Journal of Structural Geology 54 (2013) 136–155

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Rheological evolution of a Mediterranean subduction complex

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ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form
13 July 2013
Accepted 24 July 2013
Available online 7 August 2013

Keywords:
Subduction complex
Quartzite flow law
Paleopiezometry
Stress in subduction zones
Continental subduction
Pressure solution
Dislocation creep
Grain boundary sliding
Mylonites
Betic Cordillera

ABSTRACT

We use field and microstructural observations, coupled to previously published P-T-time histories, to track the rheological evolution of an intracontinental subduction complex exposed in the Betic Cordillera in the western Mediterranean region. The body of rock we focus on, known as the Nevado-Filabride Complex (NFC), was originally part of the upper crust of the Iberian margin. It was subducted into hot asthenospheric mantle, then exhumed back toward the surface in two stages: an early stage of fast exhumation along the top of the subducting slab in a subduction channel, and a late stage of slower exhumation resulting from capture by a low-angle detachment fault rooted at the brittle-ductile transition. Each stage of deformation in the NFC was punctuated by changes in the dominant deformation mechanism. Deformation during initial subduction of the complex was accommodated by pressure-solution creep in the presence of a fluid phase – the grain sizes, stress magnitudes, and estimated strain rates for this stage are most consistent with a thin-film model for pressure solution in which the diffusion length scale is controlled by the grain size. During the early stages of exhumation within the subduction channel, deformation transitioned from pressure solution to dislocation creep due to increases in temperature, which resulted in increases in both water fugacity and grain size, each of which favor the dislocation creep mechanism. Differential stress magnitudes for this stage were ~10 MPa, and are consistent with simple models of buoyancy-driven channel flow. With continuing subduction-channel exhumation, deformation remained within the dislocation creep field because sequestration of free water into hydrous, retrogressive minerals suppressed the pressure-solution mechanism. Differential stresses progressively increased to ~100 MPa near the mouth of the channel during cooling as the rocks moved into mid-crustal levels. During the final, core-complex stage of exhumation, deformation was progressively concentrated into a narrow zone of highly localized strain beneath a mid-crustal detachment fault. Localization was promoted by a transition from dislocation creep to dislocation-creep-accommodated grain boundary sliding at temperatures of ~350–380 °C, grain sizes of ~4 μm and differential stress magnitudes of ~200 MPa. Peak differential stress magnitudes of ~200 MPa recorded just below the brittle-ductile transition are consistent with Byerlee's law in the upper crust assuming a vertical maximum principal stress and near-hydrostatic pore fluid pressures. Overall, the distribution of stress with temperature, coupled to independent constraints on strain rate from field observations and geochronology, indicate that the naturally calibrated Hirth et al. (2001) flow law for wet quartzite accurately predicts the rheological behavior of mid-crustal rocks deforming by dislocation creep.

1. Introduction

A common feature of nearly all convergent orogens is the preservation of low to medium grade, high-pressure metamorphic rocks that have been subducted to several tens of kilometers depth, then exhumed back to the surface during ongoing subduction. During the burial and exhumation cycle, the deeper parts of these *subduction complexes* may occupy a channel along the interface between the down-going slab and the overriding plate. Their rheological properties exert a controlling influence over several aspects of subduction zone dynamics, including the shear stress along the plate interface (e.g. Vergnolle et al., 2007), the depth of coupling between the upper and lower plates (e.g. Stöckhert, 2002), the amounts and rates of exhumation of subducted material (e.g. Gerya and Stöckhert, 2002), and the depth of seismicity (e.g. Tichelaar and Ruff (1993)). Field and microstructural observations

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0191-8141/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2013.07.012

of exhumed subduction complexes can constrain their rheological properties and can provide unique insight into these aspects of subduction dynamics, often at a scale inaccessible to geophysical measurements.

Many models of subduction channel mechanics assume isoviscous Newtonian or temperature-dependent power-law rheologies. But during subduction and exhumation, rocks within a subduction complex undergo important changes in their bulk rheological properties. They are heated and pressurized, inducing metamorphic reactions that change the rock density and absorb or expel fluids; and they are deformed, changing the distribution and orientation of mineral phases, the average grain sizes, and the geometry and anisotropy of the rock body. During initial burial, for example, rocks at the top of the subducting slab may be unconsolidated and wet, such that they behave as low viscosity melanges in which the rheology is controlled by a weak matrix phase (e.g. clay or mica) deforming at high pore-fluid pressures (Cloos, 1982; Cloos and Shreve, 1988). During subsequent burial and associated increases in pressure and temperature, the rocks may become less porous; the clay minerals may break down to form other, less fissile, Al-rich silicates; and the strain may become distributed into different phases with different rheological characteristics (e.g. Grigull et al., 2012). The rheology at this stage will likely depend on the remaining fluid content and the load-bearing minerals, themselves dependent on the original bulk composition. As the rocks pass through peak T and P and begin to cool and decompress, retrogressive metamorphic reactions may lead to the consumption of water by the formation of hydrated minerals, and associated strengthening (Yardley, 1981). As a result, the rocks may cease to deform, or else deform by processes operative under higher differential stresses, such as dislocation creep or brittle fracture. These progressive changes in rock properties affect the active deformation mechanisms and the associated effective viscosity, likely inducing transient and complex effects on the behavior of the plate boundary interface.

In this paper we use field and microstructural observations, coupled to previously published P–T-time histories, to track the rheological evolution of an intracontinental subduction complex exposed in the Betic Cordillera of southern Spain. The body of rock we focus on was originally part of the upper crust of the Iberian margin. It was subducted into hot asthenospheric mantle, then exhumed back toward the surface in two stages: an early stage of fast exhumation along the top of the subducting slab in a subduction channel, and a late stage of slower exhumation by capture along a low-angle detachment fault rooted at the brittle ductile transition (Behr and Platt, 2012). Such two-stage exhumation histories are common to many subduction complexes in the Mediterranean region (Jolivet et al., 2003), but very little is known about the interplay between the rheological behavior of these rocks and their exhumational style. We demonstrate that the transitions from burial, to channelized exhumation, to exhumation in the footwall of a low-angle detachment fault are each punctuated by changes in the dominant deformation mechanisms, suggesting an important link between the style of exhumation and the internal rheology of the subducted rocks. We also use observational data on the rheological parameters (e.g. stress, temperature, grain size, strain rate) of the subducted rocks to test the applicability of published experimental quartzite flow laws and to examine the localization mechanisms that operated during progressive exhumation and cooling in this subduction zone environment.

2. Regional geology

The Betic-Rif Cordillera of southern Spain and northern Morocco is the western-most of the arcuate Alpine mountain belts that encircle the Mediterranean Sea (Fig. 1). The orogen has straddled the collision zone between Africa and Iberia from the early Eocene to the present, accommodating between 140 and 500 km of northward motion of Africa relative to Iberia (Dewey et al., 1989; Vissers and Meijer, 2012). The arc comprises an external, non-metamorphic, thin-skinned fold-and-thrust belt surrounding an internal extensional hinterland known as the Alboran Domain. The external zones preserve remnants of the original African and Iberian continental margins that were rifted apart during the early Mesozoic, whereas rocks in the internal zone are the subducted and exhumed equivalents of the intervening thinned continental and oceanic material that resided between the two continents prior to convergence.

We focus here on one of the subducted and exhumed bodies of rock within the internal zone of the Betic Cordillera, known as the Nevado-Filabride Complex (NFC). The NFC is the most recently subducted and exhumed complex in the Betics, showing evidence for high pressure/moderate temperature metamorphism at ∼15–18 Ma (Sanchez-Vizcaino et al., 2001; Platt et al., 2006), followed by retrogression associated with rapid exhumation to upper crustal levels by ∼8 Ma (Johnson et al., 1997). The NFC is exposed in the cores of two E–W trending, domed culminations, including the Sierra Nevada-Sierra de Los Filabres and Sierra Alhamilla-Sierra Cabrera culminations. Within these ranges, the NFC composes the footwall of what resembles a large-scale metamorphic core complex, separated from lower grade hanging-wall rocks exposed along the margins of the ranges by a well-defined, low angle brittle detachment fault that formed along precursory ductile shear zones (Jabaloy et al., 1993). The NFC is unique in that it provides a microstructural record of deformational processes during rapid intracontinental subduction and exhumation, which has not been described or quantified from any other orogen. Our study focused on the NFC as exposed in the Sierra Alhamilla, because there it preserves the most complete and well-exposed sequence of deformation associated with exhumation of the Complex.

3. Deformation history of the NFC in the Sierra Alhamilla

The Sierra Alhamilla is an E–W-trending antiform with Nevado-Filabride rocks exposed in the core and hanging-wall carbonates and phyllites exposed along the rim and as isolated klippen near the crest of the range. The footwall and hanging-wall rocks are everywhere separated by a brittle detachment fault, in some places associated with a pronounced zone of cataclasis and mylonitization in the footwall. The NFC in the Sierra Alhamilla has been divided into two tectonostratigraphic units: the Alhamilla unit and the Castro unit, distinguished on the basis of metamorphic grade, lithologic heterogeneity and style of deformation (Fig. 2) (Platt and Behrmann, 1986). The Alhamilla unit is the structurally lowest, cropping out throughout the core of the range and along its northern margin. It consists of graphitic mica schist with minor lenses of quartzite and metaconglomerate. These rocks generally show biotite and chlorite zone greenschist facies metamorphism with an average peak temperature of ∼490 °C, except at the contact with the Castro unit where there is an inverted metamorphic zonation defined by the local occurrence of garnet and local peak temperatures of ∼530 °C (Behr and Platt, 2012). The Alhamilla unit preserves crenulation cleavages of different orientations throughout the range, but they are difficult to relate to specific tectonic or metamorphic events due to a scarcity of metamorphic index minerals.

The Castro unit is structurally higher, crops out only on the southern margin of the range, and comprises several intercalated rock types, including quartzite, light-colored schist and phyllite, graphitic mica schist, marble, and granite. Most of the deformation