Earth-Science Reviews 139 (2014) 33–46

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Oceanic- and continental-type metamorphic terranes: Occurrence and exhumation mechanisms

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A R T I C L E I N F O

Article history:
Received 25 April 2014
Accepted 22 August 2014
Available online 3 September 2014

Keywords:
High pressure
Ultrahigh pressure
Exhumation
Channel flow
Diapir
Buoyancy

A B S T R A C T

Understanding the fate of subducted materials has important implications for the chemical and physical differentiation of the Earth, particularly the compositional evolution of the continental crust. Of interest here is how deeply-subducted materials return to the Earth's surface. We present a comprehensive global compilation of high-pressure, low-temperature metamorphic terranes for which peak metamorphic conditions have been constrained. These metamorphic terranes are classified based on tectonic setting: terranes in oceanic plate subduction zones were classified as oceanic-type and those in continent–continent collision zones were classified as continental-type. We show that oceanic-type terranes form under pressures less than ~2.7 GPa whereas continental-type terranes develop under greater pressure and slightly higher prograde geothermal gradients. Whereas these two terrane types probably share common descent paths (i.e. subduction), their separation in pressure–temperature space suggests that the mechanism and pathways of their exhumation likely differ. Here we present a simple buoyancy-driven model to explain the bifurcation of subducted material at depth and how exhumation regimes may change in different tectonic settings during the evolution of convergent margins. We explore two exhumation modes. In one, the hydrous nature of subducted sediments leads to a low-density, low-viscosity channel bounded by relatively rigid walls, thereby driving channel-like flow along the dipping slab surface. In the other mode, channel viscosity approaches that of the overlying mantle wedge, preventing channel flow but permitting vertical exhumation via diapirism. We show that the exhumation mode depends on slab dip and the viscosity ratio between the buoyant material and the overlying mantle (described by a dimensionless parameter, M). Due to a significant change in channel viscosity with the breakdown of hydrous minerals, we suggest that the transition in exhumation mode coincides with slab dehydration; at what depth this transition occurs depends on plate velocity and the initial thermal state of the slab. Such a model predicts channel flow to be limited to shallow depths and diapiric exhumation to greater depths, providing an internally consistent explanation for the apparent differences in peak metamorphic conditions of oceanic- and continental-type terranes if the former exhume via channel flow and the latter via diapirism. Because young, hot slabs dehydrate at shallower depths than old, cold slabs, the maximum depth to which channel flow can operate is greater in the latter. Finally, our model also predicts how the exhumation mode changes as the nature of subduction zones evolves during the closure of an ocean basin, beginning with oceanic plate subduction and culminating in continent–continent collision. In such a scenario, channel flow is favored during the subduction of dense, steeply dipping oceanic lithosphere, but a growing continental (low density) character to the subducted materials as the ocean basin closes should gradually shift the mode of exhumation to diapirism.

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http://dx.doi.org/10.1016/j.earscirev.2014.08.012
0012-8252/

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1. Introduction

High-pressure metamorphic rocks exposed at the surface in subduction zones and orogenic belts are evidence that crustal materials are tectonically transported to and exhumed from great depths, in some cases exceeding ~150 km. Peak metamorphic assemblages typically indicate transport in very low (~7 °C/km) geothermal gradients (e.g. Liou et al., 2000), implying rapid advective transport during subduction. The presence of high-pressure mineral assemblages, such as coesite, requires exhumation from such depths at rates fast enough to inhibit complete retrogression of peak metamorphic assemblages (Chopin, 1984).

The mechanisms by which these deep-seated rocks are exhumed are unclear (cf. Hacker et al., 2013). A plethora of models have been proposed, including wedge extrusion of crustal material detached from the down-going plate (Ernst, 1975; Chemenda et al., 1995; Kylander-Clark et al., 2008), channel flow or ductile return flow along the down-going slab–mantle interface (Cloos, 1982; Burov et al., 2001; Gerya et al., 2002; Raimbourg et al., 2007; Warren et al., 2008; Beaumont et al., 2009; Horodyskyj et al., 2009), extensional–erosional collapse (Platt, 1993), and diapiric ascent of continental material (eg. Hall and Kincaid, 2001; Gerya et al., 2006; Currie et al., 2007; Behn et al., 2011; Little et al., 2011).

Of particular interest is whether terranes of different peak metamorphic conditions are formed and exhumed in different ways. Traditionally, these deep-seated metamorphic rocks have been respectively classified as “high-pressure” (HP) and “ultrahigh-pressure” (UHP) by the absence or presence of coesite, corresponding to ~2.7 GPa for this seemingly arbitrary divide. However, differences in protolith composition and tectonic setting have been suggested for HP and UHP rocks (Bally, 1981; Maruyama et al., 1996; Liou et al., 2004; Ernst, 2005), suggesting that more than just a phase transformation may distinguish these two groups. Here, we present a comprehensive global compilation of P–T data for HP and UHP terranes and confirm that terranes associated with oceanic subduction and continental subduction/collision indeed show distinctly different peak metamorphic conditions. Why are the P–T conditions of subducted materials so different between these two tectonic environments?

To explain the dichotomous fate of deeply-subducted materials, we develop simple scaling models, which show that subducted crustal materials can exhume via channel flow along the slab–mantle interface, exhume via diapiric ascent through the mantle wedge, or not exhume at all, depending on the viscosity of the subducted materials, slab dip and slab velocity. In particular, the viscosity of subducted materials is sensitive to the presence of hydrous phases and is therefore a quantity controlled by protolith composition and the thermal evolution of the subducting slab. Our models can be used to predict peak metamorphic conditions of exhumed terranes in different tectonic environments.

2. Global compilation of metamorphic conditions in HP and UHP terranes

2.1. Database and tectonic classifications

We compiled peak metamorphic conditions of worldwide high-pressure, low-temperature terranes (HP–LT) for which robust thermobarometry exists (Fig. 1). For a complete list of data and references see Table 1. Instead of classifying terranes based on the presence

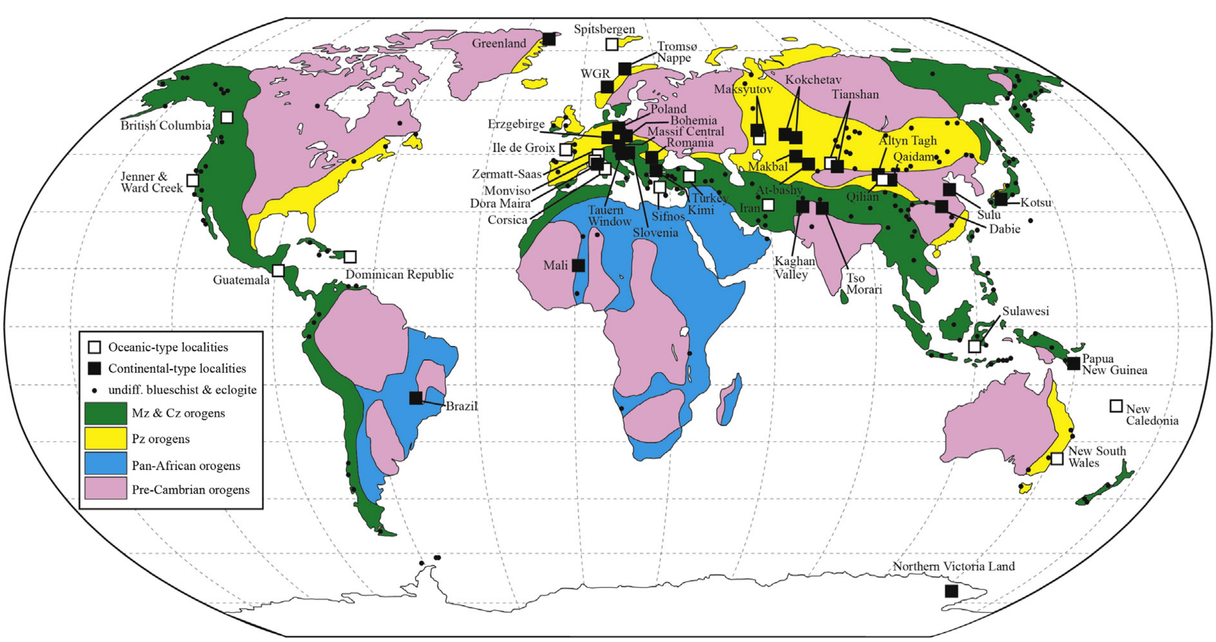

Fig. 1. Worldwide distribution of oceanic-type (open squares) and continental-type (black squares) metamorphic terranes for which peak metamorphic conditions have been well constrained (modified from Tsujimori et al., 2006). Small circles represent potential oceanic- or continental-type locations for which peak metamorphic conditions have not yet been constrained (Table S1; Maruyama et al., 1996).