Earth and Planetary Science Letters 310 (2011) 21–32

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Divergence in subduction zones and exhumation of high pressure rocks (Eocene Western Alps)

Marco G. Malusà [a,*], Claudio Faccenna [b], Eduardo Garzanti [a], Riccardo Polino [c]

[a] Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy
[b] Dipartimento di Scienze Geologiche, Università di Roma Tre, Largo San Murialdo 1, Roma, Italy
[c] Les Planes, 11400 Issel, France

ARTICLE INFO

Article history:
Received 19 April 2011
Received in revised form 1 July 2011
Accepted 2 August 2011
Available online 27 August 2011

Editor: Y. Ricard

Keywords:
tectonic exhumation
erosional unroofing
high-pressure metamorphism
plate divergence
sedimentary basins

ABSTRACT

Exhumation of high-pressure rocks has long remained a controversial issue in the Earth sciences. In this article, we analyze the tectono-metamorphic, stratigraphic and plate-motion constraints from the Western Alps region, providing new insights on exhumation mechanisms and tectonic evolution during the earliest orogenic stages. Eocene eclogites of the Western Alps form a 20–25 km wide belt on the upper-plate side of the orogen (Eclogite belt), exposed beneath extensional shear zones at the rear of a lower-pressure accretionary wedge. Units of the Eclogite belt show the youngest peak-pressure assemblages within the subduction zone, and experienced superfast tectonic exhumation since 45–40 Ma. The role of erosion was negligible during the whole of this stage. Eocene foreland basins remained starved, and the massive arrival of axial-belt detritus began well after exhumation was completed. Tectonic reconstructions based on fixed-boundaries exhumation models (e.g. channel flow), and/or implying fast erosion at the surface (e.g. slab breakoff), are thus not consistent with geological evidence. In the lack of erosion, exhumation through the overburden requires divergence within the subduction zone. We demonstrate that this was not attained by rollback of the lower plate (Europe), but was instead attained by NNEward motion of the upper plate (Adria-Africa) away from the Western Alps trench. Such motion induced localized extension within the weak portion of the upper plate, at the rear of the accretionary wedge, and allowed tectonic emplacement of the Eclogite belt in the upper crust at rates much faster than subduction rates. Tectonic exhumation ceased in the Oligocene, when oblique-divergence along the Western Alps traverse changed into oblique-convergence. The onset of slow erosional unroofing was synchronously recorded by pressure–temperature paths in all major tectonic units of the Western Alps, and by arrival of orogenic detritus in sedimentary basins. This work demonstrates that divergence between upper plate and trench is a viable mechanism to exhume large and coherent eclogite units in continental subduction zones. Our exhumation model can be applied to other eclogite belts showing a similar exhumational record, including the Western Gneiss Region, the Dabie-Sulu, and eastern Papua New Guinea.

1. Introduction

The exhumation of high pressure (HP) rocks within collision orogens is still controversial and poorly understood. Several different mechanisms have been proposed to explain how HP units travel back to the surface (Platt, 1993). Assuming a stationary trench and fixed boundaries within the subduction zone, the possibility for deep-seated rocks to rise from mantle depth to the surface requires removal of the overlying rock pile by tectonics/erosion or forced circulation in a low-viscosity wedge (e.g. Beaumont et al., 2001; Chemenda et al., 1995; Gerya et al., 2002; Yamato et al., 2008). This latter case is limited by the strength and coherence of the exhumed nappe pile, especially for the case of continental-derived units (Jolivet et al., 2003). Alternatively, in the case of freely moving trenches, boundary divergence within the subduction zone can drive exhumation of rock units from great depths to shallow levels (Brun and Faccenna, 2008; Jolivet et al., 1994; Lister and Forster, 2009). Despite the large amount of petrological and structural evidence, and of sophisticated modeling exercises, a mechanism of general validity to explain the occurrence and distribution of HP belts has not been proposed yet.

The Western Alps are a spectacular example of collisional belt (Frey et al., 1999) where widespread HP assemblages have been described since the beginning of the 20th century (Compagnoni and Maffeo, 1973; Franchi, 1902) and major HP units, both of continental and oceanic origin, have been accurately mapped in the field (e.g. Dal Piaz et al., 2010; Polino et al., 2002). They thus represent an unsurpassed natural laboratory to investigate processes leading to exhumation of HP rocks.

* Corresponding author.
E-mail address: marco.malusa@unimib.it (M.G. Malusà).

0012-821X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2011.08.002

Here, we analyze literature data concerning the tectono-metamorphic and stratigraphic record of HP-rocks exhumation in the classical Western Alps region. Results are discussed within the framework of plate-kinematics and seismic-tomography constraints, and finally compared to the geological record in other HP belts, providing new insights on exhumation mechanisms and tectonic evolution during early orogenic stages.

2. Tectonic setting

The Western Alps are located at the junction between the Adria-Africa and European plates, which is marked by a ~250 km wide deformation zone extending from the Po Plain to the Jura mountains (Fig. 1). Tertiary-age metamorphic units are exposed in the axial part of the belt, between the Insubric Fault and the Frontal Pennine Fault (Polino et al., 1990; Schmid and Kissling, 2000). These units record subduction of attenuated European continental-margin crust, and associated continental-ocean transition, within a fossil subduction zone developed beneath the Adriatic margin. In Paleocene times, the Adriatic margin included a Cretaceous orogenic wedge built at the expense of the upper plate (Frey et al., 1999). Rocks inside the subduction zone were either dragged to deep subcrustal levels, detached and subcreted at intermediate crustal levels, or offscraped at shallow structural levels thus escaping metamorphism. During subsequent exhumation, basement and cover rocks were retrogressed at lower pressures and temperatures, until they finally reached the surface (Garzanti et al., 2010; Polino et al., 1990).

Eclogite units of the Western Alps are now exposed adjacent to the Adria plate, along a 20–25 km wide belt hereafter referred to as "Eclogite belt". The Eclogite belt extends from the Lepontine dome in the north, to the Sestri-Voltaggio Line in the south (Fig. 1). It consists of large coherent units of eclogitized European continental crust, also referred to as Internal Crystalline Massifs (e.g. Dora-Maira and Gran Paradiso units), tectonically enveloped by mafic–ultramafic eclogitic slivers (e.g. Viso and Zermatt-Saas units). In the Eclogite belt, quartz–eclogite assemblages prevail, but small tectonic slices including coesite–eclogite assemblages were discovered in the Dora-Maira unit (Brossasco-Isasca slice; Chopin et al., 1991) and on top of the Zermatt-Saas ophiolites (Cignana slice; Reinecke, 1991). The Eclogite belt is today partly buried to the south beneath sedimentary successions of the Tertiary Piedmont Basin and Western Po Plain (Fig. 1).

Lower-pressure metamorphic units exposed to the west, closer to the European mainland, form a doubly-vergent accretionary wedge hereafter referred to as "Frontal wedge" (Fig. 2). The Frontal wedge, nicely imaged by deep seismic profiles on top of the European slab (Roure et al., 1996), is 35-to-55 km wide and 15–20 km thick, and includes blueschist-to-greenschist cover sequences (e.g. Combin and Lago Nero units) and basement slivers (e.g. Ambin and Leverogne units). These low-grade metamorphic units are locally capped by anchimetamorphic ophiolites (e.g. Chenaillet unit) and turbidites (e.g. Parpaillon nappe).

A major duplex of European crust, 10–15 km thick and 30–40 km long, is seismically imaged on top of the lower slab beneath the Eclogite belt (Fig. 2), whereas mantle exhumed at shallow depth (Ivrea Body in Fig. 1) is evidenced by gravity data along the Adriatic margin (Roure et al., 1996; Schmid and Kissling, 2000). Tomographic studies document European lithosphere subducted below the Western Alps down to ca 300 km depth (Piromallo and Faccenna, 2004) (Fig. 2).

3. Geological record of HP-rocks exhumation

3.1. Metamorphic record

Petrological and geochronological studies have largely enhanced our understanding of orogenic belts (e.g. Carswell et al., 2003; Liou et al., 2009). Extracting segments of pressure–temperature–time paths from rocks is not straightforward. It requires attainment of equilibrium at some point in the rock history, and unambiguous

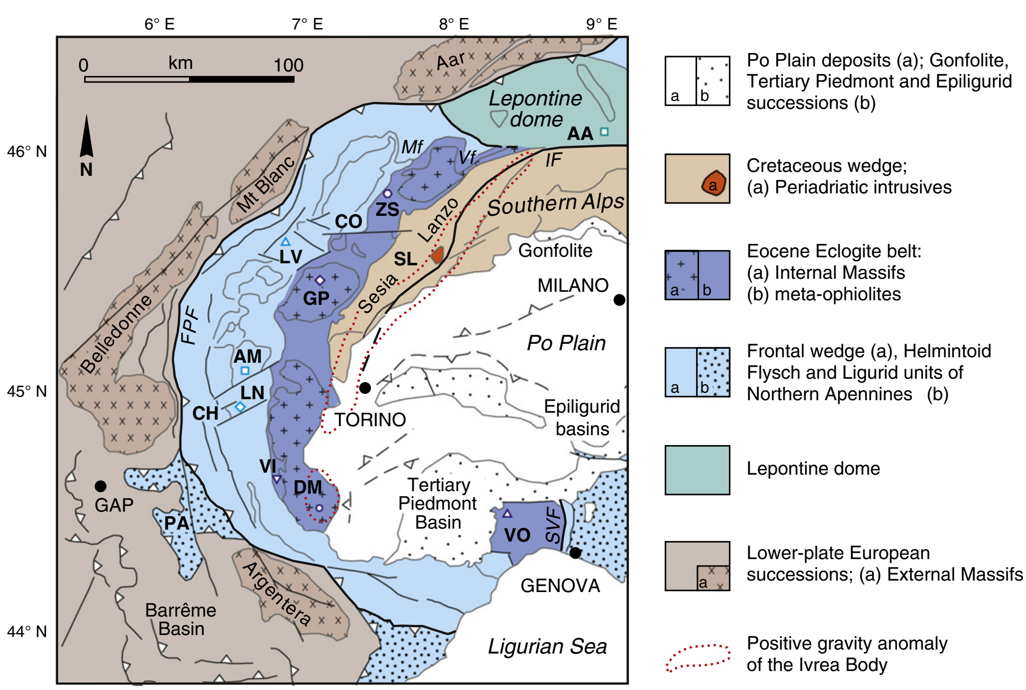

Fig. 1. Tectonic sketch of the Western Alps. The Eocene Eclogite belt (blue) is exposed on the upper-plate side of the orogen, between the Frontal wedge (light blue) and the remnants of a Late Cretaceous doubly-vergent wedge including the Sesia-Lanzo unit (brown). Major faults (acronyms in italics): FPF, Frontal Pennine; IF, Insubric; SVF, Sestri-Voltaggio. Tectonic units (acronyms in bold): AA, Alpe Arami; AM, Ambin; CH, Chenaillet; CO, Combin; DM, Dora-Maira; GP, Gran Paradiso; LN, Lago Nero; LV, Leverogne; PA, Parpaillon; SL, Sesia-Lanzo; VI, Viso; VO, Voltri; ZS, Zermatt-Saas. Mf, Mischabel backfold; Vf, Vanzone backfold. Open symbols indicate location of samples shown in Figs. 3 and 4.