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“Order from chaos”: A field-based estimate on bulk rheology of tectonic mélanges formed in subduction zones

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ABSTRACT

Many tectonic HP–LT mélanges exhibit block-in-matrix structures. In contrast to the pervasively deformed matrix, the blocks of various lithologies and PT-histories usually appear undeformed. If we accept that an HP–LT mélange reflects persistent high strain deformation in a deep (>30 km) subduction channel, the record of these rock associations can provide insight into stress state, rheology, and flow patterns along a plate interface. The bulk rheology of a block-in-matrix structure is controlled by (a) the dominant deformation mechanism of the matrix, (b) the volume fraction of blocks engulfed in that matrix and (c) the geometry of the blocks. The microstructures of the matrix indicate distributed deformation by dissolution–precipitation creep (DPC), while crystal plastic deformation is subordinate. DPC is grain size sensitive, controlled by the type of interfaces, and requires an aqueous pore-fluid at quasi-lithostatic pressure. The rheology of a rock body undergoing deformation by DPC is believed to be Newtonian viscous. Matrix viscosities are estimated to be on the order of ~10^{19} Pa s or less. Here, we explore the effect of rigid blocks embedded in a weak matrix on the bulk rheology. Using stereology, we determine the block size distributions as well as the total block volume fractions for block-in-matrix structures from several regions. The volume fractions are found to range from 2 to 70% with typical values between ~5 and 50%. Using published mixing laws, we model the subduction channel as a suspension of rigid spheres with a linear viscous matrix and predict that for the typical values of 5 to 50%, the viscosity increase is less than one order of magnitude. Consequently, the influence of blocks on the bulk viscosity of a subduction channel is minor. Instead, bulk rheology is primarily controlled by the deformation behaviour of the matrix material.

1. Introduction

A large portion of plate convergence is accommodated by subduction, whereas the interior of the plates remains relatively undeformed (Stern, 2002). At first glance, the rheological weakness of the plate interface in subduction zones may appear counter-intuitive in view of the thermal structure (Peacock, 1996; Turcotte and Schubert, 1982; van den Beukel and Wortel, 1988). Advective cooling renders the plate interface – where deformation is expected to be localised – particularly cold. Obviously this is in conflict with conventional lithospheric strength profiles, which are based on the assumption of frictional sliding along faults in the upper, and deformation by dislocation creep in the lower lithosphere (e.g., Kohlstedt et al., 1995; Ranalli, 1995). Such models predict high strength for a cool geotherm and are not compatible with localisation of deformation in a cold region. Consequently, localisation of deformation along the deeper (say >30 km) portion of the subduction interface must be controlled by intrinsic material properties and deformation mechanisms, probably combined with high fluid pressure.

For the plate interface in active subduction zones, the mechanical properties and mechanisms cannot be easily inferred from geophysical observations. Instead, information on the small scale mechanisms and properties controlling the rheology in a subduction zone may be provided by the record of exhumed high pressure–low temperature (HP–LT) metamorphic rocks (Stöckhert, 2002). The high *P*/*T* ratios recorded by the mineral assemblage in such rocks are probably invariably related to advective cooling in a subduction zone (e.g., Peacock, 1996). Unfortunately, the record of deformation at depth is more or less obliterated by subsequent processes affecting these rocks during and after exhumation to a shallow crustal level.

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In view of hundreds or thousands of kilometres of plate convergence accommodated by a narrow zone along the plate interface, strain accumulated in the materials squeezed in between the plates must be exceedingly high. Candidates for fossil very high strain zones developed in subduction zones at depths of >30 km are mélange complexes with high pressure–low temperature metamorphic rocks (e.g., Cowan, 1985; Ernst, 1988; Raymond, 1984). Several authors proposed that the characteristic block-in-matrix structures of such chaotic HP–LT mélanges may have developed in a deep-reaching subduction channel along the plate interface through a combination of slab-disintegration, tectonic erosion, mechanical mixing, hydration and chemical alteration (Bebout and Barton, 2002; Blanco-Quintero et al., 2011; Cloos, 1982; Cloos and Shreve, 1988a, 1988b; Federico et al., 2007; Gerya and Stöckhert, 2006; Gerya et al., 2002; Guillot et al., 2009; King et al., 2006; Shreve and Cloos, 1986; Spandler et al., 2008; for reviews see Bebout, 2007; Festa et al., 2010). Note that the term subduction channel is likewise used to describe sediments being underthrust along a distinct décollement at the base of accretionary complexes (e.g., Bachmann et al., 2009; Collot et al., 2011; Fagereng, 2011; Lohrmann et al., 2006; Scherwath et al., 2009), without a clear cut boundary between such a “shallow” and a “deep” subduction channel. Here we only refer to depths exceeding about 30 km, as recorded by HP–LT metamorphic rocks. We do not address the history and evolution of the tectonic mélange, taking the present structure as a snapshot of an evolved system active at depth.

The appearance of such HP–LT metamorphic block-in-matrix structures in the field and the basic concept are illustrated in Fig. 1a, using examples from the Franciscan subduction complex (California). The photographs in Fig. 1 b–c show nearly isometric, rounded blocks of HP–LT metamorphic rocks that are embedded in a serpentinite or metasedimentary matrix. Many blocks appear virtually strain free,

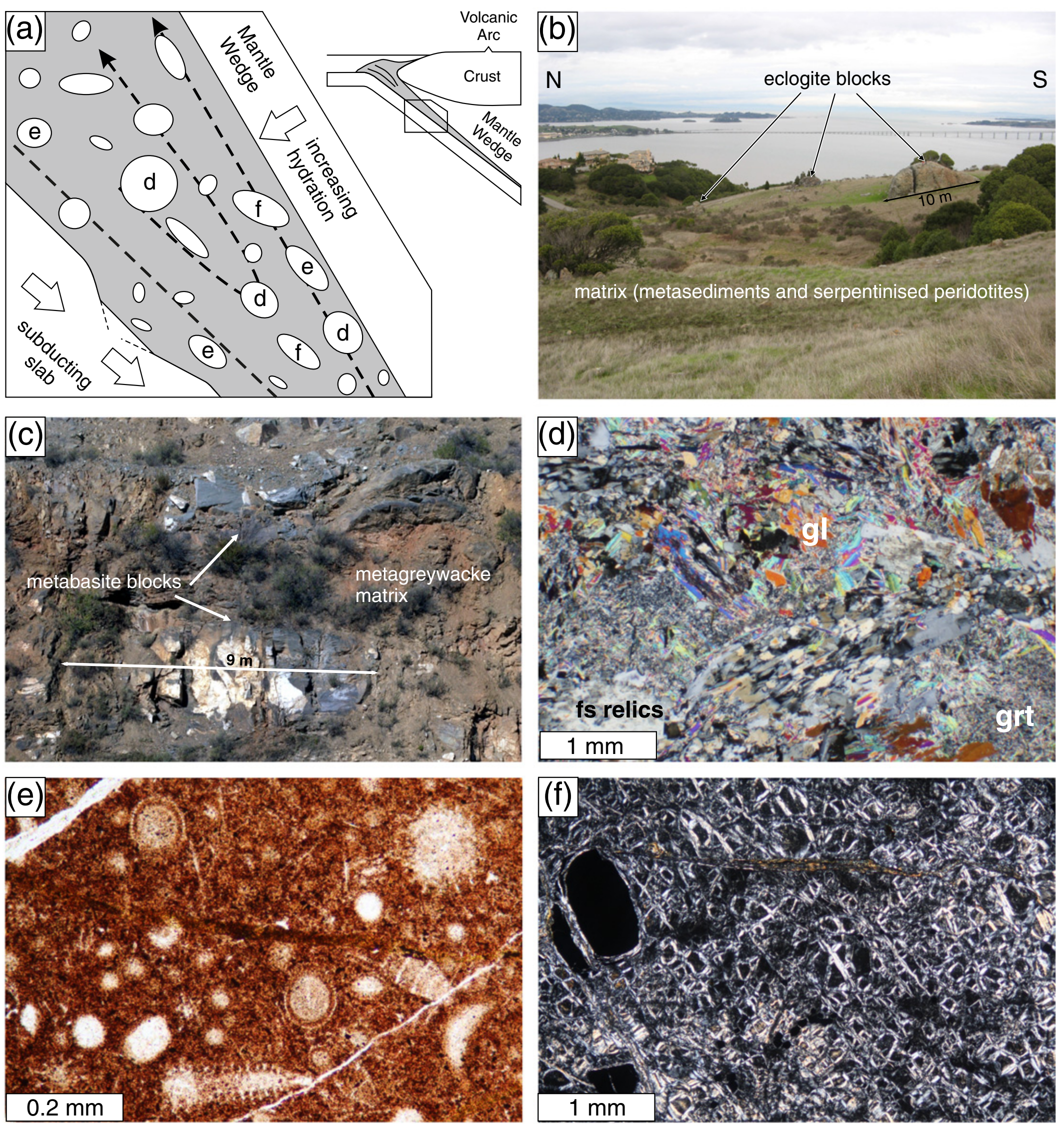

Fig. 1. (a) Schematic drawing of tectonic setting of a subduction channel and formation of a tectonic mélange with block-in-matrix structure through chaotic mixing of slab and mantle blocks with the subduction channel matrix (grey) (after Bebout and Barton, 2002). The subduction channel matrix may consist of serpentinites and/or metasediments. Characters in blocks refer to thin section photographs (d) to (f). (b) Appearance of such a block-in-matrix structure at Ring Mountain, Tiburon Peninsula, Franciscan Subduction Complex: Exotic eclogite blocks embedded in a matrix of metashale and serpentinised peridotites. (c) Blueschist-facies metabasalt blocks included in a metasedimentary matrix at Pacheco Pass, Franciscan Subduction Complex. (d) Microphotograph of preserved magmatic fabric in an eclogite-facies metabasites block from Ring Mountain, Franciscan Subduction Complex; plagioclase relics can still be recognised; fs: feldspar; gl: glaucophane. (e) Microphotograph of well-preserved, completely undeformed radiolarians in a metachert block from Ring Mountain, Franciscan Subduction Complex. (f) Microphotograph of massive serpentinite block; here olivine was replaced by serpentine, while the original microstructure is still discernible in the typical mesh structure. The microphotographs in (d)–(f) illustrate that the blocks are internally strain-free, implying a high viscosity contrast between blocks and matrix.