Investigations on fabrics and related mechanical properties of a highly anisotropic gneiss

Analyse de la texture et des propriétés mécaniques associées d'un gneiss fortement anisotrope

Untersuchungen des Gefüges und der damit verbundenen mechanischen Eigenschaften eines hochanisotropen Gneises

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ABSTRACT: The so-called "Stainzer Platten" gneiss is part of a regional ductile shear zone within the metamorphic Koralm core complex and has some practical importance due to its perfect fissility. Investigations on the rock fabrics revealed a characteristic microcrack pattern besides a distinct mineral alignment. Rock mechanics laboratory tests which were performed at core samples drilled at 30° direction intervals along the principal fabric planes resulted in a pronounced anisotropy for the determined elastic parameters. In particular the orientation and distribution of existing microfractures, as well as their readiness for activation under load are crucial for the interpretation of the obtained results.

RÉSUMÉ: Le "Stainzer Plattengneis fait partie d'une zone régionale ductile de cisaillement dans le cristallin de la chaîne de Koralm et, roche en dalles de clivage prononcé, porte un certain intérêt pratique. L'étude de la texture granulaire a démontré, outre un alignement minéral distinct, une structure caractéristique de microfissures. Les essais effectués sur des carottes remontées á des intervalles d'angle de 30° le long des plans principaux de la texture ont montré une anisotropie très nette des paramètres élastiques déterminés. Ces résultants s'expliquent en particulier par l'orientation et la distribution des microfissures présentes dans la roche ainsi que par leur tendance á la mobilisation sous charge.

ZUSAMMENFASSUNG: Der "Stainzer Plattengneis" entstammt einer regionalen duktilen Scherzone im Koralmkristallin und ist als Gestein mit ausgeprägter plattiger Spaltbarkeit von gewissem praktischem Interesse. Untersuchungen des Korngefüges ergaben neben einer deutlichen Mineralregelung ein charakteristisches Mikrorißmuster. Beim Test von Kernproben, welche in Winkelabständen von 30° entlang der Hauptebenen des Gefüges erbohrt wurden, konnte eine deutliche Anisotropie der ermittelten elastischen Parameter festgestellt werden. Die Ergebnisse lassen sich insbesondere über die Orientierung, Verteilung und Aktivierung der vorhandenen Mikrorisse im Gestein erklären.

1 INTRODUCTION

There is ample knowledge on rock anisotropy and petrophysics available in textbooks and scientific papers (e.g. Peres-Rodrigues 1966, Willard 1969, Barla 1974, Amadei 1983, Wittke 1984, Montoto 1985, Gottschalk et al. 1990, Siegesmund 1994, Ersoy&Waller 1995,)

In certain cases, however, up to 21 independent elastic constants could have to be determined just to characterise anisotropic behaviour comprehensively. This fact evidently makes it too laborious for most applications. Both mineral shape and/or lattice preferred orientation (MPO, LPO) and defect frequency/orientation (DFO), as well as their distributions in space are thought to be decisive for the observable behaviour of the rock material. In a practical sense it is a mere scale problem whether we speak of rock mass and/or rock material: It takes only a step down in the size of the region of interest to consider the so-called intact rock specimen as a mechanical system consisting of at best elastically deformable elements (minerals, components), bounded by discontinuities (grain boundaries, cleavage, microfractures, voids), and including fluids.

In analogy to rock mass inferred performance investigation via discontinuity analysis, and in order to assess both the magnitude and the directional pattern of the fabric-induced mechanical anisotropy, we selected a gneiss type of practical importance for a preliminary textural analysis and concomitant rock mechanics laboratory tests series.

2 THE ROCK MATERIAL

2.1 *General*

The selected rock type (the so-called „Stainzer Platten" gneiss from Styria/Austria) has some regional importance as paving and lining stone, as well as in masonry. The rocks belong to the poly-metamorphic series of the Middle-Austro-Alpine nappes and in particular to a highly strained regional ductile shear horizon within the crystalline core complex of the Koralm. These units underwent their main deformational and petrogenetic overprints during an eo-Alpine high-grade metamorphism (100 ± 10 ma b. p.) and northward thrusting, followed by a moderate thermal event, rapid exhumation and east-directed escape tectonics. For details see e.g. Frank et al. 1983, 1987, Krohe 1987, Neubauer & Genser 1990, Thöni & Jagoutz 1993, Stüwe & Powell 1995, Gregurek et al. 1997.

The most characteristic feature of these gneisses is a distinct near-perfect tabular fissility along the schistosity parallel to the tectono-metamorphic compositional layering (with abundant porphyroclasts as lenticular streaks and „augen") in strict parallel alignment. A penetrative (originally cataclastic) stretch lineation is responsible for the characteristic „stripes" appearance of the planar schistosity surfaces (Figure 1 and Figure 2**).** A fine crenulation at high angles (or orthogonal) to the stretch lineation can be found abundantly and, both extremely narrow faint fractures and one master joint set have developed parallel to these axes and at high angles to the schistosity plane. The mentioned stretch lineation served to determine the *X* – direction in the tectonic strain co-ordinates and consequently the *XY* – plane coincides with the macroscopic schistosity.

The mineralogical composition of rock sub-types within the particular (blasto-)mylonite gneiss units varies in detail (Table 1).

Table 1: Bulk mineral composition ranges (percentages by volume) of three blastomylonite gneiss phenotypes as determined by X-ray diffraction. Mc* = mica contains muscovite & biotite; dolomite and pyrite occur in places as secondary constituents.

Qu	Mc*	Pl	Or	Gt	Ky
40 – 51	17 - 25	8 – 15	<1 - 9	7 –17	3 - 8

Qu: quartz, Mc: mica, Pl: plagioclase, Or: orthoclase, Gt: garnet, Ky: kyanite

2.2 *Microfabrics*

At the microscopic scale (Figure 4a, b; Figure 5a, b) the penetrative schistosity (mylonitic foliation) is displayed by long undulating quartz-feldspar polycrystal ribbons (often wrapped around mm – cm large relict grains), mica (± kyanite) streaks and wings of porphyroclasts (garnet and plagioclase, predominantly in-plane features). Alternating bands of the former constituents in places generate a distinct sandwich structure at the grain-scale. Recrystallized grainsize for the equidimensional phases varies between approx. 0.03 mm and 0.9 mm; almost all grains exhibit undulous to lamellar extinction. Most of the grain strain from past shear deformation and mylonitization is obliterated by dynamic recrystallisation. On this reasons a preliminary shape estimation of the strain ellipsoid must considerably underestimate material strain (Figure 3).

The Figures 4b, 5b sketch the outlines of (assumed) original elongate grains, not the recrystallized ones, which exhibit a much finer, almost isometric mosaique.

In our opinion, Foliation Index (FI) and Texture Coefficient (TC) determinations (Tsidzi 1986, Howarth & Rowlands 1987) do not appropriately characterise these rock types:

$$\mathrm{FI} \approx 4 \sim 5;$$
$$\mathrm{TC} \approx 1.49;\ (1.33 \sim 1.61) \text{ parallel to } XZ, \text{ and}$$
$$\mathrm{TC} \approx 1.16\ (1.07 \sim 1.30) \text{ parallel to } YZ.$$

An FI- related classification of the rock as „moderately foliated“ contradicts both visual impression and decisive geotechnical properties. The value of TC, on the other hand, changes w/r to the orientation of structural axes, depends on the mechanical significance attributed to (recrystallized) grain boundaries and microcracks, and can not yet be related to any physical property of the rocks under consideration.

In particular in the *XZ* thin sections (viz. parallel to the stretch lineation and perpendicular to the schistosity plane) a great number of sub-parallel inter-granular and trans-granular microcracks attract attention (besides abundant grain-boundary cracks at the quartz-mica interfaces**,** Figure 4c). They predominantly cut through the quartzo-feldspathic ribbons and are in places well developed as intra-granular fractures in relict garnet porphyroclasts. Like their analogues on the mesoscopic and macroscopic scale, most of the microcracks are oriented sub-parallel to the *YZ* plane, i. e. they extend in a plane normal to the stretch lineation. A much lower fracture density is encountered in *YZ* sections (Figure 5c). This regular microcrack pattern is considered a brittle response to the de-stressing of the rock mass during uplift and erosion after high-grade dynamic metamorphism.

X-ray goniometric lattice preferred orientation (LPO) analyses of quartz exhibited a rather symmetric a-axes (110)pattern and crystal *c*- axes (001) forming an incomplete girdle roughly within the *YZ*- plane and predominantly sub-parallel to *Y* (Figure 6). The configuration may be interpreted as an indication for a prevailing flattening deformation with an additional shear component either in a high-temperature regime or at high strain rates (Schmid & Simpson 1983). Variable intensities of axis orientation concentrations between rock subtypes may be attributed to both the presence of other mineral phases, thereby impeding the recrystallization of quartz, and to the impact of crenulation.

3 LABORATORY TESTS

3.1 *General*

A series of tests on cores drilled in 30° direction intervals to schistosity and stretch lineation has been performed. Figure 1 shows the drilling directions and the core numbers on the rock block with the system of co-ordinates. In that case the stretch lineation and the schistosity are the visible marks for a clear assign of the co-ordinate scheme.

According to common experience and practice the schistosity plane (*XY*-plane) stands for an isotopic plane. That means the system is considered transversal isotropic. Such a transversely isotropic medium requires five independent elastic constants to characterise the elastic behaviour (elasticity matrix). In a preliminary tests suite we determined compressive strength, modulus of elasticity, deformation modulus and Poisson ratio. The evaluation of dynamic elastic constants by seismic methods applied to long intact core pieces in the X, Y, Z, directions was in good agreement with the results of the performed static tests.

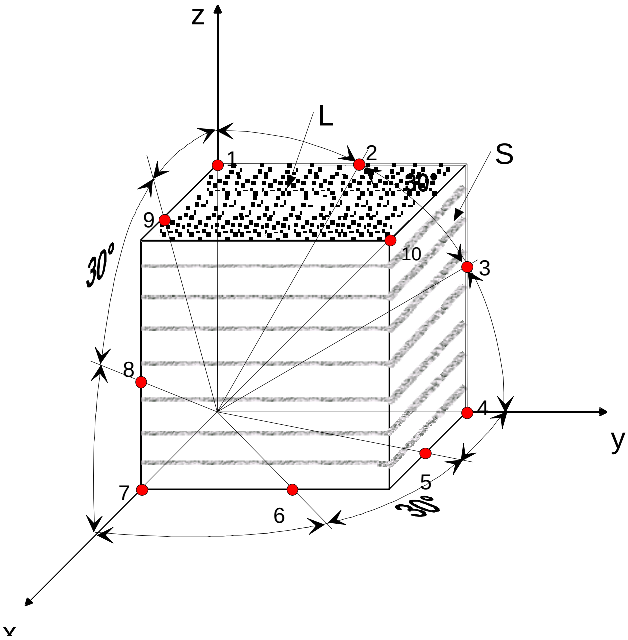


Figure 1. Sketch of tested rock sample with sample orientations (1 to 9) in relation to schistosity (S), lineation (L), and orientation of crystallographic axis (*X*, *Y*, *Z*).

Figure 2. “Platten”-gneiss: View of a schistosity plane (*XY*) with distinct stretch lineation (background) and of a fracture face roughly parallel to the *XZ* plane (left foreground); scale in cm.

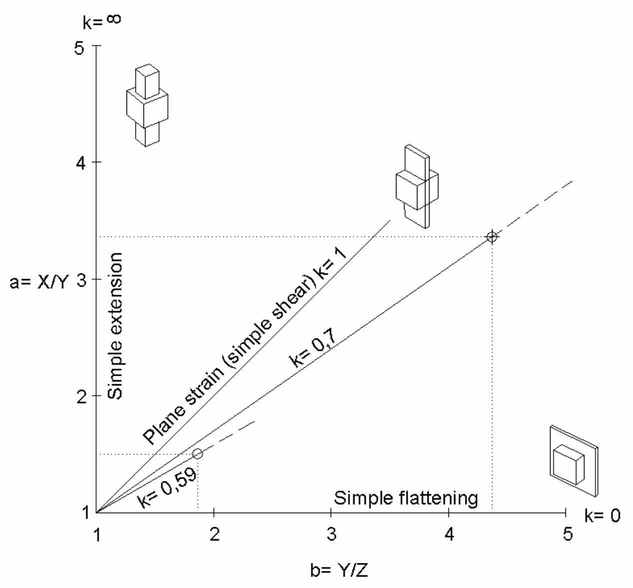
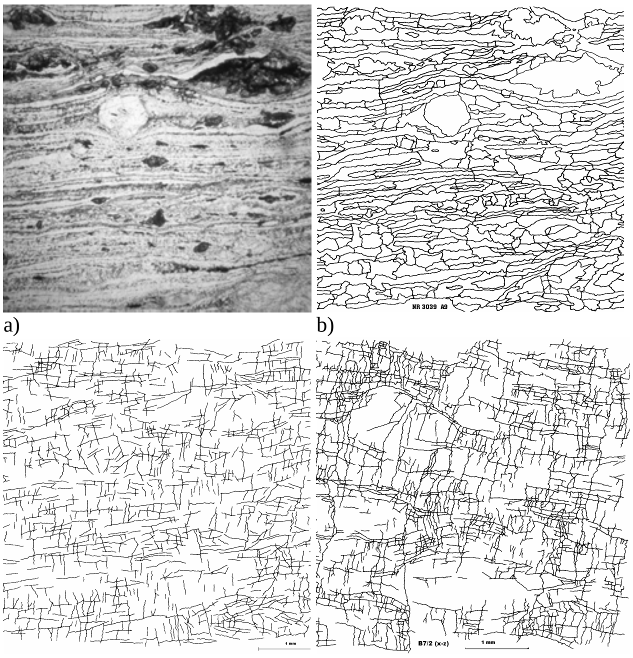


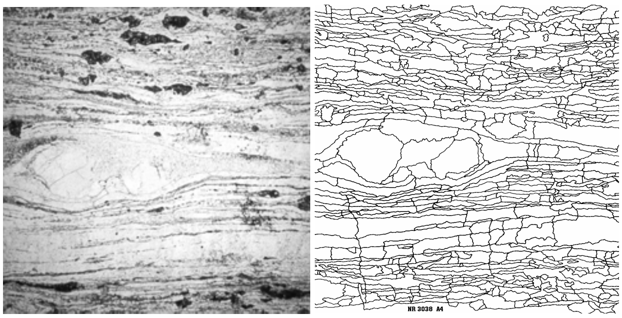
Figure 3. Flinn diagram with grain strain determination according to Panozzo 1987 (circle) and Becker 1976 (crossed circle)



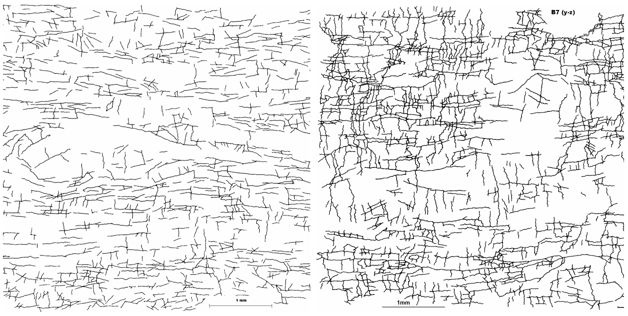
a) b)

c) d)

Figure 4. *XZ* thin-section, a) nicols parallel, b) original grain boundaries, c) inter- and trans-granular microcrack pattern of unloaded sample, d) inter- and trans-granular microcrack pattern of loaded sample



a) b)



c) d)

Figure 5. YZ thin-section, a) nicols parallel, b) original grain boundaries, c) inter- and trans-granular microcrack pattern of unloaded sample, d) inter- and trans-granular microcrack pattern of loaded sample

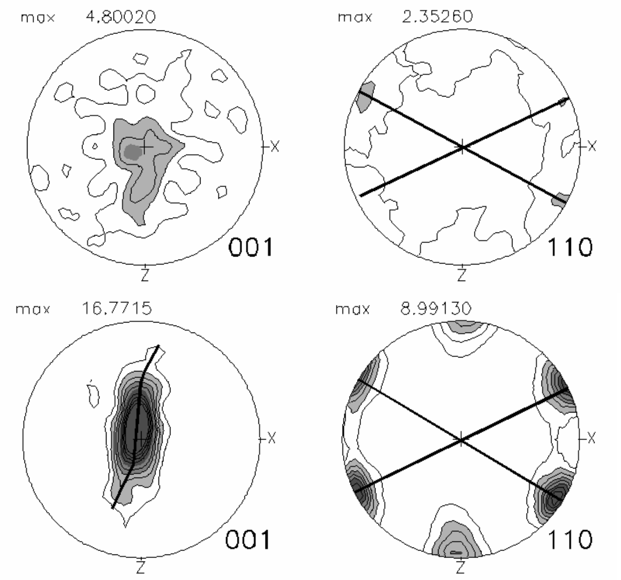


Figure 6. Quartz axis concentrations for two rock subtypes. C-axis (left, (001) and A-axis (right, 110) configurations.

Figure 7. Rock testing system

The specimens were recovered by diamond core drilling equipment. A servo-hydraulic testing machine (MTS) with a closed loop controller was used for the tests (Figure 7). Two axial strain extensometers which measure strains across the middle half of the specimen, where end effects from loading platens are minimal and one circumferential strain extensometer centred in the middle of the specimen were used in this test set-up. This uniaxial strain measurement kits are shown in Figure 13. In order to control the test in the post failure region the circumferential strain was used as the controller feedback command.

3.2 Results

Figure 8 shows the values of Young Modulus as determined for the principal planes with 30° direction intervals. As expected, the modulus is lowest for the direction normal to the plane of schistosity *(XY)* This almost symmetrical diagram gives the impression that we have an transversely isotropic body for which the *XY*-plane is the plane of isotropy.

The diagram for the direction dependent E-modulus **(**Figure 9**)** again shows an almost symmetric pattern indicating an isotropic *XY* – plane and lowest values normal to schistosity.

The modulus of elasticity (E-Modulus) which is determined in the unloading cycle is about 15% higher than the Young modulus.

However, as can be seen in the diagram (Figure 10), the Poisson ratio depends much of the direction within the *XY*- plane. It is larger for the cores tested parallel to *Y* as compared to *X*, i.e. there is a larger transverse deformation parallel to the stretch lineation (*X*) than perpendicular to it (*Y*).

Strain values at ultimate stress (Figure 11) illustrate fully brittle behaviour of the rock. The largest deformation occurs in the direction perpendicular to schistosity and a slightly higher strain could be measured parallel to *X* as compared to *Y*. The recorded severe breakdown in direction 3 must be attributed to failure along a pre-existing undetected fracture in the sample.

The results of uniaxial compressive testing are illustrated in Figure 12. It is interesting to note that highest strength was reached within the plane of schistosity (*XY*) and parallel to the stretch lineation (*X*). Figure 13 shows the core sample which is oriented parallel to schistosity as well as lineation (direction 7).

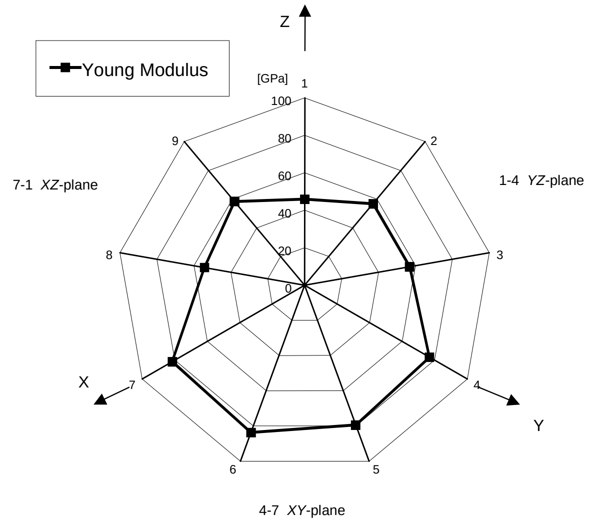


Figure 8. Young Modulus

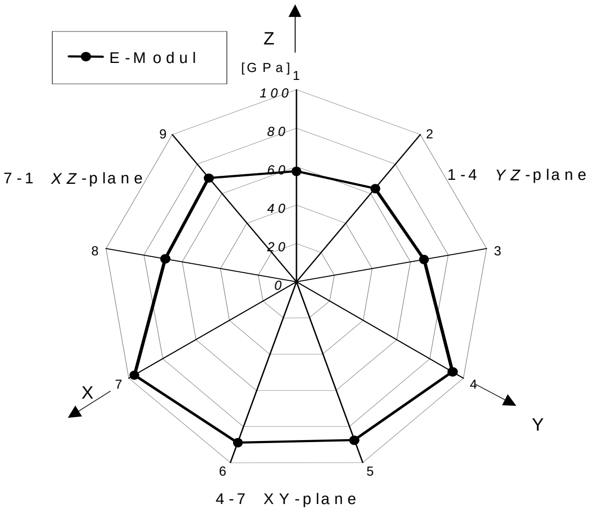


Figure 9. E-Modulus, determined from unloading cycle

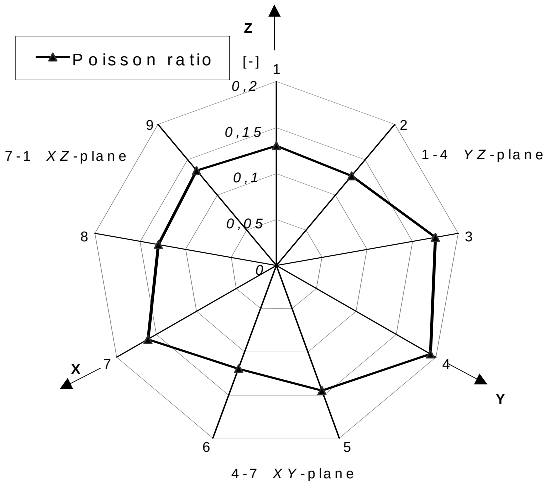


Figure 10. Possion ratio

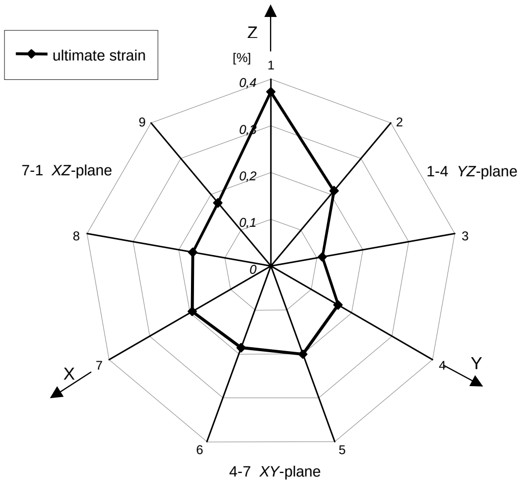


Figure 11. Ultimate strain values

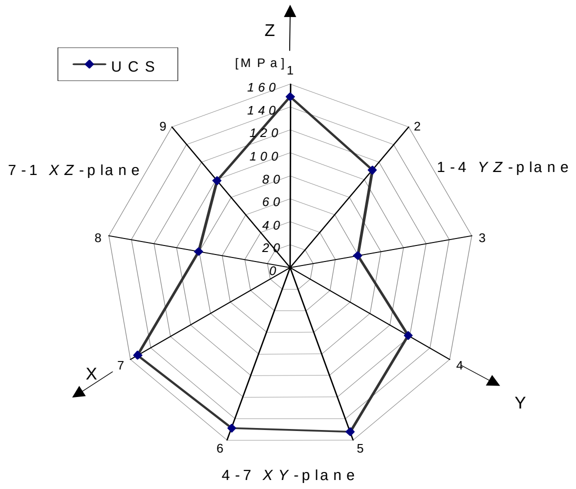


Figure 12. Unconfined compressive strength values

Figure 13. Failure by axial splitting along schistosity planes

4 DISCUSSION

Besides from the pronounced anisotropy of determined parameters parallel and perpendicular to the schistosity of this gneiss, there is at least for the Poisson ratio and UCS a distinct influence from the fabric properties within the plane parallel to the schistosity, too. Comparing the pattern of pre-existing microfractures in the rock with their configuration within the samples after testing (Figures 4d, 5d) it is clearly seen that the sample deformation was accompanied by an opening, growth, coalescence and eventually new formation of microfractures. The high transverse deformation parallel to *X* at the loading conditions 4 (*//Y*) as well as the comparatively low UCS recorded parallel to that direction can be explained by the high density and high readiness for opening of the existing microcracks along the *YZ*–plane. On the other hand, with loading normal to the schistosity (parallel *Z*) considerable UCS is achieved through an evident reinforcement action of the mica layers, although concomitant large axial deformation is encountered. Most remarkable is the determined highest UCS in loading direction 7 (parallel *X*, i.e. parallel to the stretch lineation). Apparently the existing cracks along phase boundaries, mica interfaces and cleavage planes do not as ready open and connect under axial load as one would estimate from the parallel texture and the pronounced platy fissility of the rock. Further investigations on the subject are under progress.

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