Tectonophysics 637 (2014) 150–162

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Fabric controls on the brittle failure of folded gneiss and schist

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ARTICLE INFO

Article history:
Received 16 March 2014
Received in revised form 25 September 2014
Accepted 3 October 2014
Available online 15 October 2014

Keywords:
Brittle failure
Anisotropy
Rock fabric
Folds
Uniaxial compression
X-ray CT

ABSTRACT

We experimentally studied the brittle failure behaviour of folded gneiss and schist. Rock fabric and petrography were characterised by meso-structural analyses, optical microscopy, X-ray diffraction, and SEM imaging. Uniaxial compression, triaxial compression and indirect tension laboratory tests were performed to characterise their strength and stress–strain behaviour. Fracture patterns generated in compression were resolved in 3D through X-ray computed tomography at different resolutions (30 to 625 μm). Uniaxial compression tests revealed relatively low and scattered values of unconfined compressive strength (UCS) and Young's modulus, with no obvious relationships with the orientation of foliation. Samples systematically failed in four brittle modes, involving different combinations of shear fractures along foliation or parallel to fold axial planes, or the development of cm-scale shear zones. Fracture quantification and microstructural analysis show that different failure modes occur depending on the mutual geometrical arrangement and degree of involvement of two distinct physical anisotropies, i.e. the foliation and the fold axial planes. The Axial Plane Anisotropy (APA) is related to micro-scale grain size reduction and shape preferred orientation within quartz-rich domains, and to mechanical rotation or initial crenulation cleavage within phyllosilicate-rich domains at fold hinge zones. In quartz-rich rocks (gneiss), fracture propagation through quartz aggregates forming the APA corresponds to higher fracture energy and strength than found for fracture through phyllosilicate-rich domains. This results in a strong dependence of strength on the failure mode. Conversely, in phyllosilicate-rich rocks (schist), all the failure modes are dominated by the strength of phyllosilicates, resulting in a sharp reduction of strength anisotropy.

1. Introduction

Brittle failure is a fundamental process in rock mechanics, with major implications in seismology, structural geology, geomorphology and rock engineering. Brittle failure is the result of the nucleation, growth and coalescence of micro-cracks up to the generation of meso-cracks and fractures in fracture process zones (Hoagland et al., 1973). Micro-mechanical models of brittle rock failure have been derived for basic modes of failure (tensile opening, shear, leaning, and mixed modes) of homogeneous, isotropic materials near "stress concentrators" (e.g. microscopic flaws and inhomogeneities; Griffith, 1920). In rocks, localized tensile failure around stress concentrations (associated with grain boundaries, weak mineral phases, or microcracks) initiates grain breakage and rotation, subcritical crack growth and coalescence, finally leading to progressive rock damage, onset of dilatancy and macroscopic failure, as shown by experimental studies in rock mechanics (Hoek, 1968; Jaeger et al., 2007; Martin, 1997) and rock physics (Eberhardt et al., 1997; Lockner, 1993; Stanchits et al., 2006; Zang et al., 1998).

Brittle rock failure processes and stages are strongly controlled by rock fabric (Atkinson and Meredith, 1987; Jaeger et al., 2007; Svab and Lajitai, 1981). This can be characterised and quantified using different techniques including standard microstructural analyses, quantitative microscopy, image analysis and X-ray microtomography (Akesson et al., 2003; Antonellini et al., 1994; Azzoni et al., 1996; Passchier and Trouw, 2005; Přikryl, 2006).

An important control on rock properties is exerted by textural anisotropies including primary sedimentary and igneous fabric elements (e.g. bedding, laminations, flow structures) and metamorphic fabrics (e.g. cleavage, schistosity, compositional layering). Several studies focused on the influence of a planar fabric anisotropy on physical properties (e.g. elastic anisotropy; Brace, 1965; Brosch et al., 2000), deformability, strength and failure modes of rocks. Particular attention has been devoted to the study of the dependence of rock strength on the orientation of the planar anisotropy with respect to the direction of loading in uniaxial compression (Behrestaghi et al., 1996; Gottschalk et al., 1990; Nasseri et al., 2003), triaxial compression (Attewell and Sanford, 1974; Donath, 1961; Gottschalk et al., 1990; McCabe and Koerner, 1975; Nasseri et al., 2003; Walsh and Brace, 1964), and direct tension tests (Liao et al., 1997; Nova and Zaninetti, 1990). The effects of planar fabric anisotropy on rock strength have been described by modifications of established failure criteria ("plane of weakness" Coulomb criterion, Jaeger, 1960; modified Griffith criterion, Walsh and

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http://dx.doi.org/10.1016/j.tecto.2014.10.006
0040-1951/

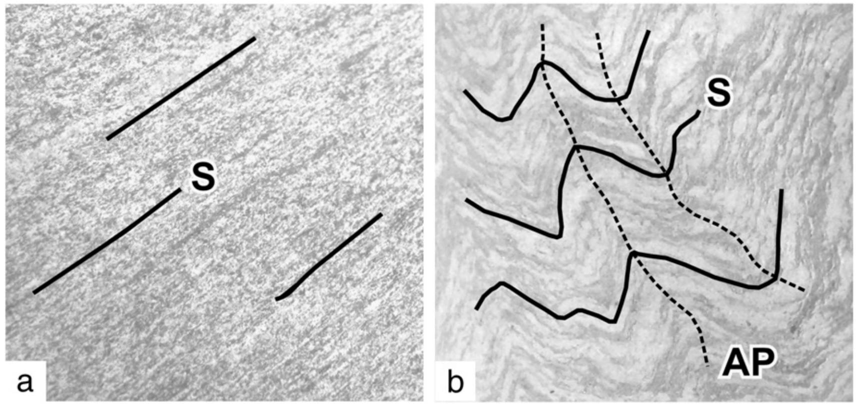

Fig. 1. Planar vs. folded fabric anisotropy. a) Foliation or compositional layering (S) related to syn-metamorphic ductile rock deformation or transposition of the pre-existing fabric result in a single planar physical and mechanical anisotropy. b) Micro- to cm-scale folding of the pre-existing fabric anisotropy results in non-planar surfaces. AP: fold axial plane.

Brace, 1964; Hoek, 1964). The micromechanics of anisotropic failure has been related to the abundance and textural arrangement of phyllosilicate minerals characterised by low frictional strength, which control crack nucleation and propagation (Gottschalk et al., 1990; Kronenberg et al., 1990; Moore and Lockner, 2004; Rawling et al, 2002; Shea and Kronenberg, 1993) and the transition from isotropic to anisotropic behaviours (Shea and Kronenberg, 1992, 1993).

Our experimental study addresses the previously unexplored interplay between the fabric of folded metamorphic rocks and their brittle failure behaviour. These rocks are characterised by a pre-existing, well developed foliation at least partly defined by phyllosilicate mineral phases, which experienced additional ductile deformation in a changing strain field, resulting in a complex mesofabric (Fig. 1) and microstructure (Fossen, 2010).

Small-scale folds characterised by centimetre scale or less and sub-parallel axial planes develop in anisotropic metamorphic rocks as a result of a variety of micro-scale deformation processes. These include crenulation, kinking of fractured mica segments, and strain recovery or dynamic recrystallization of quartz and feldspar grains (Passchier and Trouw, 2005). These processes can lead to the development of a secondary tectonic foliation (i.e. axial plane foliation), parallel or symmetric to fold axial planes. Depending on the amount of finite strain, the new foliation may eventually obliterate (transpose) the pre-existing one, thus resulting in a new, pervasive textural (and mechanical) planar anisotropy.

Fabric controls on the brittle failure behaviour of folded foliated rocks (e.g. phyllite, schist, and gneiss) have never been investigated before, although these rocks are very common in both the upper and middle Earth's crust. Relevant research issues include: 1) the mechanical effects of the geometry and spatial arrangement of a "non-planar" textural anisotropy (i.e. foliation) with respect to applied stress; 2) the controls exerted by microfabrics associated with tectonic folding on the mechanical behaviour of rocks in the brittle field (strength, deformability, failure mode). An improved understanding of these points is needed, and would provide valuable inputs to different fields of geoscience.

In this paper, we present the first experimental study of the brittle failure behaviour of two contrasting low-grade foliated metamorphic rock types from the Central Alps (N Italy), namely the Monte Canale gneiss and the Edolo schist (Fig. 2). We characterised rock petrography and fabric, performed mechanical laboratory tests with the main focus on uniaxial compression conditions, and investigated resulting 3D fracture patterns using X-ray CT analysis. Our results highlight the influence of geometrical and mechanical interplay of two distinct fabric anisotropies on brittle failure behaviour of folded rocks, and point to possible micro-scale mechanisms.

2. Tested rock types: petrography and fabric

We characterised the mineral composition, petrography and (micro)fabric of studied rock material by: a) X-ray powder diffraction (XRPD), performed through a PANalytical X'Pert PRO diffractometer (2theta range: 3–80°, step size: 0.0167°), and related quantitative analysis (Table 1) with the GSAS software (Larson and Von Dreele, 1994); b) micro-structural analysis by optical microscopy (Passchier and Trouw, 2005) on differently oriented thin sections, i.e. perpendicular to foliation, fold axes and axial planes, or parallel to axial planes and fold axes; c) scanning electron microscopy imaging using a Tescan Vega SEM on carbon-coated raw surfaces obtained from rock samples broken in laboratory tests.

Fig. 2. Locations of the rock types sampled for experimental work, within the Italian Central Alps (a). Monte Canale gneiss (MC) samples were obtained from cores recovered from deep boreholes drilled in the Spriana area (lower Val Malenco; typical outcrop in inset b). Edolo schist (ED) was sampled from rock cores drilled in the Vedello/Scais area (upper Val Venina; typical outcrop in inset c).