Originally published as:

Ring, U., Glodny, J. (2010): No need for lithospheric extension for exhuming (U)HP rocks by normal faulting. - Journal of the Geological Society London, 167, 2, 225-228

DOI: 10.1144/0016-76492009-134

No need for lithospheric extension for exhuming (U)HP rocks by normal faulting

Uwe Ring[1*] & Johannes Glodny[2]

(1) Department of Geological Sciences, University of Canterbury, Christchurch 8140, New Zealand
(2) Johannes Glodny, Deutsches GeoForschungsZentrum, 14473 Potsdam, Germany
(*) Corresponding author. Email: uwe.ring@canterbury.ac.nz

Abstract

Extensional deformation is commonly considered most important for exhuming rocks from great depths. However, the necessary space for extending the lithosphere is usually lacking. We show that significant exhumation of (U)HP rocks occurs in extrusion wedges, which have a normal fault at their top and a thrust fault at their base. The normal fault at the top of an extrusion wedge is a geometric effect and does not result from lithospheric extension. Therefore, the exhumation of (U)HP rocks in extrusion wedges allows substantial exhumation beneath a normal fault during horizontal shortening and does not cause lithospheric attenuation.

Introduction

The exhumation of most (ultra)high-pressure ((U)HP) complexes occurs soon after these rocks were metamorphosed following lithospheric convergence and deep underthrusting during early orogenic stages (Reddy et al. 1999; Gessner et al. 2001; de Sigoyer et al. 2004). It appears that the tectonic community has agreed that normal faulting resulting from lithospheric extension is the most important agent for structurally accomplishing the bulk of the exhumation of these rocks from great depths (Platt 1986). For normal faults dipping at 30° this would demand horizontal extension of 175 km for rocks exhumed from 100 km depth. Such great amounts of extension are usually not observed in the hanging walls of deeply exhumed complexes soon after the latter have formed. Likewise, not many large-scale extensional basins that formed coeval with (U)HP exhumation have been described, although the extensional sedimentary basins in the Western Gneiss Region of Norway are a notable exception (Andersen 1998). None the less, large-slip normal faults in the hanging wall have been reported from many (U)HP complexes (Reddy et al. 1999). It therefore appears that there is an apparent conundrum where large-slip normal faults move without causing large-scale extension and attenuation of the lithosphere.

Herein we describe three examples of extrusion wedges (Fig. 1) from the European Alps and the Aegean Sea area. We demonstrate that the basal thrust and the normal fault at the top of the extrusion wedges moved simultaneously. Because of that and because the described extrusion wedges formed in the lower crust or lithospheric mantle and are usually less than 5 km thick, the normal fault at the top of the extrusion wedge can hardly result from lithospheric extension. The large-slip normal fault facilitates only the upward movement of the extrusion wedge and is thus a geometric effect in a shortening environment.

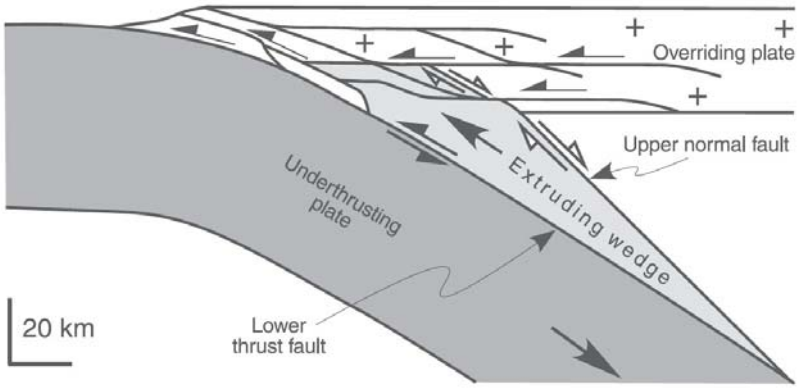

Fig. 1. Schematic sketch of an extrusion wedge in a convergent setting; the wedge is defined by a major thrust at the base and a normal fault at the top. It should be noted that in this illustration the top of the extrusion wedge is being sliced up in the middle crust by thrusts developing in the overriding plate.

Normal faults in shortening and extensional environments

Before addressing the exhumation of (U)HP rocks in extrusion wedges it seems warranted to clarify the subtle differences between extension-induced normal faults and shortening-induced normal faults (Fig. 2). The term normal fault relates to the relative sense of shear along a shear zone or fault (Neuendorf et al. 2005). Following Anderson (1951), a normal fault is traditionally regarded as being driven by gravity, with typical dip angles of about 608. However, since Anderson's time numerous new observations have demonstrated that normal faults can move at angles <30° (Wernicke 1995) and it appears that the majority of structural geologists these days would base their understanding of a normal fault on geometry rather than mechanics.

The term normal fault carries a priori no information as to whether normal faulting results from horizontal lithospheric shortening or extension. This has been demonstrated in detail by research over the last two decades in the High Himalaya by, for instance, Burchfiel et al. (1992), Grujic et al. (1996) and Law et al. (2004). They all showed that the top of the High Himalayan zone is bounded by a normal fault, the South Tibetan Detachment, and the base of the zone by the Main Central Thrust (Fig. 2a). Geophysical data have been interpreted to indicate that the bounding faults are not parallel, but converge downwards beneath the Tibetan plateau (Nelson et al. 1996). Therefore, the normal fault and the thrust fault together define an extrusion wedge. As pointed out by Yin (2006), the South Tibetan Detachment is being localized along the roof thrust of a crustal-scale duplex and is an older thrust fault reactivated as a normal fault.

None of the Himalayan extrusion wedge models calls upon any horizontal lithospheric extension for the formation of the normal fault (South Tibetan Detachment) (R. Law, pers. comm.). The South Tibetan Detachment merely facilitates the lateral upward extrusion of the High Himalayan zone during overall lithospheric shortening. We refer to this kind of normal fault as a shortening-induced normal fault (Fig. 2). As discussed by Ring & Reischmann (2002), a necessity of shortening-induced normal faults is that motion on them occurs contemporaneously and at the same rate as on the thrust faults structurally beneath them, and also that they are subparallel to these thrusts. Therefore, shortening-induced normal faults have shallow dip angles. In contrast, an extension-induced normal fault results from horizontal lithospheric extension (Fig. 2). Lithospheric extension is associated with the development of graben and their sedimentary fill. These differences are important for distinguishing whether exhumation of (U)HP rocks in the footwalls of lithospheric-scale normal faults occurred during overall horizontal shortening in extrusion wedges, or during wholesale horizontal lithospheric extension of the overriding plate.

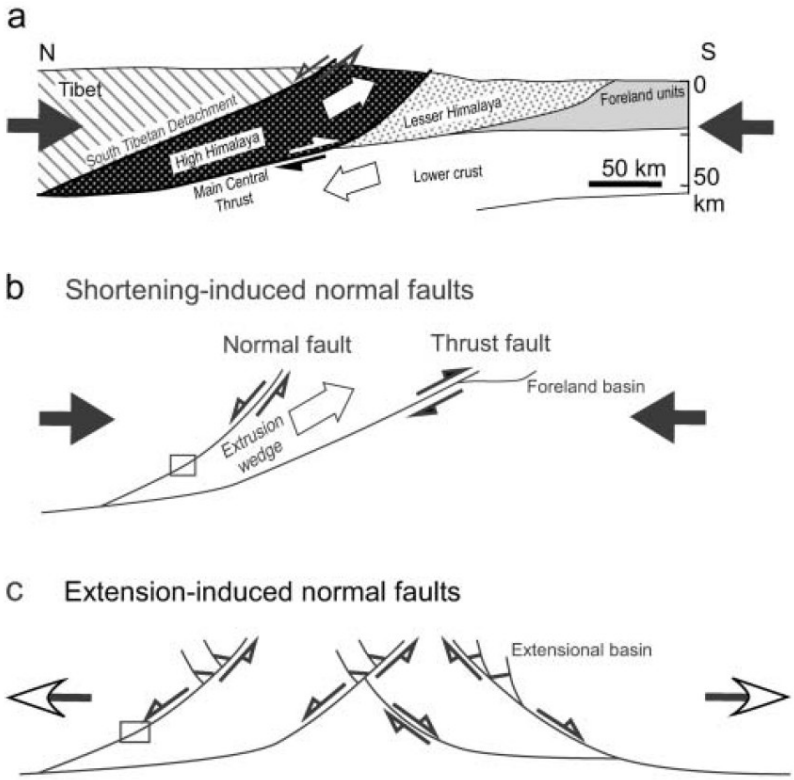

Fig. 2. Extension- and shortening-induced normal faults. (a) A classic example of an extrusion wedge below a shortening-induced normal fault is the High Himalayan zone bounded by the South Tibetan Detachment at the top and the Main Central Thrust at the base. (b) A shortening-induced normal fault develops above a basal thrust fault; the normal fault is a pure geometric effect facilitating upward movement of the extruding wedge during overall horizontal shortening. No extensional basins develop in this setting; instead foreland basins may form in front of the propagating thrust. The shortening-induced normal fault is subparallel to the thrust below it and has a low dip angle (< c. 30°). (c) Extension-induced normal faults result from horizontal lithospheric extension, are associated with extensional sedimentary basins and cause wholesale extension of a region. It should be noted that if only the portion of faults indicated by the box is studied, the distinction between an extension- and a shortening-induced normal fault is difficult.

Exhumation in extrusion wedges

For the three examples of extrusion wedges we provide a brief summary here; details have been published elsewhere (Glodny et al. 2005, 2008; Ring et al. 2007a,b). To plausibly argue for the existence of an extrusion wedge, it is critical to demonstrate that thrust-related mylonitic deformation in the footwall fault zone occurred contemporaneously with normal shearing in the hanging-wall fault zone.

Eclogite Zone, Eastern European Alps.
The Eclogite Zone in the Tauern Window of the Eastern Alps (Fig. 3a) was metamorphosed at 31.5 ± 0.7 Ma (2σ errors) (Glodny et al. 2005) in the course of initial collision between the Adriatic and European continental plates. Peak metamorphic pressures were c. 2.5 – 2.7 GPa (Fig. 3b) and put the Eclogite Zone at the verge of UHP conditions. The Eclogite Zone is sandwiched between the Venediger Nappe at the base and the Glockner Nappe at the top, both of which are of distinctly lower metamorphic grade (Fig. 3b).

Behrmann & Ratschbacher (1989) showed that the Eclogite Zone was thrust onto the Venediger Nappe during top-to-the-NNE shortening at 30.7 ± 0.7 Ma (Glodny et al. 2005, 2008). The upper contact of the Eclogite Zone is subparallel to its basal contact but has distinctly different kinematics. The mylonite foliation at the upper contact contains a gently (c. 20°) east-plunging stretching lineation associated with sinistral south-side-down kinematic indicators. Given the transpressive character of the shear zone, the

transport direction may have been steeper than the stretching lineations (Glodny et al. 2008). Dating of mylonites from this contact yielded ages of 31.2 ± 0.6 Ma and 31.4 ± 0.4 Ma (Glodny et al. 2008). The geochronological data indicate that the thrust at the base of the Eclogite Zone operated, within errors, at the same time as the oblique normal fault at the top of the Eclogite Zone.

The above data indicate that early exhumation occurred very rapidly at rates exceeding 40 km Ma^{-1}, and accomplished about 70 km of exhumation (Glodny et al. 2005). There is no evidence for any contemporaneous extensional sedimentary basins in the Eastern Alps.

Aegean Sea examples of extrusion wedges

The two examples from the Aegean Sea area are from Evia at the western side of the Aegean Sea, and Samos and the adjacent western Turkish mainland at the eastern limit of the Aegean Sea (Fig. 3a). The Cycladic Blueschist Unit exhumed here was metamorphosed at 53-40 Ma above the retreating Hellenic subduction zone (Tomaschek et al. 2003).

In Evia, the Styra Nappe of the Cycladic Blueschist Unit is sandwiched between the underlying Basal Unit and an overlying ophiolitic me´lange (Fig. 3c; Katsikatsos 1991). As is the case for the Eclogite Zone in the Eastern Alps, the Styra Nappe is sandwiched between nappes that have lower metamorphic peak pressures and thus have been less deeply buried (Shaked et al. 2000; Fig. 3c).

Shaked et al. (2000) and Ring & Layer (2003) showed that the Styra Nappe was thrust onto the Basal Unit during top-to-the-WSW shortening. Ring et al. (2007a) dated mylonites resulting from this process at 29.5 ± 0.3 Ma. This age is similar to the ^{40}Ar-^{39}Ar white mica ages from thrust-related mylonites of c. 35-30 Ma of Ring & Layer (2003). The upper contact of the Styra Nappe is subparallel to the basal contact but has an opposite shear sense (i.e. top-to-the-ENE; Ring et al. 2007a). Dating of mylonites from this contact yielded ages of 33.0 ± 1.0 Ma and 27.2 ± 0.9 Ma (Ring et al. 2007a). The geochronological data indicate that the top-to-the-WSW thrust at the base of the Styra Nappe operated, within errors, at the same time as the top-to-the-ENE normal fault at the top of the Styra Nappe. This conclusion is corroborated by the gradual reversal of the shear-sense data from top-to-the-WSW in the basal Styra Nappe to top-to-the-ENE in the upper Styra Nappe; there are no systematic cross-cutting relationships between the fabrics (Ring et al. 2007a).

Exhumation of the Styra Nappe on Evia occurred distinctly less rapidly than that of the Eclogite Zone. Exhumation rates were 0.5-2 km Ma^{-1} accomplishing 10-15 km of exhumation (Ring et al. 2007a). Extensional sedimentary basins did not form in Evia before the middle to late Miocene (Katsikatsos 1991) and thus ≥15 Ma after the extrusion-wedge stage.

In the eastern Aegean and the adjacent western Turkish mainland the Ampelos-Dilek Nappe of the Cycladic Blueschist Unit occupies a similar tectonic position to the Styra Nappe on Evia and is again sandwiched between tectonic units characterized by lower metamorphic pressures (Fig. 3d). The Ampelos-Dilek Nappe occurs beneath the same ophiolitic melange as the Styra Nappe on Evia. Beneath the Ampelos-Dilek Nappe is the Basal Unit on Samos and the Menderes Nappes in western Turkey (Fig. 3d).

Gessner et al. (2001) showed that the Ampelos-Dilek Nappe was thrust onto its underlying nappes during top-to-the-south shortening. Ring et al. (2007b) dated thrust-related mylonites to between 34.4 ± 2.6 Ma and 32.5 ± 0.4 Ma (Rb-Sr multi-mineral isochron ages) and 38.6 ± 1.2 Ma and 34.3 ± 1.2 Ma (^{40}Ar-^{39}Ar laser ablation phengite ages). These ages are corroborated by single-grain phengite ^{40}Ar-^{39}Ar step-heating ages of 42-37 Ma from mylonitically deformed samples from the base of the Ampelos-Dilek Nappe on Samos (Ring & Layer 2003). The upper contact of the Ampelos-Dilek Nappe is subparallel to the basal contact but has an opposite shear sense (i.e. top-to-the-NE; Gessner et al. 2001; Fig. 3d). Dating of mylonites from this contact yielded ages of 37 ± 5 Ma (Rb-Sr multi-mineral isochron age) and 41.5 ± 4.0 Ma to 35.3 ± 4.0 Ma (^{40}Ar-^{39}Ar laser ablation phengite ages) (Ring et al. 2007b). The geochronological data indicate that the thrust at the base of the Ampelos-Dilek Nappe operated at the same time, within errors, as the normal fault at the top of the Ampelos-Dilek Nappe. As for Evia, this conclusion is corroborated by the gradual reversal of the shear-sense data from top-to-the-SW at the base to top-to-the-NE in the top of the Ampelos-Dilek Nappe.

Exhumation of the Ampelos-Dilek Nappe occurred at rates of c. 3-4 km Ma^{-1} and caused 30-40 km of exhumation (Ring et al. 2007a). The earliest local sediments in extensional basins are middle Miocene in age (Weidmann et al. 1984) and thus ≥20 Ma younger than extrusion-wedge-style exhumation.

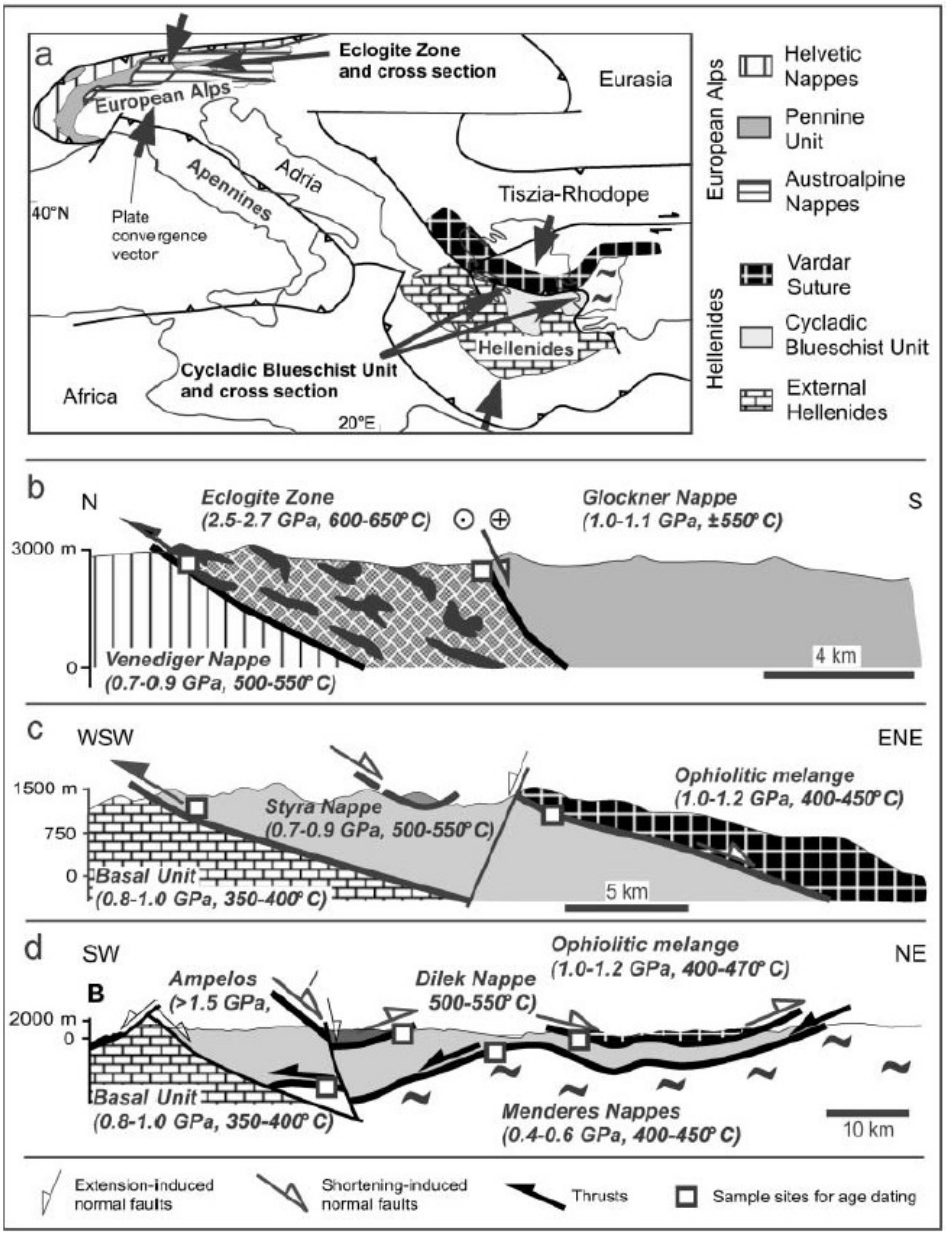

Fig. 3. (a) Tectonic sketch map of the Mediterranean region showing major tectonic units of the European Alps and Hellenide orogen and position of the cross-sections shown in (b-d). (b) North-south cross-section of the Eclogite Zone showing geometry of the extrusion wedge and P-T data for various nappes. (c) Cross-section through the Cycladic Blueschist Unit on Evia, showing thrust contact at the base of the Styra Nappe and normal fault contact at its top. (d) Cross-section through Samos and western Turkey, showing thrust contact between the Ampelos-Dilek Nappe and Menderes Nappes and subparallel normal fault contact at the top of the Ampelos-Dilek Nappe (P-T data from Selverstone et al. 1984; Shaked et al. 2000; Hoschek 2007; Ring et al. 2007b).

Discussion

In all three cases from the European Alps and the Aegean Sea structural analysis reveals complementary senses of shear for the extrusion-wedge-delimiting faults, with thrust-type shear zones at the base and normal-sense shear zones at the top of the extrusion wedges. There are no consistent overprinting relationships between the thrust and the normal-fault-related structures and the geochronological data support the interpretation that thrusting and normal faulting occurred simultaneously. We have shown that considerable exhumation of HP rocks can occur in these extrusion wedges. The exhumation is structurally accomplished beneath a normal fault that delimits the top of the extrusion wedges. In all three examples

there is no evidence for regional-scale lithospheric extension or the development of contemporaneous extensional sedimentary basins. Instead, wedge extrusion is concurrent with the development of thrust belts and foreland basins. Moreover, it is hard to imagine that the simultaneous thrust and normal fault movement across a wedge that is a few kilometres thick can result from overall lithospheric extension. We therefore conclude that all three extrusion wedges formed during overall lithospheric shortening. If this was accepted, our finding has important tectonic consequences because it would demonstrate that there is no need for large-scale lithospheric extension to exhume (U)HP rocks below a normal fault.

In a number of cases of early (U)HP exhumation the basal thrust is the plate-boundary thrust. Because motion on the normal fault at the top of the extrusion wedge occurs at the same rate as on the plate-boundary thrust, this scenario elegantly explains why early exhumation occurs at plate-tectonic rates in some extrusion wedges.

Our examples also show that diagnosing a major normal fault in the field does not necessarily mean that this normal fault indicates that the region underwent lithospheric extension. The normal fault at the top of an extrusion wedge is a geometric effect only and must not be mistaken as an effect of net horizontal extension of the region. This is a very important characteristic of extrusion wedges. Lithospheric extension is not required for very rapid early exhumation of (U)HP rocks.

Our main conclusion that considerable exhumation below a normal fault can occur during overall lithospheric shortening is supported by recent modelling work. Warren et al. (2008) put forward numerical thermal-mechanical models in which (U)HP complexes are being exhumed above subduction thrusts during overall lithospheric shortening. In the numerical models the exhuming (U)HP complexes are delimited at their top by a normal fault. Warren et al. (2008) addressed the exhumation of eclogites of the Tso Morari dome in the Himalaya and argued for coeval normal and thrust faulting closely linked to UHP exhumation processes. As in the examples from the Eastern Alps and the Aegean Sea given above, there is no evidence for any extensional basins that developed during considerable and fast exhumation of the Tso Morari eclogites (de Sigoyer et al. 2004).

Concluding remarks

Our conclusions are based on detailed work in HP belts but we have inferred that the conclusions can also been adapted to UHP complexes. The exhumation of (U)HP complexes in extrusion wedges provides a scenario in which a normal fault can accomplish considerable deep exhumation without large-scale extension and attenuation of the lithosphere. If the extrusion wedges are bounded at their base by the plate-interface thrust then this model also explains why deep exhumation occurs at plate-tectonic rates.

Acknowledgements. This study was funded by the Deutsche Forschungsgemeinschaft and the Brian Mason Technical Trust of New Zealand. Reviews by R. Law and D. Grujic were very helpful.

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