Towards an improved understanding of the mechanical properties and rheology of the lithosphere: an introductory article to ‘Rock Deformation from Field, Experiments and Theory: A Volume in Honour of Ernie Rutter’

E. MARIANI1*, J. MECKLENBURGH2 & D. R. FAULKNER1

1Earth, Ocean and Ecological Sciences, University of Liverpool, Brownlow Street, Liverpool L69 3GP, UK
2School of Earth, Atmospheric and Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL UK

*Corresponding author (e-mail: mariani@liverpool.ac.uk)

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Ernie Rutter’s influential contribution to our understanding of rock deformation spans the whole continental crust, from deformation ‘just under the grass’ (e.g. Rutter & Green 2011) to melt migration in the lower crust (e.g. Rutter & Neumann 1995). Ernie has also worked on many aspects of the deformation of oceanic crust (Rutter & Brodie 1988); however, here we reflect on the wide range of deformation conditions Ernie has studied by presenting key aspects of the strength and rheology of the continental lithosphere as we understand it today, with the aim of providing the context for the contributions included within this volume.

The continental crust forms just over a third of the Earth’s surface and it is different from the crust of any other planet in our solar system. It is rich in those elements that partition in a silicate melt and its formation and evolution determined the composition of the mantle and that of the atmosphere (Hawkesworth 2006). Thanks to its physical and chemical fingerprint, the Earth’s crust has sustained life uninterrupted for 3.8 Ga and it is the source of major natural resources such as hydrocarbons and mineral deposits and others such as geothermal energy. The continental crust is less dense than its oceanic counterpart, and is therefore more buoyant. It forms a substantial part of the cold thermal layer of the Earth and its rheology (from Greek πέλας τρέγος, ‘flow’ and λόγια, ‘logia’, ‘study’; ‘the study of the flow of matter’) is a key factor controlling plate tectonic processes at the Earth’s surface and in its interior (Davies 2011). Beneath the continental crust lies the lithospheric mantle and together they form the continental lithosphere.

Considerable variations in structure, thickness and composition of the continental lithosphere mean that, despite its importance, we currently have limited understanding of the rheology of this complex system (Thatcher & Pollitz 2008). Significant advances in our knowledge of continental rheology have been possible through:

1. field studies of exposed sections of the continental crust (e.g. Brodie et al. 1992; Khazanehdari et al. 2000; Rutter et al. 2007) and major fault zones (Chester & Logan 1986; Imber et al. 2001; Faulkner et al. 2003; Wibberley & Shimamoto 2003; Rutter et al. 2012);
2. the extrapolation of experimental constitutive equations for stable frictional sliding and quasi steady-state viscous flow to deformation in nature (e.g. Goetze & Evans 1979; Brace & Kohlstedt 1980; Carter & Tsenn 1987; Kohlstedt et al. 1995);
3. the development of empirical and theoretical models that attempt to predict the conditions under which a particular rheology is likely to dominate and evolve (Walker et al. 1990; e.g. Hirth & Kohlstedt 2003; Rutter & Brodie 2004a);
4. the study of earthquake depth distributions and gravity anomalies as proxies for continental strength (e.g. Chen & Molnar 1983; Jackson et al. 2008); and
5. the rheology of the continental lithosphere from geodetic observations such as long-term glacial rebound, flexure of the lithosphere and, more recently, the use of satellite measurements (Ryder et al. 2011; Copley et al. 2012).

Ernie Rutter’s research achievements in the field of Rock Deformation, from the 1970s to the present day, have had a significant impact on our
understanding of the rheology of the Earth’s crust. This, together with Ernie’s intention to ‘retire’ (or perhaps ‘not retire’) and be able to dedicate his time to his main passions, the rock deformation laboratory and Earth’s natural laboratory, inspired the convening of a conference in his honour. This meeting was organized at Burlington House, Geological Society of London, and was held on 30–31 May 2012. The conference included 50 participants attending from 10 different countries, and 55 contributions were presented.

Conference contributions were varied and topics, all relevant to various aspects of the mechanical properties and rheology of the lithosphere, ranged from applied studies of gas migration and permeability in shale and clays to the frictional properties (from slow to earthquake slip rates) and permeability of fault zones, to the microstructure of brittle faults and shear zones in relation to field studies in the Italian Alps and Apennines and Southern Spain. Twelve of these contributions are published in this volume and will be introduced in the following sections, where we highlight the importance of combining field observations, experimental results and theoretical models to further our understanding of deformation processes in the Earth’s crust. The concept of continental strength profiles, one of the key contributions of rock deformation studies to the Earth Sciences, is used here as a framework to present the contributions made to this volume in the context of Ernie’s work, as well as some of the challenges that still remain.

**Lithospheric strength profiles**

The idea of a continental crust divided into a shallow *schizosphere*, or zone of fracture, and a deeper *plastosphere*, or zone of flow, developed amongst geologists in the 1930s (Griggs 1936). These rheological concepts developed alongside new deconvolution methods in seismology that allowed geophysicists to determine the depth of earthquake hypocentres with more confidence (Macelwane 1936). Pioneering experimental studies on rock deformation were carried out that investigated frictional strength, through to brittle–plastic and fully plastic deformation behaviour (terminology after Rutter 1986) of a variety of rock types, at a range of pressure (*P*) and temperature (*T*) conditions simulating different depths in the continental crust (e.g. Paterson 1969, 1978). Within this new and vibrant experimental rock-deformation community, Byerlee (1978) first observed that, for most rock types, frictional strength is independent of lithology and may be represented by a simple linear relationship between shear stress and normal stress. [It is interesting to note that Leonardo Da Vinci, in his manuscript Codex Arundel (early 1500, ff. 40v, 41r), explained how his experiments showed that friction is nominally independent of material and proportional to the weight of the objects in contact. Da Vinci proposed a universal coefficient of friction of 0.25.] At the same time, the work of Goetze (1978) and the combined efforts of Heard & Carter (1968) and Christie et al. (1979) resulted in some of the first flow laws proposed in the geoscience community for olivine and quartz, respectively (Brace & Kohlstedt 1980). As a young geoscientist Ernie Rutter explored the wet and dry rheology of calcite aggregates (Rutter 1974, 1976) and, extrapolating his results to geological strain rates, contributed one of the early strength profiles for carbonate rocks (Fig. 1) (Rutter 1972). In the decades that followed, owing to calcite’s natural occurrence in active and fossil fault zones in the shallow crust (Badertscher & Burkard 2000; Ebert et al. 2007; De Paola et al. 2011; Smith et al. 2011) and its relevance as an analogue geo-material, deformable at the full range of conditions accessible in the laboratory, it became one of the most studied and better characterized minerals in the experimental rock deformation community (e.g. Schmid et al. 1980; Rutter 1995; Covey-Crump 1998; Brodie & Rutter 2000; Barnhoorn et al. 2004).

In 1980 Brace and Kohlstedt gathered existing experimental data to construct a model for the rheology of the continental lithosphere. Around the same time, Goetze & Evans (1979) developed a similar approach for the oceanic lithosphere. These and similar models have since been known as ‘strength profiles’. Brace & Kohlstedt (1980) used Byerlee’s rule of friction to represent the strength of rocks in the upper 5–10 km of the Earth’s crust. The lower crust was described with high-temperature experimental data for quartz and olivine extrapolated to the (lower) temperatures and slow strain rates predicted in nature. At depths where the highest density of earthquakes was recorded (c. 15 km, see also Fig. 2c), intersection of the brittle and plastic strength curves was interpreted to represent the brittle–plastic transition (BPT), now often referred to as the frictional–viscous transition. Field observations of fault rock structures, indicative of the depth of the BPT, suggested that the model of Brace and Kohlstedt may be plausible (e.g. Sibson 1982). Thus, despite its many limitations, from the assumption of an Andersonian stress state (Anderson 1905), to that of steady-state deformation and geothermal gradient, to the effects of fluids and pore pressures at depth (e.g. Carter & Tsenn 1987; Kohlstedt et al. 1995; Scholz 2002), the continental lithospheric strength profile proposed in 1980 has inspired fervent research activities aimed at testing its validity and providing an improved understanding of the rheology of the lithosphere.
Upper crustal deformation

Brittle faulting

As regional faults and shear zones may accommodate a large part of the deformation in the lithosphere (e.g. Kirby 1985), it is paramount to construct improved strength profiles accounting for the deformation behaviour of these large-scale structures. The strength of such faults may be considerably weaker than Byerlee friction owing to the smearing of phases with low friction coefficients over the fault surface (Moore & Lockner 2011; Rutter et al. 2013). Handy & Brun (2004) emphasize that lithospheric stresses will vary with time and displacement through an earthquake cycle. However the magnitude of these stress variations is unclear (although likely to be small) and therefore difficult to represent. Hence, in Figure 2a we show a strength profile example, based on recently published flow laws, that does not account for stress drops during the earthquake cycle. In contrast, variations of displacement as a function of time and depth may be measured using geophysical and geodetic methods. This allows us to model displacement with a certain degree of confidence (Tse & Rice 1986) (Fig. 2b). Much progress has been made recently that has improved our understanding of fault strength during earthquake slip. In these studies, high-velocity friction experiments have

Fig. 1. Strength envelope for Solnhofen limestone from experiments performed where pressure and temperature have been increased as they would with increasing depth in the Earth (Fig. 5 in Rutter 1972). The assumed geothermal gradient is 30°C km$^{-1}$ and the geobaric gradient is 23 MPa km$^{-1}$. 

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shown dramatic weakening of most geological materials at earthquake slip rates (e.g. Tsutsumi & Shimamoto 1997; Di Toro et al. 2011). However, the complexity of processes that govern deformation during and between earthquakes means that we are only just starting to model such time-dependent stress variations quantitatively (Konca et al. 2013). It is also important to bear in mind that, if stick-slip events in experiments are analogue phenomena to earthquakes along faults in the Earth, the brittle–plastic region may be considerably weaker than shown (Bos & Spiers 2002a; Mariani et al. 2006). The lower crust is defined by the rheology of dolerite (Mackwell et al. 1998) and the mantle defined by dislocation creep of olivine (Hirth & Kohlstedt 2003). The plot is drawn for a strain rate of $10^{-13}$ s$^{-1}$ and a geothermal gradient of 20°C km$^{-1}$. The dry and wet rheologies for quartz use water fugacities of 1 and 37 MPa, respectively. The wet rheology for dolerite is an estimation assuming a similar amount of weakening as in olivine. For olivine we use the dry dislocation creep parameters given in Hirth & Kohlstedt (2003) and for the wet rheology we assume an OH concentration of 1000 H/10^6 Si. How displacement might be distributed with depth through a seismic cycle and what types of fault rocks might be preserved (modified after Tse & Rice 1986; Scholz 1988; Handy & Brun 2004). For the lower crust and lithospheric mantle we have speculated on what the temporal displacements may look like. Note that the time span between $t_1$ and $t_2$ is almost instantaneous whereas $t_0$ to $t_1$ and $t_2$ to $t_3$ are large. (c) Earthquake frequency plotted against depth for different regions data taken from Jackson et al. (2008). The variation of depth of earthquakes in the lower crust and lithospheric mantle is due to variation in depth of the Moho. Some regions have very little seismicity in the lower crust and lithospheric mantle.

**Critical-state soil mechanics**

A branch of rock deformation that is generally not featured in models of crustal strength, but has typically been applied to failure in the shallower parts of the crust, is critical-state soil mechanics (Schofield & Wroth 1968; Wood 1991). Ernie Rutter became enthused by soil mechanics in the early 1990s, whilst teaching engineering geology to Manchester graduate and undergraduate students. He saw that the theory of critical-state soil mechanics could be applied more widely in structural geology and rock mechanics to systems consisting of a solid and a fluid phase. Ernie therefore went on to use this theory to explain how deformation could aid the extraction of melt from a partially molten rock by shear-enhanced compaction (Rutter & Neumann 1995). He later applied critical-state soil mechanics to model the response to stress of dehydrating serpentinite as observed in experiments (Arkwright &
et al. 2008; Rutter et al. 2009). These aspects of Ernie’s work will be considered further in the context of lower crustal deformation. More recently Ernie has used soil mechanics in a more conventional fashion, to investigate the strength of porous sandstones (Cuss et al. 2003; Rutter & Glover 2012). This research shows that the critical-state line is independent of rock type and can be related to Byerlee’s frictional sliding relationship (Fig. 3). With this knowledge, the failure envelope of any sandstone may be estimated reliably from its porosity and grain size alone.

Applied rock mechanics

In the shallowest parts of the crust, where the large majority of Earth’s natural resources are stored, understanding the strength, mode of failure and permeability of brittle rocks has become particularly important for an efficient extraction of less accessible hydrocarbons and ore minerals, and to minimize the environmental impact of such, often large-scale, extraction operations. Faulkner & Rutter (2000) for example, worked on the high-pressure fluid flow properties of clay fault gouges when different fluid phases are used, while McKernan et al. (2014) investigated the permeability of mudstones under different effective pressures, looking at the implications that this might have for the production of shale gas. A number of Ernie Rutter’s graduate students, thanks to their knowledge of geomechanics, have found employment in industry. Ernie himself has recently become a prominent figure in on-going research aimed at improving our knowledge of the mechanical and transport properties of shale and hydraulic fracturing processes related to the production of shale gas.

Four contributions that highlight the importance of applied rock mechanics are published in this volume. In particular, Heffer (2014) considers the stress field around cracks and the crack density at which they start to interact elastically. The results are used to show that these crack networks can still interact elastically, explaining how small stress perturbations, for example during oilfield production, do not lead to large-scale seismicity. Siddiqi & Evans (2015) investigate the effect of thermal cracking on an initially low-porosity quartzite. These data are important in a number of different applications involving injection or fluid interaction at depth, including geothermal energy and CO2 sequestration, and fluid circulation in the crust. In the experiments, they thermally treat their samples while under different confining pressures and then measure the permeability as a function of effective confining stress. Sinha & Wendt (2014) are concerned with the stress state around boreholes and describe a new method for estimating horizontal stress magnitudes using sonic log data from both vertical and deviated boreholes. Determination of the magnitude of subsurface stresses is vital for the planning of subsurface oil and gas extraction helping to inform well planning, wellbore stability and reservoir management. They develop the theoretical background to the work, and compare results with stress magnitudes obtained using independent

Fig. 3. Graph showing how deviatoric stress ($Q$) varies with effective mean stress ($P$) at critical state (where deformation proceeds at constant volume) defining the critical state line. Data shown for a number of different sandstones with friction data for sandstones projected into $Q$–$P$ space (after Rutter & Glover 2012).
methods in a North Sea reservoir. With a view on the general state of stress in the crust, Harper & Hagan (2015) present a reappraisal of how we should think about stresses that are locked into rocks at depth. They argue that terminology borrowed from engineering such as ‘residual stress’ is not very useful in geomechanics and propose the use of the term ‘inherent stress’ to describe the stresses that a rock can record in it from a previous stress state the rock was under. These authors show that inherent forces can have an impact on the way geological materials behave, a phenomenon that currently is not widely considered.

**Pressure solution**

The shape and character of the BPT in crustal strength profiles are still not well constrained. It is shown in Figure 1 that the BPT, even in controlled experiments on monomineralic rocks, cannot be obtained simply by the intersection of Byerlee’s rule of friction with a flow law curve, but that instead it has a more complex character. During deformation in the lithosphere the BPT may be dependent on rock type, rate and temperature of deformation, pore pressure and rock–fluid interactions. Pressure solution is a mechanism of deformation that can accommodate large strains at a range of low temperatures in the upper crust, by the diffusion of matter in a thin, intergranular aqueous film, away from high stress interfaces (Rutter 1983). Numerous field studies have reported microstructural evidence indicating that pressure solution is important in regional scale active and fossil fault zones (e.g. Imber et al. 2001; Frost et al. 2011; Gratier et al. 2011; Lena et al. 2014; Richard et al. 2014). This, combined with the low temperature sensitivity of pressure solution, suggests that slow fault creep at the BPT, under favourable conditions, may be largely accommodated by this mechanism (Rutter & Mainprice 1979).

Two seminal papers by Ernie Rutter in the 1970s and 1980s (Rutter 1976; 1983) led to: (a) a flow law for pressure solution derived using a theoretical approach; and (b) one of the first deformation mechanism maps in Geoscience to include pressure solution (in the context of calcite deformation; Fig. 4). Further experimental and field studies by Chris Spiers, one of Ernie’s past students, as well as other colleagues in the experimental rock deformation community (e.g. Spiers et al. 1990; Hickman & Evans 1995), later resulted in the development of a new microphysical model of frictional–viscous (‘brittle–plastic’) creep, where it is proposed that the combined action of frictional sliding and pressure solution may accommodate large displacements during the slow interseismic creep of faults (Bos et al. 2000; Bos & Spiers 2002b; Jefferies et al. 2006; Gratier et al. 2013). Additionally, pressure solution is proposed as one of the possible mechanisms for fluid-assisted fault healing, resulting in fault strengthening during periods of no or slow creep (e.g. Rutter & Mainprice 1978; Bos & Spiers 2002b; Gratier et al. 2013; Richard et al. 2014).

This topic has inspired the contribution of Pluymakers & Spiers (2014), who estimate the timescale of sealing and healing processes in anhydrite fault gouges using detailed and rigorous kinetic

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**Fig. 4.** Deformation mechanism map for calcite plotted in temperature stress space from with contours for log strain rate (Rutter 1976). One of the first applications to rocks of M. F. Ashby’s deformation mechanism maps (see review by Frost & Ashby 1982).
models that allow for dissolution, diffusion and precipitation control. They predict that anhydrite fault sealing is likely to occur within decades and it is rapid when compared with CO₂ storage time-scales and earthquake cycles in the Appennines. Bruijn & Almqvist (2014) present the results of a detailed experimental investigation into how compaction is affected by chemical processes in illite shale. These data are key to understanding the alteration of sediments during burial. They subject illite powders to elevated temperatures under pressure to accelerate chemical compaction processes in order to observe them under laboratory timescales. The third contribution relevant to pressure solution is that of Lena et al. (2014) who describe a spectacular example of meso-scale S-C fabrics (metamorphic fabrics where C surfaces are parallel to the main shear surface, while S surfaces are oblique to it, generally at a shallow angle) developed in a downward cutting thrust zone in central Italy. These authors interpret the structures as being formed by a combination of deformation by pressure solution and cataclasis. This work helps our understanding of how the continental crust deforms in the depth range where fracturing and thermally activated processes are both active.

The transition from upper to lower crust is diffuse and it is likely that thermally activated processes dominate in the lower parts of the upper crust. In this context Gapais & Laouan Brem Boundi (2014) contribute to this volume by presenting a field study of spectacular mylonitic pegmatites emplaced within two-mica granites in the Hercynian South-Armorican Shear Zone of Brittany, France. They interpret the plastic deformation of quartz in the pegmatite as evidence for syn-kinematic emplacement.

**Lower crustal deformation**

*Crystal plasticity and grain size-sensitive creep*

Below 10–15 km depth in the Earth, as temperature increases, the viscous strength of rocks decreases and mechanisms of plastic deformation become dominant over frictional sliding and brittle failure. The main mechanisms of plastic deformation may be subdivided into grain size-insensitive dislocation creep and grain size-sensitive grain boundary sliding accommodated by diffusion or by the motion of dislocations (e.g. Hirth & Kohlstedt 2003; Burgmann & Dresen 2008). Constitutive equations, or flow laws, that describe such mechanisms have been empirically derived from laboratory experiments and are underpinned by fundamental physical principles. With care, and bearing in mind limitations related to assumptions of steady-state deformation and geothermal gradient, spatial and temporal scaling, mineralogical and microstructural evolution and rock–fluid interactions, flow laws may be extrapolated to deformation conditions in the Earth. We have used relevant examples of such equations to plot Figure 2a, where we show the plastic strength of micas, wet and dry quartz and feldspar (Hirth et al. 2001; Rutter & Brodie 2004b; Rybacki & Dresen 2004; Mariani et al. 2006), which are abundant in the mid to lower crust, that of a wet and dry mafic lower crust (Mackwell et al. 1998) and a wet and dry upper lithospheric mantle (Hirth & Kohlstedt 2003). While the importance of dislocation and diffusion creep in rocks had been known to the rock deformation community since early in the 1930s, dislocation accommodated grain boundary sliding was recognized as a key mechanism in a number of different geo-materials only later, in the 1990s.

Following from the recognition that grain size-sensitive deformation mechanism (particularly those that lead to superplasticity) may be important in high strain shear zones (e.g. Behrmann & Mainprice 1987; Brodie & Rutter 2004a, b), Walker et al. (1990) provided the scientific community with the first deformation mechanism map (for calcite) showing an additional grain size-sensitive domain. This domain is characterized by a deformation mechanism that is transitional between dislocation creep and diffusion creep and, in calcite, has a stress exponent equal to 3 (Fig. 5a). The use of strain markers and detailed, qualitative and quantitative analysis of experimental microstructures showed convincing evidence for grain boundary sliding (Fig. 5b) ‘persisting even into the intracrystalline plastic flow regime’. Subsequently, dislocation accommodated grain boundary sliding was observed in ice (Golsdby & Kohlstedt 2001), olivine (Hirth & Kohlstedt 1995), feldspar (Rybacki et al. 2010) and perovskite (Mecklenburgh et al. 2010).

**Lower crustal structure**

In the context of lithospheric strength profiles there is debate on the degree of localization in the lower crust, below regional-scale, active brittle fault zones. The Sibson–Scholz conceptual fault model (e.g. Sibson 1982; Scholz 1988) proposes localized brittle and frictional deformation near the Earth’s surface along active fault zones, with a transition to more distributed deformation around depths of 10–15 km where the BPT is expected to occur, and a further change to aseismic viscous creep along shear zones in the middle to lower crust (see also Behr & Platt 2014). An understanding of localization is key to be able to understand lower crustal stress states, as distributed or localized deformation...
will result in several orders of magnitude differences in strain rates. As strain rate is related to stress in flow laws, this uncertainty in strain rate results in considerable uncertainty in stress prediction models.

Significant developments in geodetic techniques in the last ten years, such as the Global Positioning System and Interferometric Synthetic Aperture Radar, have allowed us to model post-seismic relaxation processes from the Earth’s surface displacement field. Some of these models suggest that lower crustal relaxation can contribute to post-seismic deformation, but it is unclear if the deformation is accommodated by distributed viscous creep or by a localized shear zone (e.g. Burgmann & Dresen 2008) (see also Fig. 2b).

Data from local and regional catalogues of earthquake location show that, under parts of Africa, India, Tien Shan and Mongolia–Baikal, for example, earthquakes occur throughout the crust to depths of 30–40 km (Jackson et al. 2008; e.g. Fig. 2c). However the nature and mechanisms of rupture and the earthquake cycle at those depths are not yet understood. Throughout his scientific career Ernie has been inspired and guided by field observations when designing and interpreting experiments, and extrapolating experimental results to nature. Field studies document large-scale spatial variations in the structure and mineral content of exposed faults and shear zones, and also of metamorphic terrains, thus providing better constraints for existing conceptual models of faults and mountain building. Ernie Rutter, with Kate Brodie and other collaborators, carried out extensive field work in the Ivrea–Verbano zone, northern Italy, and produced one of the most comprehensive studies of a section of exhumed lower crust (e.g. Brodie & Rutter 1987a; Brodie et al. 1992; Khazanehdari et al. 2000; Rutter et al. 2007). Figure 6 shows a cross-section through the upper part of the Ivrea–Verbano zone. With this section Rutter et al. (2007) contributed new structural data that identify the previously unmapped Monte Massone isoclinal antiform, which re-folds pre-existing large-scale migmatitic folds. Within the higher-grade section of the Ivrea–Verbano zone, Brodie & Rutter (1987a) observed a series of localized shear zones that they interpreted as being associated with large-scale extensional faulting in the lower crust.

Further field evidence, relevant to the lower crust, in the Lofoten complex of Norway has shown that the now exposed granulitic continental crust contains a network of pseudotachylite veins and eclogite facies shear zones with pre- and syn-kinematic relationships (e.g. Kullerud & Erambert 1999; Steltenpohl et al. 2006). Thermobarometry on mylonitic mineral assemblages indicates that these shear zones and associated pseudotachylites should have formed at depths of 35 km or deeper. If pseudotachylites are interpreted to be the result of frictional melting during earthquake rupture then this depth may reflect the rupture depth of an exhumed lower crustal palaeo-fault (Moecher & Steltenpohl 2009). In the same localized shear zones Menegon et al. (2013) report evidence of transition from brittle processes to viscous flow. Thus field evidence seems to suggest that localization is likely to be widespread in the lower crust and that
more distributed viscous deformation may coexist with an anastomosing network of localized shear zones (e.g. Burgmann & Dresen 2008).

Metamorphic reactions and partial melting

Prograde metamorphism during the subduction of oceanic crust results in metamorphic mineral changes and the release of water that produces mechanical and chemical effects in the lithospheric mantle resulting in partial melting and therefore heat transfer to the crust. Similarly, during orogenesis and post-orogenic mafic underplating the continental crust is heated, undergoes metamorphism and can ultimately melt. Metamorphism and partial melting have profound effects on the rheology of the Earth’s crust (e.g. Rubie 1984; Beaumont et al. 2001; Harris 2007). However our understanding of these processes is largely qualitative and there is a strong need to obtain flow law parameters that can describe quantitatively the rheological response of polyphase and partially molten rocks.

Experimental studies have shown that changes in rheology and significant weakening are often observed during mineral reactions (e.g. Rutter & Brodie 1988; de Ronde et al. 2005; Holyoke III & Tullis 2006). Rutter & Brodie (1988) attributed the weakening they observed during experimental dehydration of serpentinite (Fig. 7) to the nucleation of new, cryptocrystalline olivine grains along micro shear zones (Fig. 8). Such fine-grained reaction products were interpreted to be deforming by grain size-sensitive mechanisms, thus inducing localization weakening in the rock aggregate. Gypsum and anhydrite may serve as analogue materials for deeper mineral assemblages and are important in shallow crustal faults and for the cement industry. On-going experimental, microstructural and theoretical studies on these minerals (e.g. Hildyard et al. 2011; Brantut et al. 2012; Fusseis et al. 2012; Llana-Funez et al. 2012; Wheeler 2014) and on serpentinite (Llana-Funez et al. 2007; Rutter et al. 2009; Proctor et al. 2014), one of the main minerals in subduction zones, are aimed at

**Cross-section along the Valle d’Ossola**

Fig. 6. Cross-section through part of the Ivrea–Verbano zone, drawn parallel to Val D’Ossola (after Rutter et al. 2007). The isoclinal Monte Massone antiform folds pre-existing large-scale folds formed during regional migmatization associated with the Hecynian orogeny. To the east, the section of lower crust represented by the Ivrea–Verbano zone is brought into contact with upper crustal rocks of the Serie dei Laghi along two major shear zones, the Pogallo and Cossato-Mergozzo-Brissago lines. To the west it is juxtaposed with mylonites of the Insubric line (Alpine orogeny).
underpining micro-physical parameters that may be used to construct predictive models of the interaction between deformation and metamorphism.

Partial melting in the middle to lower crust leading to large scale weakness, as evidenced by the lack of large topographic variations of the high plateau of Tibet, has been used to explain the tectonic evolution of the Himalaya with a channel flow model (Beaumont et al. 2001; Harris 2007). The first experiments on partially molten granites were performed by van der Molen & Paterson (1979), who defined a rheologically critical melt percentage for granitic rocks. This concept became powerful within the geological community although, in the experiments of van der Molen & Paterson (1979), the melt viscosity varied considerably over the melt fraction range. Rutter & Neumann (1995) used increasing temperature to increase the melt fraction, thus obtaining a more constant melt viscosity over the range of melt fractions and hence a more realistic melt fraction dependence of strength. This was further improved by using synthetic granitic rocks where the melt fraction and viscosity were controlled independently (Fig. 9; Mecklenburgh & Rutter 2003; Rutter et al. 2006). Many of the geodynamic models involving partially molten material use arbitrary weakening functions rather than experimental parameters (e.g. Beaumont et al. 2001; Shen et al. 2001). Ernie and his group showed that their empirical flow law for partially molten rock could be used effectively in geodynamic modelling (Rutter et al. 2011).

**Analysis of microstructures and crystallographic preferred orientation**

Equal to Ernie Rutter’s passion for fieldwork is his conviction that it is only through petrographic and microstructural analyses of both recovered
experimental specimens and natural samples that we can gather sufficient evidence to support our interpretations of experimental results. Ernie’s microstructural work, in parallel with his experimental and field studies, extends to a range of crustal depths. Some of Ernie’s perhaps best-known studies are those on plastic microstructures in calcite rocks and brittle and frictional microstructures in fault gouge. In fact, Ernie performed one of the earliest studies on the influence of non-coaxial strain paths on the development of crystallographic preferred orientation (CPO) in experimentally deformed marble (Rutter & Rusbridge 1977). Walker et al. (1990), and after them Rutter et al. (1994), looked into the microstructures of calcite rocks deforming by grain size-sensitive mechanisms, providing evidence for grain boundary sliding occurring during dislocation creep (Fig. 5b). Ernie also proposed one of the first palaeopiezometers using calcite twinning to estimate palaeostresses (Rowe & Rutter 1990). Within the domain of brittle and frictional deformation a seminal publication reported comparison of naturally and experimentally deformed fault gouges (Rutter et al. 1986).

In this volume, and in the context of calcite microstructures, Valcke et al. (2014) investigate the effect of deformation on the evolution of recrystallization in Carrara marble using electron backscatter diffraction (EBSD). Their results show that grain boundary bulge and recrystallized grain sizes are inversely dependent on stress and that different recrystallization mechanisms evolve into profoundly different microstructures. These authors therefore conclude that calibrated palaeopiezometers should only be applied consistently to one type of microstructure. Zucali et al. (2014) use neutron diffraction techniques to determine bulk CPOs of amphibole and plagioclase within rocks from exposed upper and lower continental crust (Serie dei Laghi and Ivrea–Verbano Zone) in the Italian Southern Alps. These CPOs help determine seismic anisotropy in this complex metamorphic terrain, which is interpreted as an ancient extensional continental margin. Using microstructural parameters to obtain physical properties from tensor calculus applied to geological and geophysical problems, Mainprice et al. (2014b) present elastic wave propagation in piezoelectric crystals as an example of interaction between electric, piezoelectric and elastic properties. Anisotropic piezoelectric properties are calculated for single crystals and corresponding aggregates from a range of fabric (or texture if using material science terminology) datasets that can be obtained from electron backscatter diffraction, electron channelling pattern, Laue pattern and optical microscope universal-stage analysis. In parallel, Mainprice et al. (2014a) analyse mathematically in MATLAB, using MTEX, the strength of crystallographic preferred orientations as represented by orientation and misorientation.
distribution functions or pole figures, symmetry of pole figures and components of orientation distribution functions, and elastic tensors. These are then compared with the functionality of the M-index and the eigen-analysis. These contributions provide tools that are invaluable to the Earth Science community.

Concluding remarks

As documented in this introduction, efforts in the field of rock deformation over the last 80 years, including those of Ernie and his numerous graduate students, postgraduate researchers and collaborators, have led to a much better understanding of the mechanical behaviour, rheology and structure of the lithosphere. It is clear, however, that there is still much to be done if we want to unravel further the complex processes that shape the Earth’s outer layer. We would like to conclude this article by highlighting some of the challenges that still remain to be resolved in the fields of both brittle and plastic rock deformation:

- Understanding large-scale brittle fault strength. Observations of low-angle extensional faults and measurements on the San Andreas strike-slip fault in California suggest that Byerlee’s rule for rock friction may not be universally applied to understand brittle fault strength. Conversely, many fault zones contain a significant proportion of clays, which are known to have friction coefficients less than those predicted by Byerlee’s rule, yet a number of observations indicate that their bulk strength agrees with Byerlee’s range. As the brittle strength of faults is a key ingredient in crustal strength profiles, these observations have to be understood in order to produce useful stress estimates in the brittle crust.

- Mechanics of earthquakes. Much recent effort has been directed to understanding the mechanical evolution of faults during earthquake slip. While these efforts have advanced our understanding greatly, new experiments are still required in order to replicate more closely the physical conditions during earthquake ruptures. There is a wonderful opportunity to advance our knowledge of the mechanics of earthquakes significantly in the coming years by combining results from experimental rock deformation with those from geodesy and seismology.

- Physical properties of crustal materials. For the future well-being of our planet, we have a duty to develop and manage our natural resources responsibly, including the optimal use of new clean forms of energy such as geothermal and safe storage of hazardous material and CO₂. All of these endeavours require a better understanding of the properties of the crust, not just the strength, but also transport properties such as the permeability and seismic velocity.

- The rheology of polyphase rocks. While flow laws are generally obtained, with a certain degree of confidence, from experiments performed on simplified systems such as monomineralic polycrystalline samples, there is a pressing need to design experimental programmes aimed to investigate the flow behaviour of polyphase materials. Controls on localization and the evolution through time of phase boundaries and phase contiguity in systems under stress are key aspects to consider.

- The effect of fluids on rock strength and fluid pathways in plastic shear zones. Despite growing evidence to suggest that fluid-flow is focused in fault zones all the way from the lower crust to the surface, there is a lack of experimental data to indicate exactly how this occurs, and how it might depend on coeval deformation (dynamic permeability), as opposed to occurring under static conditions. The process of localization of strain in plastic shear zones is poorly understood but the weakening effect of fluids both chemical and mechanical may be key. More experiments are needed that measure the dynamic permeability of rocks deforming plastically.

- The feedback between stress and chemical reactions. Equilibrium thermodynamics assumes stress to be isotropic; however, we know that stresses within the Earth cannot be isotropic. Theories that include anisotropic stress states need to be developed and tested experimentally to assess the effect that deviatoric stress may have on metamorphic reactions. Furthermore, how metamorphic reactions can lead to weakening and strain localization and how this can in turn lead to deep earthquakes is not fully understood. Using X-ray and neutron diffraction to measure the stresses and strains in product and reactant mineral phases during reactions occurring under an anisotropic stress state may provide some of the answers.

- Quantifying rheological behaviour resulting from the interaction of brittle and plastic processes. This is possibly one of the least understood aspects of rock deformation. A large number of qualitative and quantitative studies of brittle–plastic (or semi-brittle) processes are based on field observations. Experiments under controlled conditions have provided us with comparative measurements of crack and dislocations properties and crack-dislocation interactions. However, constitutive equations are needed if we want to improve strength profiles as interpretative tools of lithosphere deformation.
Thank you Ernie for your past, present and future work and your legacy, which will continue to inspire generations of geologists to tackle these challenges.

We would like to thank the numerous reviewers of the contributions in this volume for the time they spent on this task and for their constructive comments, which greatly improved the volume. We would also like to thank all the authors for their effort and their patience. We thank the GSL chief books editor, Rick Law, for his constructive review of this introductory article, and both Rick Law and Angharad Hills, the GSL commissioning editor, are sincerely acknowledged for their continuous constructive review of this introductory article, and both thank all the authors for their effort and their patience. This task and for their constructive comments, which contributions in this volume for the time they spent on work and your legacy, which will continue to acknowledge NEER-funded research projects NE/H012486/1 and NE/J024449/1.

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