CATACLASTIC SLIP BANDS IN POROUS SEDIMENTARY ROCKS IN BARMER BASIN, RAJASTHAN

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
of

INTEGRATED MASTER OF TECHNOLOGY
in
GEOLOGICAL TECHNOLOGY

By

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CERTIFICATE

I hereby solemnly declare the work presented in this dissertation, entitled ***"Cataclastic Slip Bands in Porous Sedimentary Rocks in Barmer Basin, Rajasthan"*** *in partial fulfilment of the requirements for the award of the degree of* ***'Integrated Master of Technology'*** *in* ***Geological Technology*** *submitted to the* ***Department of Earth Sciences, Indian Institute of Technology Roorkee,*** *is an authentic record of my own work carried out during the period August 2011 to June 2012, under the supervision of* ***Professor D. K. Mukhopadhyay,*** *Department of Earth Sciences, I.I.T. Roorkee,* ***Professor Stuart Burley,*** *Head- Geosciences, Cairn India Ltd. and* ***Dr. Premanand Mishra,*** *Chief Geologist, Jubilant Oil and Gas Pvt. Ltd.*

The matter embodied in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

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CANDIDATE'S DECLARATION

I, **Nivita Sehgal**, a student of Integrated M. Tech. Geological Technology, hereby solemnly declare that the dissertation entitled **"Cataclastic Slip Bands in Porous Sedimentary Rocks in Barmer Basin, Rajasthan"** being submitted by me towards partial fulfillment of the requirements for the award of **Integrated M. Tech. Geological Technology Degree** is a record of my own work and that I have not copied the work of any other person(s) including published literature and material from any web site. Where ever the work of other person(s) has been used, it has been duly acknowledged and quoted with proper reference to the original work.

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Abstract

Deformation bands are commonly thin tabular zones of crushed or reorganized grains that form in highly porous rocks and sediments. Unlike a fault, typically the slip is negligible in deformation bands. In this dissertation the field characteristics, microstructure of deformation bands (reported for the first time in any sedimentary basin in India) from Barmer-Jaisalmer Basin, Rajasthan have been investigated through structural mapping, statistical analysis of collected data and microscopy. The microscopic studies have been conducted by preparation of vacuum impregnated thin sections, which highlights the pore spaces in blue to show the difference between the petrophysical properties of band and host rock. The microscopic studies have helped in identification of the types of bands found in the area and the mechanism by which they have developed. Also porosity calculations of the host rocks in which these deformation bands develop have been done using software called JMicroVision, designed especially to analyze high definition images of rocks in thin sections. The overall study establishes the importance of these bands in reservoir management and the need to understand their spatial distribution and abundance in the study area.

Contents

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Chapter 1: Introduction

Strain in low-porosity rocks within the top few kilometres of the crust usually gets concentrated in narrow zones of variable width. This can lead to the formation of fractures with zero width, e.g., extensional fractures (joints) or shear fractures (faults), or tabular deformation zones with finite width, such as ductile shear zones, shear bands or mylonite zones. Strain localization in sedimentary rocks, such as sandstones or unconsolidated sediments, with a porosity of about 10–15% or higher may behave differently and the strain may manifest through the development of deformation structures commonly known as Deformation Bands (DB) (e.g., Aydin, 1978; Fossen *et al.*, 2007, Fossen, 2010). They are also called Cataclastic Slip Bands (CSB, Fowles and Burley, 1994) or slipped deformation bands (Rotevatn *et al.*, 2008). They can be classified based on the mechanism by which they form or the kinematics they follow. Deformation bands affect porosity and thus fluid flow in sedimentary rocks (Antonellini and Aydin, 1995, Antonellini *et al.*, 1994). Consequently, they are important for hydrocarbon or ground water exploration. In this dissertation we report the occurrence of these bands (for the first time from any sedimentary basin in India) in the hydrocarbon-bearing Barmer-Jaisalmer Basin in Rajasthan.

1.1 Deformation Bands

Deformation bands are tabular, thin (mm to cm wide), low displacement primary structures, which form at the onset of strain localization into narrow zones of localized compaction, shear or dilation in highly porous deformed sedimentary rocks. They are distinct from deformation structures like extension and shear fractures formed in low porosity rocks.

There are many reasons why deformation bands should be distinguished from these ordinary fractures. Firstly these bands are thicker than the ordinary fractures and also exhibit small shear displacements. That is why they are called tabular structures as opposed to sharp discontinuities for fractures. Secondly cohesion is lost or reduced across regular fractures whereas most deformation bands either maintain or increase cohesion. Thirdly most regular fractures show increased permeability in low permeable or impermeable rocks, whereas deformation bands represent low permeability structures in otherwise highly permeable rocks. This distinction is very important when considering fluid flow in reservoir rocks. Lastly, deformation bands are associated with strain hardening whereas fractures are associated with strain softening.

This difference in the type of structures formed in porous and non-porous rocks is due to the fact that porous rocks have sufficient pore volume for reorganization of grains. Porous rocks have sufficient space for grain movement by rolling or frictional sliding. Even if grains are crushed the fragments formed can be reorganized into the available pore space. This leads to the formation of special class of structures called deformation bands.

1.2 Characteristics of Deformation Bands

Some of the important characteristic features of deformation bands include the following (Fossen *et al.* 2007, 2010): (1) Deformation bands are restricted to highly porous granular media, most commonly porous sandstones. (2) Formation of deformation bands involves grain rotation, frictional sliding or cataclastic flow and, therefore, requires a significant amount of porosity. (3) They occur hierarchically as single structures, complex linked systems (zones), zones associated with slip surface (faulted deformation band) and faults with larger offset (> 1 m). Thus they are precursors to faults and are also termed as small faults owing to the smaller offsets across them. (4) They are common within fault damage zones and near the fault tips.

According to the evolutionary model first suggested by Aydin and Johnson (1978), deformation-band zones are precursors to faults in porous sandstone. A consequence of this fault model is the formation of a zone of deformation bands in front of, as well as around, the fault-slip surface. Hence, any fault in porous sandstone will have a deformation-band damage zone, provided that the porosity of the sandstone is not too low for deformation bands to form. Deformation bands are commonly associated with local pore space collapse (compaction bands) although simple shear bands or even dilational deformation bands do exist. Their growth from single structures to swarms of bands is generally attributed to strain hardening associated with pore collapse and cataclasis (Aydin 1978).

1.3 Types of Deformation Bands

Deformation bands can be classified in a kinematic framework or based on the mechanisms being operative during their formation. The kinematic based classification has three end members: simple shear bands, pure compaction bands and pure dilation bands (Fig. 1.1). The mixed mode includes dilational shear bands and compactional shear bands, *i.e.*, shear with volume increase and decrease, respectively. Formation of dilational and compactional bands, with or without shear, leads to growth and collapse of pore spaces, respectively (Fig. 1.1). The dilational and compactional bands may be grouped together as volumetric deformation bands.

1.3.1 Volumetric Deformation Bands

Deformation bands that lack evidence of macroscopic shear offset form predominantly by volumetric deformation and are therefore called volumetric deformation bands. Volume change, expressed in terms of porosity change, may be either positive (dilation) or negative (compaction).

1.3.1.1 ***Compaction deformation bands:*** Compaction bands are characterized by volume decrease with respect to the undeformed parent rock. They are associated with compaction of grains through grain reorganization or cataclasis (Fig. 1.2).

The porosity may decrease from about 20% or more in the undeformed rocks to about 5% or less within the deformation bands. Since no shear is involved, compaction bands are equivalent to anti mode-I cracks, a mechanism that leads to the formation of stylolites.

1.3.1.2 ***Dilation deformation bands:*** Dilation bands are deformation bands characterized by porosity increase with respect to the undeformed state and no macroscopic shear offset (Fig. 1.3). Such deformation bands have been reported from many locations but the shearing component along these bands or the lack thereof is unclear in many cases. Du Bernard *et al.* (2002) have described dilation bands in which shear offset has been unambiguously ruled out.

1.3.2 Shear Deformation Bands

Bands predominated by shearing are referred to as shear deformation bands. The diagnostic feature of shear bands is a macroscopic shear offset across a tabular zone of finite but small width with respect to the other two dimensions. Shear offset can be determined by previously continuous markers such as beds or older shear bands. Shear bands in granular rocks have limited offsets on the order of a few millimetres to centimetres.

Although a majority of shear bands reported in the literature are associated with grain size reduction resulting from grain fracturing, the process of grain fracturing is not a pre-requisite for shear band formation. Although rare, shear bands without any significant volumetric component of deformation also occur for the same range of porosity values of corresponding parent rocks within the accuracy of the measurements. This type of shear bands are referred to as 'isochoric' shear bands representing the type of deformation known as 'simple shear' in geological literature.

Most shear bands however, undergo volumetric deformation in addition to shearing (Aydin, 1978; Antonellini and Aydin, 1994, Aydin *et al.,* 2006, Aydin and Johnson, 1983). These mixed mode bands, regardless of the relative magnitude of shear and volumetric components of deformation, are referred to as 'compactive shear bands' or 'dilatant shear bands'. Compactive and dilatant shear bands are characterized predominantly by shearing but are also associated with volume decrease or increase, respectively.

1.4 Mechanisms of Deformation

Deformation mechanisms for the formation of deformation bands depend on internal and external conditions such as mineralogy, grain size, shape, sorting, cementation, porosity and state of stress. Different mechanisms produce bands with variable textural change resulting in variation in petrophysical properties. The dominant deformation mechanisms are granular flow, phyllosilicate smearing, cataclastic flow and dissolution/cementation (Fig. 1.4; Fossen *et al.,* 2007).

1.4.1 *Disaggregation bands:* Disaggregation of grains through rotation, sliding and breaking of cementing material gives rise to disaggregation deformation bands (Fig. 1.4a). This process of grain disaggregation is called *granular or particulate flow.* Little or no cataclasis (grain crushing) is involved. Factors that favour formation of disaggregation bands include poorly consolidated host rock as friction between the grains in unconsolidated rocks is significantly less than that of consolidated rocks and shallow burial depth and/or excess fluid pressure, because at shallow burial depths the stress generated across the grain contacts is generally not high enough for cataclasis. Disaggregation bands are difficult to recognize in outcrops and their presence is usually indicated by offset of sedimentary lamination.

1.4.2 *Dissolution and cementation bands:* Dissolution and cementation (Fig. 1.4b) along deformation bands usually take place after deformation but they may also be syn-kinematic. The term solution band is used where chemical compaction or pressure solution is significant. Solution bands typically consist of tightly packed grains smaller in size than the matrix, but showing little evidence of cataclasis. Although dissolution of quartz grains becomes prolific at depths greater than 3 km, dissolution is a common feature of deformation bands formed at shallower depths. This suggests that quartz dissolution is promoted by other processes such as, presence of clay minerals on grain boundaries or by fresh and highly reactive surfaces formed during grain crushing and/or grain boundary sliding. Deformation bands may preferentially localize tensile fractures providing easy passage for fluid flow and subsequent precipitation of calcite, anhydrite, salt, hydroxides and quartz.

1.4.3 *Cataclastic deformation bands:* The classic cataclastic deformation bands (Fig. 1.4c) occur when mechanical grain fracturing is a significant deformation mechanism. Such deformation bands occur within a volume of compacted rock as a result of granular flow and are characterized by wide variation in grain-size, grain-size reduction and angular grains, which may lead to extensive grain interlocking promoting strain hardening and distinct reduction in pore space and permeability.

1.4.4 *Phyllosilicate bands:* Phyllosilicate bands (Fig. 1.4d), a type of disaggregation bands, form in sandstone and unconsolidated sand if the content of platy phyllosilicates grains exceeds 10–15%. The platy mineral grains promote frictional grain-boundary sliding as opposed to cataclasis. Permeability reduction of 2-3 orders of magnitude is common. If the phyllosilicate content of rock changes across bedding or lamina interfaces, a deformation band may change from an almost invisible disaggregation band to phyllosilicate band.

1.5 Faults and Deformation Bands

Deformation bands are distinct from fractures such as faults or joints. Faults are characterised by sharp fractures and discontinuous displacement (Fig. 1.6a) whereas deformation bands are tabular with discontinuous displacement (Fig. 1.6b). In outcrops and hand specimens, deformation bands occur as isolated structures (Fig. 1.6c), linked systems, complex zones of multiple, and interconnected deformation bands, (Fig. 1.6 d) zones associated with slip surface (Fig. 1.6e) and in fault damage zones (Figure 1.5). Faults are generally considered to be fractures or surfaces across which there is appreciable relative discontinuous displacement. Deformation bands are small faults with continuous displacements of a few millimetres or centimetres. In some places the small faults or deformation bands are associated with large faults, with several meters of offset. However, in many places there are small faults or groups of small faults (zone of deformation bands) not associated with any large fault. Deformation bands are significant *primary* structures, and they precede the formation of the larger faults. They occur as single deformation band, zones of deformation bands, faulted deformation bands. They appear to play an important role in the generation of larger faults, which may have offsets of several tens of meters. They also occur in damage zones associated with large faults (Fig. 1.5). The complex variation of deformation band geometry in damage zones has the potential to influence fluid flow in a complex manner.

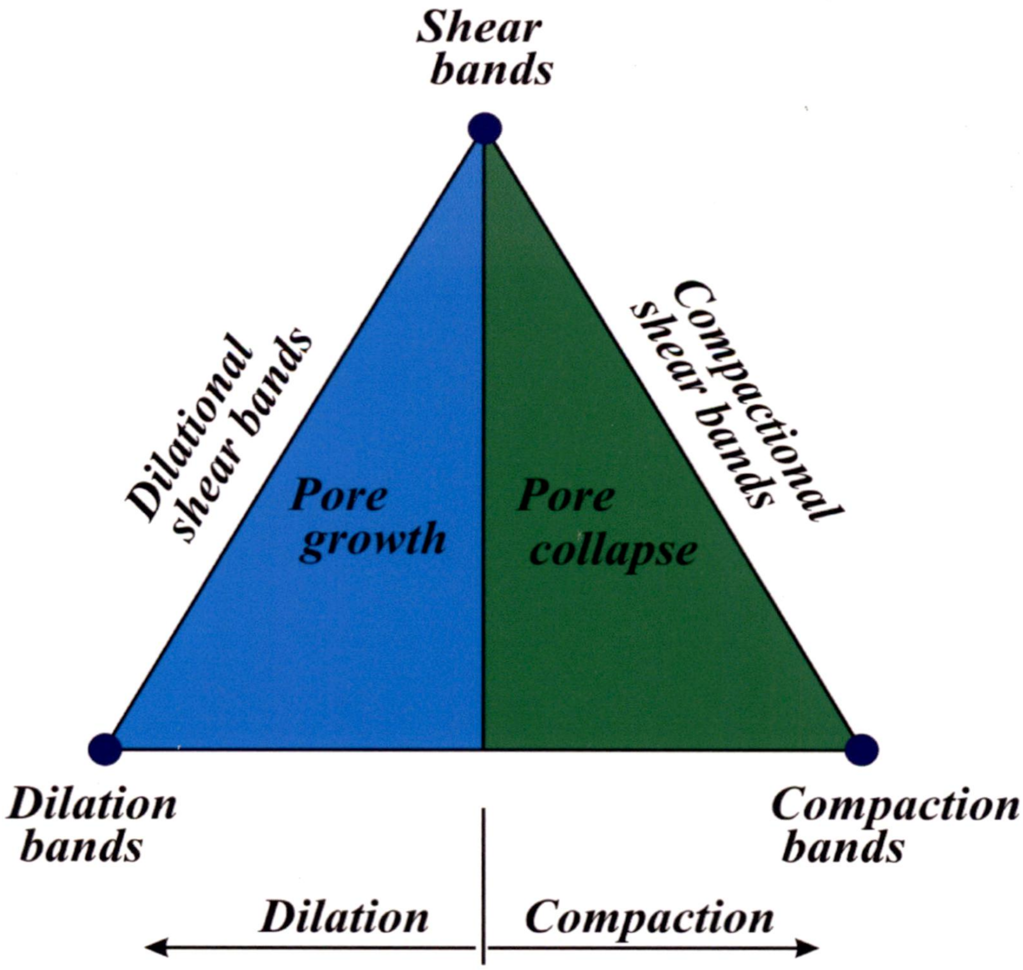


Figure 1.1 Types of deformation bands in porous sediments and sedimentary rocks (after Schultz and Fossen, 2008, Schultz and Siddharthan, 2005).

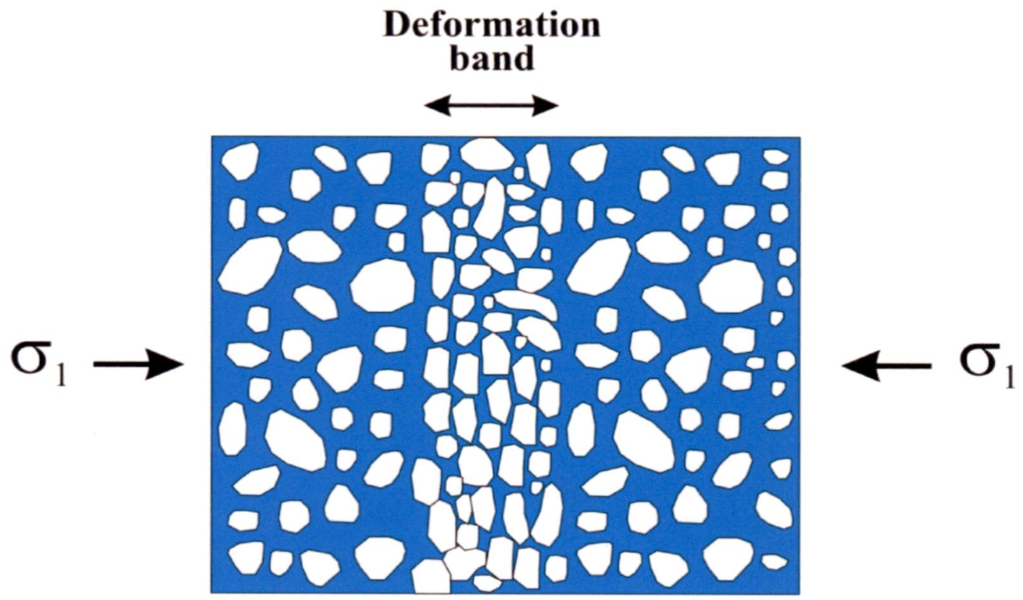


Figure 1.2 Compaction deformation band. Note that the porosity (dark area) in the deformation band has decreased.

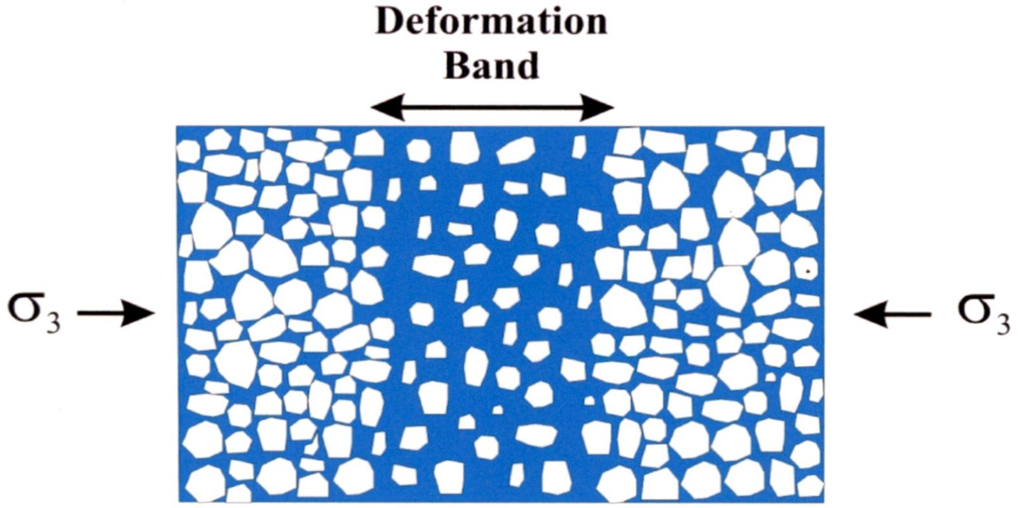


Figure 1.3 Dilation deformation band. Note that the porosity (dark area) in the deformation band has increased.

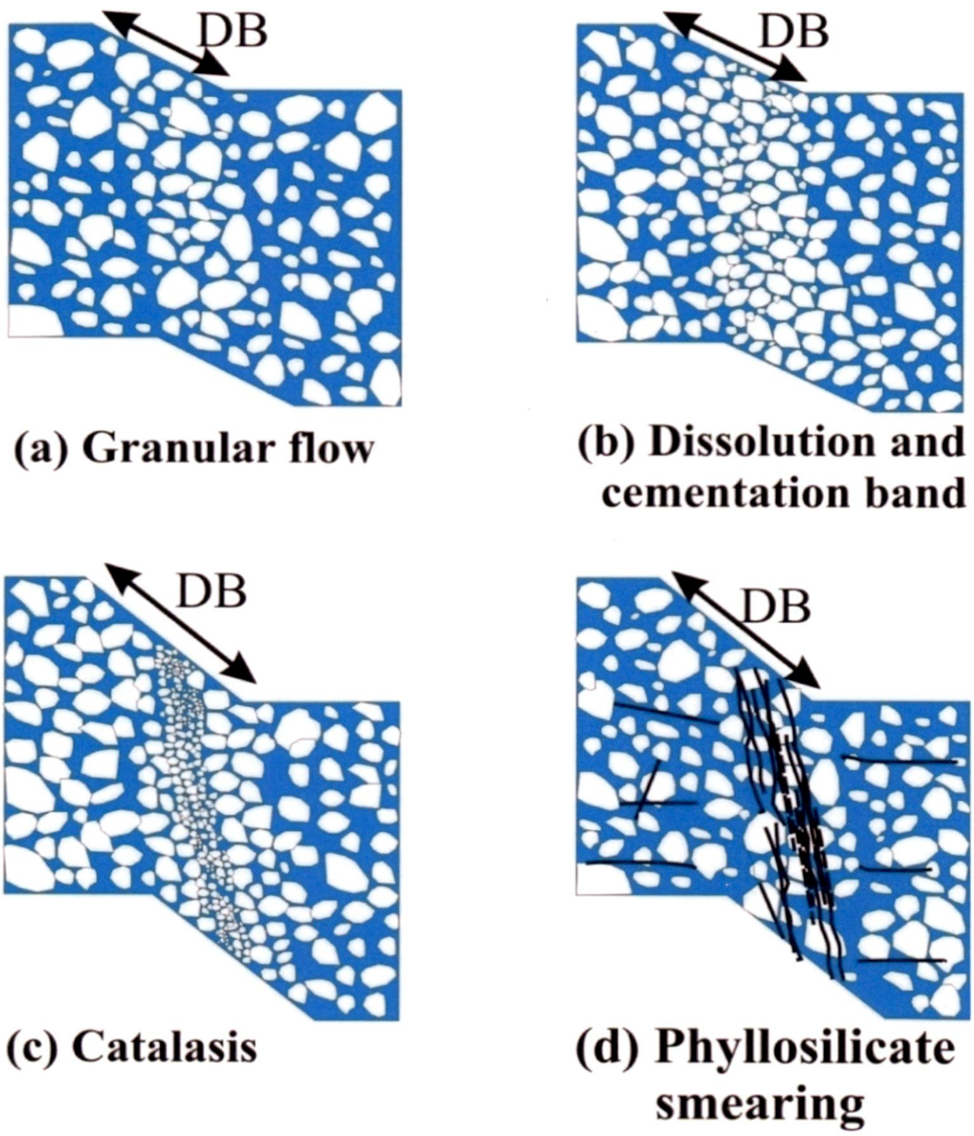


Figure 1.4 Deformation mechanisms for the formation of deformation bands (DB) (after Fossen *et al.* 2007).

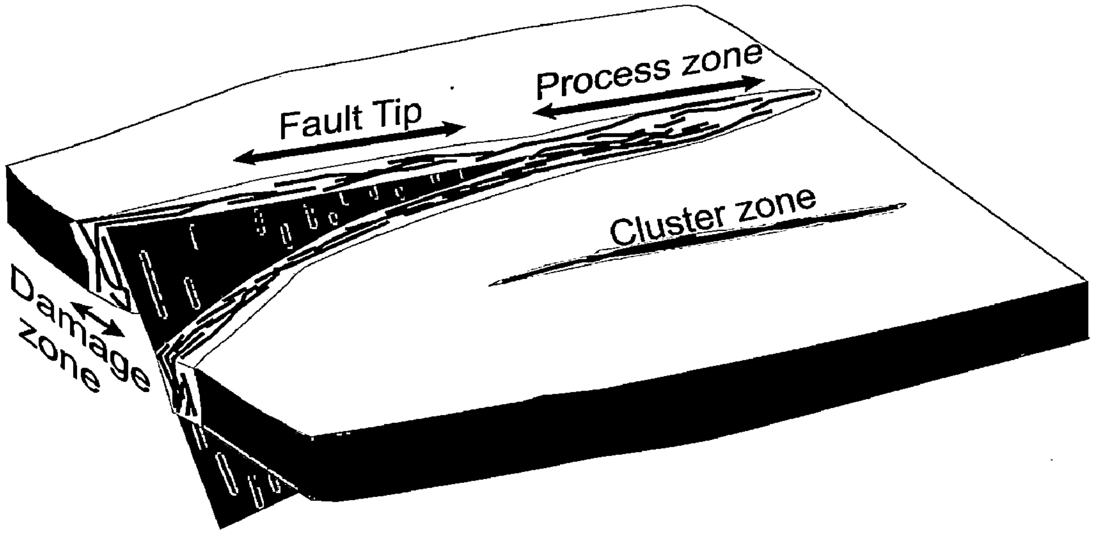


Figure 1.5 Damage zone associated with large faults. Deformation bands occur in the damage zone and fault termination. (after Fossen *et al.* 2007).

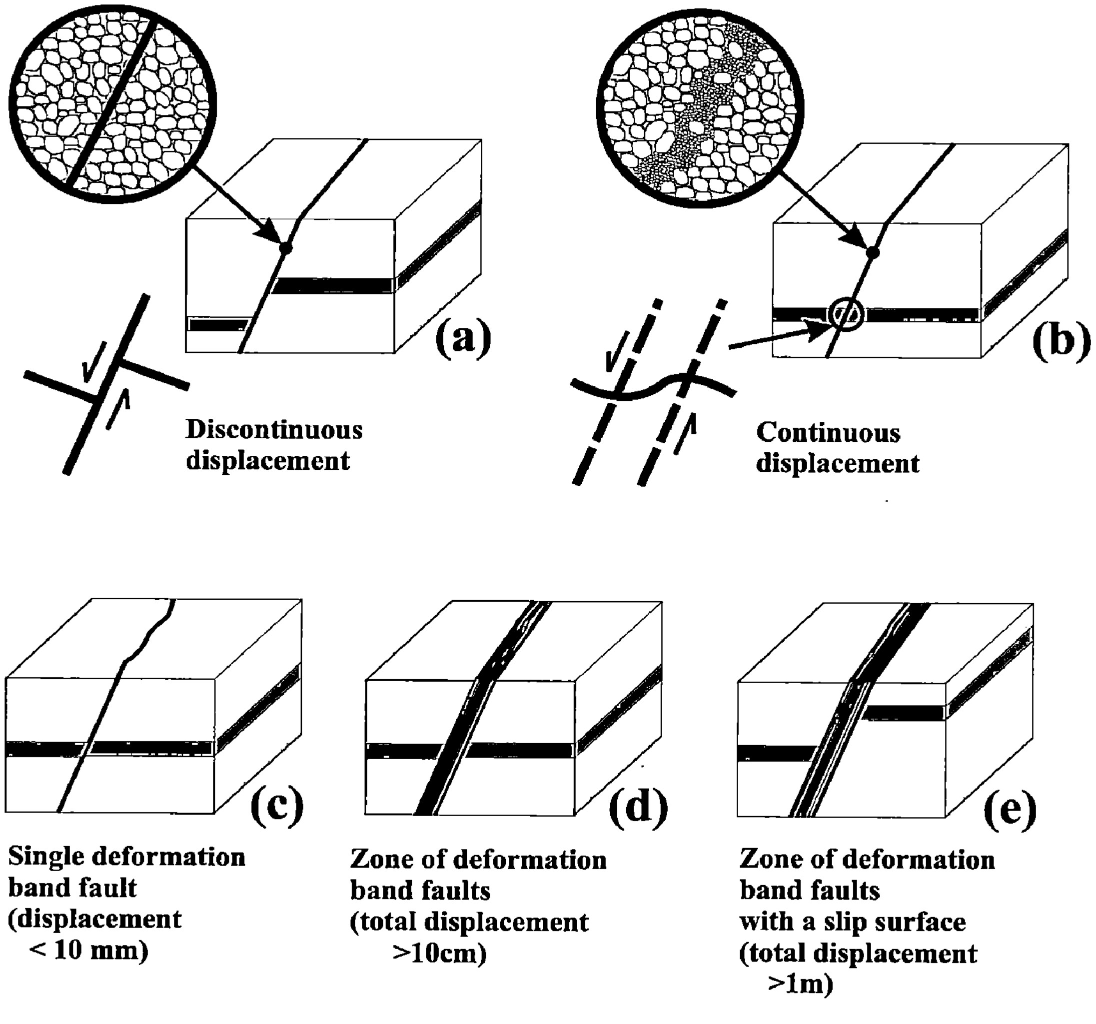


Figure 1.6 Fault and deformation bands (a) Fault with discontinuous displacement. (b) Deformation band with continuous displacement. (c) Single deformation band. (d) Zone of linked deformation bands. (e) Faulted deformation band. (after Draganits *et al.* 2005)

Chapter 2: Geology of the Study Area

The purpose of this study is to understand the formation of deformation bands in the porous sedimentary rocks in **Barmer-Jaisalmer Basin, Rajasthan** (Fig. 2.1). It is one of the three important basins in the western Rajasthan shelf located to the west of Aravalli ranges and the northerly arm of an extensive system of rift basins (Fig. 2.1) that formed along the western side of India during the Late Cretaceous to Early Tertiary. The Barmer Basin is a narrow NNW-SSE rectangular basin with well-defined basin margin faults between Barmer high on the west and the Indian shield in the east. With more than 25 oil and gas discoveries so far, the Barmer Basin is now established as rivalling the adjacent Cambay Basin in significance for hydrocarbon exploitation. Most of the oil reserves are contained within fluvial sands of the Fatehgarh Formation, which probably ranges in age from Cretaceous to Early Paleocene.

Geology of the area

The narrow NNW-SSE trending Barmer Basin is thought have formed due to rifting of continental crust dominated by the rocks of the Late Proterozoic Malani Igneous Suite. The western margin is defined by a NNW-striking basin margin fault, which is very well exposed west of Barmer town. Its southern extension is restricted by a NE-SW trending fault scarp exposed near Sarnu village. A ridge exposing Fatehgarh Formation underlain by Lathi Formation shows its northern limit while its eastern margin is not well exposed. The faults exposed in the west and south at Fatehgarh, Barmer, Sarnu and a Jurassic high in the north, have shaped Barmer basin into the NNW-SSE trending rectangular basin. These faults are the signatures of the break-up of Indian craton in the latest Cretaceous-early Paleocene which led to the formation of the Cambay rift and the constituents basin (Datta, 1983; Sisodia *et al*., 2005; Sisodia and Singh, 2000).

The rifting is a major tectonic disturbance in the geological history of the basin based on which the sediments of the Barmer Basin can be classified into three categories: Pre-rift, Syn-rift, Post- rift. The Pre-rift sediments constitute siliceous Randha Formation, calcareous Birmania Formation; both Lower Palaeozoic in age, Lathi Formation of Liassic age and Sarnu Formation of Cretaceous age. These sediments are deposited on a Late Proterozoic basement of Malani Igneous Suite. The Syn-rift formations include Barmer Formation and Fatehgarh Formation. Barmer Formation comprises poorly cemented sandstones and intraformational conglomerate and represents alluvial fan environment. Fatehgarh Formation is mixed sand, mud and phosphorite formation deposited on an intertidal flat environment. It is highly fossiliferous; the phosphorite in this formation is correlated with global Cretaceous upwelling. The Post-rift sediments were deposited as thickening and coarsening-upward claystone-siltstone-sandstone cycles. They include Akli Formation and Kapurdi Formation. They are of Palaeocene to Eocene age (Bhowmick and Misra, 2010). Overlying Akli and Kapurdi Formations is a grit and gravel bed of Miocene age (Fig. 2.2). The generalized stratigraphy of the Barmer basin is shown in Table 2.1.

Malani Igneous suite - The Malani Igneous suite is the most extensive of the older rocks exposed in the area. It comprises mostly of rhyolite and trachytic flows. The rhyolite vary in colour from dark brown to pink, they are generally massive and usually prophyritic. The rhyolite flows are green to grey in colour with profuse vesicles and cavities. The vesicles are filled with secondary calcite and quartz.

Sarnu Formation – The Sarnu formation has restricted occurrence and does not have wider distribution. It is mapped in isolated hills, which stand out on the peneplained surface. It is dominantly composed of sandstone, which is hard, whitish, silica cemented quartz arenite with occasional quartz pebbles of 2-5 cm diameter. This sandtone unit cyclically grades into fine sandstone to siltstone.

Barmer Hill Formation- The white and grey silicified sandstone exposed as a high ridge west of Barmer town was described as the Barmer Formation (Dasgupta *et al.,* 1988). This formation rests unconformably on Malani Rhyolite Basement. The basal part of the formation comprises of reddish, medium to coarse-grained, lithic quartz sandstone and conglomerate. The upper part of the formation is characterized by the presence of siltstone, sandstone and conglomerate.

Fatehgarh Formation- The exposure of Fatehgarh formation is limited to the Northwestern part of Barmer basin. It overlies the Lathi formation (Jurassic) with an unconformable contact and is overlain by the Mataji-Ka-Dunger Formation. The major part of Fatehgarh formation comprises soft, parallel-laminated, pinkish-white, fine to medium grained sandstone. The sandstone shows textural and mineralogical maturity, the matrix is occasionally calcareous.

Mataji-Ka-Dunger Formation- The lithology is dominantly sandstone, siltstone and claystone. The formation overlies Fatehgarh formation and is exposed along the northern and western margins of the basin. It is interpreted as a shallowing upward fluvio-deltaic complex.

Akli Formation- It comprises bentonitic claystone, grey bituminous claystone and light yellow claystone. It is virtually sand free and occurs in the central part of the basin.

The sandstones of the Fatehgarh Formation are highly porous (porosity > 30%) and extremely permeable (> 10 Darcy) and are the main reservoir rock. The sandstones of the

Lathi Formation are also highly porous. The deformations bands are well developed in these porous sandstones in the area lying between Barmer and Jaisalmer towns, which includes the northern part of the Barmer Basin and the Jaisalmer Basin.

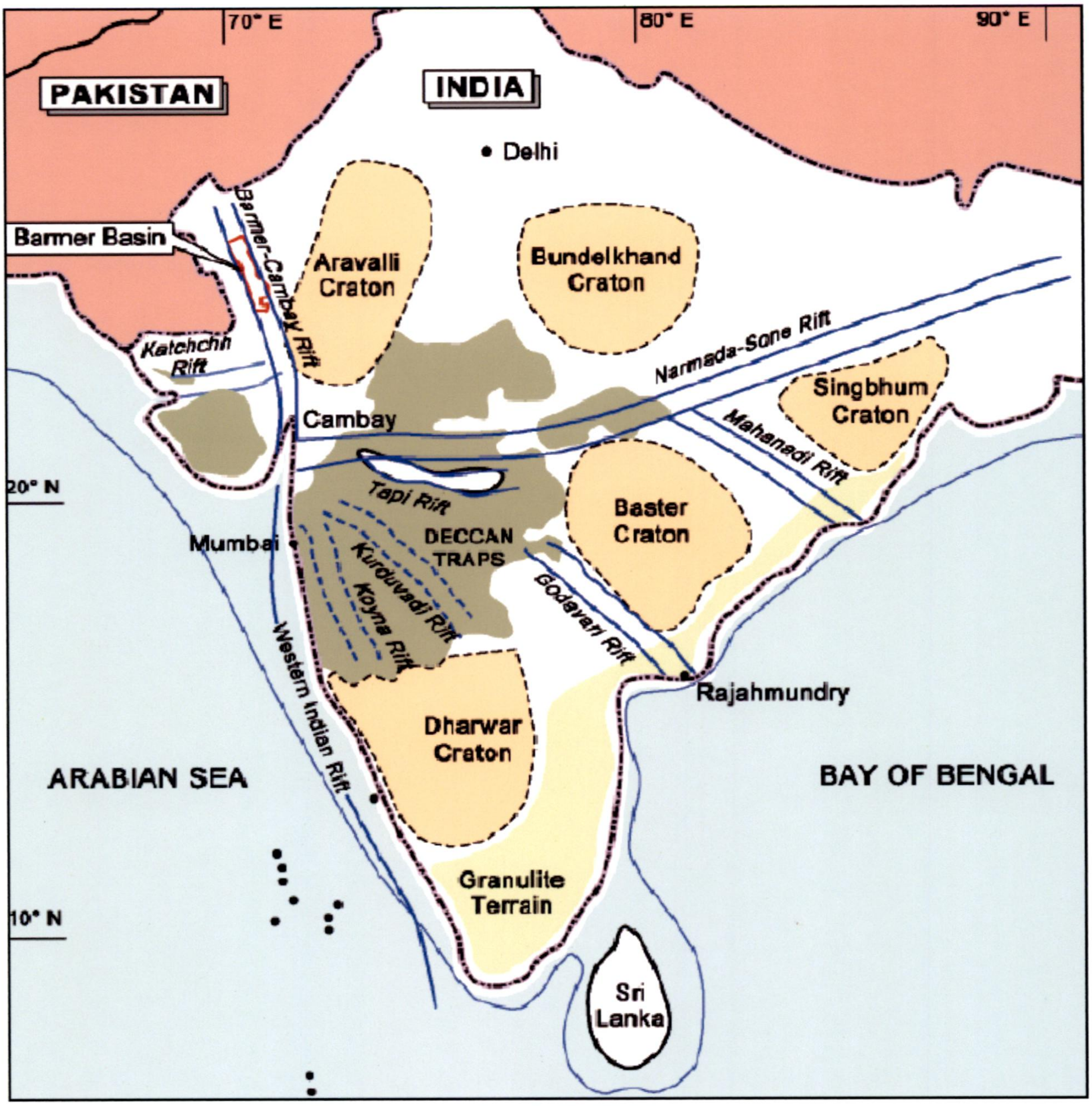


Figure 2.1 Structural map of India. (from Compton, 2009)

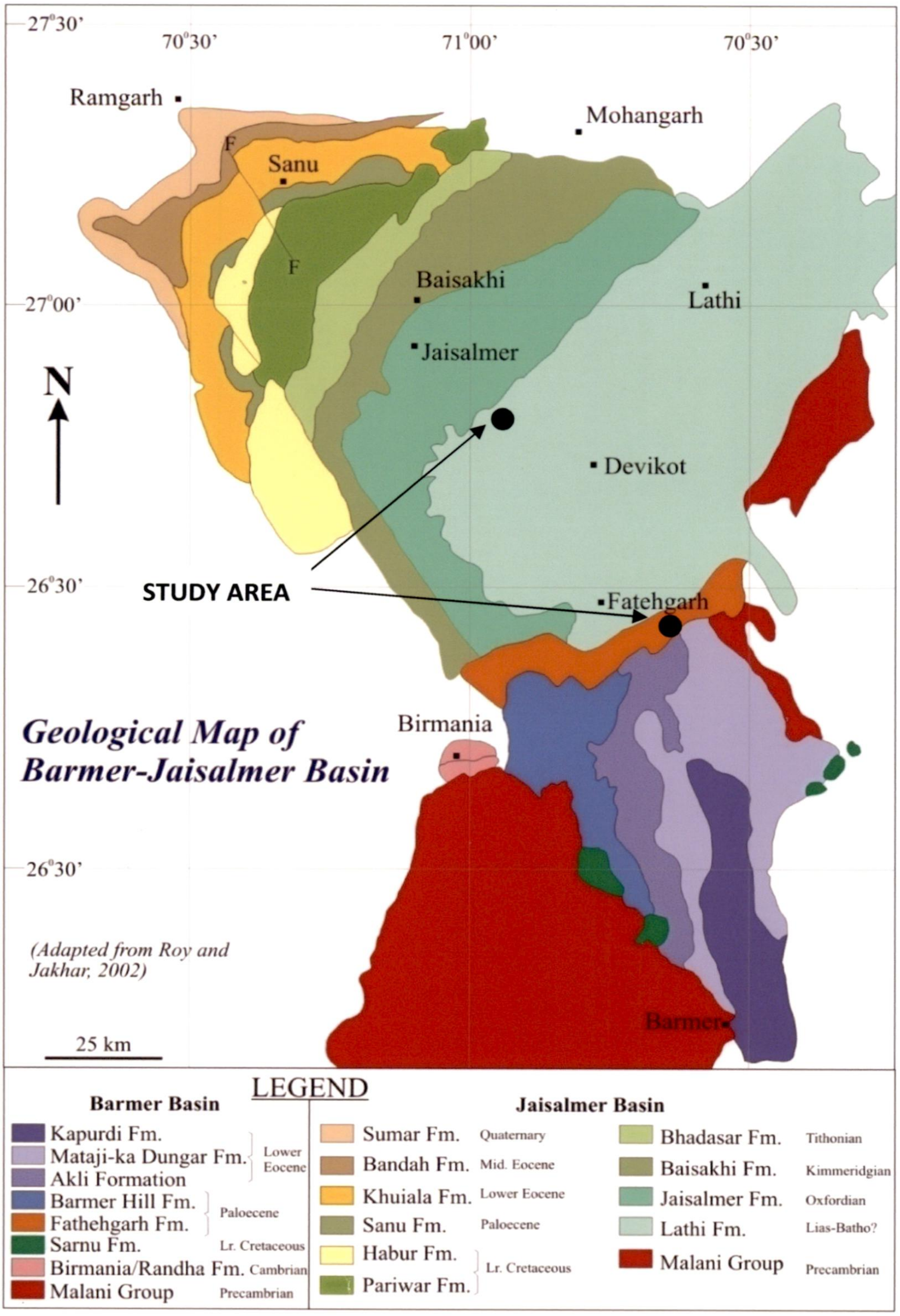


Figure 2.2 Geological Map of Barmer-Jaisalmer Basin.

Table 2.1 Generalised Stratigraphy of the Barmer Basin. (Das Gupta, 1974)

Age	Formation	Facies and gross lithology
Recent	Dune sand and sediments	Alluvium sands, river alluvium and gravel wash
Sub-Recent and (?) older	Uttarlai Formation (3-4m)	Thin gypseous limestone and salt sequence, with unconsolidated sand and gravel beds
		Unconformity
Lower Eocene	Kapurdi Formation (30)	Lacustrine Fuller's Earth deposits (?) interbedded with marine bioclastic limestone
	Mataji- ka Dungar Formation (180)	Shallow marine orthoquartzite and hard sandtone with pisolites and ball clay and impure bentonitic clay bands at the base
		Unconformity
	Akli Formation (280 m) Akli Bentonite Member Thumbli Member	Volcanogenic bentonite sequence at the top and sandstone lignite sequence in the basal part.
		Unconformity
	Barmer Formation (80 m) Madai Member Barmer Hill Member	Shallow marine sandstone with rare plant fossils and orthoquartzite bands grading into conglomerate, sandstone with plant fossils and volcanogenic clays
Paleocene	Fatehgarh Formation (520 m) Fatehgarh scarp Member Vinjori Member	Sandstone layer with mixed bivalve and gastropods casts at the top, Dominantly of ochreous clay bands, variegated sandy siltstone and sandstone sequence with coquina beds.
		Unconformity
	Volcanic Formation (?)	Acid to basic volcanic rocks mainly in forms of sills and dykes and local intrusive porphyrites
		Intrusive contact
Cretaceous	Sarnu Formation (80 m)	Indurated, terrestrial sandstone and siltstone with plant fossils
		Unconformity
Callovo-Oxfordian	Jaisalmer Formation (15 m)	Marine, fossiliferous, arenaceous limestone
Bathonian to Lias	Lathi Formation (?)	Terrestrial arenaceous sequence with wood fossils and fossilferous tree trunks
		Unconformity
Precambrian	Malani Suite of Igneous Rocks	Rhyolite and granite

Chapter 3: Field Characteristics of Cataclastic Slip Bands

Cataclastic Slip Bands or deformation bands in Rajasthan are most abundant in the sandstones of the Fatehgarh and Lathi Formations which are fairly well exposed in the northern part of the Barmer Basin. The area lies between Barmer and Jaisalmer towns which include the northern part of the Barmer Basin and the southern part of the Jaisalmer Basin.

3.1 Cataclastic Slip Bands in the porous Lathi sandstones

CSB's in the study area occur as thin elongate isolated bands (Fig. 3.1) or as a zone of upstanding ridges crosscutting each other at varying angles (Fig. 3.2). At some places perpendicular sets of bands have also been observed. Thickness varies from a few mm to few cm for individual isolated CSB to a few meter for zones of deformation bands (Fig. 3.3). The strike length varies from tens of cm to tens of meters (Fig. 3.2, Fig. 3.4). They also occur in complex linked systems defining a zone whose width may exceed one meter (Fig. 3.5). Within a zone of deformation bands, there are many preserved undeformed pods (Fig. 3.3). These bands occur in parallel sets (Fig. 3.6) and three such sets- N-S, NW-SE and NE-SW (Fig. 3.7) have been recognized based on statistical analysis of orientation data (Fig. 3.8 a,b,c) using StereoStat. Cross-cutting sets may enclose rectangular (Fig. 3.6), rhombic or triangular (Fig. 3.7) areas where original textures of the sandstones are preserved. At places, two parallel deformation bands are linked by oblique thinner bands giving the appearance of *pseudo* S-C Fabric (Fig. 3.9) or duplex structure (Fig. 3.10). A great majority of deformation bands are vertical to very steeply dipping (Fig. 3.4). All the deformation bands in these figures are seen on horizontal outcrop surface. Deformation bands in general do not show any offset. Only at a few instances strike-slip displacement of earlier formed deformation bands have been observed (Fig. 3.11, 3.12, 3.16). The general lack of offset in outcrop scale can be attributed to the fact that deformation bands are sub-vertical and bedding plane are sub-horizontal (Fig. 3.13) and the slip is strike-slip type. The strike-slip sense of displacement is contradictory to the supposedly rift setting for the Barmer Basin. Mapping of the deformation bands (DB) and variation in density of deformation bands within unit area (Fig. 3.28, Fig. 3.29) suggest that the deformation bands in the Barmer Basin are not necessarily related to particular faults but developed in response to the overall stress field (Mukhopadhyay *et* al. 2012).

As mentioned earlier, sandstones in this area are highly porous. The host rocks, though highly porous, do not show evidence of significant dissolution and precipitation. The catacalstic flow and cementation increase cohesion of the rocks in the deformation band. Parallel sets of deformation band zones are observed at many places forming a conjugate pair (Fig. 3.14). At some places a N-S deformation band set is seen offsetting a NE-SW deformation band set (Fig 3.15). While at some places the N-S DB set is being offset by the NW-SE DB set (Fig. 3.11), at other places, the N-S DB set also offsets the NW-SE DB set (Fig 3.12). Oblique deformation bands are also observed at the intersection of two major sets of deformation band (Fig. 3.17). Within a zone of deformation band, many parallel oblique deformation bands bounded by two sub-parallel DB set (striking N-S) were observed (Fig. 3.18).

Also within a zone, pseudo S-C like fabrics (as mentioned earlier) along with small sinistrally offset DB's were observed (Fig 3.19 a, b, c). At some places it was seen that two DBs parallel for some distance curve into one another but do not join (Fig. 3.20). Undeformed host rock was seen preserved between two deformation bands (Fig. 3.21) and at some places a fracture was observed between two bands (Fig. 3.22).

3.2 Cataclastic Slip Bands in Fatehgarh sandstones

Deformation bands in Fatehgarh sandstones occur as thin isolated single bands as well as zones of deformation bands. Here however the width of the zones is very less (few cm) compared to the meter wide zones seen in Lathi sandstones (Fig. 3.23). The deformation bands stand up as resistant ridges because of the late calcareous cementing material infilling them and is easily recognized under pocket lens. Its presence is also confirmed by reacting these bands to dilute acid. Statistical analysis of orientation data shows that there are two major perpendicular sets of deformation bands in the area as shown in Fig. 3.24. The NE-SW and NW-SE band sets are both steeply dipping Fig 3.25 (a, b). The bedding in the area has a moderate dip striking N 250^0 (Fig 3.25 c). Fig 3.26 shows the NW-SE deformation band set in the area. Fig 3.27 shows thin deformation band cross-cutting each other at low angles.

3.3 Mapping of Cataclastic Slip Bands

Mapping of CSB's was done for two areas in the Lathi sandstones where they were present extensively. Area 1 as shown in Map 1 (Figure 3.28) is 10 m x 20 m in extent and Area 2 as shown in Map 2 (Figure 3.29) is 15 m x 20 m in extent. Both the areas mapped were adjacent to each other in Wood Fossil Park. In both the maps the CSB's are shown in blue and red symbol indicating their strike and dip. From both the maps it is evident that there are three dominant sets of deformation bands in the Lathi sandstones, N-S, NE-SW, NW-SE. It can also be seen that the density of these bands is high in the study area and their development is not related to any particular fault but have developed in response to an overall stress field, which makes them even more important because they may be present in a wide area. Also in Map 1 we can see a 20 m long zone of CSB which is varying in width from a few centimetres to more than a meter at places. Also the whole map shows a set of parallel N-S striking band linked by a complex network of cross-cutting NE-SW and NW-SE bands. Area 1 is more densely populated as compared to Area 2. The lengths of these bands as seen on the outcrop varied from less than a meter to more than 20 meters. Most of the bands in the area dip steeply while the bedding plane is sub-horizontal. That is why we do not observe the bedding plane being offset by these bands. Only at some places we note the offset of a set of CSB by another set.

Most of these bands have continuous lengths except for a few which are discontinuous and are shown by dotted blue lines in both the maps.

Figure 3.1 Thin elongate isolated bands in porous sandstones.

Figure 3.2 Looking East. Compass pointing towards North. Two sets of deformation bands striking N 14^0 and N 314^0.

Figure 3.3 RHS of scale points towards North. Looking vertically down. Preserved undeformed pod in a zone of deformation band. Each DB is approximately 1-2 mm thick in a zone that is approximately 20cm thick. Note coarse grained sandstone between DBs.

Figure 3.4 Looking N 335^0. Two sets of DB. DB to the right strikes approximately North and DB to the left strikes approximately N 300^0, both steeping dipping.

Figure 3.5 Complex linked system of zone of deformation bands.

Figure 3.6 Two orthogonal sets of deformation bands giving rectangular zones of undeformed areas.

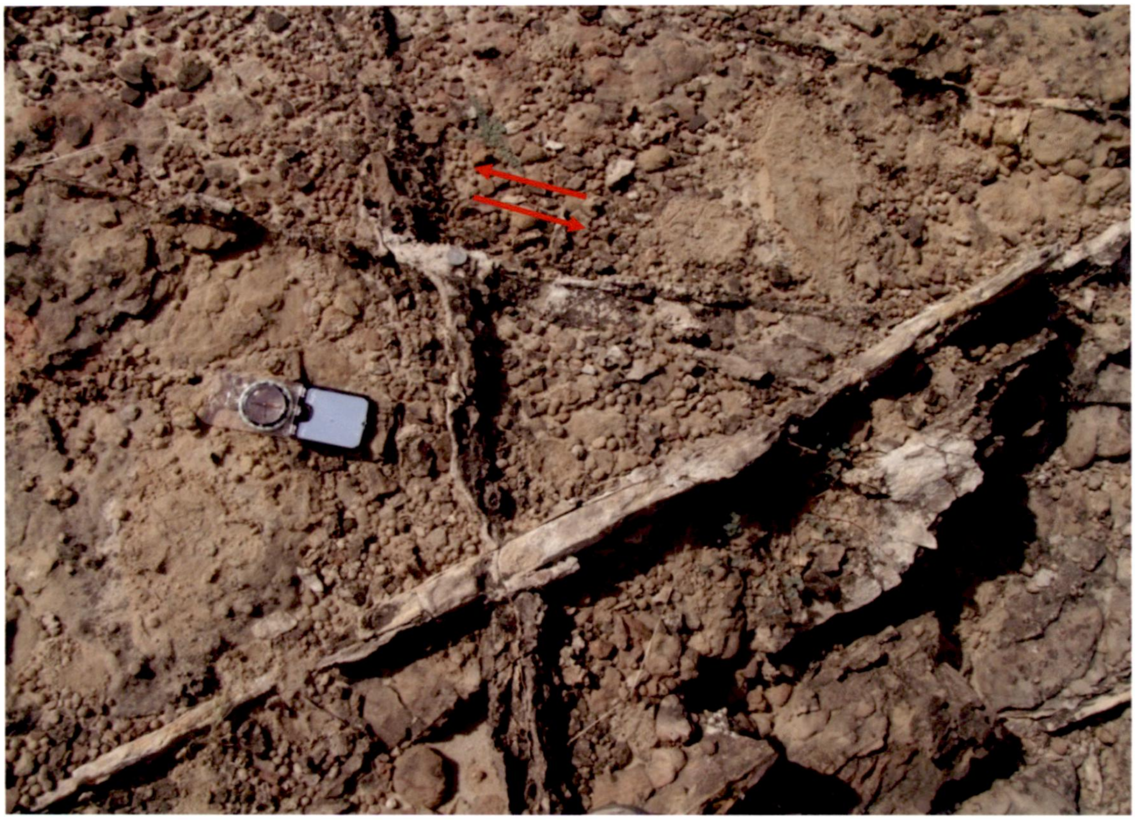


Figure 3.7 Three sets of deformation bands. Offset can be seen in the upper left part of the photograph. Note that the deformation bands stand up against eroded porous sandstones due to increased cohesion. N 66^0 striking DB shows sinistral offset along N-S DB (near coin).

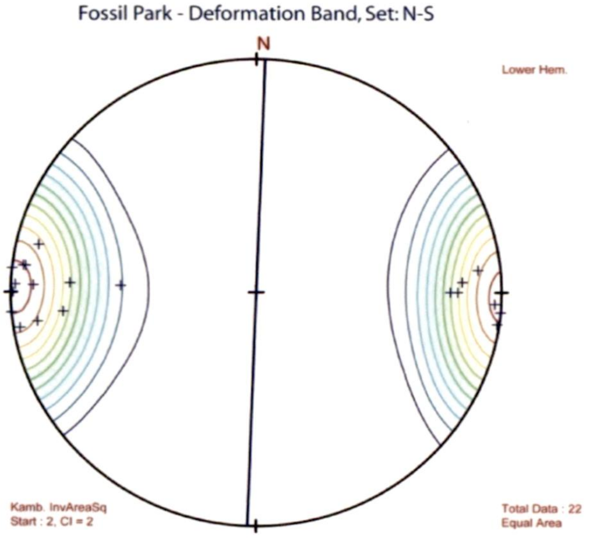


Fig 3.8 a

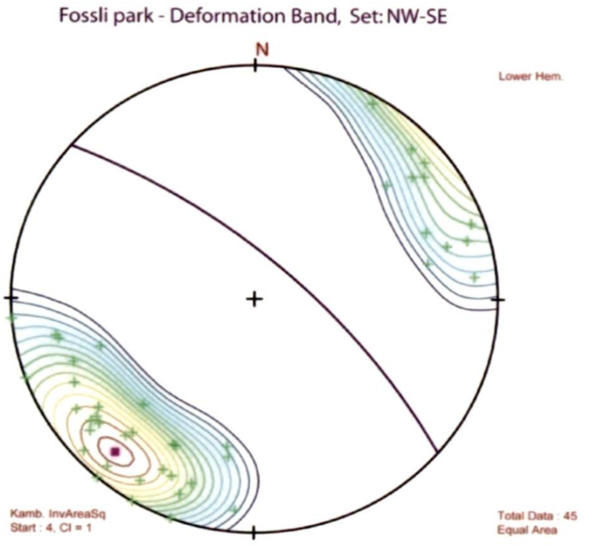


Fig 3.8 b

Figure 3.8 (a) Stereographic projection of N-S CSB in Lathi sandstones. Total data-22 (b) Stereographic projection of NW-SE CSB in Lathi sandstones. Total data-45 (c) Stereographic projection of NE-SW CSB in Lathi sandstones.

Red dot shows maximum.

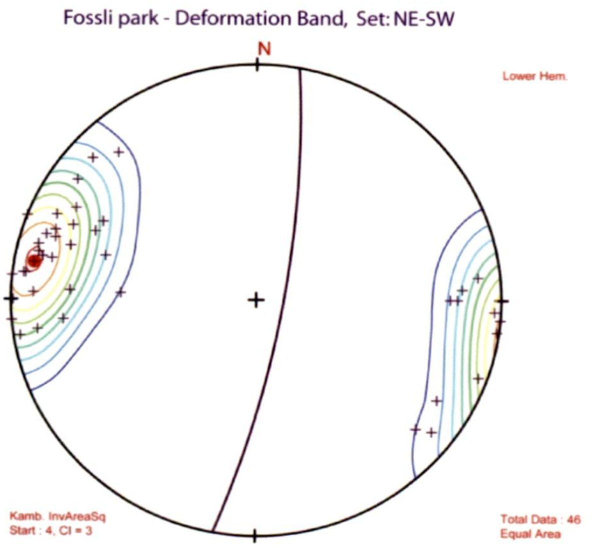


Fig 3.8 c

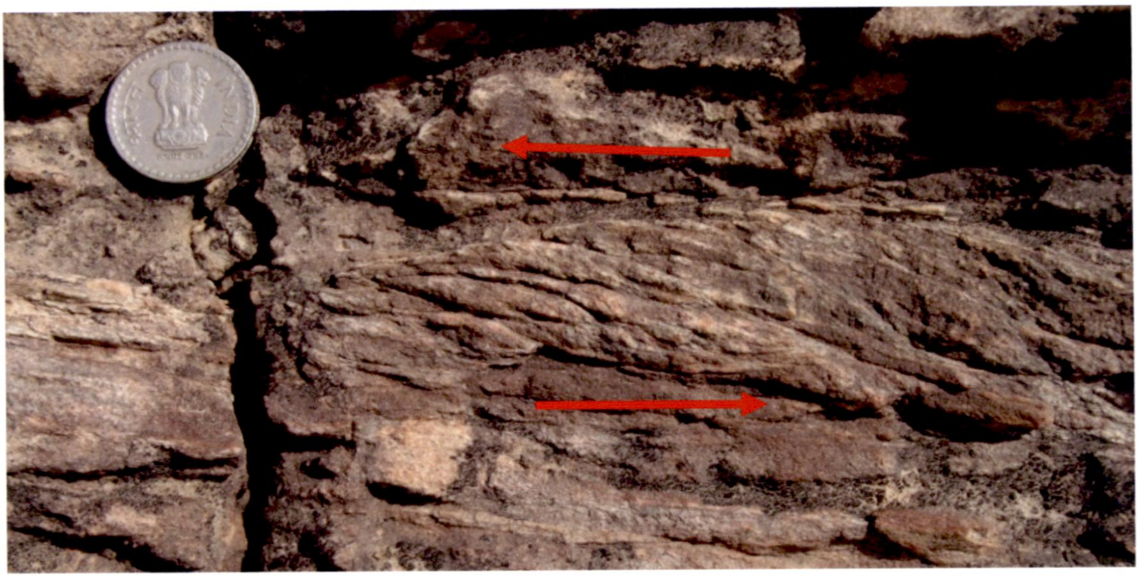


Figure 3.9 Pseudo S-C like fabric within a zone of deformation band.

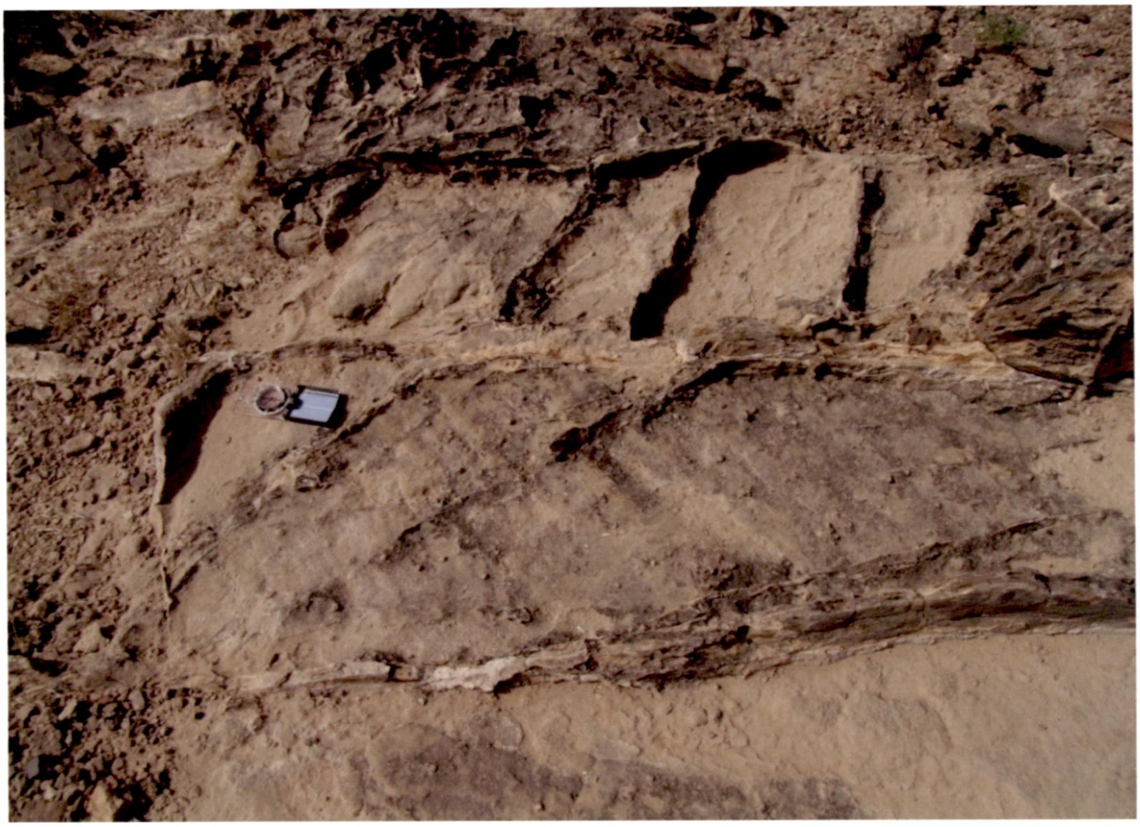


Figure 3.10 Compass pointing North. Approximately N-S striking DBs are cross linked by N-W striking DBs. Note variable orientation of NW DBs. The angle between two sets of DBs varies approximately between 10^0 to 80^0.

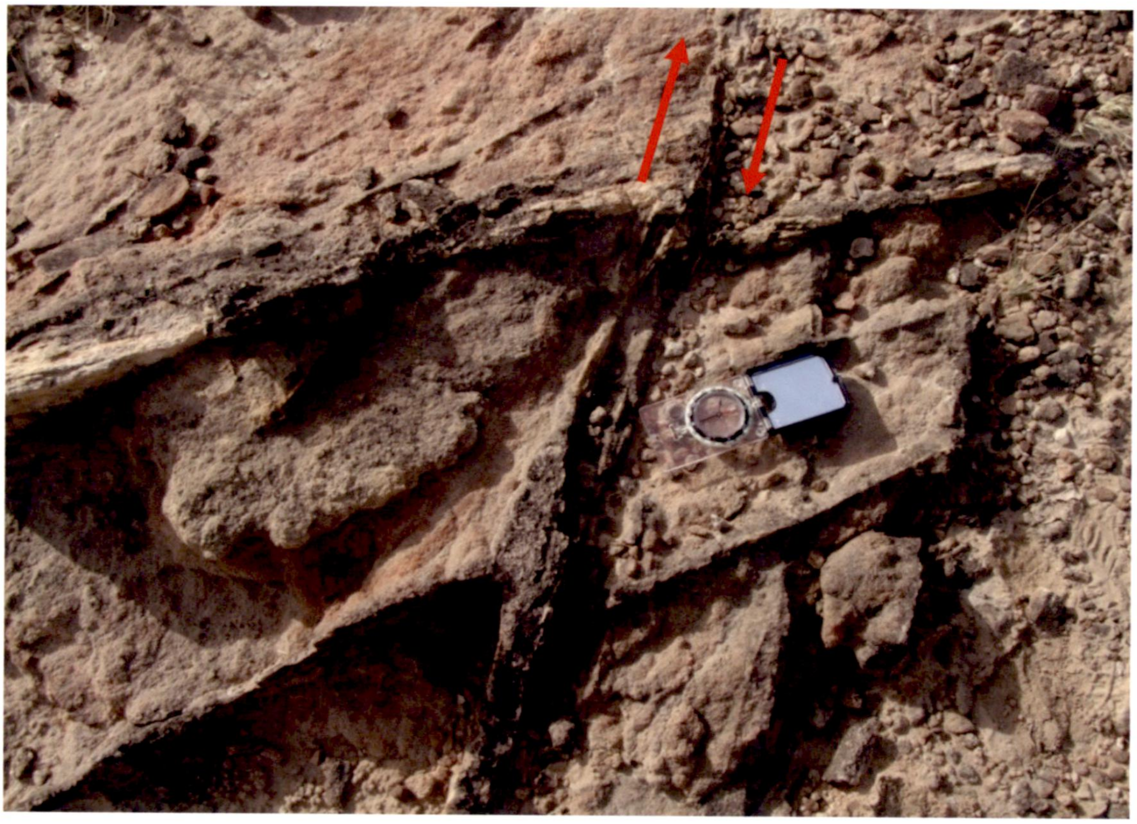


Figure 3.11 Looking vertically down. N-S striking DB is dextrally offset by N-W striking DB.

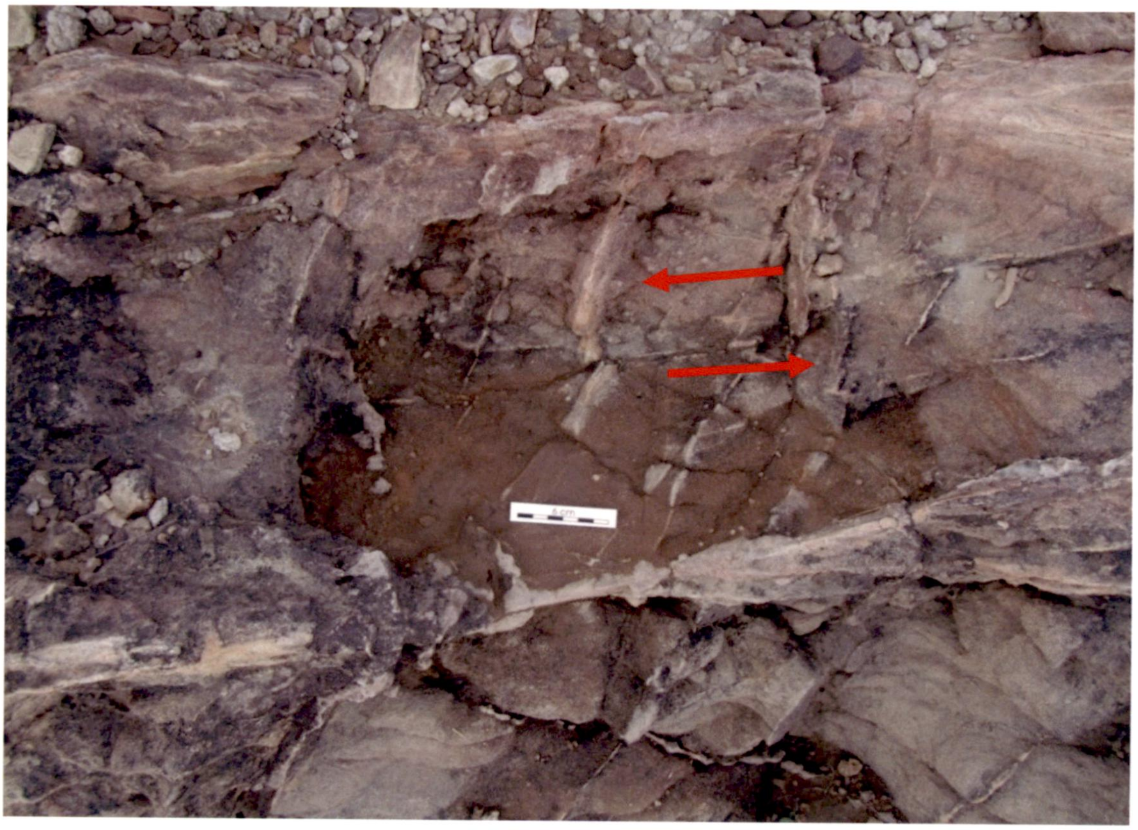


Figure 3.12 RHS of scale points towards North. N-W striking deformation bands within anastomosing N-S striking deformation bands. N-W striking deformation band are sinistrally offset by N-S striking deformation bands.

Figure 3.13 Looking N 340^0. Hammer head points E. DBs (North and North West) is relation to bedding surface (near pencil).

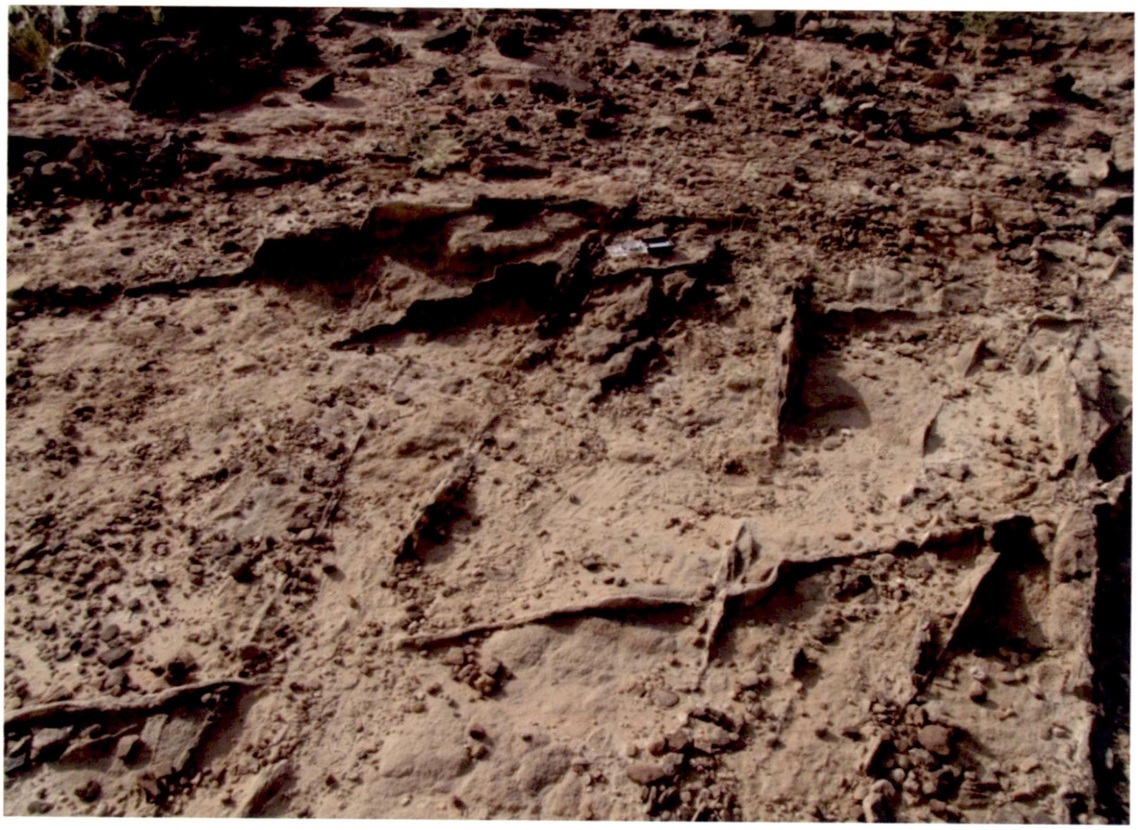


Figure 3.14 Looking N 280^0. Compass pointing north. Two sets make a conjugate pair.

Figure 3.15 Looking vertically down. RHS of scale points towards North. N-S DB sinistrally offsetting N 68^0 striking deformation band. Note a slight drag effect at the offset zone.

Figure 3.16 Vertically down. LHS of scale points towards east. Dextral offset along NW DB.

Figure 3.17 Looking vertically down. LHS of scale points towards East. Oblique DB at the intersection of two major DBs.

Figure 3.18 LHS of scale points towards North: A set of oblique DBs bound by two sub parallel or N-S trending DBs in zone of DBs.

Figure 3.21 Some DBs seems to be composed of two DBs with thin undeformed sandstone occupying the space between them.

Figure 3.22 Thin fracture observed is mm to cm scale between two DB's.

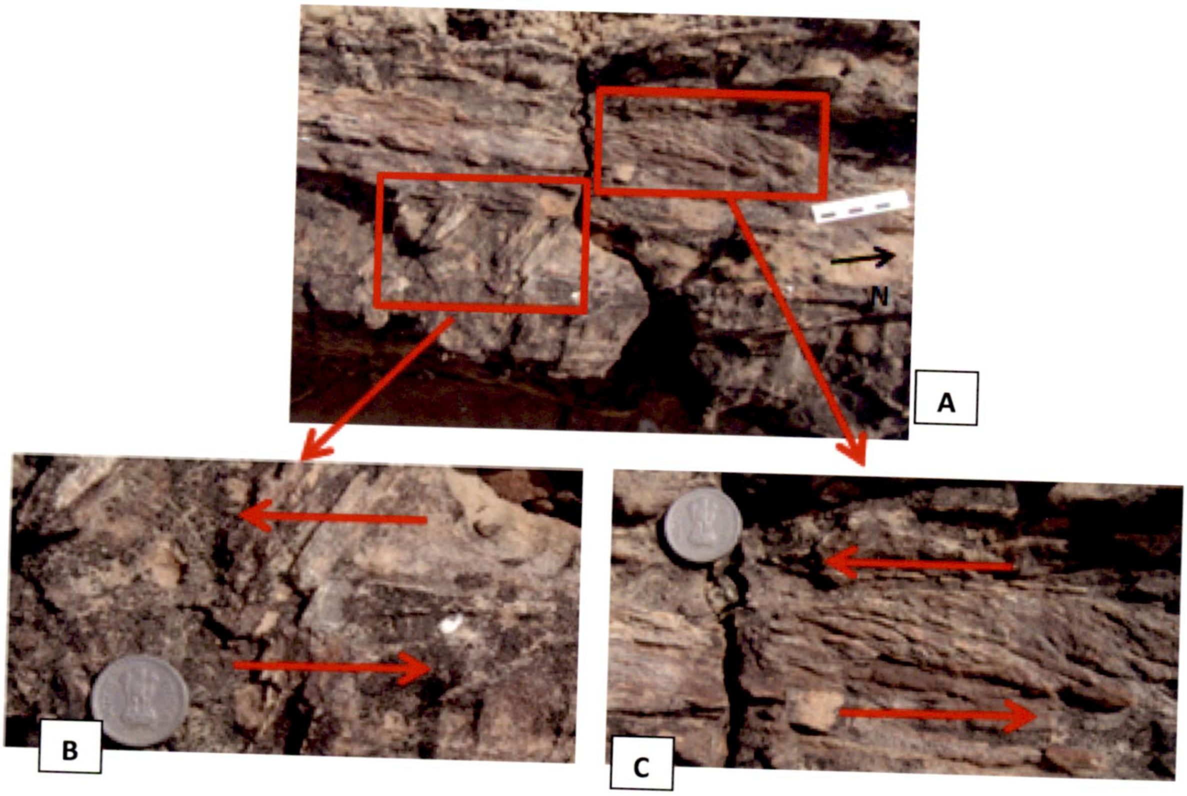


Figure 3.19 (a) A wide zone of DB (striking N-S) showing pseudo S-C like fabric (c) and sinistral offset of small DB (b).

Figure 3.20 LHS of scale points towards N. Looking vertically down. Two DBs parallel for some distance and then one curve into the other but do not join.

Figure 3.23 Shows thin zones of deformation band in Fatehgarh sandstone. Looking vertically down. LHS of scale points towards N 250^0.

Figure 3.24 LHS parallel to scale N 270^0: Two sets of nearly perpendicular deformation bands.

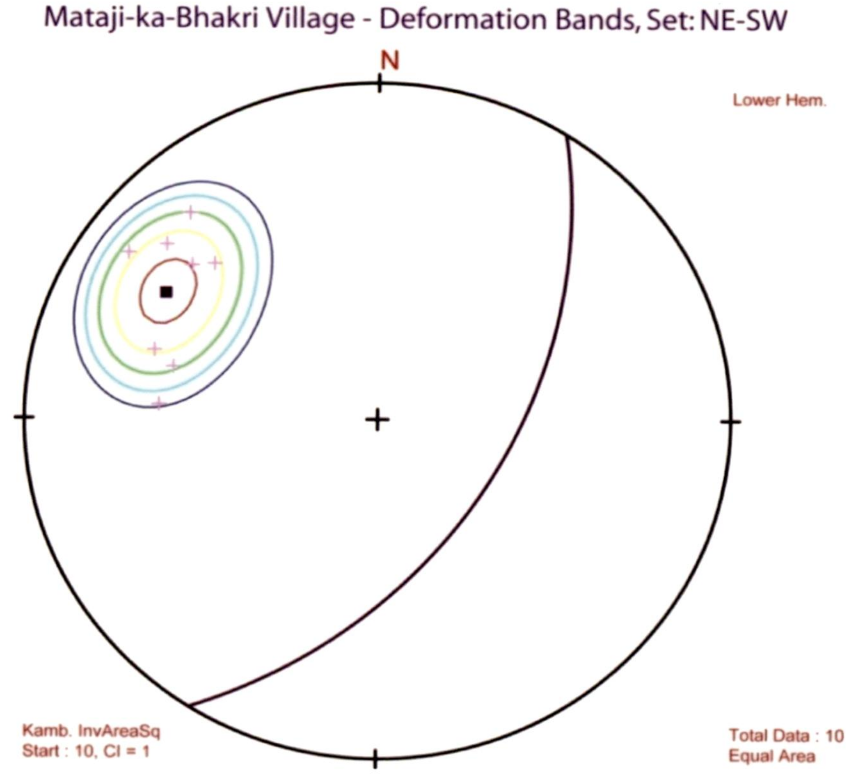


Figure 3.25a Stereographic projection of orientation data (poles) showing NE-SW deformation band set. Purple dot- maximum

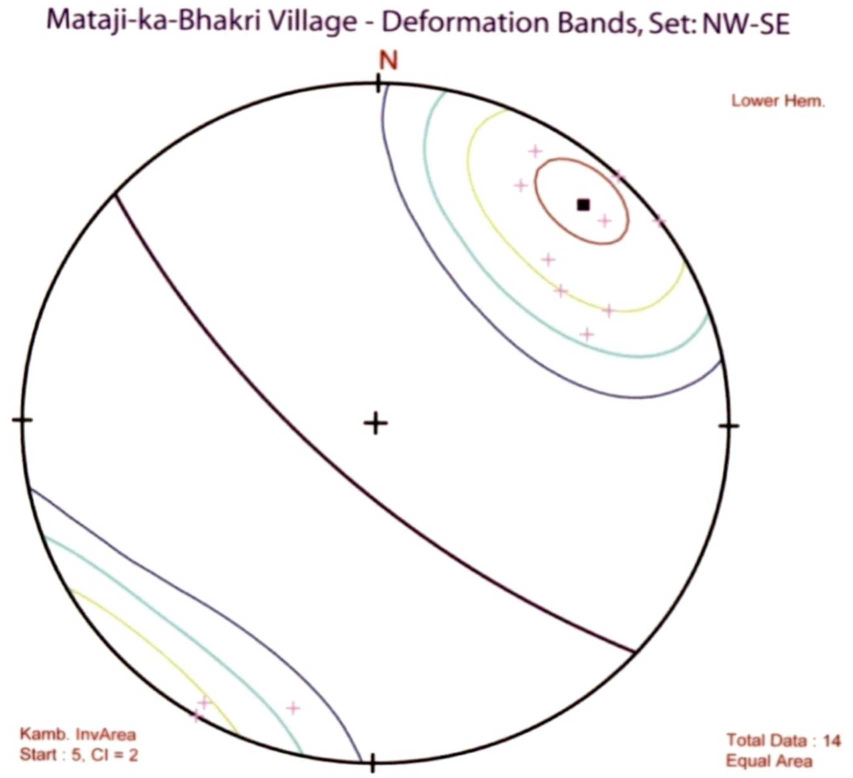


Figure 3.25b Stereographic projection of orientation data (poles) showing NW-SE deformation band set. Purple dot- maximum

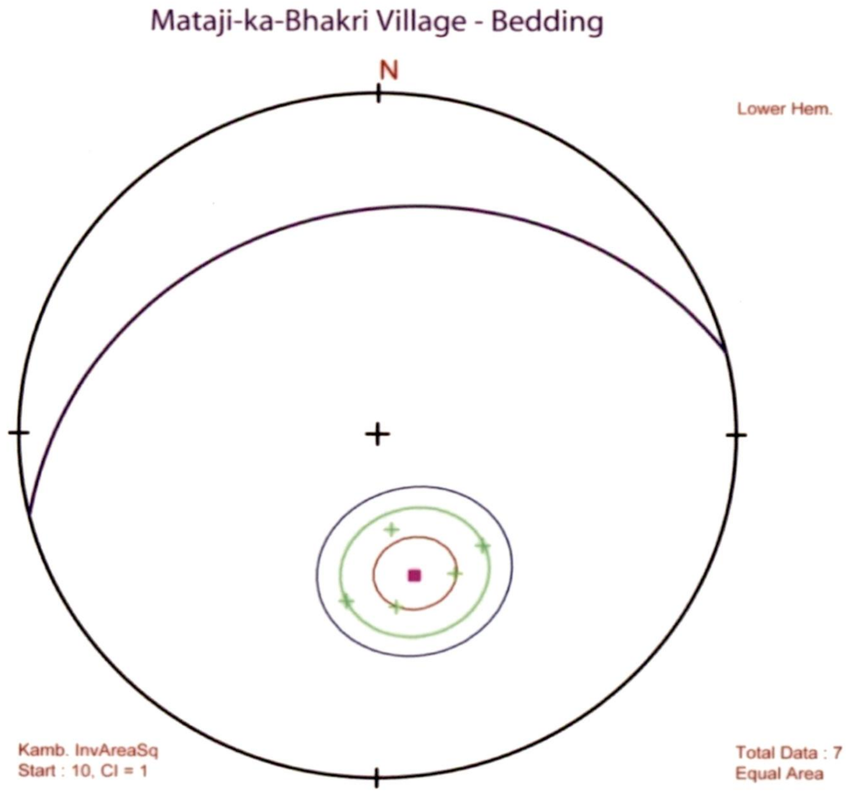


Figure 3.25c Stereographic projection showing the orientation of bedding plane in this area.
Purple dot –maximum

Figure 3.26 Showing the NW-SE deformation band set. Clinometer points towards North.

Figure 3.27 Shows thin deformation bands in Fatehgarh sandstone. Compass points towards North.

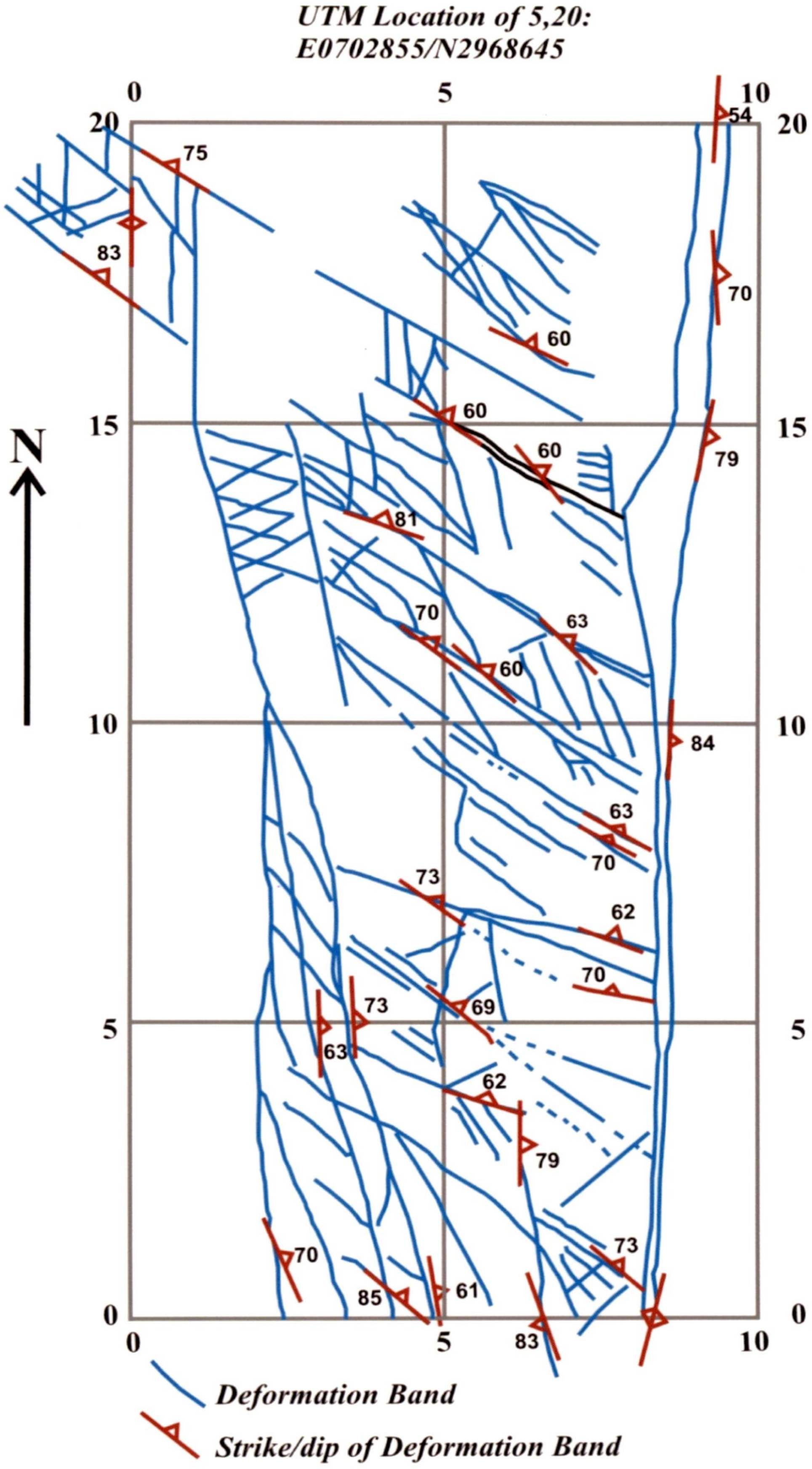


Figure 3.28 Outcrop-scale map of cataclastic slip bands in Lathi formation, Wood Fossil Park area

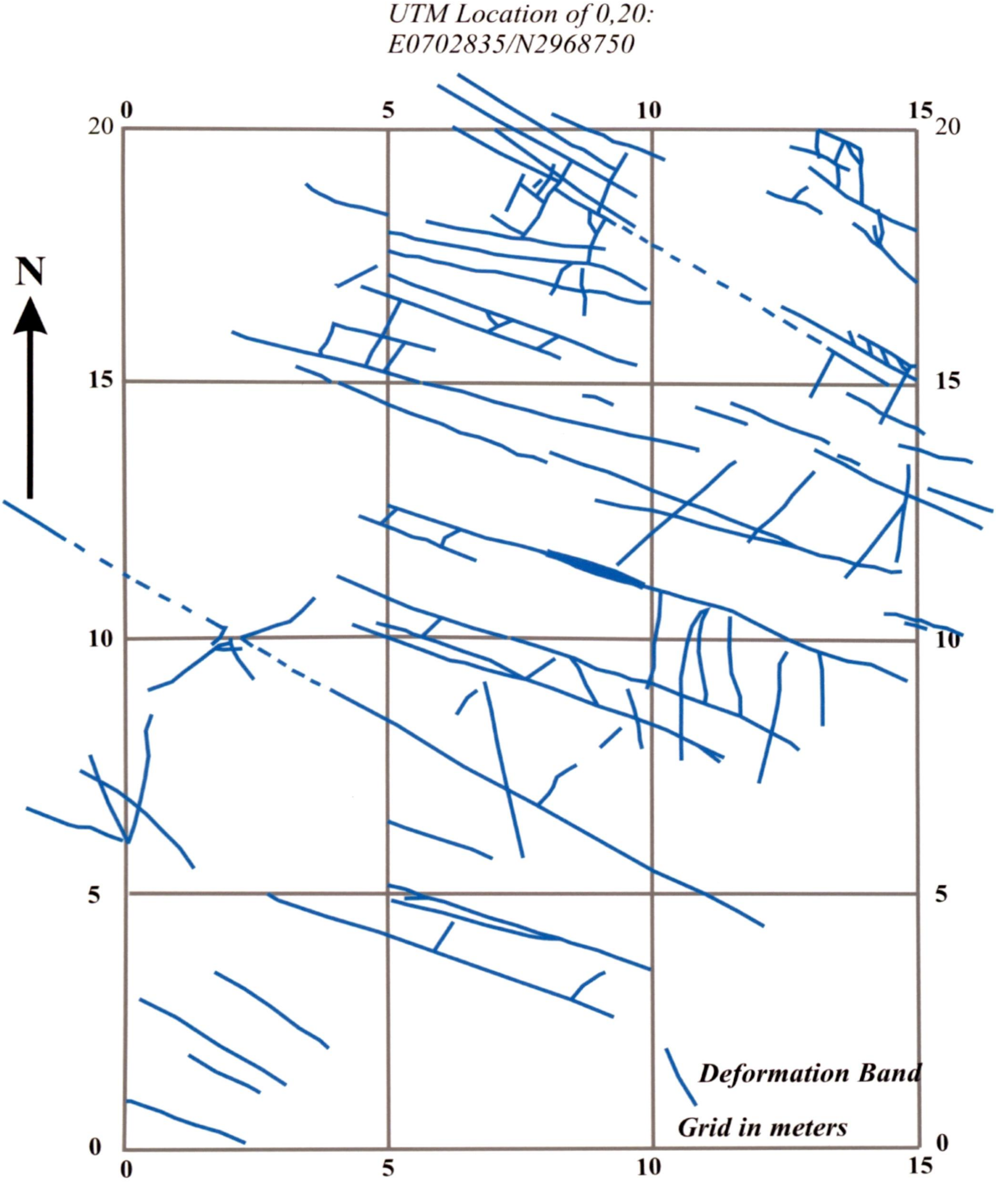


Figure 3.29 Outcrop-scale map of cataclastic slip bands in Lathi formation, Wood Fossil Park area

Chapter 4: Methods of Thin section preparation

4.1 Preparation of vacuum impregnated thin sections

4.1.1 Purpose- Impregnation with a resin for a soft, powdery, cracked, brittle, friable, or broken sample is helpful to: (a) fill the voids, pores and cracks; (b) improve the overall integrity and ease of handling; (c) preserve the original microstructure and distribution of components and edges in the sample; (d) keep the detached, de-bonded, fragmented portions adhered to the rest of the sample; and (e) prepare a solid mass of the original fragmented or powdery sample for sectioning, grinding, thin-sectioning, or polishing. Impregnation indicates injecting or penetrating a liquid resin into a porous sample to improve its internal as well as external integrity. Epoxy-based resins are best for impregnation.

In this work Epothin resin and hardener (Buehler make) were used with a blue colorant mixed with the epoxy to highlight the cracks voids and pore spaces in samples, while observing in the plane-polarized light mode in a petrographic microscope. The dye is soluble in epoxy resin and imparts a uniform blue colour to the epoxy. The major objective was to highlight the pore spaces and distinguish between the actual porosity and grain loss during grinding and polishing of the section.

4.1.2 Vacuum Impregnation – Buehler Make vacuum impregnation equipment available in the department was used for injecting the liquid resin in the pore spaces. The rugged vacuum pump supplies sufficient vacuum to quickly evacuate entrapped air from any porous specimen. Without the presence of air, the liquid resin fills the specimen pores completely. The cure time for the resin used is 9 hours at room temperature and can be decreased by slightly heating the resin before mixing with the hardener. This also helps lower the viscosity of the epoxy and thus deepen its depth of penetration into the sample during impregnation, increasing the strength of the mechanical bond to the constituents.

The following procedure is helpful for effective epoxy penetration. A small and thin slice of a sample (5-10 mm thick) is slightly heated on a hot plate to remove internal moisture. Resin is also slightly warmed to decrease its viscosity. Then 5 parts (by weight) of Epothin resin is mixed with 1.95 parts of Epothin hardener. The mixing should be gentle for a minute and then the colorant should be added and thoroughly mixed. Epoxy was poured on the sample to completely cover it. Drawing a vacuum on epoxy causes it first to evolve its entrapped air, then eventually to "boil" forming additional air. Breaking and restoring the vacuum several times at intervals of a minute helps to expel all trapped air from inside the sample and to allow the air pressure to force the epoxy into all voids, cracks and open spaces in the sample. Curing time generally increases with decreasing epoxy viscosity (e.g., Epo-Thin cures in 9 hours at room temperature), which can be accelerated by slightly warming the epoxy and sample in an oven or a hot plate at 40-45°C.

The purpose of impregnation in vacuum is to remove air out of the voids, pores, and cracks so that the epoxy can easily flow into these open spaces. Also, vacuum impregnation removes air bubbles within the epoxy, which usually prevent good bonding. In the absence of such sealing with epoxy, pores and margins of cracks or air voids may be enlarged during sectioning, grinding, or polishing operations and may entrap various foreign materials like grinding and polishing abrasives, solvents and stain-producing etchants. Impregnation with a colored or fluorescent dye mixed low-viscosity epoxy can highlight pores, voids, and cracks.

This is particularly useful to highlight the porosity difference between the host rock and the cataclastic slip band.

4.1.3 Results - The thin sections prepared show clear distinction in the petrophysical properties in the band and the host rock in plane polarised light. The thin section photographs illustrate that there is substantial amount of porosity in the host rock but becomes almost zero in the cataclastic slip bands. This drastic difference in the petrophysical properties can have huge implications for reservoir management in the area. The abundance and continuity of these bands in the subsurface are critical factors to be considered along with their microstructure for analysing their effect on fluid flow in reservoirs. In this work the microstructures of these bands have been studied.

Chapter 5: Microstructure of Cataclastic Slip Bands

Based on the microstructural studies of cataclastic slip bands from the Barmer area, Rajasthan, it is possible to distinguish two kinds of bands in the area: (1) Compaction bands; (2) Dilational shear bands. These bands are being reported from three different locations in the porous sandstones of Fatehgarh and Lathi Formations. The compaction bands from the area show virtually no porosity in the band compared to the host rock which is highly porous. Fig. 5.1 shows a compaction band in the Fatehgarh sandstone from one of the locations. The band in Fig. 5.1 is mainly formed by granular flow i.e. grain reorganization with little or cataclasis. The presence of dark iron minerals in the entire section shows the movement of iron rich fluid in the area. Fig. 5.2 shows porosity (blue) in the host rock of Fatehgarh sandstones from the same location. The poor sorting and high porosity in the rocks allow easy grain reorganization by effective rolling and frictional sliding of grains for the formation of these bands. The image shows porosity adjacent to the deformation band. The porosity near the band calculated from this image using JMicroVision is 10%.

In some of the samples there were circular areas with absolutely no porosity at all. Fig. 5.3 shows such an example with the circular area adjacent to the band. Such kind of small circular areas of absolutely no porosity have not been reported in literature before and the cause for their formation is has not been established. Fig. 5.4 shows another sample with a circular area surrounded by highly porous host rock. The porosity is shown in blue.

Cataclastic slip bands or deformation band's were very extensive in the Lathi sandstones at another locality. The sandstone in the area is very friable indicating extremely high porosity. The porosity calculated using photomicrographs of these sections indicates 30-

32% porosity for the host rock (Fig. 5.5). The host rock showing poor sorting and high porosity explains the large spatial extent and dense network of bands in this area. There were single as well as zones of deformation bands in the area cross-cutting each other at low angles and forming a dense network. The zones of deformation band were half a meter thick and stood like resistant ridges a meter above the host rock at places. Another sample taken from a location with all three sets of deformation band in the area shows alternating bands in thin section images (Fig. 5.6). An example of dilation band was found in this area. Fig. 5.7 (a, b) show deformation band with a component of dilation along with grain size reduction within the band. Dilation resulted in increase of porosity in the band forming a conduit for fluid flow. The black minerals within the band show the movement of iron solution through these bands. Also note that the grains here are moderately sorted and are almost equal in size. There is some cataclasis (grain size reduction) in their formation suggesting a shearing mechanism along with dilation.

There were 3 major sets of deformation bands in the area – N-S, NW-SE, NE-SW. Fig. 5.8 shows a thin section image of a sample collected from N-S striking deformation band. This figure shows a dilation band with very few grains within the band indicating porosity increase at the time of formation along with shearing. The increased porosity led to fluid flow within the band eventually sealing it. The shearing component in their formation mechanism is also seen in outcrop studies where a N-S deformation band offsets another set of band. Fig. 5.9 shows another thin section photograph of a sample collected from N 10^0 striking DB. It shows a dilation band (Left to Right) filled with calcareous material. The porosity adjacent to this band calculated from a mosaic image is 12 % (Fig. 5.10). The extremely high host rock porosity is thus seen reduced from approximately 32 % to 12 % near the band. The thickness of the band also varies ranging from very thin bands (Fig. 5.11) to very thick bands in Lathi sandstones (Fig. 5.7).

Dilation bands are also present in the Fatehgarh formation (sample taken from a location near Jhak village) which shows intense grain cataclasis and calcareous cementation in the band (Fig. 5.12).

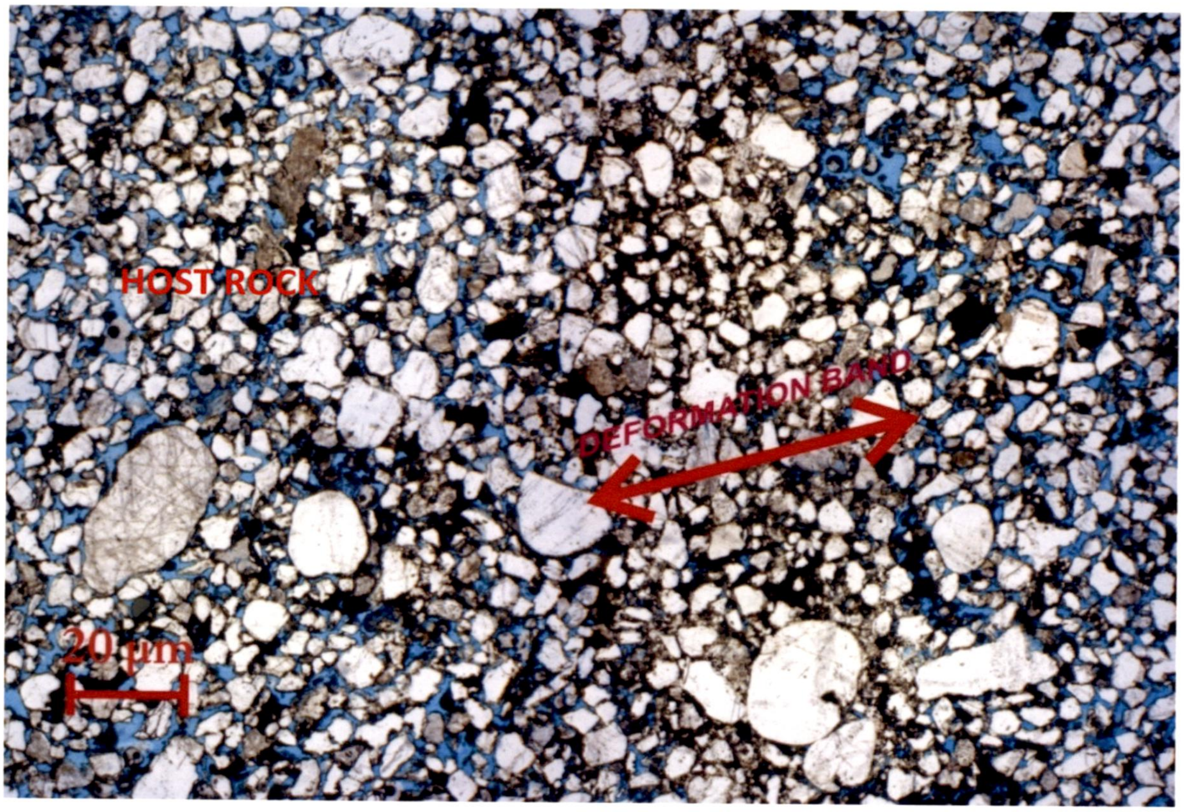


Figure 5.1 Compaction band in the Fatehgarh sandstones. Note the extreme porosity reduction and the poor sorting. The porosity adjacent to the band is nearly 10-12 % calculated from 2-D images using JMicroVision. Pore spaces are shown in blue.

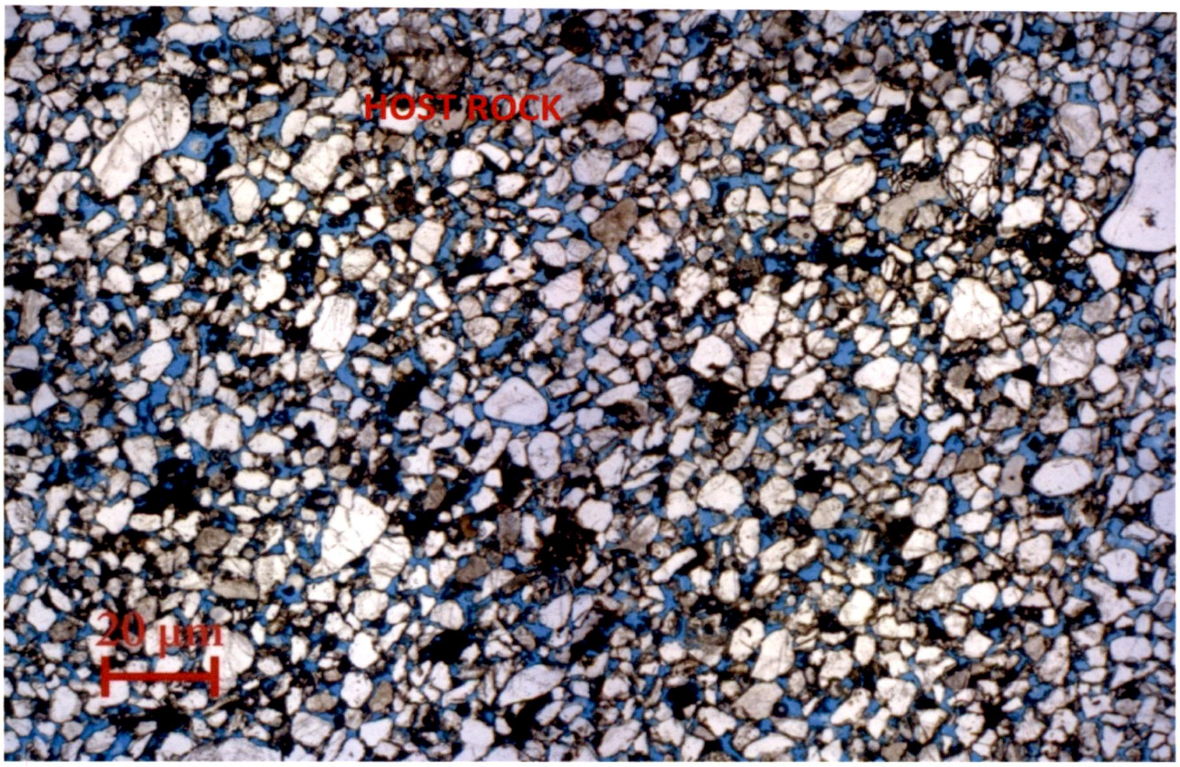


Figure 5.2 Photomicrographs of host rock samples. Note the high porosity and grain size variation in the Fatehgarh sandstones. The samples were treated with epoxy prior during thin section preparation, which makes the pore space stand out in blue colour.

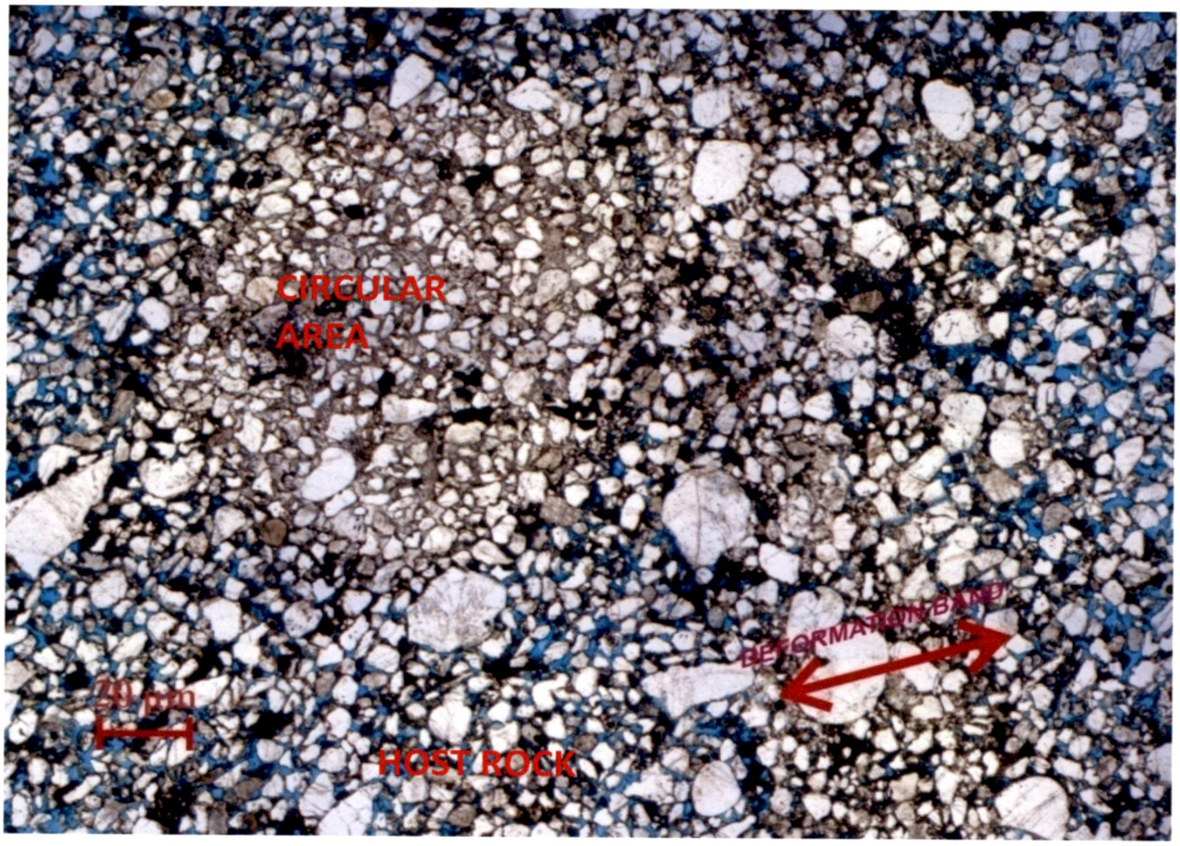


Figure 5.3 Shows a circular area adjacent to the deformation band with complete porosity loss in Fatehgarh sandstone. Pore spaces are shown in blue.

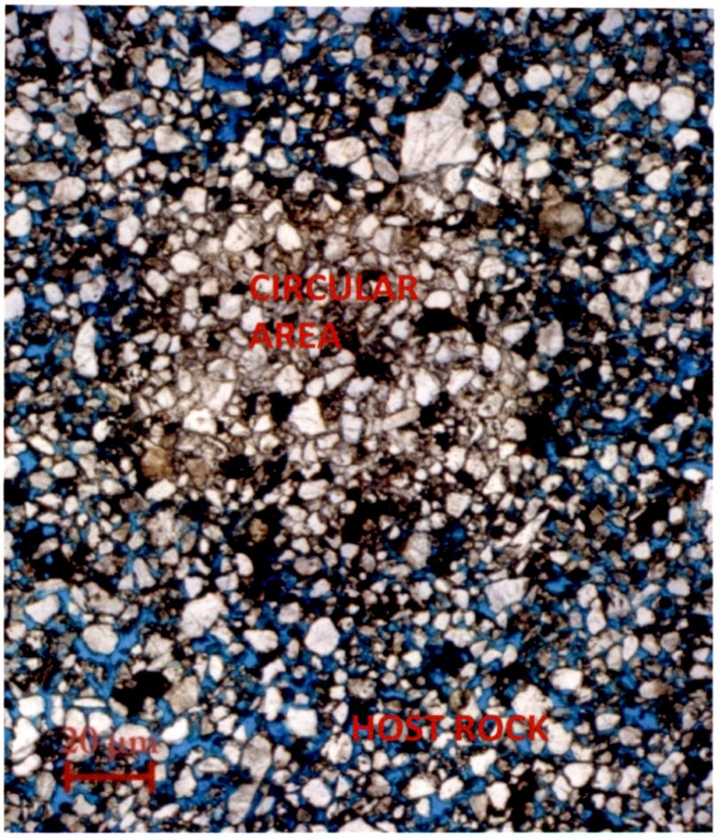


Figure 5.4 Circular area of no porosity in Fatehgarh sandstone. Pore spaces are shown in blue.

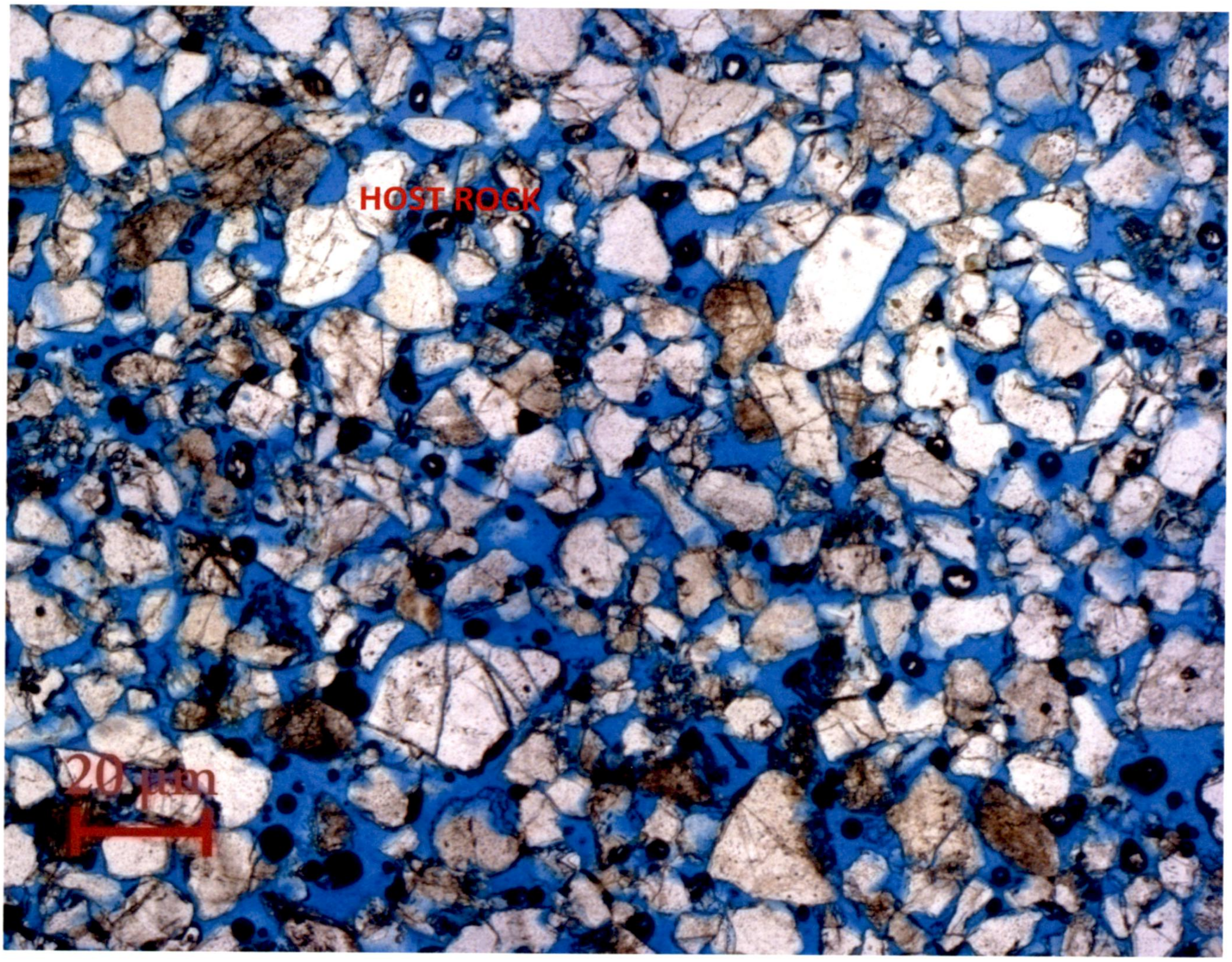


Figure 5.5 Shows high host rock porosity (approximately 32 %) in the Lathi sandstone. Pore spaces are shown in blue.

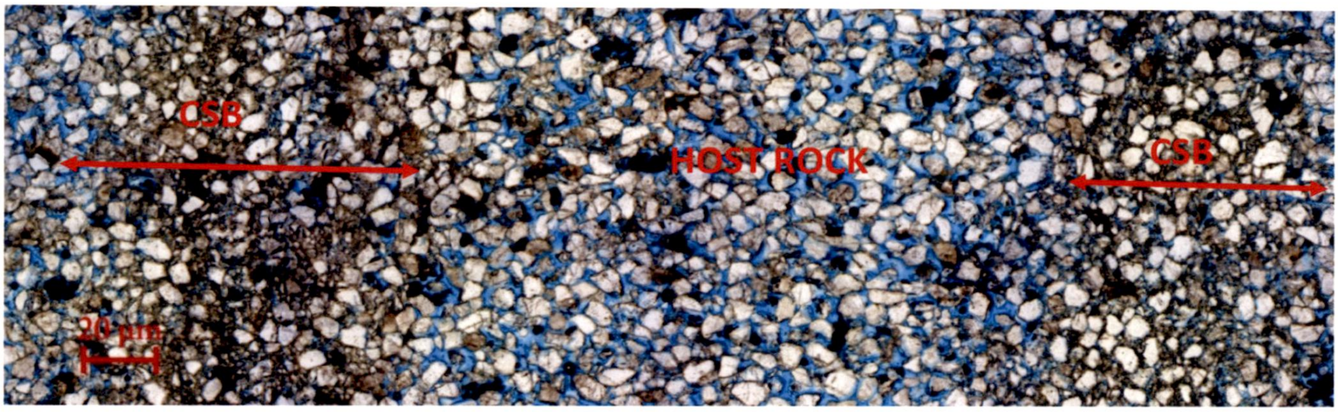


Figure 5.6 Photomicrograph of alternating deformation bands in Lathi sandstone. Pore spaces are shown in blue.

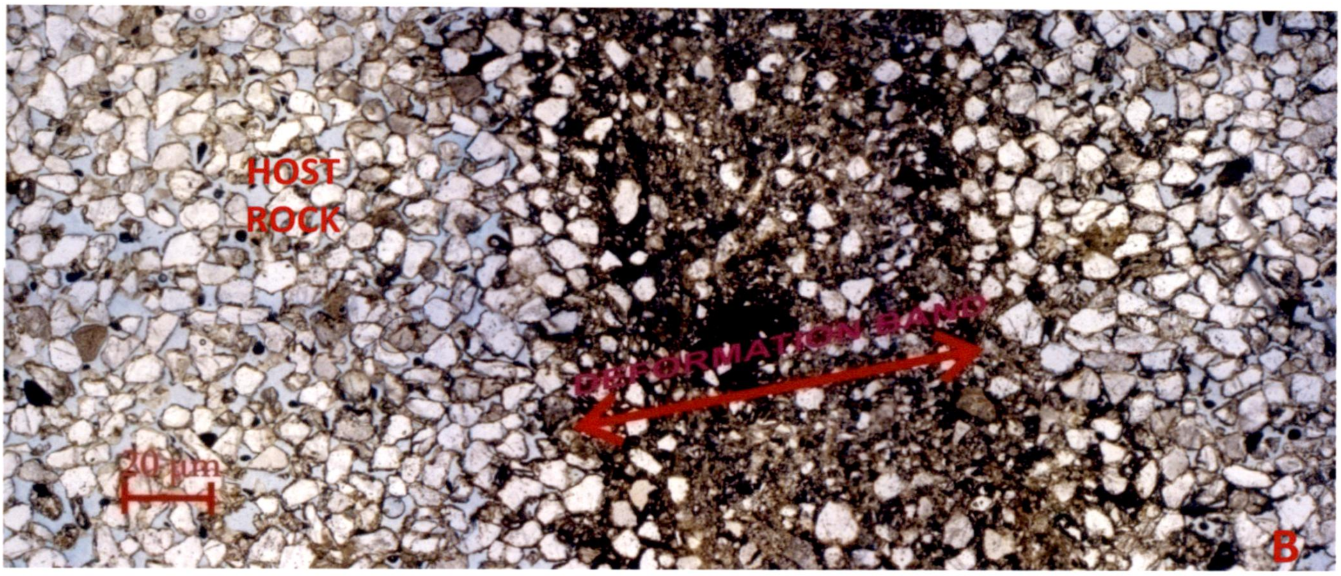
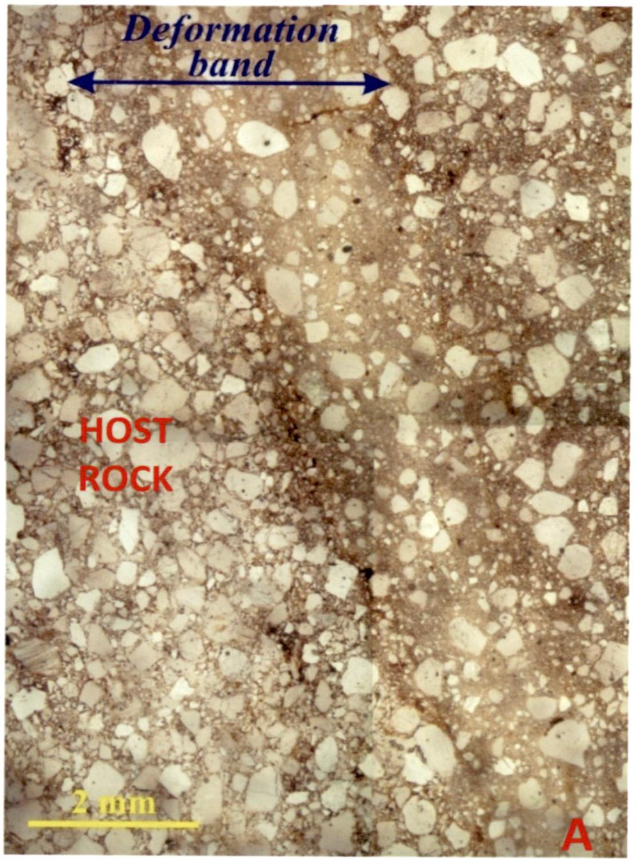


Figure 5.7 (a, b) Dilation band in Lathi sandstone filled with iron solution. Pore spaces are shown in blue.



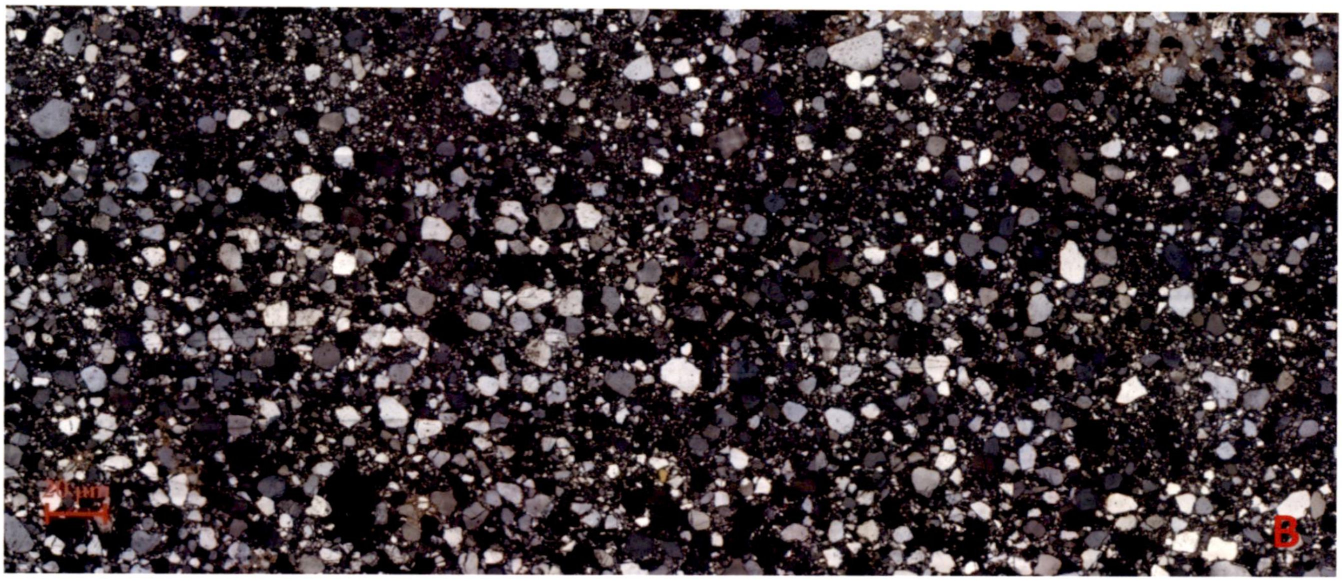


Figure 5.8 (a, b) Photomicrograph of sample collected from N-S striking DB in Lathi sandstone in plane polarized light. Same sample in crossed nicols shows intense cataclasis.

Figure 5.9 Photomicrograph (crossed nicols) of a sample collected from N 10^0 striking Deformation band in Lathi sandstone.

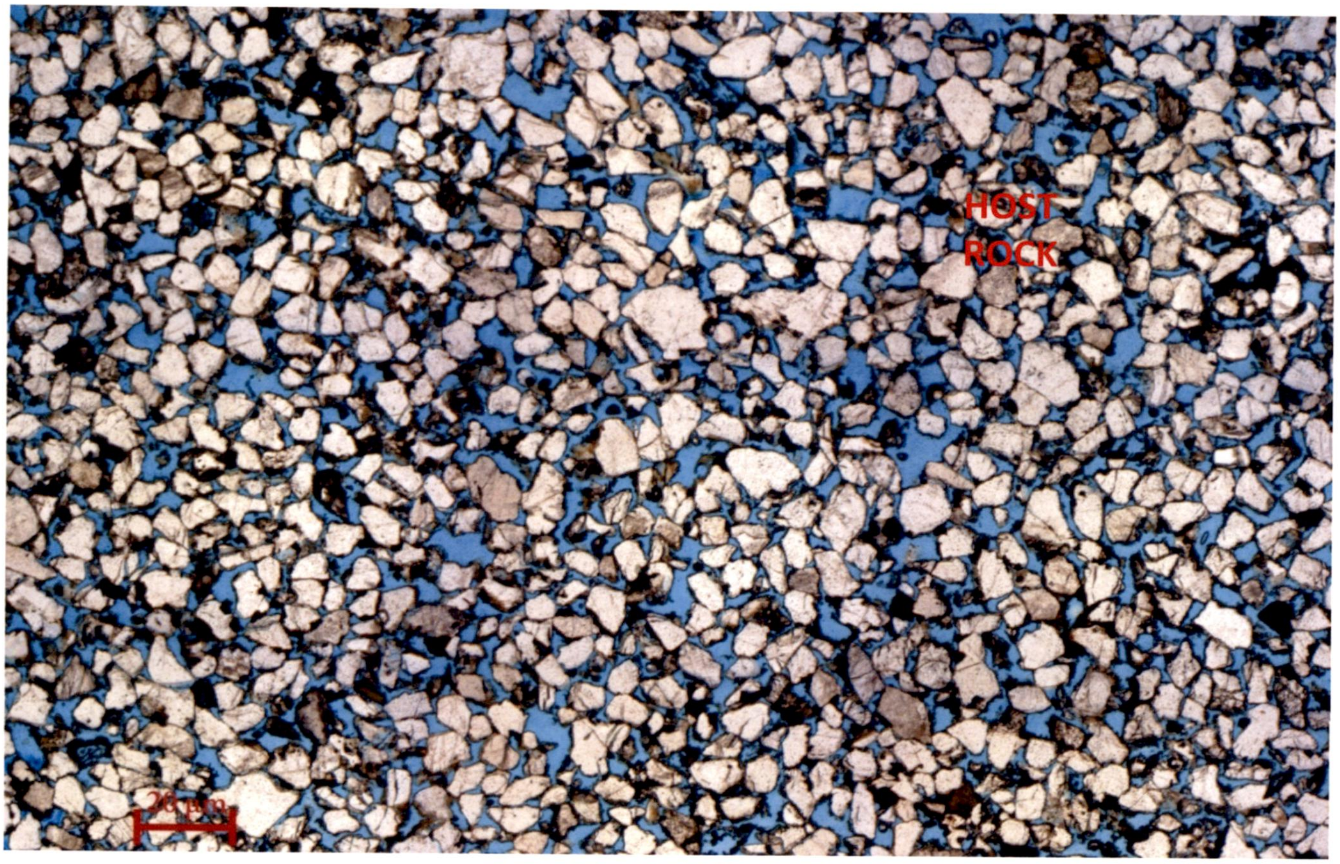


Fig. 5.10 Porosity shown in the same sample collected from N 10^0 striking band in Lathi sandstone.

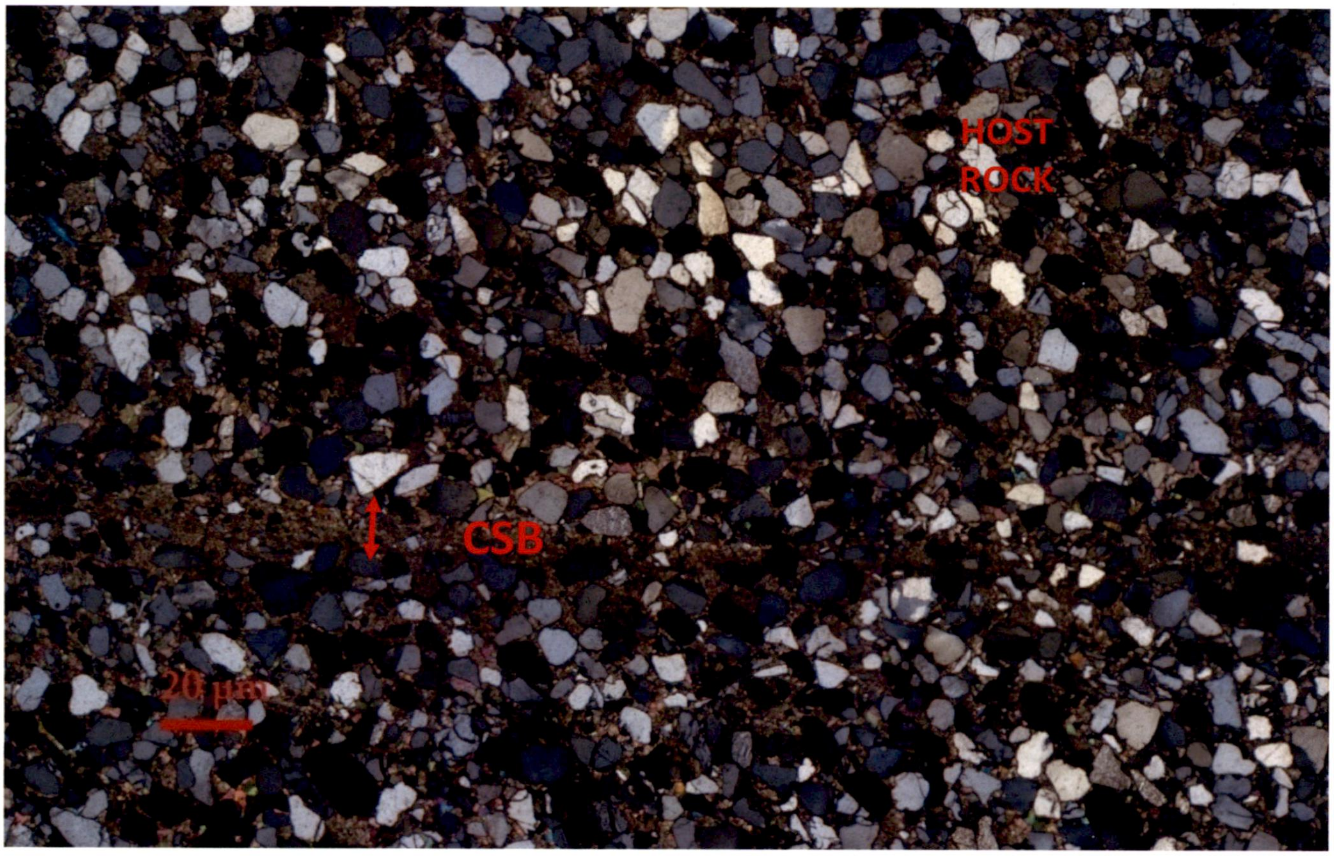


Figure 5.11 Photomicrograph (crossed nicols) of a very thin deformation band in Lathi sandstones.

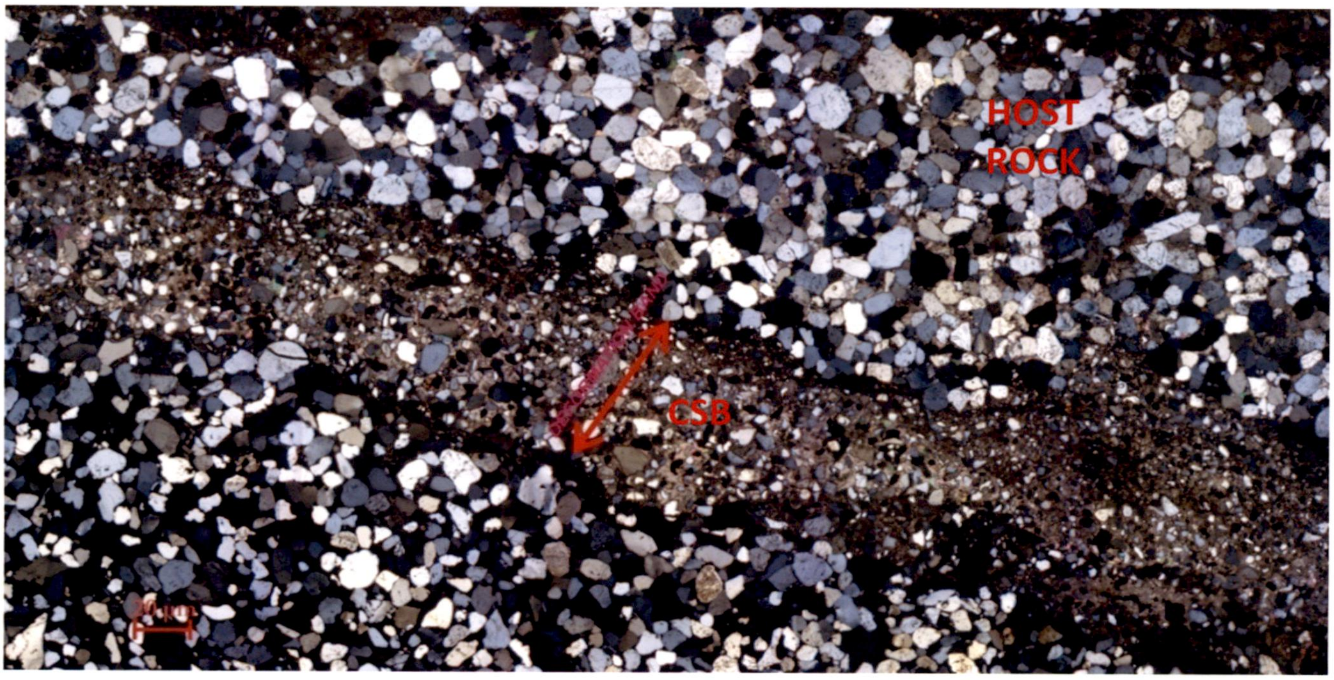


Figure 5.12 Dilation band showing grain size reduction through cataclastic deformation in Fatehgarh sandstone. Calcareous material has preferentially entered the band.

Chapter 6: Petrophysical Properties

Porosity or **void fraction** is a measure of the void (i.e., "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0–1, or as a percentage between 0–100%. It is measured in particular using a porosimeter or by obtaining porosity (density, neutron and sonic) logs while drilling. Permeability is the ability of a rock to pass a fluid (air, water. oil or gas) through its porous network. In the petroleum industry, this parameter controls productivity of a tank, while the porosity provides information on the capacity of the tank to store hydrocarbon fluids. This dissertation addresses deformation bands, their microstructure, and evolution, and their effect on porosity and permeability (petrophysical properties) in porous sandstones. The ultimate goal is to improve our understanding of hydrocarbon flow within reservoirs.

6.1 Effect on fluid flow

Cataclastic slip bands are sub-seismic in scale and effect production from hydrocarbon reservoirs because the porosity and permeability in these bands is very less compared to the host rock which contributes to high pressure drop. However they may also act as conduits for fluid flow with increased porosity and permeability in case of dilation bands and shear induced dilation bands. They occur in highly porous reservoir rocks (>15% porosity) mainly in fault damage zones. Their small thickness makes them invisible on seismic data. Poor well performances and poor communication between wells can be explained by these bands or sub-seismic faults or both.

Their effect on fluid flow depends on many factors like permeability and porosity contrasts (which is primarily dictated by deformation mechanisms and mineralogy), number of bands, their orientation, lateral continuity and connectivity, thickness variations and variation in permeability and porosity in three dimensions. Permeability of these bands is governed by the deformation mechanism operative during their formation. The mechanism again depends on number of lithological and physical factors. Disaggregation bands show little porosity and permeability reduction whereas permeability reduction in phyllosilicate and particularly cataclastic bands is up to several orders of magnitude. Since the CSB's are thin so the number of bands is important when understanding their role in influencing flow in petroleum reservoirs.

Being sub-seismic in scale, it is imperative that attempts are made to identify and characterise CSB's in cores and drill cuttings from drilled wells.

6.2 Assessing the petrophysical properties of deformation bands from 2 D images

Techniques for estimating the porosity by image analysis have been presented in several studies. It shows that the porosity must be studied at different scales to obtain a overall assessment. The sample has been impregnated with a blue dyed epoxy to facilitate the segmentation of the pores. The porosity is extracted from the image using **JMicroVision.** It is a software developed especially to analyze high definition images of rock thin sections. In this software components can be extracted as objects or particles with the Object extraction tool or as backgrounds with the background tool.

6.3 Porosity calculations using JMicrovision

Digital images of thin sections are used in JMicrovision to calculate porosity of the host rock. The magic wand tool in this software is designed to select an object based on its color similarity. It starts selecting when you click at a spot in the image, and expands the selection to the contiguous pixels whose color is similar to that of the starting pixels (Fig. 6.1). The threshold of similarity can be controlled by adjusting the tolerance values.

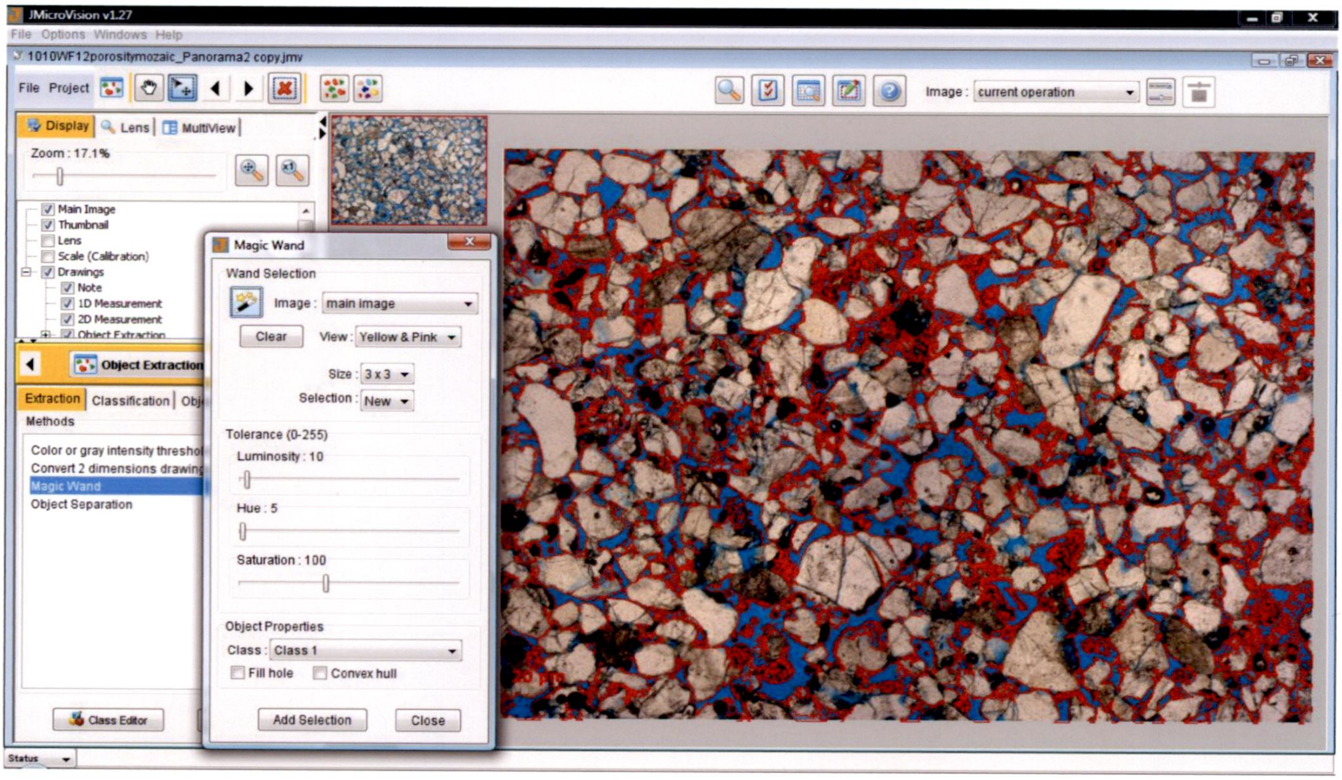


Figure 6.1 Shows porosity calculation using the magic wand tool in JMicroVision.

Chapter 7: Conclusion

Based on orientation, structural relations and microstructural properties, we report two kinds of cataclastic slip bands from the porous sedimentary rocks in the Barmer-Jaisalmer Basin, Rajasthan- Dilational shear bands and Compaction bands (or disaggregation bands). Samples showing compaction in the area are very few. Hence there are mainly dilational shear bands in the area. The mechanism by which these bands have formed is dilation along with shearing. The component of dilation is deduced as the porosity in the band increases relative to the host rock. Besides, the intense cataclasis observed in the microstructural studies along with shear offsets observed in the field study confirm the presence of shearing mechanism in their formation. The increased porosity in the dilational shear bands caused the movement of carbonate and iron solutions through them and thus completely sealed them off.

Porosity was calculated for the host rock of Fatehgarh and Lathi sandstones by thin section image analysis using the software JMicroVision. The measured porosity for the Fatehgarh is between 10-12% and for the Lathi sandstone is 32%. The porosity in the host rock of the Lathi sandstone (32%) is drastically reduced to 10-12% in the vicinity of the cataclastic slip bands. Also it is clearly evident from the photomicrographs that the porosity within these bands is virtually zero which proves that the permeability through these bands is also zero. The fact that the permeability through these bands is zero makes them extremely important for reservoir management in the area. Mapping of deformation bands and observing the variation in the density suggests that these bands are present extensively in the area and are not necessarily related to particular faults as suggested by some authors, but are developed in response to the overall stress field. Hence they can be widespread in their extent and further study is required to understand their spatial distribution and abundance.

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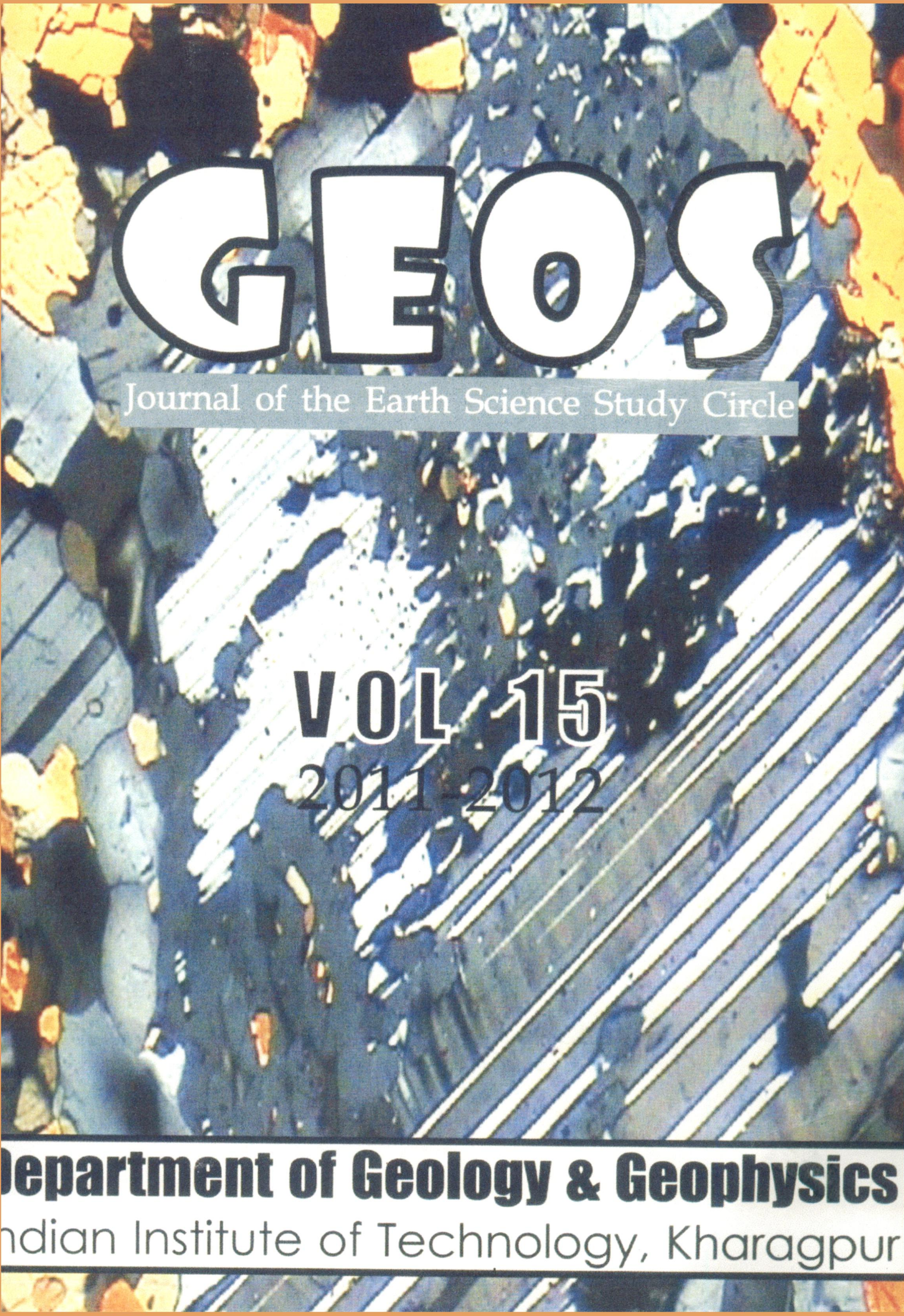

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formation bands in porous sedimentary rocks

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ACT

Deformation bands are primary structures that form in highly sedimentary rocks due to strain localization into narrow tabular They are distinct from deformation structures formed in low y rocks and are confined within a few km depths from the surface of rth. The high porosity is required because the deformation nism is dominated by grain rotation, grain boundary sliding and sis. The deformation bands are important for reservoir ement for hydrocarbon and ground water because petrophysical ies within deformation bands are altered relative to the rmed host rock. They may also be used as a palaeostress indicator. ation bands are very well preserved in the porous sandstones of rh and Lathi Formations in Rajasthan.

UCTION

Strain in low-porosity rocks within the top few res of the crust usually gets concentrated in narrow zones ble width. This can lead to the formation of fractures with dth, e.g., extensional fractures (joints) or shear fractures or tabular deformation zones with finite width, such as shear zone, shear band or mylonite zone. Strain localization mentary rocks, such as sandstones or unconsolidated ts, with a porosity of about 10–15% or higher may behave tly and the strain may manifest through the development of tion structures commonly known as deformation bands g., Aydin 1978; Fossen et al., 2007). They are also called ic slip bands (CSB, Fowles and Burley, 1994) or slipped tion bands (Rotevatn et al., 2008). Deformation bands porosity and thus fluid flow in sedimentary rocks. ently, they are important for hydrocarbon or ground water ion (Antonellini and Aydin, 1994, 1995; Fossen and Bale, n this article we describe the characteristic features of ion bands and give examples from hydrocarbon-bearing nd Jaisalmer Basins in Rajasthan.

TION BANDS

Deformation bands are mm to cm thick, tabular and low-nent deformation zones in highly porous sedimentary d unconsolidated sediments. Some of the important istic features of deformation bands include (Fossen et al., 10): (1) Deformation bands are restricted to highly porous media, most commonly porous sandstones. (2) Formation nation bands involves grain rotation, frictional sliding or c flow and, therefore, requires a significant amount of (3) They occur hierarchically as single structures, linked systems (zones), zones associated with slip surface leformation band) and faults with larger offset (> 1 m). y are precursors to faults and are also termed as small ring to the smaller offsets across them. (4) They are within fault damage zones and near the fault tips.

According to the evolutionary model first suggested by d Johnson (1978), deformation-band zones are precursors n porous sandstone. A consequence of this fault model is tion of a zone of deformation bands in front of, as well as around, the fault-slip surface. Hence, any fault in porous sandstone will have a deformation-band damage zone, provided that the porosity of the sandstone is not too low for deformation bands to form. Deformation bands are commonly associated with local pore space collapse (compaction bands) although simple shear bands or even dilational deformation bands do exist. Their growth from single structures to swarms of bands is generally attributed to strain hardening associated with pore collapse and cataclasis (Aydin, 1978).

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TYPES OF DEFORMATION BANDS

Deformation bands can be classified in a kinematic framework or based on the mechanisms being operative during their formation. The kinematic based classification has three end members: simple shear bands, pure compaction bands and pure dilation bands (Fig. 1). The mixed mode includes dilational shear bands and compactional shear bands, i.e., shear with volume increase and decrease, respectively. Formation of dilational and compactional bands, with or without shear, leads to growth and collapse of pore spaces, respectively (Fig. 1). The dilational and compactional bands may be grouped together as volumetric deformation bands.

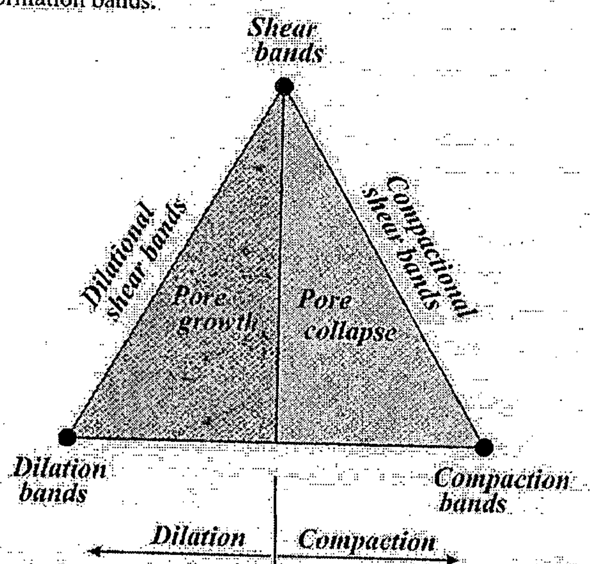


Figure 1: Types of deformation bands in porous sediments and sedimentary rocks (after Aydin et al., 2006; Schultz and Fossen, 2008).

VOLUMETRIC DEFORMATION BANDS

Deformation bands that lack evidence of macroscopic shear offset form predominantly by volumetric deformation and are therefore called volumetric deformation bands. Volume change, expressed in terms of porosity change, may be either positive (dilation) or negative (compaction).

Compaction deformation bands: Compaction bands are characterized by volume decrease with respect to the undeformed parent rock. They are associated with compaction of grains through grain reorganization or cataclasis (Fig. 2). The porosity may decrease from about 20% or more in the undeformed rocks to about 5% or less within the deformation bands. Since no shear is involved, compaction bands are equivalent to anti mode-I cracks, a mechanism that leads to the formation of stylolites.

Dilation deformation bands: Dilation bands are deformation bands characterized by porosity increase with respect to the undeformed state and no macroscopic shear offset (Fig. 3). Such deformation bands have been reported from many locations but the shearing component along these bands or the lack thereof is unclear in many cases. Du Bernard et al. (2002) have described dilation bands in which shear offset has been unambiguously ruled out.

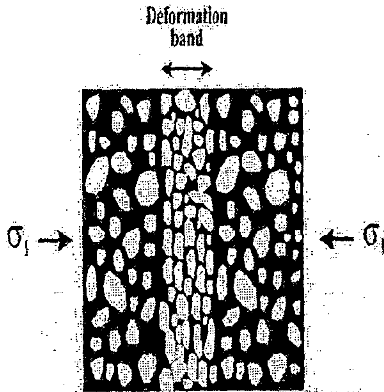


Figure 2: Compaction deformation band. Note that the porosity (dark area) in the deformation band has decreased.

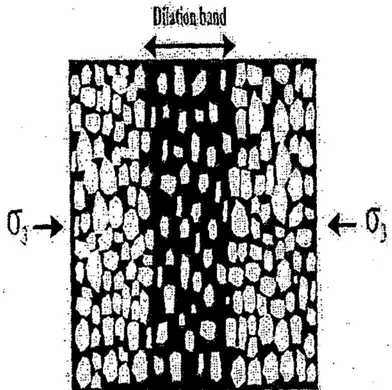


Figure 3: Dilation deformation band. Note that the porosity (dark area) in the deformation band has increased.

SHEAR DEFORMATION BANDS

Bands predominated by shearing are referred to as shear deformation bands. The diagnostic feature of shear bands is a macroscopic shear offset across a tabular zone of finite but small width with respect to the other two dimensions. Shear offset can be determined by previously continuous markers such as beds or older shear bands. Shear bands in granular rocks have limited offsets on the order of a few millimetres to centimetres. Although a majority of shear bands reported in the literature are associated with grain size reduction resulting from grain fracturing, the process of grain fracturing is not a pre-requisite for shear band formation.

Although rare, shear bands without any significant volumetric component of deformation also occur for the same range of porosity values of corresponding parent rocks within the accuracy of the measurements. This type of shear bands are referred to as 'isochoric' shear bands (Aydin et al., 2006) representing the type of deformation known as 'simple shear' in geological literature.

Most shear bands, however, undergo volumetric deformation in addition to shearing (Aydin 1978; Antonellini and Aydin 1994). These mixed mode bands, regardless of the relative magnitude of shear and volumetric components of deformat are referred to as 'compactive shear bands' or 'dilatant sl bands'. Compactive and dilatant shear bands are characteri predominantly by shearing but are also associated with volu decrease or increase, respectively.

MECHANISMS OF DEFORMATION

Deformation mechanisms for the formation deformation bands depend on internal and external conditions su as mineralogy, grain size, shape, sorting, cementation, poros and state of stress. Different mechanisms produce bands w variable textural change resulting in variation in petrophysic properties. The dominant deformation mechanisms are granu flow, phyllosilicate smearing, cataclastic flow a dissolution/cementation (Fig. 4; Fossen et al., 2007).

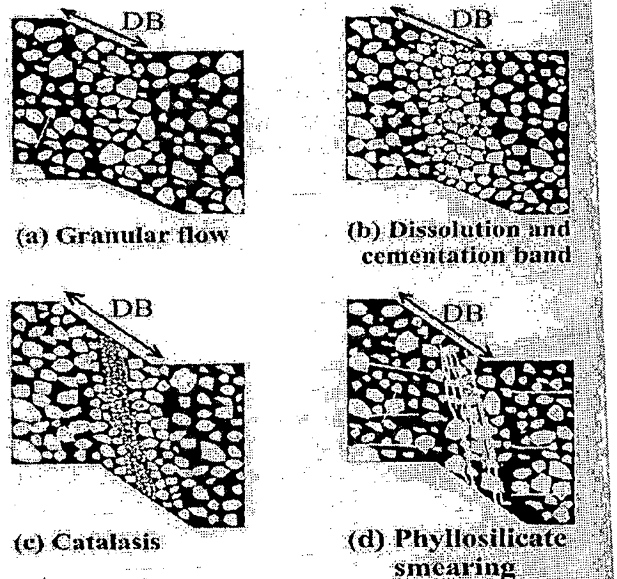


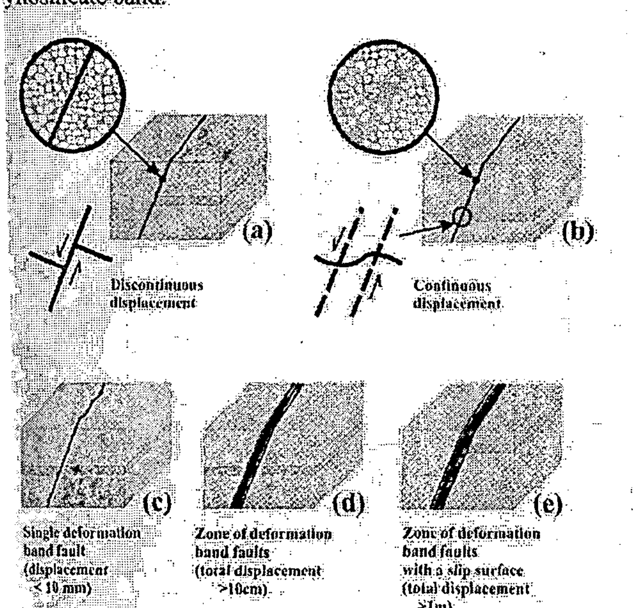
Figure 4: Deformation mechanisms for the formation of deformation bands (DB) (after Fossen et al., 2007)

Disaggregation bands: Disaggregation of grains through rotation, sliding and breaking of cementing material gives rise to disaggregation deformation bands (Fig. 4a). This process of grain disaggregation is called *granular or particulate flow*. Little or no cataclasis (grain crushing) is involved. Factors that favour formation of disaggregation bands include poorly consolidated host rock as friction between the grains in unconsolidated rocks is significantly less than that of consolidated rocks and shallow burial depth and/or excess fluid pressure because at shallow burial depths the stress generated across the grain contacts is generally not high enough for cataclasis. Disaggregation bands are difficult to recognize in outcrops and their presence is usually indicated by offset of sedimentary lamination.

Dissolution and cementation bands: Dissolution and cementation (Fig. 4b) along deformation bands usually take place after deformation but they may also be syn-kinematic. The term solution band is used where chemical compaction or pressure solution is significant. Solution bands typically consist of tightly packed grains smaller in size than the matrix, but showing little evidence of cataclasis. Although dissolution of quartz grains becomes prolific at depths greater than 3 km, dissolution is a common feature of deformation bands formed at shallower depths. This suggests that quartz dissolution is promoted by other processes such as, presence of clay minerals on grain boundaries or by fresh and highly reactive surfaces formed during grain crushing and/or grain boundary sliding. Deformation bands may referentially localize tensile fractures providing easy passage for uid flow and subsequent precipitation of calcite, anhydrite, salt, ydroxides and quartz.

ataclastic deformation bands: The classic cataclastic deformation ands (Fig. 4c) occur when mechanical grain fracturing is a gnificant deformation mechanism. Such deformation bands occur ithin a volume of compacted rock as a result of granular flow and e characterized by wide variation in grain-size, grain-size duction and angular grains, which may lead to extensive grain terlocking promoting strain hardening and distinct reduction in ore space and permeability.

ıyllosilicate bands: Phyllosilicate bands (Fig. 4d), a type of saggregation bands, form in sandstone and unconsolidated sand the content of platy phyllosilicates grains exceeds 10–15%. The aty mineral grains promote frictional grain-boundary sliding as posed to cataclasis. Permeability reduction of 2-3 orders of agnitude is common. If the phyllosilicate content of rock anges across bedding or lamina interfaces, a deformation band ay change from an almost invisible disaggregation band to yllosilicate band.



ıre 5: Fault and deformation bands. (a) Fault with discontinuous ılacement. (b) Deformation band with continuous displacement. (c) ıle deformation band. (d) Zone of linked deformation bands. (e) lted deformation band. (after Draganits et al., 2005)

LTS AND DEFORMATION BANDS

Deformation bands are distinct from fractures such as ts or joints. Faults are characterised by sharp fractures and ontinuous displacement (Fig. 5a) whereas deformation bands tabular with discontinuous displacement (Fig. 5b). In outcrops hand specimens, deformation bands occur as isolated ctures (Fig. 5c), linked systems, complex zones of multiple, connected *deformation bands, (Fig. 5d) zones associated with* surface (Fig. 5d) and in fault damage zones (Fig. 6). Faults are ırally considered to be fractures or surfaces across which there ppreciable relative discontinuous displacement. Deformation ls are small faults with continuous displacements of a few imetres or centimetres. In some places the small faults or mation bands are associated with large faults, with several rs of offset. However, in many places there are small faults or ps of small faults (zone of deformation bands) not associated any large fault. Deformation bands are significant *primary* tures, and they precede the formation of the larger faults. They occur as single deformation band, zones of deformation bands, faulted deformation bands. They appear to play an important role in the generation of larger faults, which may have offsets of several tens of meters. They also occur in damage zones associated with large faults (Fig. 6). The complex variation of deformation band geometry in damage zones has the potential to influence fluid flow in a complex manner.

PALAEOSTRESS ANALYSIS FROM DEFORMATION BANDS

Conjugate shear fractures or ductile shear zones are routinely used for definitive determinations of the orientations of the three principal stress axes during deformation, popularly called palaeostress analyses (e.g., Mukhopadhyay and Haimanot, 1989; Angelier, 1994). The basic principle of palaeostress analysis follows the enumeration of Anderson (1951) (Fig. 7): (1) the intermediate compressive stress axis (σ_2) coincides with the line of intersection between the two planes of the conjugate shear fracture, (2) the maximum compressive stress axis (σ_1) is normal to the line of intersection and directed along the line that bisects the acute conjugate angle, and (3) the minimum compressive stress axis (σ_3) is normal to the line of intersection and oriented along the line that bisects the obtuse conjugate angle. In areas where conjugate shear fractures/faults are plentiful, palaeostress determination is a rather straight exercise.

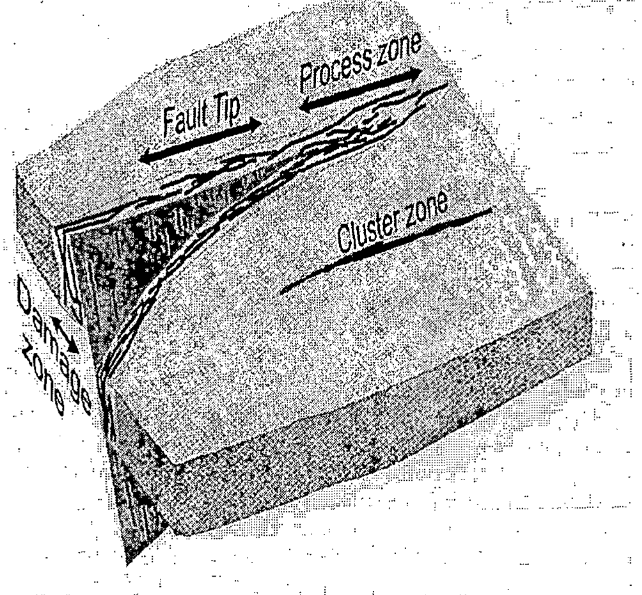


Figure 6: Damage zone associated with large faults. Deformation bands occur in the damage zone and fault termination. (after Fossen et al., 2007).

Shear displacements along deformation bands are small and typically vary in mm to cm scales. Also in majority of the instances, it is rather difficult to demonstrate unambiguous shear displacement along deformation bands. Nevertheless, if shearing can be demonstrated, deformation bands have the potential for palaeostress analysis and the methods *are same as in case for shear* fractures/faults (e.g., Crider and Peacock, 2004; Olsson et al., 2004). If conjugate deformation bands give (sub) vertical σ_1, the dominant deformation is characterized by normal dip-slip offset. It can then be concluded that either crustal extension or the weight of the overburden provided the maximum compressive stress at the time of deformation banding. If σ_1 is horizontal and σ_2 is either horizontal or vertical the dominant deformation is reverse dip-slip or strike-slip, respectively (Fig. 7). The σ_1 and σ_3 axes should be oriented at high angles to compaction and dilation deformation bands, respectively. However, precise determination of stress axes could be difficult in such cases as well as in cases where failures are mixed mode.

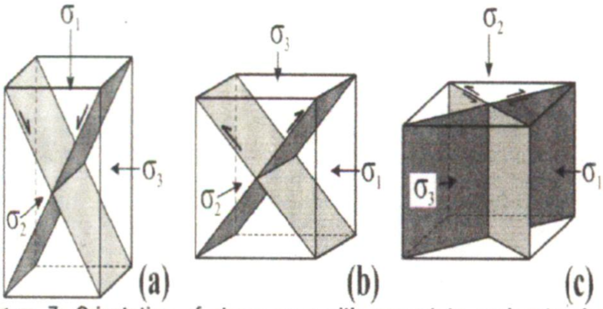


Figure 7: Orientation of stress axes with respect to conjugate shear fractures. (a) Normal dip slip. (b) Reverse dip slip. (c) Strike-slip.

DEFORMATION BANDS IN RAJASTHAN

In most discussions on the geology of Rajasthan, the Aravalli-Delhi mobile belt takes the pride of place! Though the sedimentary rocks in the western part of the Rajasthan are known for a long time (see Roy and Jakhar, 2002) they are now being looked into with renewed interests for the purpose of hydrocarbon exploration (e.g., Sisodia and Singh, 2000; Compton, 2009). Cairn Energy India has recently discovered huge hydrocarbon reserves in the Barmer Basin. The narrow NNW-SSE trending Barmer Basin is thought have formed due to rifting of continental crust dominated by the rocks of the Late Proterozoic Malani Igneous Suite. The western margin is defined by a NNW-striking basin margin fault, which is very well exposed in the west of Barmer town. Its southern extension is restricted by a NE-SW trending fault scarp exposed near Sarnu village. A ridge exposing Fatehgarh Formation underlain by Lathi Formation shows its northern limit while its eastern margin is not well exposed. The sandstones of the Fatehgarh Formation are highly porous (porosity > 30%) and extremely permeable (> 10 Darcy) and are the main reservoir rock. The sandstones of the Lathi Formation are also highly porous. Much of the rocks of the Barmer Basin are covered by desert sand but the sandstones of the Fatehgarh and Lathi Formations are fairly well exposed in the northern part of the basin. The deformations bands are well developed in these porous sandstones (Fig. 8) in the area lying between Barmer and Jaisalmer towns, which include the northern part of the Barmer Basin and the Jaisalmer Basin.

In outcrops, the deformation bands in the study area occur as thin isolated bands or as a group of deformation bands cross cutting each other at low angles (Fig. 8a). Thickness varies from a few mm to few cm for individual isolated deformation bands and the strike length varies from tens of cm to tens of meters. They also occur in complex linked systems defining a zone whose width may exceed one meter (Fig. 8b, e). Within a zone of deformation bands, there are many preserved undeformed pods (Fig. 8e). They occur in parallel sets (Fig. 8c, d), three such sets (Fig. 8f) have been recognized based on statistical analysis of orientation data. Cross-cutting sets may enclose rectangular (Fig. 8d), rhombic or triangular (Fig. 8f) areas where original texture of the sandstones are preserved. At places, two parallel deformation bands are linked by oblique thinner bands (Fig. 8c) giving the appearance of *pseudo* S-C Fabric or duplex structure.

A great majority of deformation bands are vertical to very steeply dipping. All the deformation bands in Fig. 8 are seen horizontal outcrop surface. Deformation bands in general do not show any offset. Only at a few instances strike-slip displacement of earlier formed deformation bands have been observed (Fig. 8f). The general lack of offset in outcrop scale can be attributed to the fact that deformation bands are sub-vertical and bedding plane are sub-horizontal and the slip is strike-slip type. The strike-slip sense of displacement is contradictory to the supposedly rift setting for

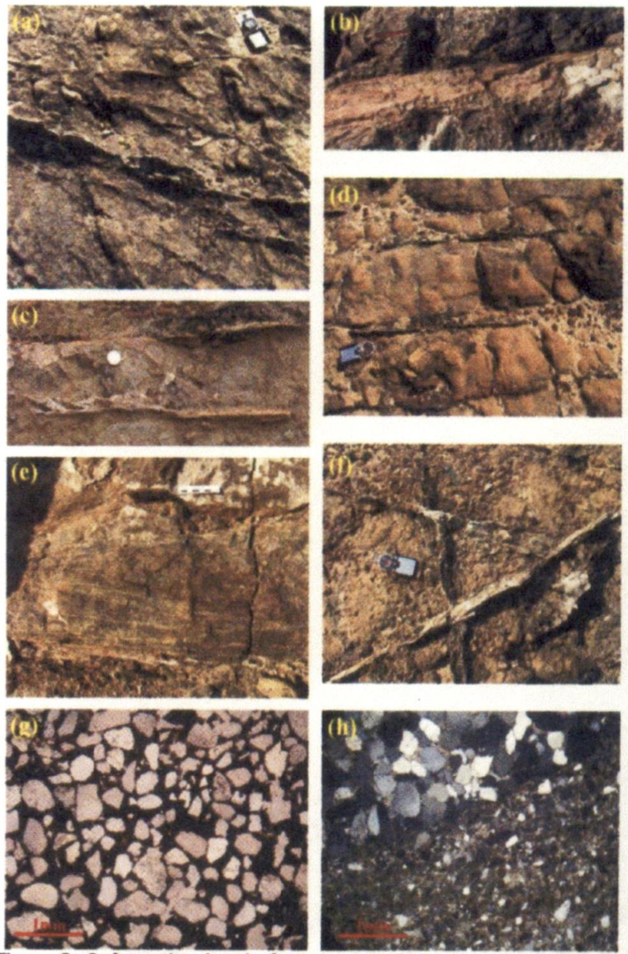


Figure 8. Deformation bands from western Rajasthan. (a) A group of deformation bands cross-cutting each other at low angles. (b) Zone of linked deformation bands. (c) Two parallel deformation bands cross linked by thinner and oblique deformation bands. (d) Two orthogonal sets of deformation giving rectangular zones of undeformed areas. (e) Undeformed pod within a zone of linked deformation bands. (f) Three sets of deformation bands. Offset can be seen in the upper left part of the photograph. Note that the deformation bands stand up against eroded porous sandstones due to increased cohesion. (g) Thin section of original porous sandstone. Dark area is pore space filled with epoxy. Plane polarized light. (h) Deformation band in thin section. Note compaction in the upper left part and cataclasis and calcite cementation in the lower right part (Crossed nicols).

the Barmer Basin. Mapping of the deformation bands and variation in density of deformation bands within unit area suggest that the deformation bands in the Barmer Basin are not necessarily related to particular faults but developed in response to the overall stress field.

As mentioned earlier, sandstones in this area are highly porous (Fig. 8g). The deformation bands show overall compaction cored by a zone of grain size reduction through cataclastic flow (Fig. 8h). Many deformation bands also acted as conduit for fluid flow resulting in cementation through silica and/or calcite precipitation from the circulating fluid (Fig. 8h). The host rocks, though highly porous, do not show evidence significant dissolution and precipitation. The catacalstic flow and cementation increase cohesion of the rocks in the deformation band.

CONCLUDING REMARKS

The deformation bands in porous sandstones are primary deformation structures. Although these structures are known for some time, but of late their importance in management of the is hydrocarbon and groundwater reservoirs has been nized. The effectiveness of deformation bands as fluid flow rs or baffles depends on whether they decrease or increase ion. The petrophysical properties are altered relative to the unding rock depending on deformation mechanism, the er of bands (collective thickness), their orientation and their uity, and the variation in permeability and porosity along and dip. Additionally, they may prove to be useful stress indicator if they occur in conjugate pairs and icement recorded by offset markers.

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ABSTRACT VOLUME

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CATACLASTIC SLIP BANDS IN HIGH POROSITY SANDSTONES OF THE BARMER BASIN, RAJASTHAN

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There is a renewed interest in the Barmer Basin of western Rajasthan owing to discovery of huge hydrocarbon reserves by Cairn Energy India. The NNW-SSE trending Barmer Basin is thought to have been formed by rifting of continental crust composed dominantly of late Proterozoic Malani igneous suite of rocks. The sandstones of the Fatehgarh and Lathi formations in this basin are highly porous with porosity and permeability exceeding 30% and 10 darcy, respectively.

Deformation of these high porosity sandstones typically produces deformation bands referred to as cataclastic slip bands (CSBs). Characteristic features of CSBs include: (1) they are mm to cm thick, tabular and low-displacement deformation zones, (2) they are restricted to highly porous sandstones or unconsolidated sediments, (3) they occur as single bands or zones of complex linked systems, (4) displacements across the bands are very small as compared to length of the bands, (5) they are commonly associated with fault damage zones or occur near fault tips and (6) the dominant deformation mechanisms within CSBs are grain rotation, frictional sliding and cataclastic flow. Shear offsets in CSBs may be used for paleostress analysis following the same method used for conjugate shear fractures or ductile shear zones.

In the outcrop sections of porous sandstones of the Fatehgarh and Lathi formations exposed at the northern end of the basin, CSBs occur as thin, isolated bands or as wide (up to about one meter thick) zones where a group of thin CSBs cross-cut each other at very low angles. The CSBs dip very steeply and their strike lengths vary from a few meters to few tens of meters. Three parallel sets (based on orientation analysis) of CSBs have been recognized and cross-cutting sets of CSBs separate rectangular or triangular zones of undeformed pods where original sedimentary textures are preserved. A set of parallel CSBs may be linked by thin CSBs giving the appearance of a duplex structure or pseudo S-C fabric. In a few exposures, strike-slip displacements across CSBs are observed. This type of displacement is not consistent with the rift origin of the Barmer Bain and suggests a later period of compressional deformation, possibly related to the Indo-Himalayan collision and inversion of the northern parts of the basin. In thin sections, CSBs are defined by a grain size reduction and increase is grain angularity as a result of cataclastic flow and brittle fracturing of grains. In some outcrops, they acted as conduit for fluid flow that led to precipitation of carbonate or siliceous material and reduced prorosity and permeability.

CSBs are unlikely to seal hydrocarbons, but they do alter the petrophysical properties of the porous sedimentary rocks and may act as a baffle for fluid flow. Thus an understanding of their characteristics, orientation and continuity are important for both hydrocarbon exploration and reservoir management.

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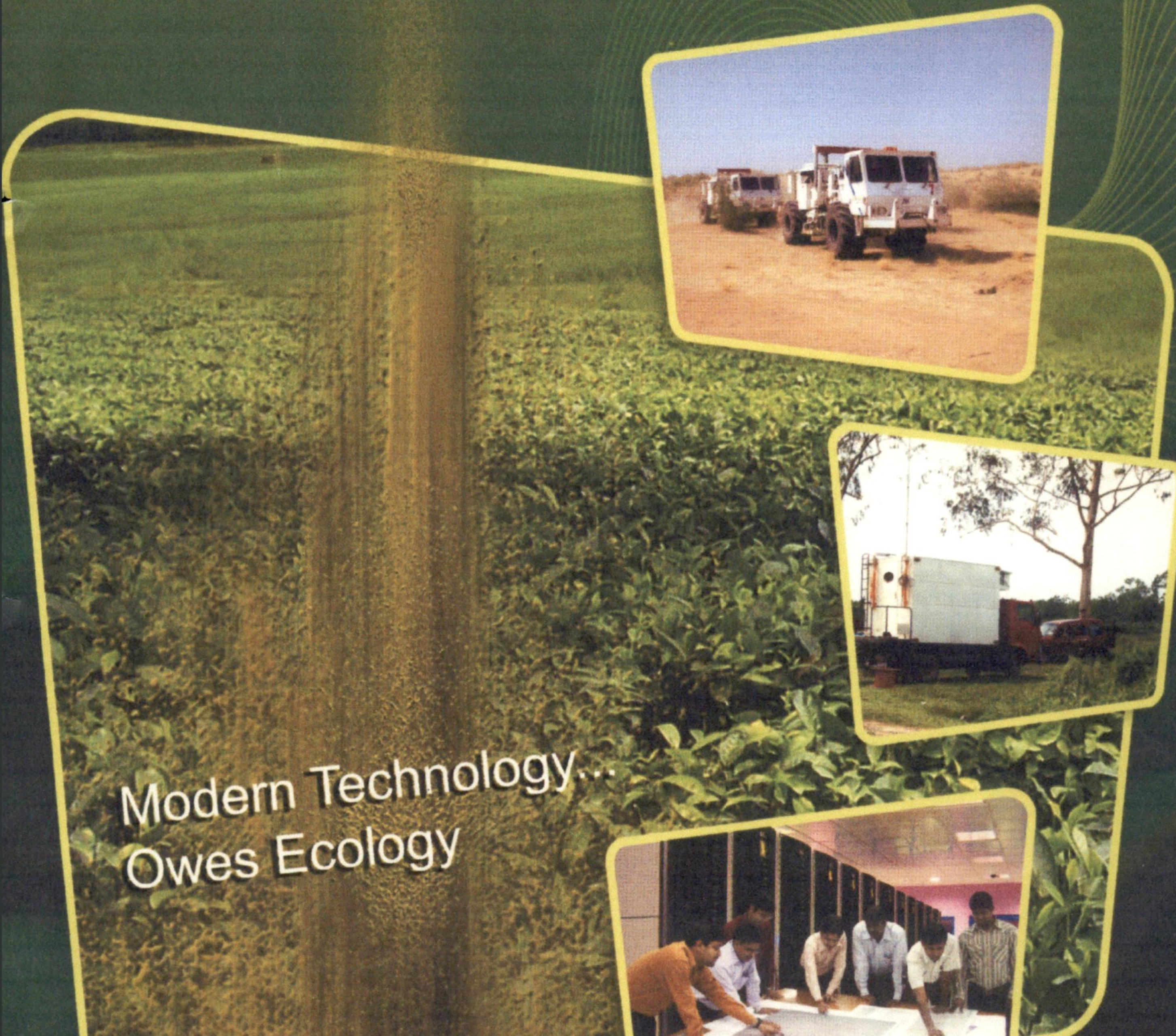

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Inversion Tectonics

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Introduction

The term *inversion* was coined by K.W. Glennie and P.L.E Boegner in 1981 but inverted petroliferous sedimentary basins are known for a long time. Structural inversion occurs when basin-controlling extensional faults reverse their movement during subsequent compressional tectonics. This leads to uplift of part of the basin and it is called positive inversion. The converse is also possible, i.e., compressional tectonics may invert to extensional tectonics leading to subsidence of the basin. This is the so-called negative inversion. suggested that the term should be restricted to the basins whose extensional phase was controlled by normal faulting and in which the stress regime would undergo a fundamental change resulting in extensive re-use or reactivation of pre-existing faults. According to this definition, tectonic inversion effectively excludes flexural, thermal or isostatic uplift of sedimentary basin. In an inverted structure one usually locates a point, a *Null point*, which represents a change on the fault surface from net normal to net reverse displacement.

Structural and petroleum geologists have paid much attention to inversion structures because of their importance in oil prospecting, as indicator of the history of regional stress fields and orogenic processes. There are classic cases of inversion in marine environments in North America, Andean subduction margin, Abanico basin (Principal Cordillera of central Chile), Jiuquan Basin (western China), Broad Fourteen Basin (offshore of Holland) and others.

Types of Inversion

Structural inversion can be considered to be of four types:

Classical positive inversions: In a classical positive inversion extensional half grabens are inverted as compressional or transpressional uplifts (Fig. 1). The positive inversion structures are characterized by reverse offset in the upper part and net extensional displacement retained in the lower part.

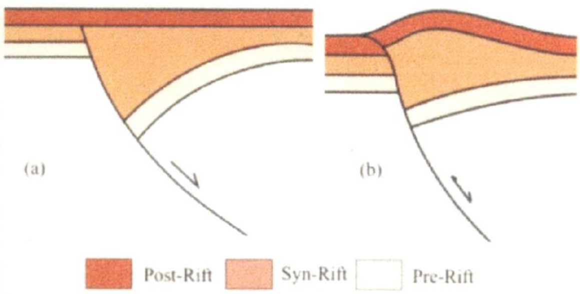


Figure 1: *(a) Normal fault. (b) Normal fault reactivated as reverse fault.*

Negative inversion: In negative inversion thrust fault uplifts are inverted as half grabens in extensional reactivation (Fig. 2). The negative inversion structures are characterized by normal fault at the top and compressional thrust displacement at the bottom.

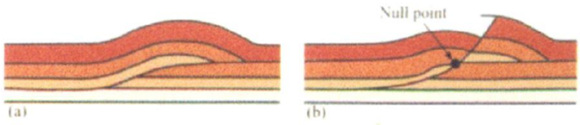


Figure 2: *(a) Thrust fault. (b) Thrust fault reactivated as normal fault.*

Double inversions: Negative/Positive double inversions occur when negative inversion half grabens are in turn partially inverted as faulted anticlines due to transpressional reactivation of master fault (Fig. 3).

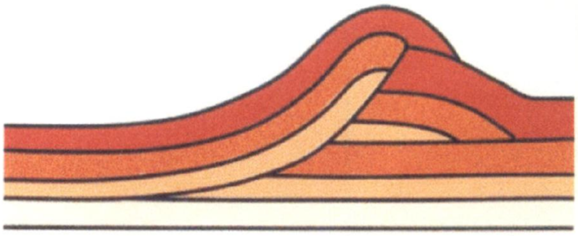


Figure 3: *Double inversion*

Atypical positive inversion: Atypical positive inversion takes place when a compressional syncline is inverted as a compressional anticline. Inversion is atypical as it is implemented by a renewal of compression rather than a reversal in stress field polarity.

Types of Positive Inversion

Following types of positive inversions have been suggested in the literature:

Fault-reactivated inversion: In this type of structure reverse slip by compression is accommodated along a pre-existing normal fault. Commonly syn-depositional normal faults developed during the rifting period may remain dormant or show little movement during post-rift subsidence. Such faults may be reactivated as reverse faults when the region undergoes compression.

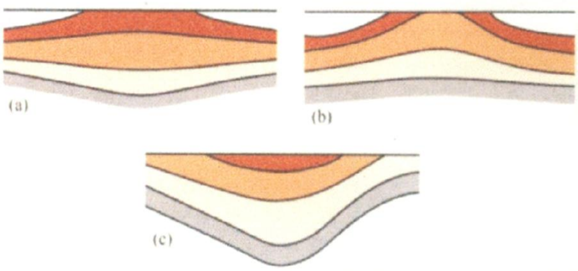


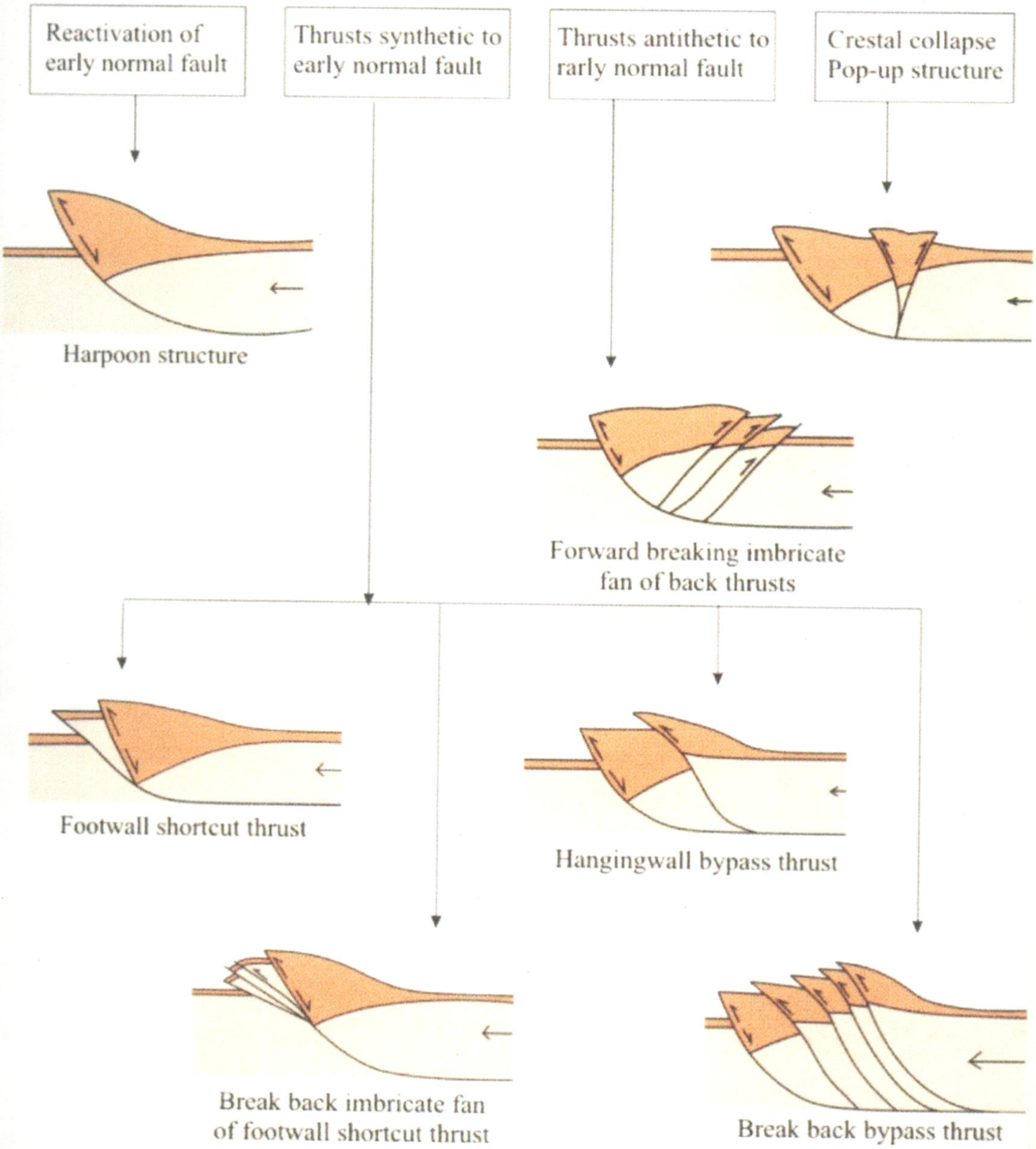
Figure 4: *(a) Lens geometry of inverted subsidence. (b) Antiformal inverted subsidence formed at advanced stages of basin inversion. (c) Synformal inverted subsidence due to minor inversion*

Cover-folded inversion: Cover folded inversion usually occurs in saucer-shaped basins (Fig. 4). The basin which is not affected by significant syn-rift faulting is deformed during the inversion movement resulting in a lens-shaped geometry with antiformal structure at upper levels and synformal structure at lower levels. The compressional movement does not reactivate the pre-existing fault controlling the graben or only causes little displacement of the fault due to large fault dip. Cover-folded inversion structures normally occur in basins where the sedimentary thickness is large.

Strike-Slip inversion: When the geometry of a reactivated fault indicates inversion of strike-slip motion sense it is called strike slip inversion. This type of inversion structure may be related to transformation of the strike-slip movement from sinistral to dextral resulting in the development of both negative and positive flower structures.

The most commonly observed positive inverted structures can have widely varying geometry and kinematic evolution. Figure 5 is a summary diagram showing main types of positive inversion structures.

Inverted structures are increasingly recognised in many sedimentary basins. The variations in the geometry of these structures can have significant bearing on exploration for hydrocarbon in inverted basins. An understating of the geometry and kinematics of these structures are of paramount importance for reliable interpretation of seismic profiles as well as for hydrocarbon exploration.



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