Effects of tectonically induced fabrics on geomechanical properties of rocks, NW Pakistan

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Abstract
The Chakdara Granitic Gneisses (CGG) of the Indian plate and Kamila Amphibolite of the Kohistan Island Arc (KIA) along the Main Mantle Thrust (MMT) in Shigo Kas, Talash Dir Lower, indicate that tectonically induced foliations and lineations strongly affected the geomechanical properties of these rocks. The earlier S1 crenulated cleavages are well preserved in the microlithion of a well-developed ENE-WSW trending S2 crenulation cleavage. The pervasive S2 foliations, D2 fold axes, and L2 lineations are induced by NNW-SSE horizontal bulk shortening. The core samples obtained parallel and perpendicular to the main ENE-WSW trending S2 have higher and lower uniaxial compressive strength (UCS) values, respectively. The UCS and uniaxial tensile strength (UTS) average values of four core samples obtained parallel and perpendicular to the main S2 are 51.8 MPa and 12.21 MPa versus 45.65 MPa and 12.45 MPa, respectively. Core samples from the weakly foliated S-2 specimen shows little variation in the UCS and UTS values. The variation in the UCS values in the core samples cut perpendicular and parallel to the main tectonic fabric has been controlled by micro-shear zones at the contact zones of crenulated and crenulation cleavages and sigmoidal mica fish. The UCS values are higher in the core samples parallel to the pervasive S2 and L2 because the parallel shear on the sigmoidal crenulated cleavages in microlithion of the S2 and S2 mica fish counterbalance the parallel external applied load. However, the UCS values decrease in the core samples that were cut perpendicular to the pervasive S2 and L2 because the perpendicular shear on the sigmoidal crenulated cleavages in microlithion of the S2 and S2 mica fish enhances the external applied load, which lead to the failure of core samples.

Keywords MMT · Microscopic to mesoscopic structures · Geomechanical properties · Mica fish

Introduction
Geomechanical properties play important role to predict rocks strength and failure under an applied load for safe engineering purposes. Millions of years deformations, metamorphism, tectonic stresses, and thermal processes associated with crust thickening induce anisotropies in rocks in the form of foliations, lineations, fractures, and shears that affect strength behavior of rocks (Hudson and Harrison 1997; Milnes et al. 2006). Determining geomechanical properties without understanding pre-existing anisotropies at all scale of observations may lead to unrealistic rock strength calculation (Ramamurthy et al. 1993; Hudson and Cosgrove 1997). Tectonically induced penetrative foliations, mineral lineations, mica fish, S-C fabrics, mantle porphyroclast, and shear zones can be used to derive movement of planes along which a rock can potentially collapse during or after construction (Lister and Snoke 1984; Priest 1993; Hudson and Cosgrove 1997; Passchier and Trouw 2005; Chamine et al. 2013; Barton and Quadros 2015; Watkins et al. 2015). Similarly, the planes, which truncate asymmetric crenulated cleavages (S-fabric) in the microlithion against the main crenulation cleavage (C-fabric), can provide additional shear planes for applied loaded stresses. These tectonically induced anisotropies in deformed rocks can potentially affect the engineering characteristics of rocks (Duan and Kwok 2015). Therefore, it is critical to take into account the pattern of metamorphic fabrics, which distinctly exhibit coordinated geometric planes of weakness in tectonically deformed rocks (cf. Miskovsky et al. 2004; Punturo et al. 2014). Most of the times less attention is paid to study

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tectonically induced fabrics, mineral lineations, and intersection lineations in the rocks that eventually are used in construction and as bedrocks. These structures that are produced as a result of multiple deformations could affect mechanical strength of rocks, which make construction designs more complex and elaborative (Milnes 2006). Indian plate and KIA collision induced multiple penetrative foliations and lineations at all scale of observations in the rocks exposed south and north of the MMT (DiPietro et al. 2008; Ali et al. 2016). This research insight into the affects of tectonically induced geometric structures on rocks compressive and tensile strengths and thus provides a better understanding of the effect of tectonic fabrics on the engineering properties of a rock.

Regional geology

The MMT formed as a result of the Indian plate collision with the KIA ~ 60 to 40 Ma (Fig. 1; Yin 2006). The KIA is formed as a result of intra-oceanic subduction of the Neo-Tethys in the Cretaceous. The MMT mélange zone is the western continuation of the Indus Tsangpo Suture Zone, which is comprised of deformed and metamorphosed northernmost and southernmost marginal rocks of the Indian plate and KIA, respectively (Fig. 1; DiPietro et al. 2008 and references therein). Four penetrative tectonic fabrics have been established in the northernmost rocks of the Indian plate (DiPietro et al. 2008; Ali et al. 2016). NW-SE trending D1 structures are mostly preserved in the microlithons as crenulated cleavages or in the garnet porphyroblasts. At outcrop scale D1 are transposed by NE-SW to ENE-WSW trending D2 structures, which is the most dominant fabric of the northernmost Indian plate. The D2 structures are later overprinted by D3 structures that also resulted into regional-scale domal and syntactical structures. D3 associated fabric is counterclockwise rotated by D4 tectonic event (Ali et al. 2016). Chlorite replacement by biotite in the main S2 crenulation cleavage domain indicates prograde metamorphic conditions associated with the D2. It has been interpreted that the garnet growth predated D2, D3, and D4 tectonic events because the main S2 fabric is wrapped around the garnet porphyroblasts (Ali et al. 2016).

The study area comprises MMT hanging and foot walls (Fig. 1). The hanging wall comprises the Indus suture zone and Kamila Amphibolite, whereas the foot wall consists of the
Cambrian to Ordovician CGG (Kazmi and Jan 1997) and Permian to Late Mesozoic Alpurai Group metasediments of the Indian plate (DiPietro et al. 2008).

**Methodology**

Penetrative planar and linear fabrics were measured from the CGG, melange zone, and Kamila Amphibolite exposed north and south of the MMT respectively (Fig. 1). Petrographic and micro-structural analyses were made from 19 oriented samples that were cut parallel to the main crenulation cleavage. Respectively four and one bulk samples were collected from the CGG and Kamila Amphibolite to study the effect of the metamorphic fabric on the mechanical properties of rocks. A total of two core samples perpendicular and parallel to the main tectonic fabric were obtained according to ASTM specification (ASTM D-3976 1986) from each bulk sample to calculate the UTS and UCS. These tests were conducted at the Department of Mining Engineering, University of Engineering and Technology, Peshawar.

**Detailed petrographic investigations**

A total of 19 oriented samples were collected from CGG, melange zone, and Kamila Amphibolite exposed north and south of the MMT respectively. These samples were cut parallel and perpendicular to the main crenulation cleavage. Detailed petrographic investigations distinguished granitic gneisses, siliceous chloritized marble, amphibolite, undifferentiated quartz rich foliated rock, and epidote chlorite schist on the basis of mineralogy (Table 1). The granitic gneisses are mainly comprised of quartz, alkali feldspar, plagioclase, biotite, and muscovite with minor garnet and epidote. These rocks are characterized by well-developed cleavage domain (crenulation cleavages/C-fabric) dominated by muscovite, biotite, and stretched quartz grains, and microlithon/Q-domain shows concentrated quartz, feldspar, and plagioclase (Fig. 2a–c). Plagioclase and feldspar exhibit sericitization (Figs. 2b, c and 3a–d). The crenulation cleavage that is defined by elongated biotite and muscovite deflected around the pre-existing feldspar and plagioclase grains (Fig. 3a–d). Intense deformation imparted undulose extinction to quartz grains in all samples. The replacement of feldspar and plagioclase by muscovite indicates retrograde metamorphic conditions in the region. The partitioning of deformation into coaxial and non-coaxial zones around feldspar and plagioclase grains nicely developed strain shadows (Fig. 3c, d). Coarse-grained amphibolite exposed north of the MMT mélange zone mainly consists of amphibole with well-developed epidote and retrograde chlorite. The preferred orientation of elongated amphibole imparted foliation to amphibolite (Fig. 3e). The epidote chlorite schist from the mélange zone comprises mainly epidote, chlorite, and quartz (Fig. 4a–d). The main gneissosity in

| Rock types                        | Sample. no. | Qz | Bt | Ms | Pl | Afs | Amp | Grt | Ep | Chl | Cal |
|-----------------------------------|-------------|----|----|----|----|-----|-----|-----|----|-----|-----|
| Granitic gneiss                   | S1          | 44 | 15 | 15 | 5  | 20  | –   | –   | 1  | –   | –   |
|                                   | S2          | 36 | 20 | 17 | 21 | 6   | –   | <1  | –  | –   | –   |
|                                   | S4          | 35 | 4  | 24 | 13 | 20  | –   | <1  | 1  | –   | –   |
|                                   | S5          | 56 | 2  | 7  | 10 | 25  | –   | –   | –  | –   | –   |
|                                   | S6          | 36 | 22 | 20 | 13 | 9   | –   | –   | –  | –   | –   |
|                                   | S7          | 40 | 15 | 15 | 20 | –   | –   | –   | –  | –   | –   |
|                                   | S8          | 27 | 20 | 30 | 12 | 11  | –   | –   | –  | –   | –   |
|                                   | S9          | 34 | 25 | 25 | 7  | 9   | –   | –   | –  | –   | –   |
|                                   | S10         | 38 | 20 | 12 | 12 | 18  | –   | –   | –  | –   | –   |
|                                   | S11         | 40 | 3  | 20 | 7  | 30  | –   | –   | –  | –   | –   |
|                                   | S12         | 44 | 25 | 10 | 5  | 16  | –   | –   | –  | –   | –   |
|                                   | S13         | 45 | 8  | 20 | 20 | –   | 2   | –   | –  | –   | –   |
|                                   | S15         | 50 | 13 | 20 | 7  | 5   | 5   | –   | –  | –   | –   |
|                                   | S16         | 45 | 20 | 12 | 22 | –   | 1   | –   | –  | –   | –   |
|                                   | S17         | 50 | 1  | 15 | 7  | 27  | –   | –   | –  | –   | –   |
| Siliceous chloritized marble      | S18         | 30 | –  | –  | –  | –   | –   | –   | 20 | 50  | –   |
| Amphibolite                       | S3 (Core)   | Traces | –  | –  | –  | 84  | 13  | 2   | –  | –   | –   |
| Foliated rock                     | S19         | Undifferentiated quartz-rich foliated rock | –   | –  | –  | –   | 45  | 35  | –  | –   | –   |
| Epidote chlorite schist           | S20         | 20 | –  | –  | –  | –   | –   | –   | 20 | 50  | –   |
the rock is cut across by a quartzo-feldspathic vein (Fig. 4a). Detailed observation of the specimens from thin section in plane polarized and cross-polarized lights revealed that the larger crystals of epidote with high relief and well-developed cleavages are preferentially oriented (Fig. 4c). Rounded epidote clusters are randomly fractured (Fig. 4b). Mineral rims, fractures, and cleavages are replaced by chlorite (Fig. 4c, d).

**Mesoscopic structures**

Multiple deformed rocks of the CGG, melange zone, and Kamila Amphibolite preserved progressive fabric development in the form of $S_2, L^2_2$, and $L_3^2$ in the rock matrix and at outcrop. $D_2$-related $S_2$ forms the dominant regional foliation and is ornamented by $L_{2}^2$ mineral stretching lineations (quartz and feldspar) in the CGG (Fig. 5a–d).

A total of 22 measurements of $S_2$ were plotted on the stereonet (Fig. 6a). A total of 15 $L_{3}^2$ intersection lineations are measured, and their plunge directions are plotted on stereonet (Fig. 6b). Intersection lineations are plunging in ENE direction. $L_{2}^2$ mineral stretching lineations data were collected at outcrop and from oriented photographs. A total of 322 ENE-WSW trending $L_{2}^2$ were measured, and their orientation was plotted on rose diagram (Fig. 6c). About 239 and 83 $L_{2}^2$ mineral stretching lineations were measured at outcrop and from oriented photographs, respectively. All $L_{2}^2$ mineral stretching lineations are parallel to $D_2$ fold axis. A total of 19 vertical thin sections parallel to lineation were prepared to study the mineral elongation lineation at microscopic scale. Microscopically the $S_2$ parallel lineations are defined by elongated muscovite, quartz, biotite, and feldspar grains.

**Microscopic structures**

Mica fish orientations were measured from oriented thin sections (Fig. 7a–f) in the plane parallel to the stretching lineations. Morphology of mica fish allowed a subdivision into several groups based on orientation of lattice plane and shape. Most of the mica fish lie in the range of sigmoid to lenticular shape with few in the composite shape. Measurement of the angle of long axis of 335 mica fish with main foliation gives a mean value of $22.21^\circ$ (Table 2). These mica fish show top-to-SSE shear sense south of the MMT.

The sigmoidal quartz grains exhibit similar shape strain shadows and shape preferred orientation to the mica fish. The quartz grains are elongated in shape and contain small recrystallized grains dominantly at the tips of the fish (Fig. 7d, f). These fish-like quartz crystals were formed by crystallastic deformation (ten Grotenhuis et al. 2003). This sigmoidal recrystallized quartz fish shows a dextral shear sense (Fig. 7d, f). The presence of mica fish in the microlithon and C-fabric in CGG is defined by the concentration of muscovite, biotite, and stretched quartz to the top of the SSE dextral shear sense (Fig. 3b, c, d).
Based on detailed petrographic observations five bulk samples, four from CGG and one from Kamila Amphibolite, were selected for detailed geomechanical analyses. The presence of foliations and lineations at all scales of observations in these rocks indicates that these structures are pervasively developed in the region. To look into the impact of penetrative fabrics on the strength of rocks the selected bulk samples were cored perpendicular and parallel to the main S2 foliations using core drilling machine housed at the Department of Mining Engineering, University of Engineering and Technology Peshawar. Porosity, water absorption, and specific gravity of the above cored samples were determined at the Rock Cutting Laboratory, Department of Geology, University of Peshawar.

**Strength of the Core samples**

The strength of core samples was determined through UCS (ASM D-7012 2010) and UTS using universal testing machine (UTM). The UTS values were measured by Brazilian method (ASTM D-3967 1986).

**Shear strength**

The shear strength was indirectly calculated from UCS and UTS in two-dimensional graphical representations using the Mohr’s circle (Fig. 8). The cohesion ($c$) was determined by...
measuring the distance between the points of intersection between $X$ and $Y$ and the point at which the tangent cuts the vertical axis, whereas the maximum shear strength ($\tau$) was calculated by plotting the failure point along $Y$-axis (Table 3). The angle of internal friction ($\Phi$) was calculated from the angle of tangent with the $X$-axis (Table 3).

**Results**

Mesoscopically ENE-WSW trending $S_2$ pervasive foliation and $L^2_2$ developed parallel to $D_2$ fold axis (Fig. 6c). The $D_2$ tectonic event is overprinted by ENE plunging $L^3_2$ intersection lineations (Fig. 6b). The sigmoidal $S_1$ crenulated cleavage
was not observed mesoscopically. To look into the impact of penetrative fabrics on the strength of rocks the selected bulk samples are cored perpendicular and parallel to the main $S_2$ foliations. Microscopically, the $S_2$ crenulation cleavage/C-fabric microlithon nicely preserved $S_1$ crenulated cleavage and is defined by sigmoidal muscovite, biotite, and stretched quartz (Fig. 2a–c). Microscopic differential stresses anastomose the well-developed matrix $S_2$ around coarse-grained plagioclase and feldspar grains (Fig. 3b, c). $S_2$ intensification around rigid plagioclase and feldspar grains at strain caps led to precipitation of quartz and fine mica in the strain shadows (Fig. 3c, d). The $S_2$ crenulation cleavage also deflects around sigmoid to lenticular mica fish trending $22.21^\circ$ with top-to-SSE shear sense (Fig. 7; Table 2).

The UCS average value of four core samples that were taken parallel to the main $S_2$ tectonic fabric from the CGG is 51.8 MPa as compare to UCS average value of 45.35 MPa obtained from the core samples taken perpendicular to the $S_2$ main foliation. The UCS values of amphibolite rock from the KIA are 91.31 MPa and 59.23 MPa parallel and perpendicular to the $S_2$ main foliations, respectively (Table 3). The $S_2$ sample obtained from comparatively massive part of the CGG shows less variation in strength in core samples cut parallel and perpendicular to the $S_2$ foliations and lineations. The UCS, $c$, and $\tau$ values are higher in the core samples that were cut parallel to the pervasive $S_2$ and $L_2^2$ because the parallel shear stress on the sigmoidal crenulated cleavages in the microlithon of the $S_2$ and layer parallel top-to-SSE shear sense on $S_2$ mica fish with a mean value of $22.21^\circ$ counterbalances the parallel applied load (Fig. 9). The UCS differs from sample to sample due to difference in tectonically induced penetrative planar and linear fabrics. The strength of selected core samples varies with orientation of the tectonically induced fabric. The $S_1$ crenulated cleavage, ENE-WSW trending $S_2$ main foliation, $D_2$ mesoscopic folds, $L_2^2$ lineations, petrography, preferred oriented sigmoidal grains, and mica fish have implication for the overall in-situ engineering constructions and tunnels that will be built on the northernmost Indian plate rocks, Indus Suture Zone, and southernmost rocks of the KIA.

Non-coaxial dextral shear sense on strongly preferred oriented sigmoidal grains (plagioclase and feldspar) that formed by crystal-plastic deformation and mica fish enhances foliation parallel strength of the CGG rocks (Figs. 3a–d and 7a–f). However, the UCS values decrease in the core samples that were cut perpendicular to the pervasive $S_2$ and $L_2^2$ because the perpendicular shear on the sigmoidal crenulated cleavages in the microlithon of the $S_2$ and $S_2$ mica fish enhances the applied load, which lead to the failure of core samples (Fig. 9).
The lower UTS values were observed in the core samples, which were cut parallel to the main $S_2$ foliation and $L^2_2$ lineation compared with the core samples cut perpendicular to the tectonic fabric (Table 3; Fig. 9). Core samples obtained parallel and perpendicular to $D_2$ associated ENE-WSW axial plane $S_2$ foliations show variable UCS and UTS values, respectively. The $S_2$ parallel core samples have higher UCS, $c$, $\tau$, and UTS values than those cut perpendicular to the $S_2$ main fabric (Table 3).

Table 2  Average values of all the measured angles of mica fish

| Thin sections | Average angle of mica fish (°) |
|---------------|-------------------------------|
| 6             | 23.33                         |
| 7             | 24.73                         |
| 8             | 21                            |
| 9             | 22.13                         |
| 10            | 23.61                         |
| 11            | 23.28                         |
| 12            | 18.22                         |
| 13            | 20                            |
| 15            | 21.18                         |
| 16            | 24.64                         |
| Overall average | 22.21                        |

Discussion

Tectonically induced structures including foliations, lineations, mineral alignments, mineral alteration, metamorphic textures, and veins at microscopic to mesoscopic scales
significantly affect geomechanical properties of tectonized rocks (Ramamurthy et al. 1993; Singh et al. 2012; Ozbek et al. 2018). Genetic complexity in the form of penetrative foliations and lineations makes geomechanical behavior of metamorphic rocks unpredictable (Behrestaghi et al. 1996). According to Everall and Sanislav (2018) tectonically deformed rocks dominantly fail by reactivation of pre-existing planes of weakness that include foliations, fractures, and veins. The above arguments imply that each rock should be analyzed independently for anisotropies because the UCS is significantly reduced in the presence of pre-existing weaknesses developed during multiple tectonic events. In general, affects of penetrative fabrics on geomechanical properties of anisotropic rocks are mostly looked at microscopic to mesoscopic observations without assessing the overprinting fabrics. However, in the current study multiple penetrative foliations that have significantly affected geomechanical properties of rocks collected south of the MMT would have most likely been studied without looking at the affect of strongly preferred oriented sigmoidal porphyroblasts, mica fish, and crenulated cleavages in the microlithon of the main S2. The UCS and UTS values differ from sample to sample due to variably induced penetrative fabrics (Table 3). The orientation of mica fish, sigmoidal porphyroblasts, and crenulated cleavages to the applied load directly affected the strength of rocks. The UCS significantly increased in the S2 parallel core samples containing mica fish and S1 crenulated cleavages in the microlithon by opposing the applied load as result of load parallel shear at the main matrix crenulation cleavage (Fig. 9). Mica fish and S1 in the microlithon of the S2 that respectively counterbalanced and facilitated the applied load in foliation parallel and perpendicular core samples would not be detectable without a detailed petrographic analyses. Therefore, the main differential stresses that are

Fig. 8 Mohr’s circle diagrams of shear strength measured for all parallel (pa) and perpendicular (pe) core samples using UCS and UTS values. UCS and UTS values are plotted against positive and negative X-axes, respectively. \(c\) and \(\tau\) values are plotted on Y-axis.
preserved in rocks in the form of simple or complex foliations and lineations must be determined before the use of tectonites in any engineering constructions or as aggregates.

Conclusions

- This study displays some more complicated behavior of multiple deformed rocks under very simple load conditions, which need to be assessed under load and numerical simulation models.
  - It is observed that microscopic pervasive crenulation and crenulated cleavage intersection planes and mica fish could potentially induce layer parallel slips that remain perpendicular or parallel to the applied stresses.
  - Pervasive slip layers parallel to the applied stresses enhance the strength of tectonically deformed rocks. However, the same planes when perpendicular to the applied stresses decrement the strength of these rocks.

### Table 3

| Sample                      | UCS (MPa) | UTS (MPa) | Shear strength (τ; MPa) | Cohesion (c; MPa) | Angle of internal friction (ϕ) (°) |
|-----------------------------|-----------|-----------|-------------------------|-------------------|-----------------------------------|
| 1–parallel (CGG)            | 24.67     | 13.33     | 12.62                   | 9.8               | 17                                |
| 1–perpendicular             | 14.8      | 12.83     | 7.27                    | 6.89              | 4                                 |
| 2–parallel (CGG)            | 61.69     | 12.83     | 22.15                   | 14.07             | 41                                |
| 2–perpendicular             | 71.56     | 11.35     | 23.84                   | 14.25             | 47                                |
| 4–parallel (CGG)            | 71.56     | 16.28     | 27.6                    | 17.07             | 39                                |
| 4–perpendicular             | 54.29     | 17.76     | 23.36                   | 15.5              | 30                                |
| 5–parallel (CGG)            | 49.35     | 6.41      | 16.27                   | 8.8               | 50                                |
| 5–perpendicular             | 41.95     | 7.89      | 14.84                   | 9.1               | 43                                |
| 3–parallel (amphibolite)    | 91.31     | 11.35     | 30.2                    | 16.1              | 51                                |
| 3–perpendicular             | 59.23     | 12.33     | 22.55                   | 13.51             | 41                                |
USC is respectively increased or decreased by reactivation of mica fish and $S_1$ crenulated cleavage parallel and perpendicular to the applied load.

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