Microstructures, textures and material properties of marble rocks; an introduction

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June 17, 2013

Abstract

A brief review is given on relationships between microfabrics and material properties of marbles. First, different types of marbles microfabrics are illustrated, as the natural conditions of their development, thereafter the role of microfabric in mechanical properties development of marble rocks is discussed.

1 Introduction

Marbles are rocks with simple mineralogical composition, but despite this, investigations on weathering phenomena of marble artifacts show very distinct behaviour for different marble types. This is largely due to the extremely anisotropic physical properties of calcite crystals and therefore of the rock fabric, i.e. the microstructure (grain size, grain aspect ratio, grain-shape preferred orientation) and the texture (crystallographic preferred orientation) of the rock.

A rock fabric is the result of all the processes that the rock experiences throughout its geological history. Usually is the result of polyphase deformation events and metamorphism that occurred over a long time in varying conditions of pressure, temperature, types of deformation, chemistry of nearby rocks, etc. Therefore studying the processes that led to fabric development and take quantification of rock fabric is crucial to understand and predict rock weathering and deterioration.

2 Fabric of deformed rocks

Earth scientists investigate marble rocks in order to study crystal-scale mechanism of rock deformation and to understand deformation mechanisms operating in mountain building. Laboratory experiments are carried out to observe flow behaviour of rock-forming minerals and to extrapolate it to natural conditions. Starting the pioneering work of Griggs (Griggs and Miller 1951, Handin and Griggs 1951, Turner et al. 1954) marble rocks and limestones are extensively investigated in experimental studies (Rutter 1974, Schmid et al. 1977, 1980, 1987, Walker et al. 1990, De Bresser and Spiers 1993, Rutter 1998, Pieri et al. 2001, Bruijn et al. 2011, and reference therein) and results are compared with natural deformed rocks. In material science investigations of marble rocks have gained peculiar interest because of

capability of marble to suffer permanent deformation at lower temperature and high strain rate, compared with natural conditions. This led to general inferences about mechanisms of intracrystalline plasticity in minerals, slip systems active during plastic deformation, recovery processes and texture development (Schmid 1982, Wenk 1985, De Bresser and Spiers 1990)

How a rock subjected to stress deforms is a function of many factors. It is a function of some external parameters such as pressure, temperature, magnitude of stress applied, presence and nature of fluids, etc., and of rock-related parameters such as its mineralogical composition, grain size, porosity, permeability. The set of processes active in a rock undergoing deformation is referred as the *deformation mechanism* operating. The deformation mechanisms that can operate in rocks are: a) *cataclasis*: deformation occur by fracturing, loss of cohesion and frictional sliding at all scales; b) *crystal plasticity* (or *plasticity*): intracrystalline deformation occurring by movements of line defects (dislocations) or twinning; c) *viscous flow*: deformation achieved by diffusional mass transfer; d) *pressure-solution*: deformation occur by diffusional mass transfer assisted by inter-granular fluids. Discussion of deformation mechanisms in rocks is beyond the scope of this contribution, the reader is referred to Nicolas and Poirier (1976), Schmid (1982), Poirier (1985), Twiss and Moores (1992), Passchier and Trouw (1996), Blenkinsop (2000), and references therein, for a general overview.

Cataclasis produces highly fractured rock mass and therefore marble quarries are usually not developed in such rocks; viscous flow and pressure solution are more efficient in rocks with small (some μm) grain size and typically found in limestone or low temperature metamorphic rocks, i.e. seldom are the main deformation mechanism in marble rocks. Most of marble occurrence is therefore related with the crystal plasticity deformation mechanism; we will discuss this deformation mechanism in the following.

We define, using material science usage:

- 1. *Microstructure*: the small-scale arrangement of geometric and mineralogical elements within a rock. The term "microstructure" therefore refers to the sizes and shapes of grains, the relationships between neighboring grains, and the orientation of grains within a rock.
- 2. *Texture*: distribution of crystallographic orientations within a rock. A rock with fully random orientations it is said to have no texture. If the crystallographic orientations are not random, but have some preferred orientation, then the sample has a weak, moderate or strong texture. The degree is dependent on the percentage of crystals having the same preferred orientation.
- 3. Fabric (or microfabric): the microstructure and the texture of a rock.

2.1 Microstructures and plasticity in marble rocks

Plasticity is a therm that encompasses deformation mechanisms where deformation is intracrystalline and linked to movement of line defects (dislocations). Onset of plasticity occur at different temperature in minerals and occur at about 180-200 °C in calcite rocks (Burkhard 1990).

At lower temperature dislocation movements occur on some crystallographic planes only, without vertical climb of dislocations (*dislocation glide*). This led to dislocation tangle, strain hardening and to cataclasis if applied stress increase. Microstructures typical for lower temperature plasticity are dislocation lamellae, wavy extinction, deformation bands, kink bands and, very common in marble, deformation twinning.

Deformation twinning is very common in calcite crystals and occur at low temperature at the very beginning stages of deformation. During deformation twinning develops if some crystal lattice points (atoms) in a crystal are slipped parallel to a plane, the twin-plane (Fig. 1); the twinned part has a mirror symmetrical structure respect the original part. It is important to note that if at this stage additional stress is applied, no further displacement of atoms occur, because following crystallographic rules twinning exists only if the two parts of the crystal are formed in a symmetrical fashion. This means that twinned atoms cannot be





Fig. 1. (a) Stereographic projection of important planes and crystallographic directions in calcite. (b) Vertical section in a calcite crystal lattice normal to *e*-planes. (c) Vertical section normal to *e*-planes, in a twinned calcite crystal. Twinning occur along *e*-planes, gray is the twinned part. Angle between planes are indicated and from this follows that a line normal to shear plane during twinning is rotated of an angle $\psi = 34.5^{\circ}$; this rotation angle led to a shear strain $\gamma = 0.69$. Note that twinning due to a sinistral shear cause a dextral rotation of calcite *c*-axis, i.e. twinning led to calcite *c*-axes systematically rotated against the direction of shear.

furthermore be displaced though an overall increasing stress is applied to the crystal. From crystallographic structure of calcite and taking into account angles between planes (Fig. 1a,b) it follows that twinning in calcite can accommodate only small amount of strain: no more than a shear strain of $\gamma = 0.69$ (Fig. 1c). If stress increases, the only way during twinning to accommodate larger strain it is to increase the volume of twins (Fig. 2). This can be achieved moving the twin planes toward the not-slipped part of the crystal (twin boundary migration, Fig. 2b-d), until fully twinning of the crystal occur (Fig. 2e). In nature seldom a crystal can be fully twinned, because this imply grain rotation (compare Fig. 2a and Fig. 2b) and this is to some extent prevented from adjacent grains. This imply that twinning can go almost to completion only in the internal part of the crystal, i.e. twinning volume increase toward the center of the crystal (Fig. 2f). The resulting microstructure shows characteristic lensoid shaped twins with constricted end at grain boundaries.

If higher temperature is applied during deformation, dislocations move along slip planes but also climb normal to their slip planes (*dislocation creep*). This enables alignment of dislocations along planes and rearrangement in low energy and stable configuration, as illustrated in Fig. 3; this result in dislocation-free crystal lattices and surfaces along which





Fig. 2. (a) Calcite single crystal. (b) - (d) Progressive twinning (twin boundary migration), gray is the twinned domain of the crystal. (e) Fully twinned calcite crystal. (f) Twinning in a calcite crystal where lattice near grain boundary is not free to rotate, due to presence of neighboring crystals.

dislocations concentrate. These dislocation-rich planes are can be easily recognized in thin section as grain boundary. With a low number of dislocations along the boundary the angle between the adjacent crystal lattices is small, and in thin section the two crystals are indicated as two subgrains (Fig. 3a); ongoing stress application result in piling up of dislocations along the grain boundary and the misfit angle, i.e. rotation of a crystal lattice respect to the neighbor lattice, increase. When the misfit angle is large (> 15°), the two crystals are indicated as two grains (Fig. 3b). In a progressive deformation when dislocation creep is allowed, therefore, we have first subgrains formation and then new grains development; this mechanism of new grain formation is often referred as subgrain rotation recrystallization or polygonization. From the above discussion it follows that plastic deformation is always accompanied by recrystallization, also indicated as dynamic recrystallization or syntectonic recrystallization.

Syntectonic recrystallization is therefore the primary mode to reduce elastic energy in a crystal lowering dislocation density. In addition to rearrangement of dislocations along grain boundaries, at higher temperatures dislocation density it is also reduced by migration of grain boundaries across the grain from regions of lower dislocation density into regions of higher dislocation density (grain boundary migration). Grain boundary migration typically produces lobate grain boundaries and grain shapes elongated in the shear direction. Hence strong Shape Preferred Orientation (SPO) of grain boundaries (i.e. a well developed microstructure) occur.

In natural conditions rocks experience recrystallization not only during tectonic deformation (dynamic or syntectonic recrystallization), but if temperature remained relatively high after deformation, recrystallization and microfabric changes occur (static recrystallization or *annealing*). Static recrystallization carbonate rocks usually led to grain growth in the rock and partial to complete obliteration of earlier microstructures (Griggs et al. 1960, Olgaard and Evans 1988, Covey-Crump 1997a,b, Barnhoorn et al. 2005).

In Fig. 4 are some photos of laboratory deformed Carrara marble showing some of the microstructures earlier described.

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Fig. 3. (a) Movements of dislocations along slip planes, two subgrains developed. (b) Arrangement of dislocations along a plane that represent a grain boundary. (c) Two grains separated by a grain boundary, more the number of dislocations along the grain boundary, higher is the misfit angle θ between crystal lattices in two adjacent grains.

2.2 Texture

As already introduced, *texture* is intended here as the Crystallographic Preferred Orientation (CPO) of rock forming minerals. Different geological settings during deformation can produce in a rock (Fig. 5):

- 1. no shape preferred orientation of grains (weak or non-oriented microstructure), and no crystallographic preferred orientation (no texture) (see Fig. 5b);
- 2. no shape preferred orientation of grains (weak microstructure), and strong crystallographic preferred orientation (strong texture) (see Fig. 5c);
- 3. strong shape preferred orientation of grains (oriented microstructure), and no crystallographic preferred orientation (weak or no texture) (see Fig. 5d);
- 4. strong shape preferred orientation of grains (oriented microstructure), and strong crystallographic preferred orientation (strong texture) (see Fig. 5e).

Some are the mechanisms that during deformation led to preferred orientation of crystal lattice, as: passive rotation of grains, twinning, dislocation glide and dislocation creep (rotation recrystallization and grain boundary migration). In natural conditions at high temperature and strain, dynamic recrystallization accompanied by dislocation creep is the main mechanisms developing crystallographic preferred orientation in rocks.

In Fig. 6a an highly schematic representation of a deformed crystal is illustrated. In nature crystals are deformed by movement of dislocations along planes where easy slip is allowed (i.e. planes with low Critical Resolved Shear Stress) and the most deformation (strain) of a crystal is achieved when the easy slip planes are parallel to the shear zone boundaries. Crystals with easy slip planes not parallel to the shear zone boundaries are "hard" to deform and therefore are grains with high dislocation density; during dynamic recrystallization accompanied by grain boundary migration these grains will tende to reduce their size or disappear. In an ideal deformed rock aggregate only grains with easy-slip planes parallel to the shear zone boundaries survive. If for a rock the crystallographic orientation normal to the slip planes for each crystal is reported in a stereographic projection (Fig. 5b) a maximum will occur oblique to the foliation plane in the shear direction: this is the common



results in Schmid et al. 1980). Čolors are due to extremely low thickness of the thin sections $(< 2\mu m)$ (a) Undeformed Carrara marble, starting material for all the experiments; photo width 5.67 mm. (b) Low temperature and low stress applied, at beginning of deformation marble shows widespread twinning; photo width 5.67 mm. (c) Lensoid shaped twins, red arrows indicate twinned domains, blue arrows indicate the original, not twinned portions; photo width 1.42 mm. (d) Same as (c), increasing deformation led to coalescence of twins; photo width 1.42 mm.



Fig. 4 continued. (e) Lensoid shaped twins, red arrows indicate twinned domains, blue arrows indicate the original, non-twinned portions. At higher strains increases the volume of the twinned domains, portion with the original untwinned orientation are restricted to narrow triangular domains along the grain boundaries; photo width 1.42 mm. (f) As increasing deformation twinning went to completion, red arrow indicate a fully twinned crystal; photo width 0.71 mm. (g) Subgrain development in marble; see bar for scale in the lower left corner of the photograph. (h) Ongoing deformation led to fully recrystallized marble, with new grains formation, completely obliterating the former microstructure; see bar for scale.

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Fig. 5. Schematic representation of microfabrics, arrows indicate the same significant crystallographic direction in grains. (a) Single crystal with crystal lattice. (b) Rock with no shape preferred orientation of grains and no crystallographic preferred orientation. (c) Rock with no shape preferred orientation of grains and strong crystallographic preferred orientation. (d) Rock with evident shape preferred orientation of grains and no crystallographic preferred orientation. (e) Rock with strong shape and crystallographic preferred orientation.



Fig. 6. (a) Relationships between foliation, lineation in rock, slip planes, and shear/slip direction for a crystal deformed in a shear zone. The deformed crystal is schematically represented by an ellipse. (b) The same planes and directions in a stereographic projection.

texture usually recognized in deformed rocks. In stereographic projections of natural marble rocks very different distributions of crystallographic directions will result because slip along slip planes not parallel to shear zone boundary may occur. For a more exhaustive discussion of mechanisms leading to texture formation in deformed rocks the reader is referred to Nicolas and Poirier (1976), Lister et al. (1978), Lister and Hobbs (1980), Wenk (1985), Etchecopar and Vasseur (1987), Gapais and Cobbold (1987), Jessel (1988), Law (1990), Schmid and Casey (1986), Schmid et al. (1987), Wenk and Christie (1991), Twiss and Moores (1992), Passchier and Trouw (1996), Kocks et al. (2000), Wenk (2002) and references therein.

3 Microfabric and mechanical properties of marble rocks

Microstructures and textures are responsible for mechanical properties of rocks as: *strength* (in laboratory test the value of uniaxial compressive stress reached when the material fails), *elastic modulus* (the ratio between the axial stress change and the axial strain change), *Poisson's ratio* (the negative ratio between the lateral and the axial strain), *thermal expansion* (change in volume in response to a change in temperature).

Strength, elastic modulus and Poisson's ratio are intrinsic parameters of the rock and important to indicate the rock tendency to be deformed when a force is applied to it and are of great significance in engineering applications of marbles. Thermal expansion instead strongly controls the behaviour of rock also at low temperatures and is responsible for marble deterioration, weathering phenomena, bowing, reduction in rock strength as measured by Young's modulus of elasticity and durability in general. For these reasons it is discussed here in more detail.

To better evaluate marble behaviour during thermal exposure we have to investigate volume expansion, anisotropy of the thermal expansion and the residual expansion, i.e. the permanent length an volume change. Thermal expansion is the relative length change in a



Fig. 7. Linear thermal expansion in calcite, quartz and feldspar, parallel and normal to *c*-axis; from Winkler (1994), after data from Skinner (1966). The expansion of calcite crystals begins to occur at low temperatures.

sample with changing temperature. The degree of expansion with temperature is usually non-linear and the *thermal expansion coefficient* $\alpha [k^{-1}]$ describes the length change per unit temperature on the considered temperature interval: $\alpha = \Delta L/L \times \Delta T$. For calcite (as for many minerals) the thermal expansion coefficient change over the range of temperatures and in different crystallographic directions (Fig. 7), i.e. is non-linear and anisotropic. A calcite crystal subject to temperature expand parallel to crystallographic *c*-axes ($\alpha > 0$ parallel to *c*-axes) and contract in the perpendicular directions ($\alpha < 0$ normal to *c*-axes).

In an ideal rock aggregate if crystal expansion is isotropic and temperature change is small, after heat removal crystals return to its initial state and no change in volume or in length (strain) occur. In nature for marble rocks anisotropic calcite crystals expansion occur parallel to *c*-axes, and this produce tensile strains within the rock which can lead to fracture to release internal stress (Fig. 8a). Fractures due to thermal stress are referred to as "microfracture" as they have small dimensions, and usually develop along grain boundaries.

In many laboratory test marble specimens are subject to thermal cycles and induced strain is measured (Kessler 1919, Rosenholtz and Smith 1949, Sage 1988, Battaglia et al. 1993, Franzini et al. 1984, Widhalm et al. 1996, Goudie and Viles 2000, Leiss and Weiss 2000, Zeisig et al. 2002, Siegesmund et al. 2004, Siegesmund and Dürrast 2011, and references therein). In Fig. 8b is reported a common observed behaviour of marble that suffered thermal cycles: after the first thermal cycle the strain path shows an open hysteresis loop where a *residual thermal strain* can be measured, due to microfracturing. Following thermal cycles show a linear strain path, indicating no further fracture development. Residual strain indicate volume increase due to thermal expansion fracturing and fractures are preferred path for fluids, leading to deterioration.





Fig. 8. (a) Thermal stresses in polycrystalline aggregate. (b) Strain path for marble after three thermal cycles. From Sage (1988).

Many samples of marble rocks shows a strong directional dependence of thermal strain, this occur notably in rocks with a strong crystallographic preferred orientation, i.e. in rocks where syntectonic recrystallization led to development of a strong texture in rock.

This anisotropic thermal dilatation of calcite crystal has also severe influence in deformation of marble slabs after their emplacement, that can experience bowing behaviour (Lord Rayleigh 1934, Logan et al. 1993, Royer-Carfagni 1999b, Koch and Siegesmund 2002, Åkesson et al. 2006, Marini and Bellopede 2007, Siegesmund et al. 2008a,b).

The role of texture in the development of internal stresses in rocks that may lead to microfractures formation is also successfully investigated and reproduced using finite elements simulations (Evans 1978, Royer-Carfagni 1999a, Tschegg et al. 1999, Weiss et al. 2003, Shushakova et al. 2011). In Fig. 9 a simple simulation is shown. In the A configuration the shear stress σ_{xy} is zero but normal stress σ_{yy} has its higher values (tensile stress): this is the more suitable configuration for development of cracks at the triple point grain boundary. The B configuration is comparable to A, but compressive stress at grain boundary occur: only minor cracks are expected. In the C configuration one grain is rotated 90° compared to B, normal and shear stresses show an asymptotic trend: cracks formations is more significant than in the B configuration, but less severe than in A.

In summary, marbles are thermally sensitive rocks because calcite anisotropic behaviour causes damages already at low temperature. Investigating microstructure and texture preferred orientations in rocks, i.e. a detailed fabric analysis, is an appropriate tool for the assessment of marble quality and to better set recovery and preservations of marble artifacts.



Fig. 9. Change of stress along grain boundaries at triple point of an arrangement of three grains with anisotropic thermal expansion; after Evans (1978) and Tschegg et al. (1999). Normalised stress is: $\sigma(1 + \nu)/E\Delta a\Delta T$, where E: modulus of elasticity, ν : Poisson number, α : thermal expansion coefficient, ΔT : temperature change. Ellipse in grains represent elongation direction. Here is used material science convention for stress sign: positive stresses are tensile and negative stresses are compressive.

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