted as extensional due to their occurrence parallel to the structural and bedding trend (Figure 10).

### Case Study 2

In this case, two wells were drilled along the forelimb of a north/south-oriented structure to test hydrocarbons in the Chorgali and Sakesar reservoirs of the Potwar plateau (Jadoon, et al., 2002). Fractures occurred as tensional and shear sets based on the image log interpretation in the two wells. Well 1 was a producer. Well 2 turned out to be a dry hole. It is not clear, why one well produced and the other did not. However, the presence and absence of hydrocarbons in the two wells may be related to fracture linking and connectivity to storage. In this case, systematic fractures were interpreted as dominantly tensional, developed perpendicular to the bedding strike.

### Case Study 3

In this example of the Chorgali and Sakesar limestone, systematic and unsystematic (micro-fractures) sets of fractures were detected on the image logs. A production test of a zone of systematic fractures yielded only a nominal amount of hydrocarbons (105 BOPD) from the Sakesar reservoir. Whereas, a production test of another zone characterized by relatively higher resistivity and a dominance of micro-fractures (unsystematic) yielded good quantities (1830 BOPD) of hydrocarbons from the same reservoir. This example documents the positive role of unsystematic fractures in production.

## CONCEPTUAL GEOLOGICAL AND RESERVOIR MODEL

Fractures develop in a predictable manner in a fold-and-thrust structure, with uncertainties related to the complexities of the fracture network distribution and strain distribution. The most common sets of open Fractures (Nelson, 1979; Stearns and Friedman, 1972; Cooper, 1991) are recognized as tensional (transverse), extensional (longitudinal), and shear (oblique).

Tensional, extensional and shear fractures are considered as planar features of systematic orientation. However, fractures occur as continuous and discontinuous features with zones of abundant fractures along faults and shear bands in Northern Pakistan (Figure 13, 14 & 15), similar to the occurrence of fractures described from Triassic dolomite in

from Northern Italy (Antonellini and Mollema, 2000) and from the sub-andean fold-and-thrust belt in Bolivia (Florez-Nino, et al., 2005).

Higher density of fractures near faults in carbonate strata is observed (Antonellini and Mollema, 2000). Faults with minor offset of 0.530 m are characterized by en echelon arrays of localized fractures, whereas large-offset faults (1200 m) are characterized by a wide breccia zone with high fracture density near the faults. Fractures can provide significant amount of localized porosity (0.2-2.4%) and permeability (about 3000 md) in the fracture zones and next to large-offset faults (1200 m). The porosity of the breccia in faults with 1-10m offset is fairly high, up to 10%. Whereas the breccia in faults with 10- to 200-m offset have a low porosity (<1%). Similarly high permeability along fractures is reported in the literature (Belhaj, et al., 2002b).

An outcrop example of fractures in Cretaceous Kawagarh limestone from Hill Ranges in Northern Pakistan (Figure 15) shows a high density of multiple, well-connected fracture sets in one zone and negligible fractures in the nearby zone due to strain variation, similar to outcrop analogs from the Alps and the Andes (Antonellini and Mollema, 2000 and Florez-Nino, et al., 2005) this possibly explains why some wells in a fractured carbonate reservoir are better producers than others. Therefore, we need to develop fracture models to predict the distribution of faults and fractures and the associated zones or streaks of higher and lower porosity and permeability (Figure 16&17). Fig. 16 shows formation resistivity image data with a zone of higher secondary porosity (vugs, leached features, fractures) representing sweet spots in a tight carbonate reservoir. The porosity analysis derived from the resistivity tool data is based on the conversion of high-resolution (0.2 in.) resistivity curves around the borehole into high-resolution porosity curves. With external control of log porosity and shallow resistivity, an azimuthal porosity histogram with the average and secondary porosity distribution is provided at closely spaced levels by image log analysis to address the zones and streaks of higher secondary porosity and cementation (Akbar, et al., 2001) and permeability (Russel, et al., 2002). Figure 17 shows a modified fracture model of a folded structure with continuous and discontinuous fractures, shear bands, jogs, and horsetail fractures to illustrate the possible distribution and occurrence of fractures in carbonate reservoirs. The model emphasizes field studies of fracture distribution with integrated surface and subsurface geological and geophysical data to recognize sweet spots for hydrocarbon resource management in Kohat/Potwar plateau. Finally, Figure 18 represents a flow chart (Antonellini and Mollema, 2000), as a guide for fracture modeling (Bourbiaux, 2003). Thus, field-wise analysis of fractures can serve as a basis for hydrocarbon exploration in Northern Pakistan.

## CONCLUSIONS

A descriptive classification of fractures for subsurface fracture analysis is presented. This classification attempts to recognize the impact of systematic and unsystematic sets of fracture on production and may be used as a basis for geometrical and genetic classification of fractures.



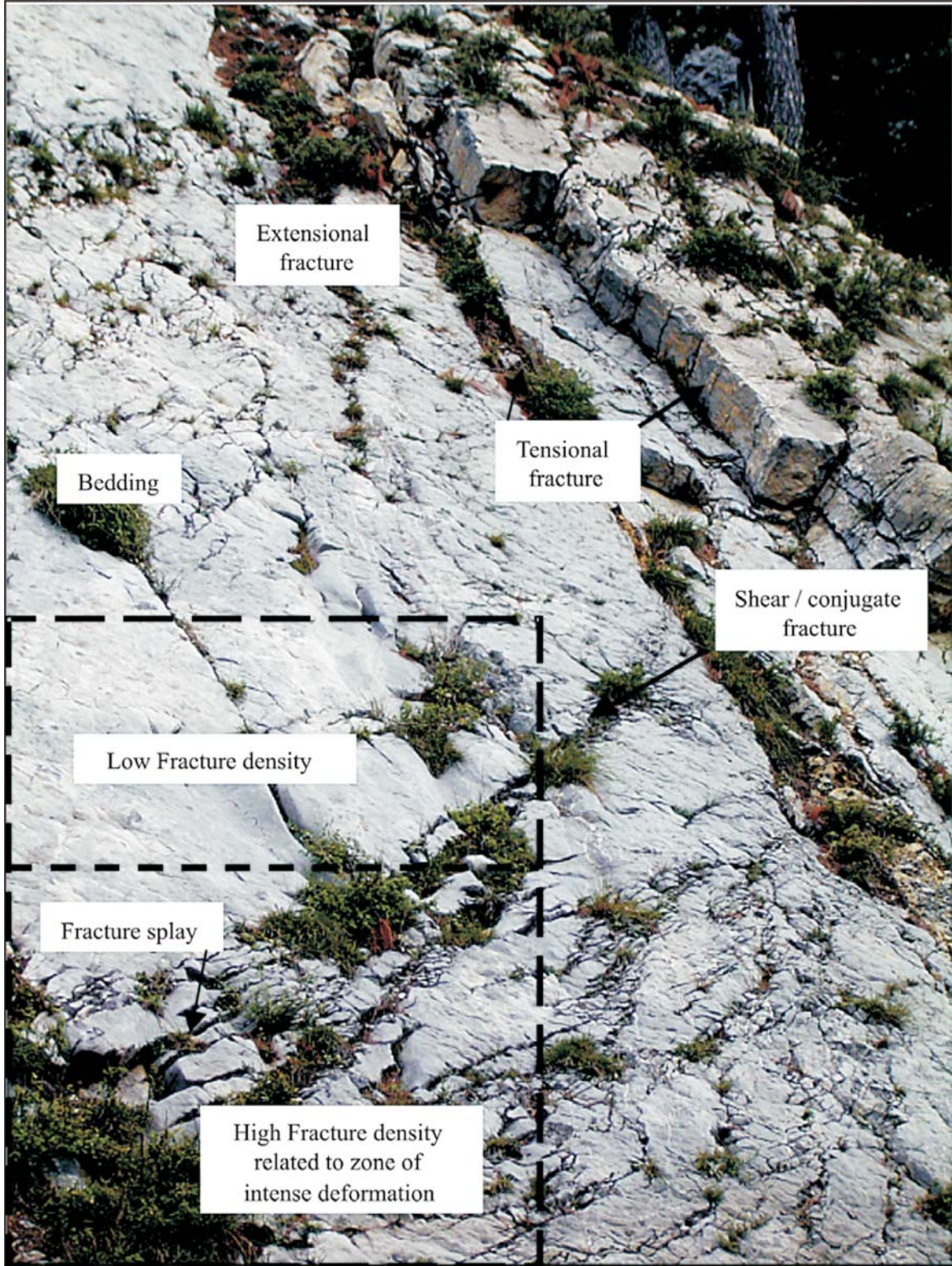


Figure 15 - Outcrop example of tensional, extensional,, and shear fractures with zones of excessive fracturing in tight carbonate strata, North Pakistan.



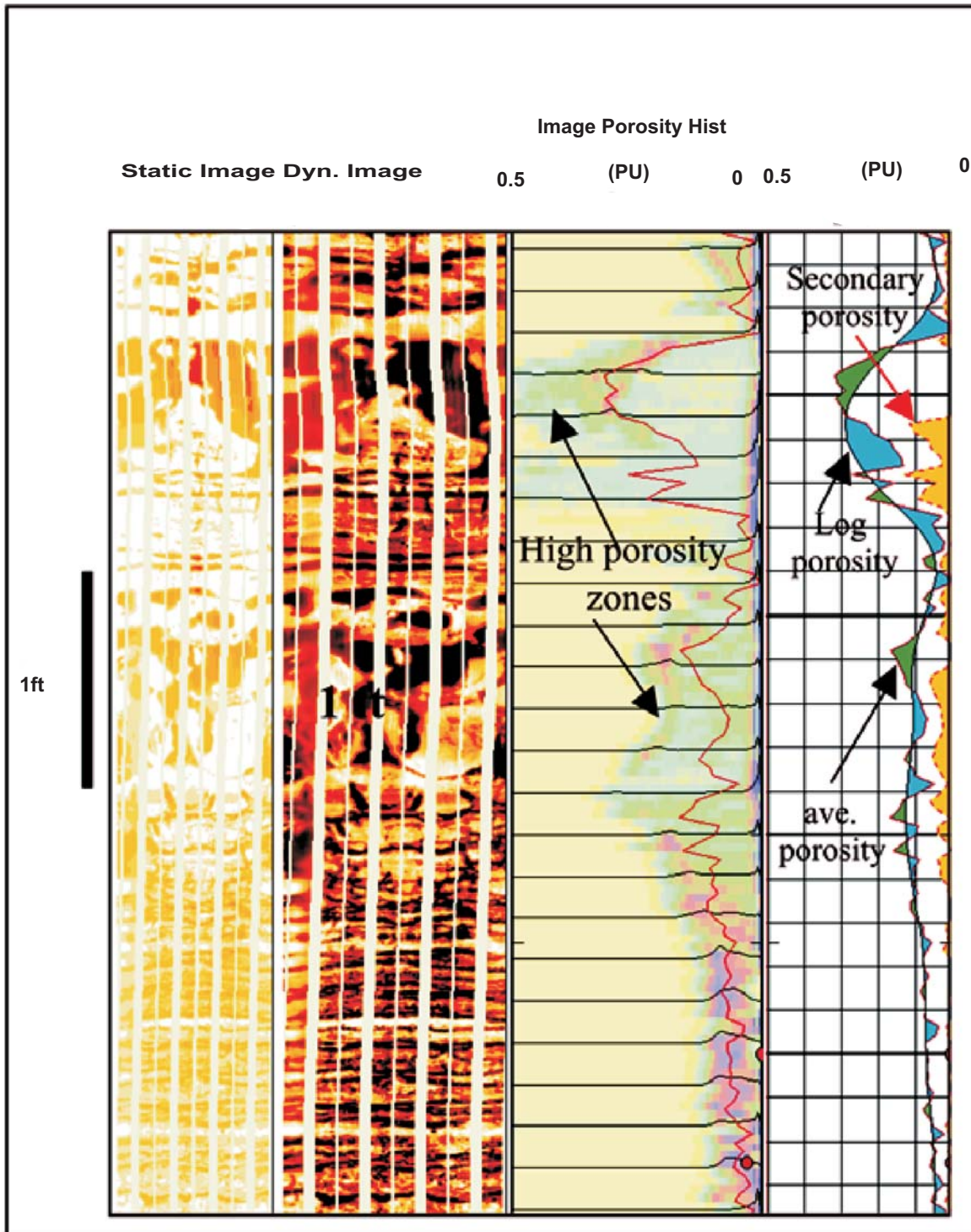


Figure 16- Porosity analysis based on high-resolution image logs to detect zones of higher secondary porosity in tight carbonate reservoirs (Sakesar limestone) from the Himalayan foredeep (Punjab Platform) in Pakistan.



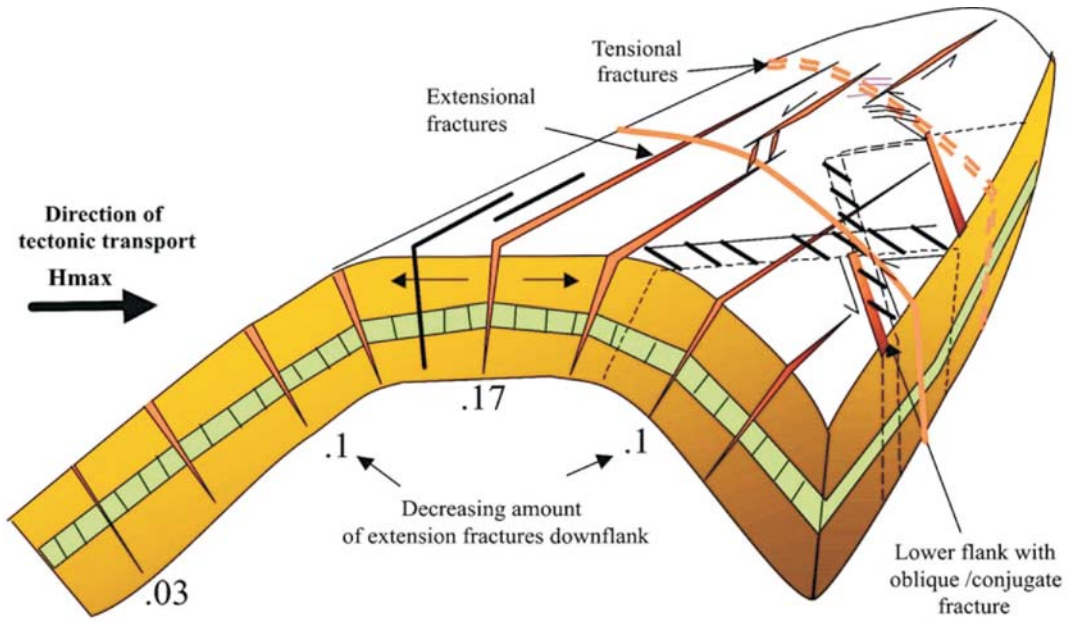


Figure 17 - Conceptual model of fractures in folded strata. Model attempts to revise classical interpretation of fractures (Nelson, 1979 and Stearns, 1968) with addition of continuous/discontinuous fractures, and fracture swarms as shear bands and horse-tail fractures, in zones of excessive deformation and porosity for hydrocarbon exploration in tight carbonate reservoirs.

## Workflow for Fracture Analysis in Carbonate Reservoirs

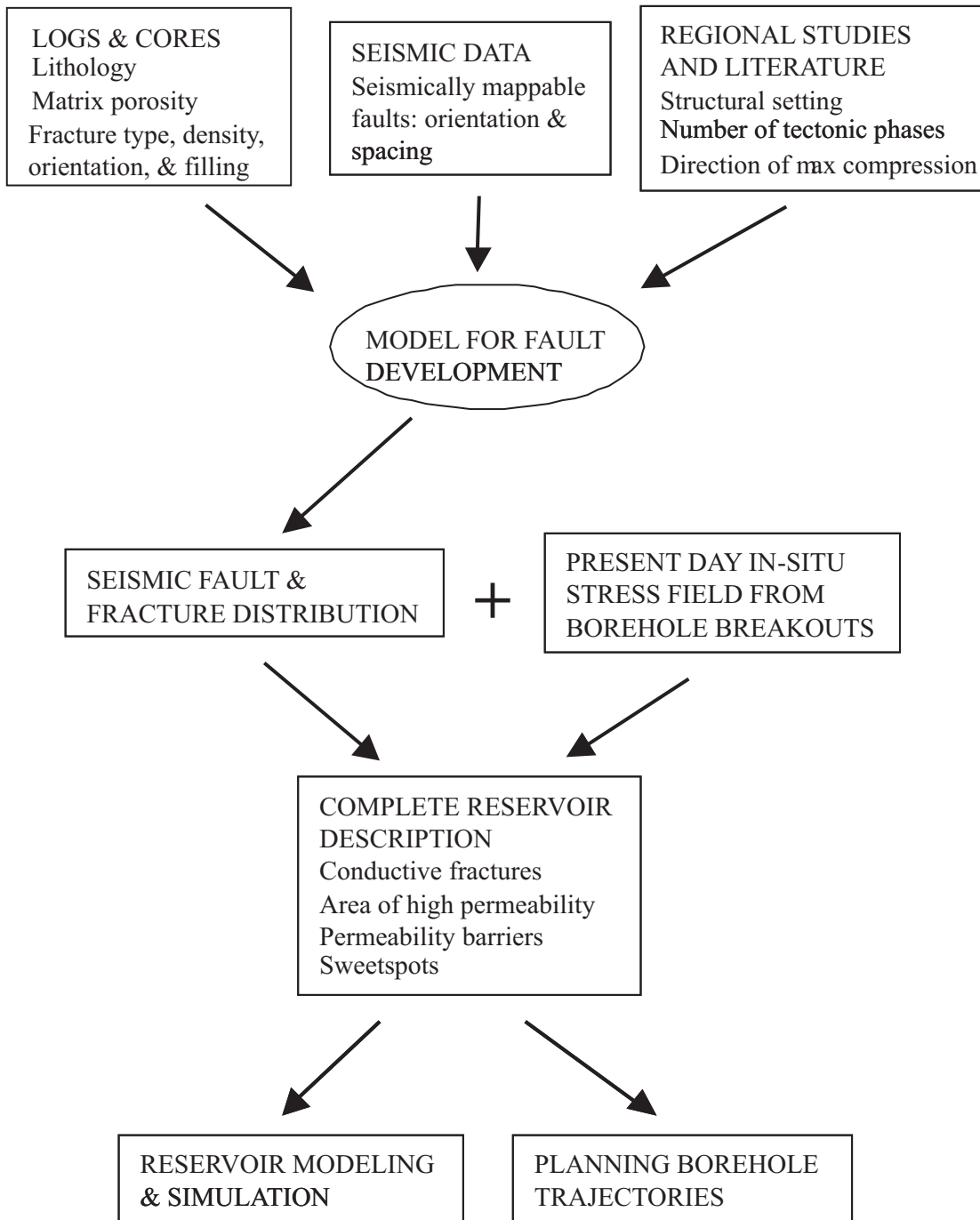


Figure 18 - Fracture analysis for field studies (Antonellini and Mollema, 2000).



Case histories from Northern Pakistan document production from longitudinal (extensional), transverse, (tensional) and chicken-wire fractures. Longitudinal fractures develop due to bending of layers and die out at depth. They are observed to mostly produce from carbonate reservoirs in Northern Pakistan. Transverse fractures are generally more uniformly distributed and are important for fluid flow. They extend deeper in the subsurface reservoir and may connect an oil zone with the water zone.

Hydrocarbon discoveries have been made in tight carbonate reservoirs both in the Kohat and Potwar plateau. Nonetheless, uncertainties related to fractures and locating new wells remain. Our analysis of fractures documents their occurrence as continuous and discontinuous features, as steps (jogs), and en echelon shear bands of excessive porosity. They grow in size with increasing strain and interact with each other to create zones of abundant fractures, porosity, and permeability. The porosity of the breccia, elsewhere, in faults of 1- to 10-m offset is reported to be fairly high, up to 10%, similar to what is seen in outcrop data from Northern Pakistan. Whereas, low porosity (<1%) of the breccia in faults of 10- to 200-m offset has been reported (Antonellini and Mollema, 2000). This implies that excessive strain along faults may cause an increase or a decrease in porosity and permeability. Thus, zones of variable strain and porosity are required to be identified by a fracture model for reservoir characterization and to locate sweet spots in tight carbonate reservoirs.

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