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# Shear failure mechanism in granite inferred from multi-scale brittle structures

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A B S T R A C T

The brittle structures of a Hercynian granite (La Borne, French Massif Central) observed at several scales, from regional to microscopic, are presented and interpreted on mechanical terms. Emphasis is placed on strike slip faults, joints, and cracks related to incipient shear fracturing during horizontal compression. Three compressive tectonic phases have been identified according to their brittle structures and characterised by the burial depth at the time of their generation.

The two first phases (H1, H2) are Hercynian and occurred while the granite was deeply buried (~5 to 3 km depth) whereas the last phase (P) is Pyrenean and occurred at very low depth. The geometric organizations of cracks, joints and faults are clearly similar at various scales from about 10 μm to several m.

These field observations are strong arguments for the occurrence of shear structures at microscopic to macroscopic scales during tectonic events. Following this inference, it is proposed that, at least in the case of Hercynian phases, cracks, joints and macroscopic strike slip faults have been generated by the same mechanical process under high overburden weight. Therefore, incipient fractures seem to be generated as shearing structures and to evolve by coalescence with neighbouring ones with the same direction.



## 1. Introduction

Granitic massifs which are a major component of the continental upper crust, are almost systematically deformed in brittle conditions resulting in planar discontinuities referred to cracks (discontinuities at the scale of crystals), joints (visible discontinuities without displacement), or faults (discontinuities where relative displacement of both sides is visible). The genesis and evolution of these discontinuities is a major geological question (Paterson, 1978; Kranz, 1979; Engelder, 1987; Pollard and Aydin, 1988; Kranz, 1983; Mandl, 2005; Pollard and Fletcher, 2008; Scholz, 2009). This problem covers fundamental mechanical and geological questions on the origin of discontinuities and more practical ones such as the triggering of earthquakes and the evolution of transport properties (e.g. permeability, electrical conductivity …) of the upper continental crust.

Many crustal rocks (and in particular granitic ones) have been experimentally tested for failure (e.g. Paterson, 1978). In such tests, natural samples are introduced in tri-axial cells and loaded both by lateral confinement and deviatoric stress, leading finally to their failure and destruction (Friedman et al., 1970; Wawersik and Brace, 1971; Wong, 1982; Haimson and Chang, 2005). Well before complete failure, tested rocks are affected by more or less diffuse damage. In hard rocks such as granite, this damage is characterized by the generation and development of micro fractures and cracks (Hadley, 1976; Tapponnier and Brace, 1976; Kranz, 1979). Since this type of observations may be biased by spurious phenomena occurring during unloading, indirect method of observations have been designed such as acoustic emission analysis associated with crack generation (Cox and Meredith, 1993; Lockner and Madden, 1991) or local density variation deduced from X-ray tomography results (Raynaud et al., 1989, 2012).

The development of damage during compressive rock tests has received considerable attention in order to track the evolution from

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cracks to actual shear faults. In the 60's it was currently assumed that shear faults result from coalescence of evolving cracks (Friedman et al., 1970; Paterson, 1978 p.168; Kranz, 1983; Petit and Barquins, 1988). This process would lead to the complete failure of the rock according to the general (Coulomb's) failure criterion. However this idea has been revised with the development of acoustic emission measurements, (Lockner and Byerlee, 1977) which emphasizes the role of fault nucleation associated with the crack interaction. Once nucleated, the fault appears to propagate in its own plane by inducing cracks growth at its front (Paterson, 1978; Reches and Lockner, 1994; Moore and Lockner, 1995). The characteristics (shape and direction) of the cracks generated during development of this process appear to be very sensitive to the imposed confining pressure (Wawersik and Brace, 1971; Shimada and Cho, 1990; Shimada, 1992; Katz and Reches, 2004).

The relevance of laboratory data to geological problems remains a major question since geological time and space scales are much larger than those in rock laboratory testing. Therefore natural observations of brittle structures on available outcrops of hard rocks such as granites offer an alternative direct way of testing hypotheses on the natural generation and development of faults.

In fact such a geological study is only possible in the cases when natural loading (i.e. the stress field applied in geological times including the depth of burial) can be reconstructed or at least estimated. This is the case of the La Borne granite, a Hercynian (Variscan) granite, which has been submitted to three compressive tectonic phases while it was buried at different depths (Raynaud, 1979). The La Borne granite presents outcrops of high quality where faults, joints and cracks can be measured at three scales: regional (10 km), outcrop (1–10 m) and microscopic (0.001–1 mm). Field structural measurements (orientation, shape …) at several scales can be deciphered and attributed to the compressive phases.

The objective of the present study is to discuss the characteristics of natural damaging and faulting processes in connection with what is observed in laboratory experiments and to suggest alternative interpretations. Our proposition based on geological observation is that, when taking place at a depth of several km, natural brittle deformation of granite occurs systematically in shear mode at any scale, from microscopic to major fault structures.

In the following, the general setting of the La Borne granitic massif is first presented with emphasis on the brittle deformation, which affected the massif at large scale for different depths of burial. Then, brittle structures from a large outcrop are analysed at both visible and microscopic scales. At various scales (from regional to microscopic one), the main tectonic phases are identified and characterised. These data are discussed using the general framework of rock mechanics and the role of burial depth on the type of deformation is emphasized.

## 2. Regional geological framework of the La Borne Massif

The La Borne granite is a porphyritic monzogranite. It is mainly composed of quartz, biotite, plagioclase and potassic feldspar with mm to cm size crystals. However 10–12% of potassic feldspar phenocrystals have a larger size of one to a few cm (Van Moort, 1966). The spatial distribution of crystals and their orientation are isotropic (Fernandez, 1977). Therefore the rock can be considered isotropic at metric to hectometric scale.

The La Borne granite is intrusive into the metamorphic Cevennes rocks. Since these granitic rocks presents a negative density contrast with their surrounding rocks (Talbot et al., 2004) they induce a negative gravity anomaly which can be interpreted in terms of thickness of the granitic massif. As reported in the Appendix, the present 3-D geometry of the granitic body can be sketched as a half ellipsoid with a major semi-axis of 9 km in the horizontal WNW-ENE direction and a minor one of 2–3 km in the vertical direction (laccolith morphology).

The La Borne granite belongs to the large granitic province of the French Massif Central, which corresponds to the basement of the ancient Hercynian orogeny (Bard et al., 1980). The La Borne massif itself is the oriental part of the larger Mont Lozère Massif (Fabre and Thomas, 1889), which has been shifted horizontally (about 12 km) northward by a sinistral strike slip movement along the Villefort fault (Fig. 1).

This granite as well as its companion – the Mont Lozère – was emplaced at 315 ± 5 Ma (Mialhe, 1980) at the end of the Hercynian orogeny. Microthermometric fluid inclusion data of the contact zone between Lozère granite and the surrounding metamorphic series indicate that the both Mont Lozère and La Borne granite have been cooling when submitted to a lithostatic pressure of about 100 MPa (Cathelineau et al., 1990). This corresponds to a depth of emplacement of the order of 5 km.

North-South trending vertical aplitic and pegmatitic dykes are intrusive in the monzogranite massif. They are dated 301–306 Ma by Ar40/Ar39 (Chauvet et al., 2012). The end of the emplacement of these later intrusive structures coincides with the beginning of the major late-Hercynian brittle event (Arthaud et al., 1977). One of the resulting tectonic structures is the Villefort fault, the strike slip movement of which occurred in relation with the subsidence and sedimentation of the Cevennes Basin (Gras, 1970). The large scale structure composed of the basin and the associated faults corresponds to the southern damping of the Villefort fault slip movement along a 'horsetail' type termination of the main fault as shown by Granier (1985) (Fig. 1). It is possible to develop sedimentologic and structural arguments proving that the La Borne-Mont Lozère granitic massifs were still buried at the time of the strike slip movements. Indeed the clastic levels of the Cevennes Basin (Stephanian age i.e. Upper Pensylvanian) include only detrital material of metamorphic origin. Moreover, the sedimentary and tectonic structures of the Cevennes Basin (Gras, 1970) indicate that the activity of this major late-Hercynian brittle event vanishes before Permian age.

During Permian age (295–285 Ma) and later, the La Borne massif and its surroundings were eroded down to the granite. A thin arkosic level, decimetre to meter thick which was provided by the granite destruction has been deposed over the Triassic peneplain. There is no evidence for late Jurassic or Cretaceous sedimentation on the granite and in its vicinity. Later the Hercynian basement has been submitted to the s. l. Alpine orogen, which induced only minor effects on the studied granite.

## 3. Regional tectonics at the scale of the La Borne Massif

The tectonic history of the La Borne granite can be reconstructed on the basis of published regional informations (Arthaud and Matte, 1975; Raynaud, 1979) and of new tectonic observations of regional significance on outcrops.

### 3.1. Hercynian brittle compressive phase

Two systems of vertical conjugate strike slip faults are clearly defined in many places in the granitic massif, implying a succession of two phases labelled H1 and H2. Their relative chronology is deduced from the observation that the faults generated during the first phase H1 are offset by the faults generated during the second phase, H2.

The early H1 phase, with relatively sparse evidence, is characterized by the association of dextral strike-slip faults striking around N0 with conjugate sinistral ones striking around N60. The major principal stress $\sigma_1$ deduced from the bisector of the dihedron