Earth and Planetary Science Letters 451 (2016) 208–220

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Plate interface rheological switches during subduction infancy: Control on slab penetration and metamorphic sole formation

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ARTICLE INFO

Article history:
Received 17 March 2016
Received in revised form 28 June 2016
Accepted 30 June 2016
Available online 1 August 2016
Editor: M. Bickle

Keywords:
subduction
metamorphic sole
rheology
plate interface
slab dehydration
mechanical coupling

ABSTRACT

Subduction infancy corresponds to the first few million years following subduction initiation, when slabs start their descent into the mantle. It coincides with the transient (yet systematic) transfer of material from the top of the slab to the upper plate, as witnessed by metamorphic soles welded beneath obducted ophiolites. Combining structure–lithology–pressure–temperature–time data from metamorphic soles with flow laws derived from experimental rock mechanics, this study highlights two main successive rheological switches across the subduction interface (mantle wedge vs. basalts, then mantle wedge vs. sediments; at ∼800 °C and ∼600 °C, respectively), during which interplate mechanical coupling is maximized by the existence of transiently similar rheologies across the plate contact. We propose that these rheological switches hinder slab penetration and are responsible for slicing the top of the slab and welding crustal pieces (high- then low-temperature metamorphic soles) to the base of the mantle wedge during subduction infancy. This mechanism has implications for the rheological properties of the crust and mantle (and for transient episodes of accretion/exhumation of HP-LT rocks in mature subduction systems) and highlights the role of fluids in enabling subduction to overcome the early resistance to slab penetration.

1. Introduction

Understanding subduction initiation, in both space and time, has been a challenge since the advent of plate tectonics (Dewey, 1976; Regenauer-Lieb et al., 2001; Gurnis et al., 2004). What is referred to as “subduction initiation” in the literature encompasses two different concepts and periods: (i) how and where subduction nucleates (i.e., what triggers the beginning of subduction; e.g., Regenauer-Lieb et al., 2001; Stern, 2004), and (ii) how subduction proceeds over the first few million years of its history (“subduction infancy”; Stern and Bloomer, 1992).

This study focuses on subduction infancy, when a newly born slab starts its descent into the mantle and when the thermal regime of the subduction zone progressively cools down before reaching steady-state (e.g., Syracuse et al., 2010; Plunder et al., 2015; Figs. 1a, b). The only rock remnants of this elusive geodynamic step are thin (∼10–500 m) metamorphosed slivers of oceanic crust (metamorphic soles; Williams and Smyth, 1973; Wakabayashi and Dilek, 2000) found beneath pristine, 100–1000 km long, ≤10–15 km thick fragments of oceanic lithosphere emplaced on top of continents as ophiolites (Coleman, 1981; Nicolas, 1989; Fig. 1c).

Metamorphic soles correspond to upper crustal material from the downgoing slab (with variable proportions of basalts and pelagic sediments; Spray 1984; Boudier et al., 1988) and have long been recognized as formed during the first few My of intra-oceanic subduction (Fig. 1b; Dewey, 1976; Spray, 1984; Dewey and Casey, 2013). Their formation would result from heat transfer from the upper plate mantle and/or shear heating when the slab enters the mantle and heats up (Dewey, 1976; Hacker, 1990). Explaining how such thin metamorphosed tectonic slivers of oceanic crust get welded (“underplated”) to the upper plate along hundreds of km (e.g., Oman, Turkey: Hacker and Gnos, 1997; Çelik et al., 2011)

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http://dx.doi.org/10.1016/j.epsl.2016.06.054
0012-821X/

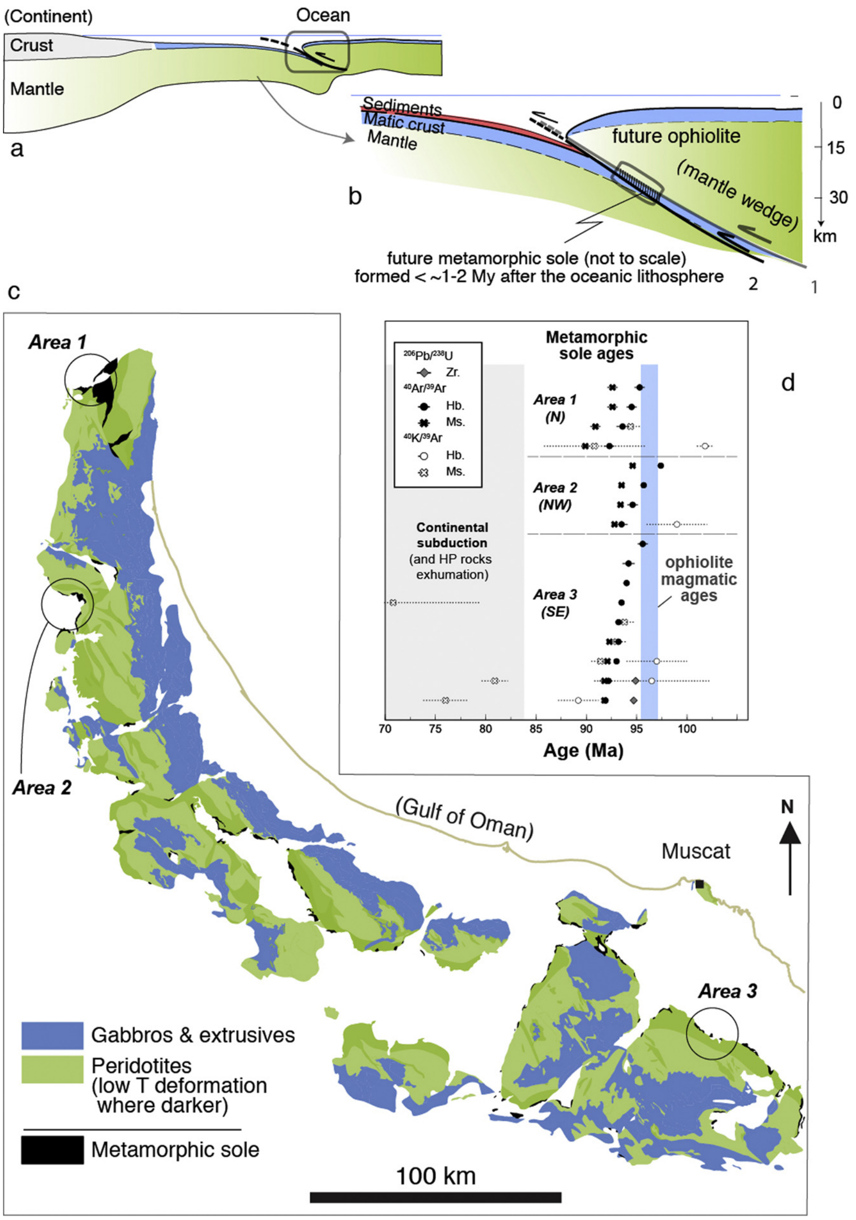

Fig. 1. (a) Geodynamic setting of metamorphic sole formation during subduction infancy, following intra-oceanic subduction initiation. The later geodynamic evolution will lead to continental subduction and obduction s.s. (i.e., emplacement of the oceanic lithosphere onto continental lithosphere; after Agard et al., 2007); (b) Close-up view of Fig. 1a: the formation and accretion of metamorphic soles imply a shift of the subduction interface during subduction initiation (from thrust 1 to thrust 2); (c) simplified geological map highlighting the striking continuity of the metamorphic sole beneath the mantle of the Oman ophiolite (modified after Nicolas et al., 2000); (d) age constraints for metamorphic sole formation along the Oman ophiolite (Hb: hornblende; Ms: white mica; Zr: zircon; see Table 1 for references). Radiometric ages for the ophiolite are shown for comparison (after Rioux et al., 2013; see discussion in Section 5.2).

is essential for understanding mechanical coupling during subduction infancy (and possibly during later subduction), but has so far remained enigmatic (Jamieson, 1981; Dewey and Casey, 2013).

This problem is herein addressed by (i) compiling worldwide characteristics of metamorphic soles (i.e., lithologies, internal organization, thicknesses, thermobarometric constraints), augmented by refined estimates for their pressure–temperature (P–T) conditions of formation using thermodynamic modeling and by (ii) calculating effective viscosities of materials present along the plate interface from known rheological properties for the crust and mantle (i.e., peridotite, basalt, sediment, serpentinite).

This study reveals the existence of rheological switches across the subduction interface, and proposes that these changes in rheological properties control slab penetration into the mantle and the formation of metamorphic soles during subduction infancy. This mechanism has implications for effective rheologies of the crust and mantle and for the general understanding of accretion processes and early slab dynamics.

2. Metamorphic soles: the record of subduction infancy

2.1. Metamorphic sole constitution

The main characteristics (i.e., structural position, lithologies, constitution) and P–T conditions of metamorphic soles worldwide are reviewed in Fig. 2 and Table 1. This synthesis shows that metamorphic soles are ubiquitous beneath non-metamorphosed ophiolites (e.g., Oman, Turkey, Papua, Newfoundland) and share similar characteristics regardless of the ophiolite or the detailed geological/geodynamical setting (Spray, 1984; Wakabayashi and Dilek, 2003). Radiometric ages of metamorphic soles and ophiolites gen-