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Rotated and displaced clay balls as kinematic indicators along shear zones in sandstones of the Siwalik Group of Surghar-Shinghar Range, Trans-Indus Ranges, Pakistan

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ABSTRACT: *Neo-tectonic events in the Siwalik Group of Surghar-Shinghar Range are characterized by compressional, extensional and conjugate shear fractures. The compressional fractures are in the form of reverse faults mainly along clay ball scoured surfaces. The sense of shear in these fractures is interpreted from rotated and displaced clay ball geometry. Shearing along these weak planes provide kinematics of clay ball geometrical behavior and their mechanical/strength characteristics under surface P/T conditions. Most of the displaced clay balls are moderately hard due to the presence of carbonates, while others constitute some fine carbonaceous material. Thus, the displacement in the clay balls is controlled by their hardness. Some displaced clay balls show nice geometrical arrangement of Riedel fracture sets accommodating strain during shearing. Despite near-surface conditions (i.e., incohesive-brittle) the clay balls, due to the inherited plastic character of clays, form structures resembling those in plastic regimes of deformation. These structures include asymmetric rotated clay balls with tail edges just like in porphyroclasts, while others are equantly rotated forming oxidized boundaries within the sandstone matrix with no tail edges. The kinematics of both rotated and displaced clay balls show reverse sense of shear all along the compressional faults.*

INTRODUCTION

Kinematic indicators are key to tell the sense and direction of shearing across the shear zones, and are formed in cataclastic (very low/low P/T), transitional (medium P/T) and mylonitic (high P/T) fault rocks (Mawer, 1989). Various structures have been identified as kinematic indicators. Some of the most useful include, assemblage of Riedel pattern in cataclastic shear zones (Riedel, 1929; Tchalenko, 1970; Logan et al, 1979; Chester et al, 1985; Mawer & White, 1987), grooves and striations on slickensided surfaces, fibrous crystal growths along fractures (Ramsay, 1967; Hancock & Barka, 1987; Petit, 1987), *s-c* fabric (Lister & Snoke, 1984), shear-band foliation (Mawer & White, 1987; Mawer, 1988) and rotated porphyroclasts in mylonitic shear zones (Passchier & Simpson, 1986; Lister & Snoke, 1984; Mawar, 1989; Twiss & Moores, 1992). Other structures commonly used as shear-sense indicators include boundins and pinch-and-swell structures, (Hanmer, 1986; Mawer, 1987), asymmetric drag intrafolial folds (Sanderson, 1979; Ramsay et al., 1983) and asymmetric vein arrays (Durney & Ramsay, 1973).

The Siwalik Group of Surghar-Shinghar Range (SSR), Sub-Himalayan mountain belt of Pakistan, is characterised by several sets of compressional, extensional and conjugate shear fractures (Sayab et al., 2001a; Sayab et al, *in press*). Of these, the compressional fractures are in the form of reverse faults concordant with the bedding planes mainly along scoured surfaces. Such fractures are normally devoid of any shear sense indicators. In the studied area, however, clay balls involved in compressional fractures are not only displaced but have several asymmetrical structures resembling closely with porphyroclasts in mylonites. This is because of the inherited plastic behaviour of clay balls during deformation under surface P/T conditions. In this paper we describe the geometry of such structures and show their application in determining sense of shearing.

GEOLOGICAL SETTING

The western part of the upper Indus Basin of Pakistan is composed of Kohat Plateau in the north and Trans-Indus Ranges to the south. The Trans-Indus Ranges include Surghar-Shinghar, Marwat-Khisor and Bhattani, which flank the Bannu Basin (Fig. 1; Gee, 1989). These ranges are a part of Himalayan Frontal Fold and Thrust Belt of Pakistan. They constitute the western extension of the Salt Range displaced by the active Kalabagh Fault (Yeast, 1948; McDoughall & Khan, 1990). The Surghar-Shinghar Range forms an anticlinal structure plunging towards south (Gee, 1989) near the Kurram River (Akhtar, 1983). However, the inner flank (concave side) of the range is deeply eroded, and rarely overfolded forming steep cliffs exposing older formations (Gee, 1989). The range is thrust over the Punjab plains by an active thrust system corresponding to the Surghar Thrust (Main Frontal Thrust) (Gee, 1989; Bender & Raza, 1995; Sayab et al, 2001b).

Regional strike of the SSR from Qabul Khel to Thatti-Nasrati is north-south dipping towards west, however, from Thatti the strike of the strata gradually changes and becomes east-north-east dipping to the north-west. The tectonic impression of the recent thrust system (Surghar Thrust) can be studied in the Siwalik sediments of the SSR in the form of compressional, extensional and conjugate shear fractures. Stress and strain analyses of these fractures show that they are structurally and geometrically related with the Surghar Thrust (Sayab, *in press*; Sayab et al, 2001a).

SHEAR ZONES AND DEFORMATION MECHANISM

Geometry of shear zones and their deformational mechanism largely depend upon syn-shearing breakage style and P/T conditions (Fig.2) and classified as cataclastic, transitional and mylonitic types (Sibson, 1977). Generally, a shear zone is defined as a long, narrow, broadly tabular zone of concentrated inhomogeneous deformation across which one block of rock is displaced with respect to second one (Marwer, 1989). This definition is scale dependent; shear zones can develop at any scale from lithospheric plates to that of single grain. Micro- or meso- structures developed at shear zone boundaries and within the shear zones, which are asymmetric with respect to the internal fabric and their asymmetry is directly related to the direction and sense of displacement are referred to as "Kinematic indicators" (e.g., Berthe et al., 1979; Lister & Snoke, 1984; Passcheir & Simpson, 1986; White et al., 1986; Cobbold et al., 1987; Marwer, 1987; Marwer & White, 1987). These must be interpreted parallel to the displaced direction or in the plane perpendicular to the shear zone boundaries or foliation (Mawer, 1988).

Cataclastic deformation is characterized by fractured rocks, which may be either incohesive/brittle (gouge, breccia) or

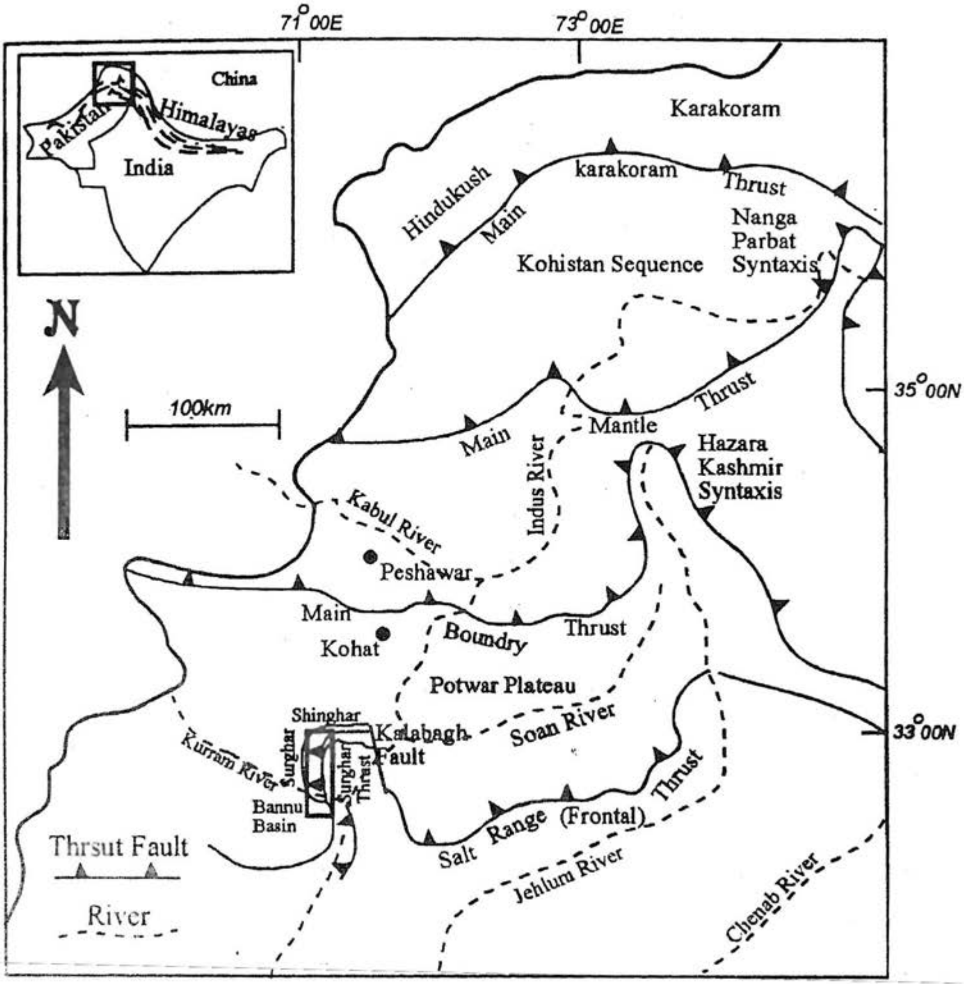

Fig. 1. Outline structural map of northern Pakistan. The box shows the location of the study area.

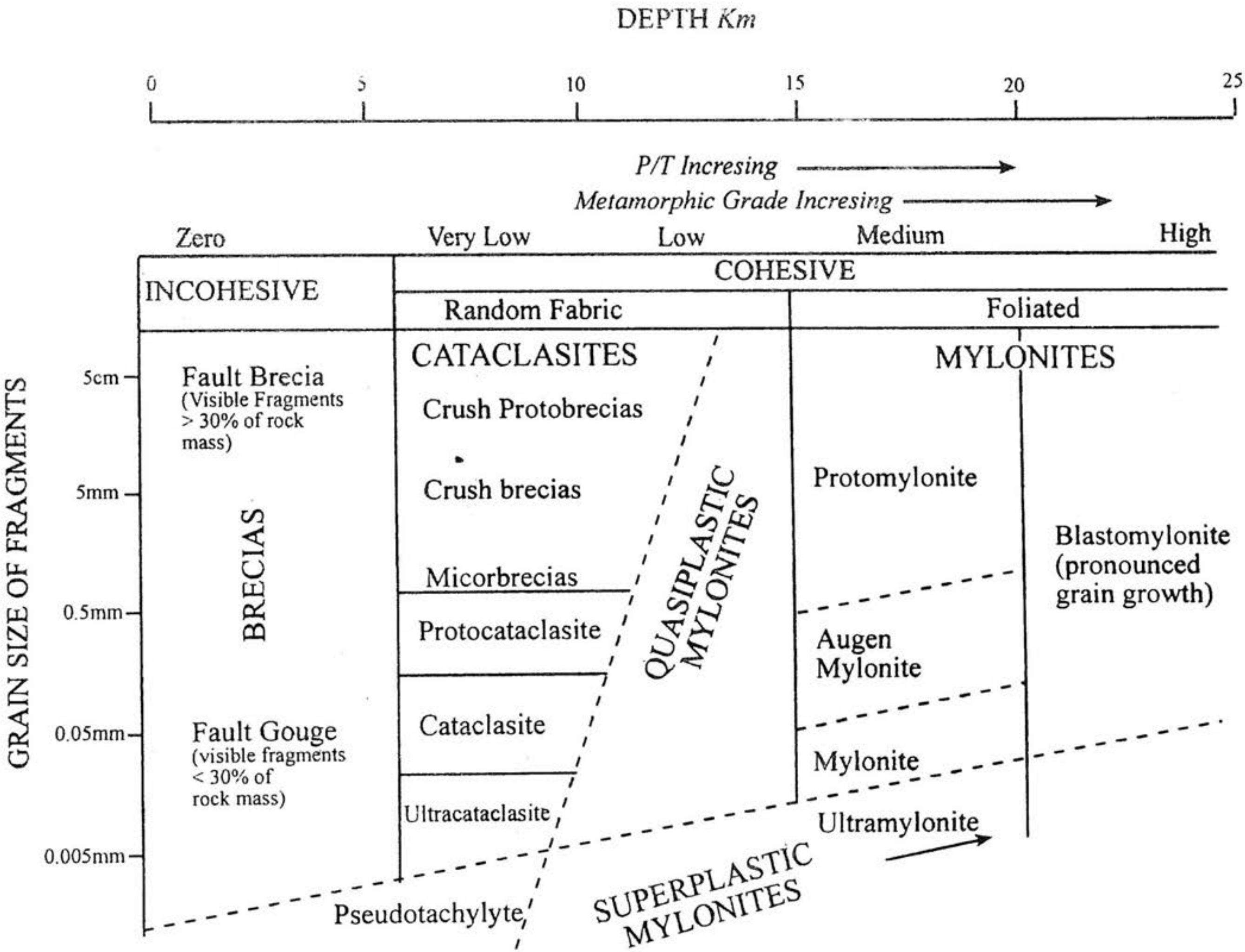

Fig. 2. Classification of fault rocks (Sibson, 1977).

cohesive (cataclasites) (Sibson, 1977). However, the incohesive cataclastic shear zones show grain rolling, reduction in grain size and comminution by brittle fracturing (Sibson, 1977; McKlay, 1997; Mawer, 1988). The shear zones along the clay ball scoured surfaces in the Siwalik Group of SSR show incohesive/brittle cataclastic deformation. Therefore, we will concentrate on the clay ball kinematics under this deformational mechanism.

Range providing weak planes for deformation (Fig.3). The deformed clay balls observed along sheared scoured surfaces range in size from few millimeters to tens of centimeters grounded and displaced within the sandstone matrix (Figs.4,6,7). Generally, the color of the clay balls varies within the Siwalik Group. The clay balls observed in the Dhok Pathan Formation are light-yellowish brown to dark brown, while those found in the Nagri Formation are dark-gray and occasionally greenish gray in color. Greenish

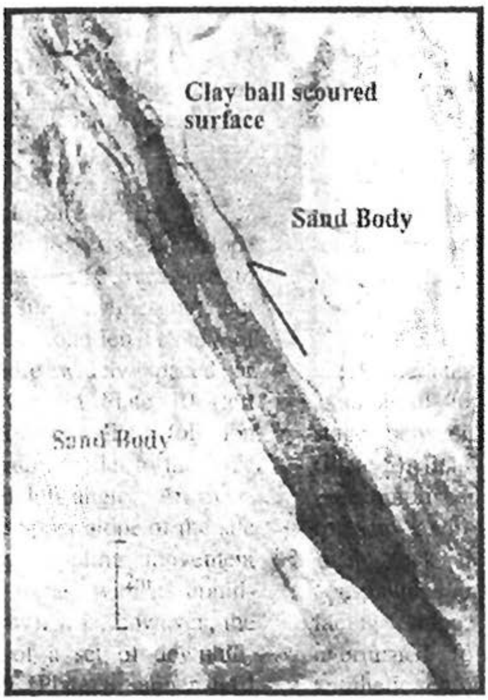

Fig. 3. Clay ball scoured surface within the sandstone body of the Siwalik Group (Dhok Pathan Fm.) provides weak plane for shearing.

SIGNIFICANCE OF CLAY BALL KINEMATICS

Clay ball scoured surfaces are frequently exposed within the massive sandstone bodies of the Siwalik Group of Surghar-Shinghar

gray, maroon to light brown clay balls are observed in the Chinji Formation. To understand the geometry and kinematics of rotated and displaced clay balls with respect to their internal fabric, we can deal them separately.

Displaced clay balls

Clay balls, which are moderately hard due to calcification or with some black, very fine carbonaceous material, are totally displaced along shear planes (Fig.4a,b). Their displacement clearly shows the reverse sense of shear and amount of shear. It appears that their hardness is responsible for their displacement along the shear planes.

(facing to the south)

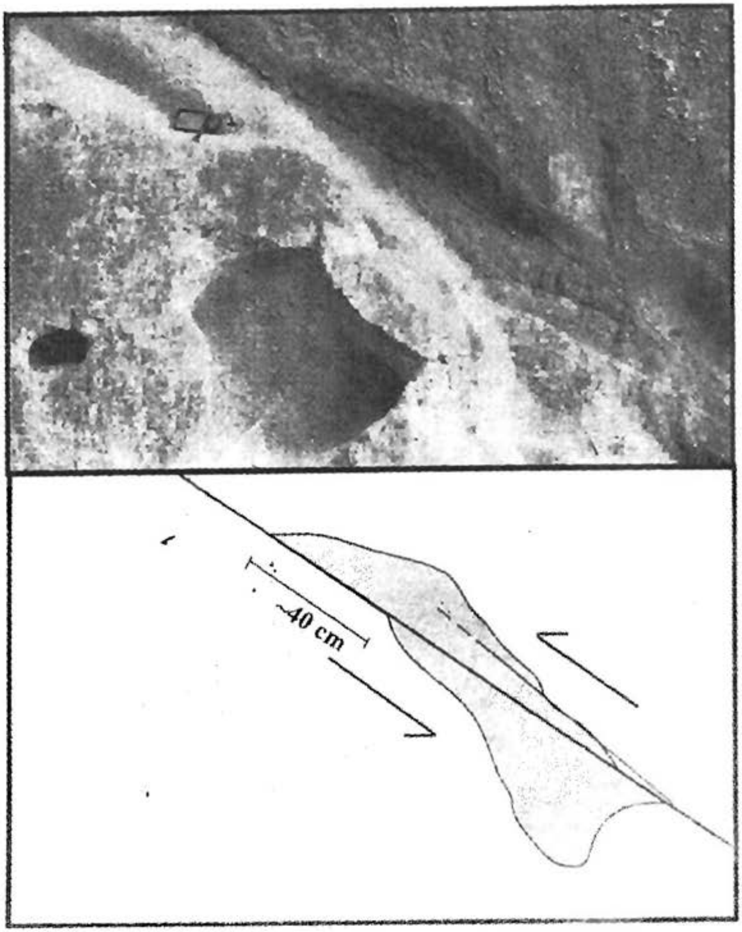

Fig. 4a. Displaced clay ball with maximum 40 centimeters displacement exposed within the Nagri Fm.

Some of the displaced clay balls form internal fabric in the form of riedel fractures (Fig.4c). Two sets i.e., synthetic R_1 and antithetic R_2 conjugate riedel patterns have been recognized within the strained clay balls. Experimental deformation of a clay block induced by shearing the substrate of the clay is carried out by Twiss and Moores (1992). Two sets of fractures, R_1 and R_2 are formed at an angle of about 15° and 75°, respectively (Fig.5). The R_1 Riedel fabric is parallel to the imposed shear, whereas R_2 fractures have opposite sense of shear. The geometrical pattern of R_1 and R_2 help to resolve the sense of shear in most of the brittle shear zones (Mawer, 1988). Therefore, besides the clear-cut indication of

Fig. 4b. Moderately hard clay ball totally displaced along the shear plane, showing reverse sense of shear exposed in the Dhok Pathan Formation.

Fig. 4c. Displaced clay balls with Riedel fracture sets indicating sense of shear.

reverse sense obtained from displaced clay balls, the geometric pattern of R_1 and R_2 fabric within some of the clay balls also suggests the reverse sense of shear.

Most of the rotated clay balls observed along shear zones form asymmetric tails (Fig.7a,b) just like asymmetric tailed porphyroclasts formed in mylonitic shear zones. As the sense of asymmetry of the tails defines the sense of shear in the deformed rocks, therefore, the leading and trailing edges, which are common in most of the rotated clay balls observed along shear zones, are consistent with the shear sense. In most of the rotated clay balls the leading and trailing tails do not pass the center line, just like the σ-type porphyroclasts, indicating reverse movement (Fig.7a,b). Other rotated clay balls along the scoured surfaces are equantly rotated with no tail edges. Within this category two types are recognized regarding their internal fabric. Rotated clay balls with attached tails wrap around the body of the clay ball to a greater extent in some cases and to lesser extent in all cases, indicating shear sense (Fig.7c). The rotation of these clay balls is similar to that of equantly rotated garnets or staurolites with internal helical trains (Fig.7d). The second type forms discrete fractures, clearly

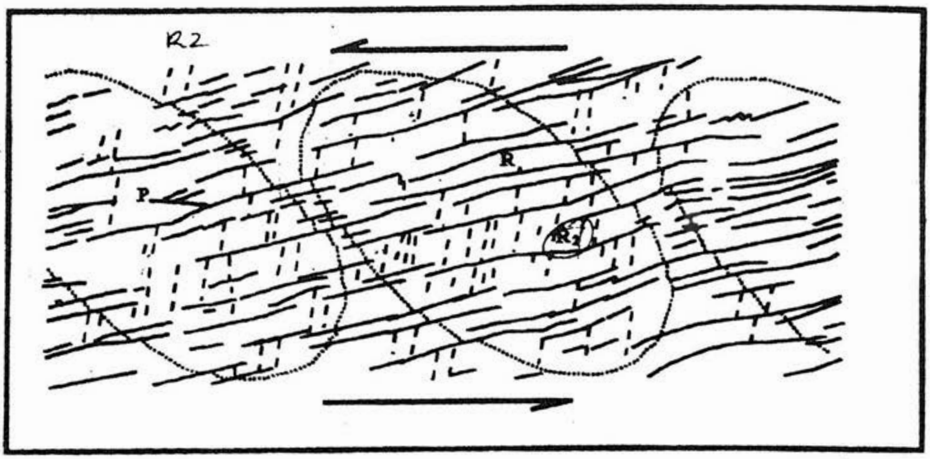

Fig. 5. Sinistral simple shear in a clay block model induced by shearing the substrate of the clay. Note the formation of R_1 and R_2 Riedel fractures (after Twiss & Moores, 1992).

Rotated clay balls

Before going to the descriptions and strain analysis of the rotated clay balls observed along the scoured-shear zones, the geometry of rotated porphyroclasts is important to discuss here, irrespective of their P/T conditions. As both clay balls and porphyroclasts behave plastically during deformation, their mechanism of deformation is same. Twiss & Moores (1992) distinguished two different types of tailed porphyroclasts, σ-type and δ-type in mylonitic shear zones (Fig. 6a & 6b). The σ-porphyroclasts show fine-grained tails attached to their leading and trailing edges, and the tails do not cross the line parallel to the foliation through the center of the grain, indicating the shear sense. The δ-type is derived from the σ-porphyroclasts by continued deformation and rotation in a sense consistent with the shear, and the tail do cross the center line.

indicating reverse shear sense with oxidized boundaries of yellowish brown color (Fig.7e,f,g). Further justification of the reverse sense along these shear zones, where the rotated clay balls are observed, is obtained from the associated displaced clay balls.

Compressional incipient movements, concordant to the bedding, have also been observed within the channel conglomerates of the Siwalik Group (Fig.8). Pebble-size gravels are displaced with two sets of fractures showing reverse sense of movement along the channel scoured surfaces.

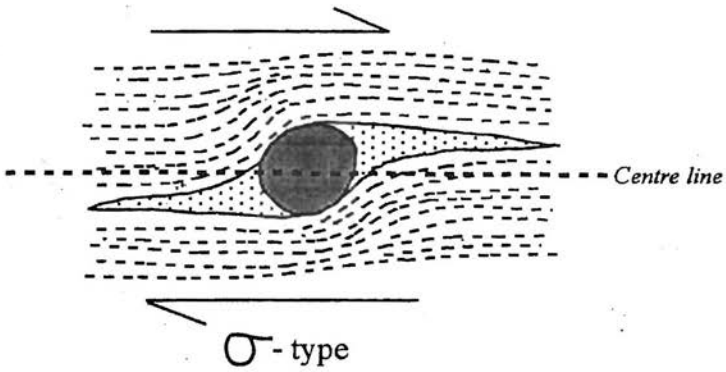

Fig. 6a. -type porphyroclast, showing sense of shearing. Note the tails do not cross the line parallel to the foliation through the centre of the grain (Twiss & Moores, 1992).

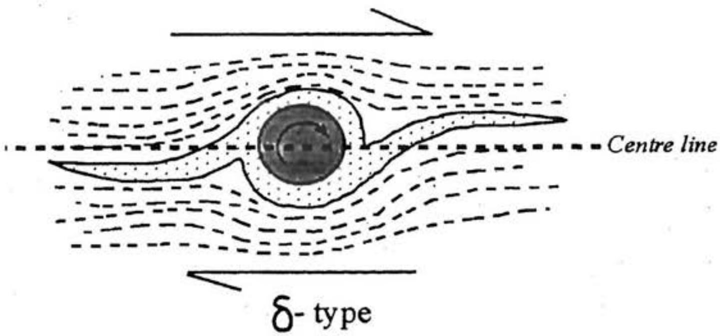

Fig. 6b. -type porphyroclast, derived from the rotation of -type. Note the tails do cross the central line (Twiss & Moores, 1992).

(facing to the south)

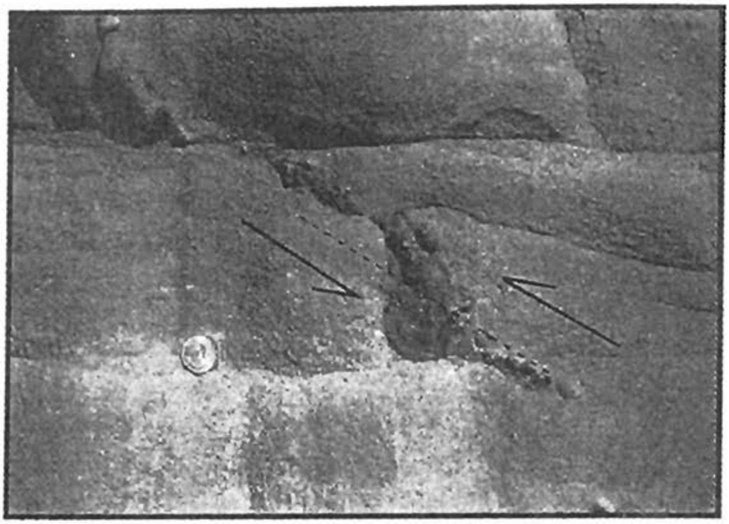

Fig. 7a. A rotated clay ball along the shear zone with asymmetric tails showing sense of movement.

(facing to the south)

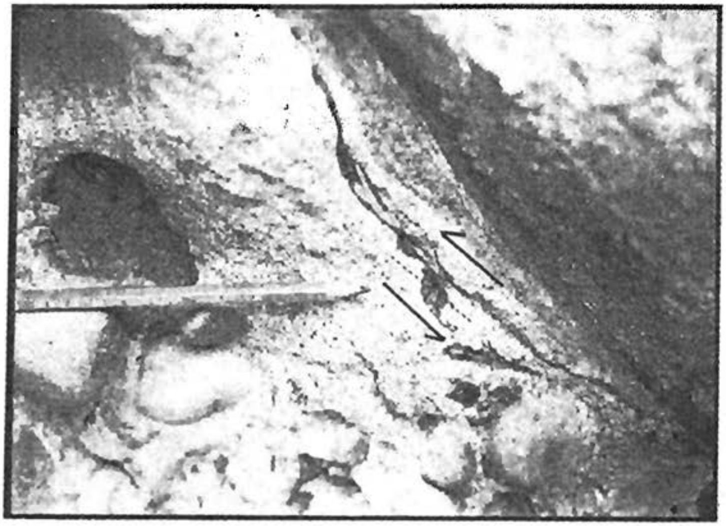

Fig. 7b. The kinematic geometry of the tailed clay ball shows reverse sense of movement.

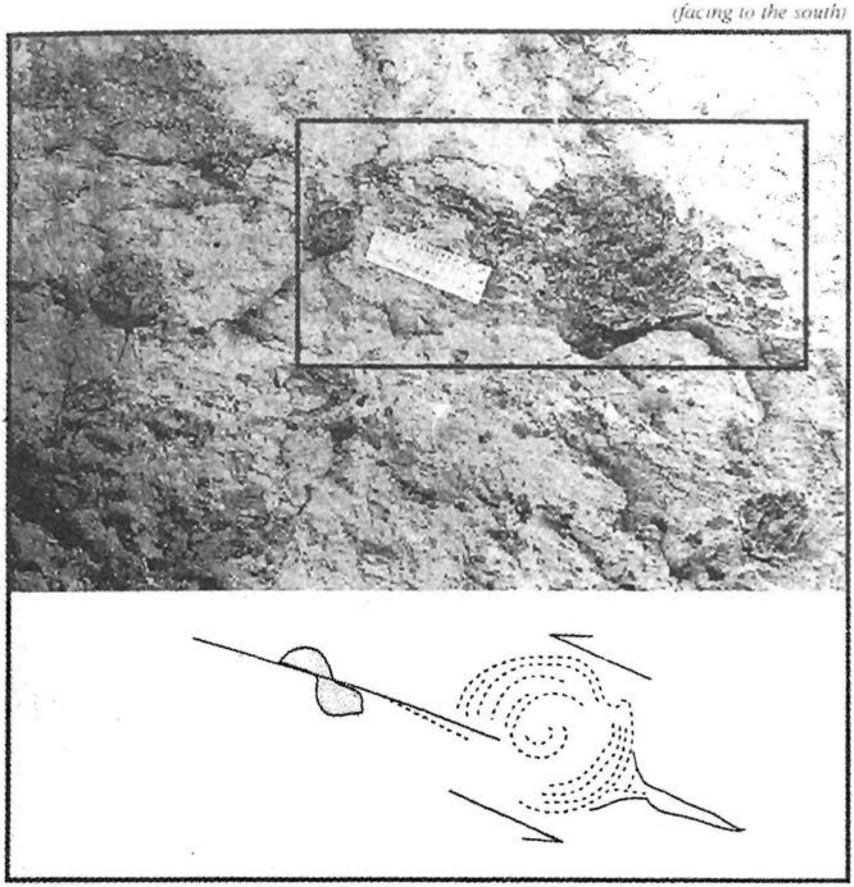

Fig. 7c. The internal fabric of this clay ball is in the form of helical train shows reverse sense of shear.

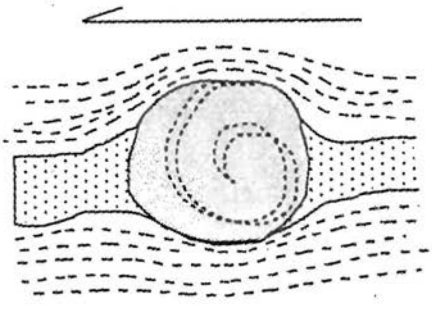

Fig. 7d. The helical train within the porphyroblast shows the sense of rotation and shear (Twiss & Moores, 1992).

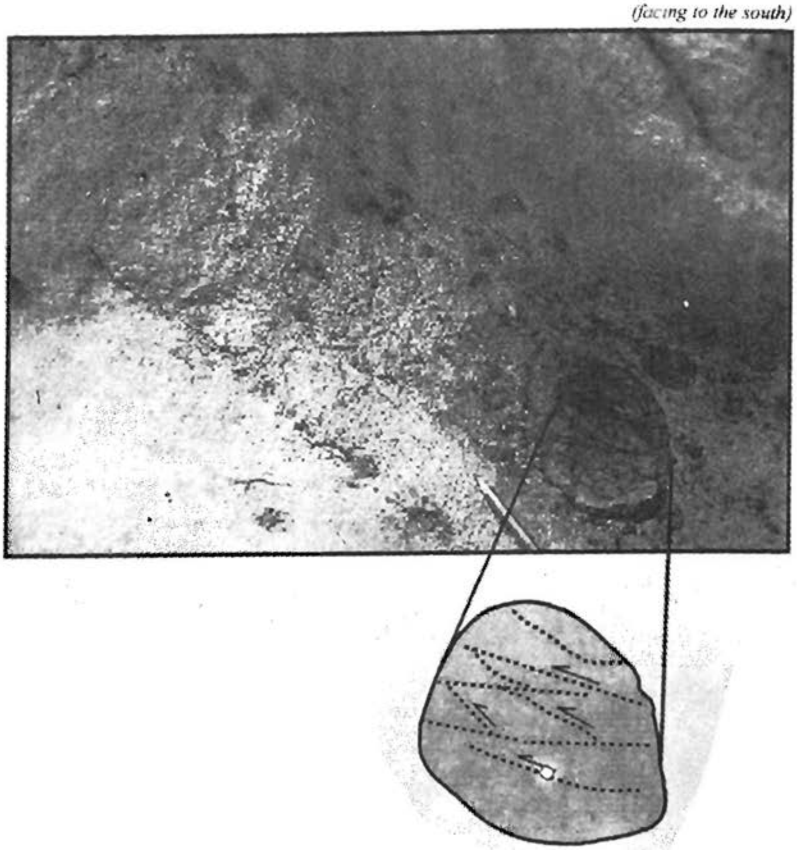

Fig. 7e. Strained clay ball showing reverse sense of shear along the discrete fracture sets.

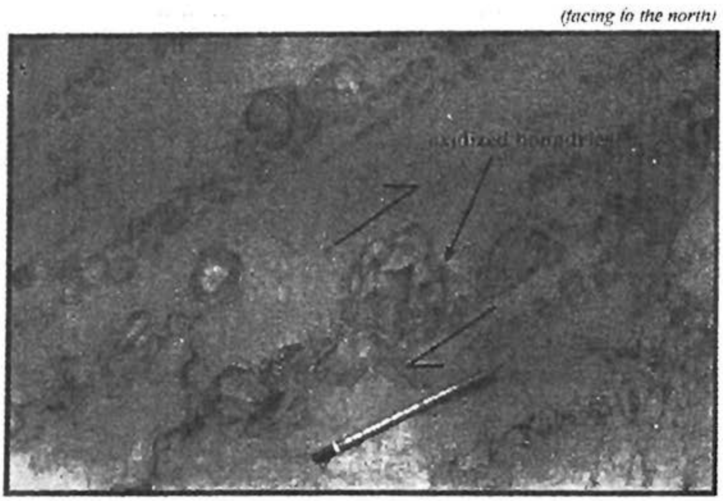

Fig. 7f. Rotated clay balls with oxidized boundaries and discrete fractures accommodating strain, showing reverse sense of movement.

CONCLUSION

The north-south oriented compressional faults in the SSR make an orthogonal relationship with the east-west oriented dilational fractures with a set of conjugate fractures (Sayab et al., 2001). Stress and strain analyses of these fractures sets indicate systematic stress system (Fig.9). These fracture sets are nicely exposed in the western exposed flank of the Siwalik Group of SSR. To accommodate stresses the range forms these fracture sets, which are geometrically controlled by the Surghar Thrust (ST) (Sayab et al., 2001a,b; Sayab, *in press*).

The kinematics of clay balls along compressional faults in the Siwalik sandstones of the SSR have developed under surface P/T conditions. Reverse sense of shear has been interpreted from asymmetric displaced and rotated clay-ball kinematic geometry. The geometry and kinematics of strained clay balls resemble closely with porphyroclasts in mylonites, despite considerable difference in the P/T conditions. Their deformation mechanism is same, both clay balls and porphyroclasts behave plastically during deformation. For instant, garnet or staurolite under high P/T behaves plastically to form asymmetric tails, whereas clay balls, at surface P/T conditions behave

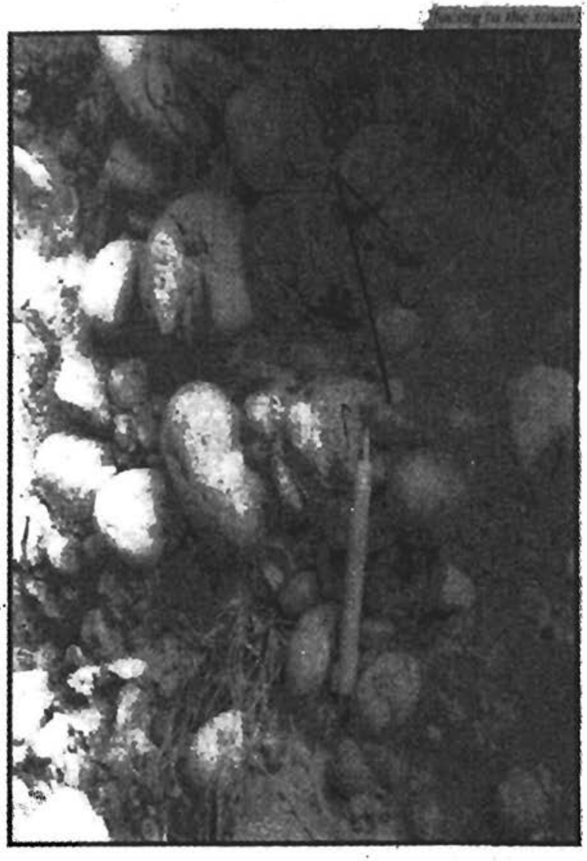

Fig. 8. Fractured (displaced) channel conglomerates showing reverse sense of movement.

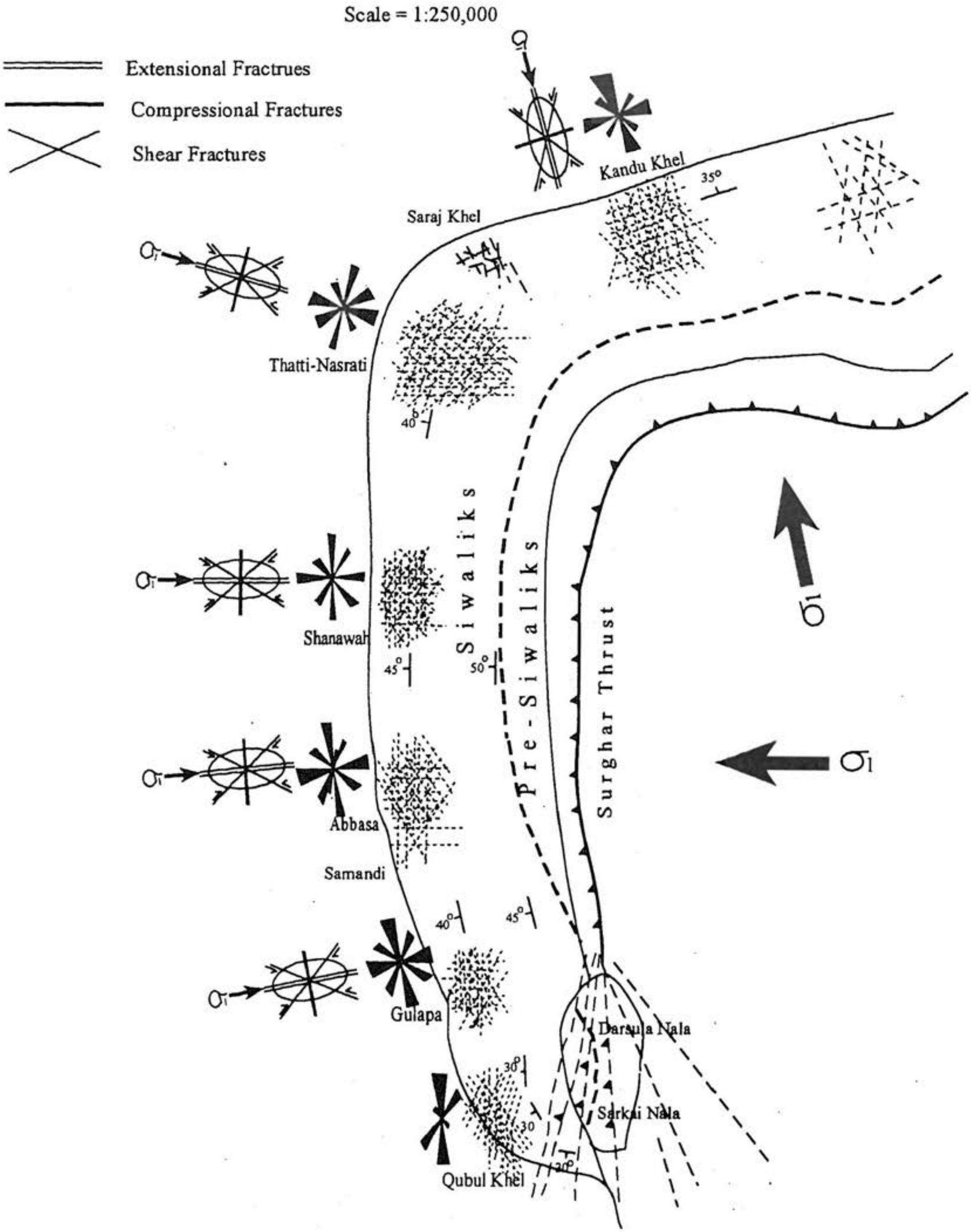

Fig. 9. A preliminary structural map of fractures recorded in the Siwalik Group at different stations, illustrated by rose and stress diagrams, Surghar-Shinghar Range, Bannu Basin.

plastically to form asymmetric tails, as they are composed of very fine detritus. This is probably due to the inherited plastic nature of the clay balls.

Rotated and displaced clay balls in the Siwaliks sediments can be used as kinematic indicators to resolve the sense of movement along shear zones in other foreland terrains of the Himalayas. The understanding of these kinematic structures can help to explain the possible dynamics and kinematics of regional tectonics of the area.

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