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Arrested orogenic development: eclogitization, delamination, and tectonic collapse

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Abstract

Fluids are key in the process of eclogitization and delamination of crustal roots in collisional orogens, and this process is not solely constrained by pressure–temperature conditions. Partially eclogitized amphibolites, gabbros, and granulites from the Western Gneiss Region of Norway, the Marun-Keu Complex in the polar Urals, and the Dabie-Sulu belt in China demonstrate that fluid is required for complete eclogitization. Conventionally, orogeny proceeds in a cycle that progresses from collision and uplift, to metamorphism and delamination of the crustal root, to completion when the orogen undergoes tectonic collapse. The south Ural Mountains and the southern Trans-Hudson orogen are type examples of arrested orogenic development in which delamination and post-orogenic extensional collapse have not occurred. Because the eclogitization of crustal roots leads to delamination and tectonic collapse of orogens, it is likely that the base of the Uralian crust has not undergone major eclogitization and therefore is under fluid-absent conditions. The lack of post-orogenic tectonic collapse and extensional faulting of some ultrahigh-pressure (UHP) orogens has major implications for exhumation models of UHP metamorphic terranes. Extension on the Main Uralian fault in the south Urals did not play a important role in the exhumation of the UHP Maksyutov Complex; the dominance of quartzofeldspathic rock types in the Maksyutov Complex and widespread retrograde metamorphism indicate that buoyancy rather than extensional faulting was likely the dominant cause of exhumation in the south Urals.

Keywords: eclogite facies; orogeny; Urals; Hudsonian Orogeny

1. Introduction

Eclogitization of the crustal roots of orogens is likely responsible for the subsequent delamination of the crustal root and the post-orogenic extensional collapse of those mountain belts. If we fail to recognize the factors that drive eclogitization, we will lack a complete understanding of processes active at depth. In addition to the specific pressures and temperatures (*P–T*) required for eclogite stability, the kinetics of eclogitization require fluid to be present to complete these metamorphic reactions. Worldwide occurrences of partially eclogitized mafic rocks indicate that rocks can remain metastable at depth under fluid-absent conditions. Both geophysical evidence and petrological con-

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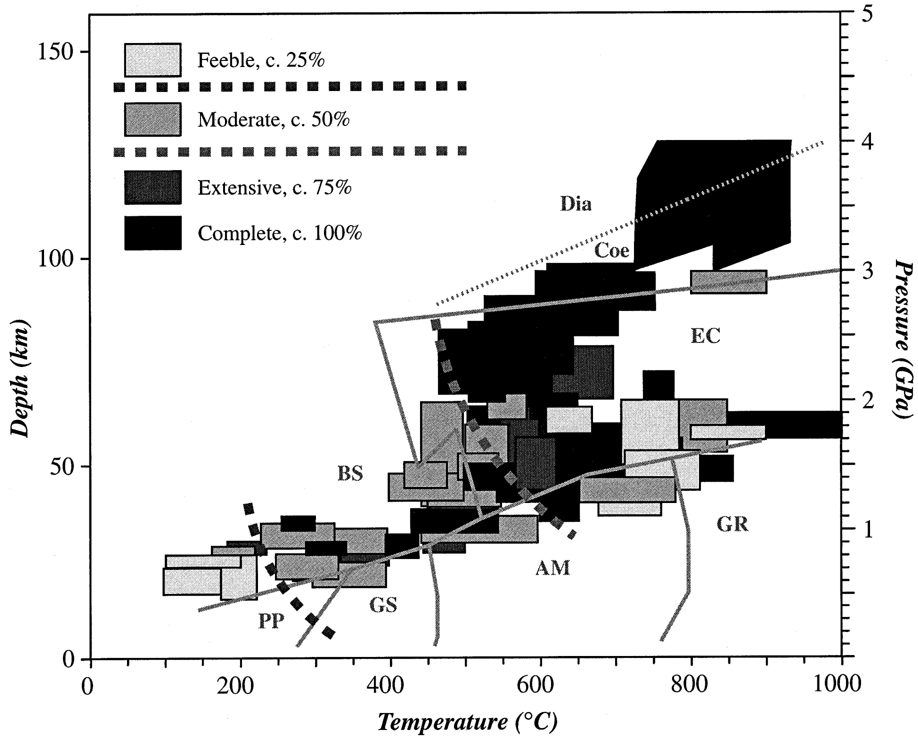

Fig. 1. Extent of reaction in gabbro to blueschist- and eclogite-facies assemblages (modified after [8]); compilation is based on reports of partial to complete transformation, and pressure and temperature estimates.

straints help us to understand processes at the base of the crust and their effects on the evolution of orogens.

In general, a 'complete' orogenic cycle can be defined by three stages of development: (1) collision, thickening, and formation of topography and the crustal and lithospheric root; (2) metamorphism of the crustal root and/or delamination of the crustal root or lithospheric mantle; and (3) extensional collapse of the orogen and re-equilibration of the Moho (e.g. [1]). 'Incomplete' orogens include active mountain belts such as the Himalaya, and old mountain belts such as the Urals that have apparently stalled during this cycle prior to stage 3 (e.g. [2]).

Ultrahigh-pressure (UHP) collisional orogens pose unique tectonic problems. Surface exposure of UHP terranes requires either exhumation along extensional faults or buoyant exhumation due to density differences [3,4]. Recent work in the Urals may provide answers to problems of eclogitization and delamination of crustal roots and their role in the orogenic cycle, and has implications for exhumation mechanisms in UHP terranes that link these two concepts.

2. Influence of fluids on eclogitization

Eclogitization typically occurs at two locations in a collisional orogen, in the subducting crust and at the base of the crustal root of the overriding crust. An influx of fluids into the subduction zone or from the underlying mantle is key to these metamorphic reactions going forward – fluids play a much more significant role in eclogite metamorphism than either temperature or pressure [5]. Without H_2O, reactions will not proceed to completion, leaving metamorphic rocks metastable at temperatures and pressures other than predicted by equilibrium petrological constraints. Pressure and temperature overstepping of reactions can be seen in incompletely eclogitized rocks from several locations worldwide where rocks have experienced *P–T* conditions great enough to form eclogite, but reactions were incomplete due to a lack of sufficient fluids.

2.1. Field occurrences of partial eclogitization

Field occurrences of cm-scale transitions from amphibolite, gabbro, and granulite to eclogite are found in the Marun-Keu Complex in the polar Ural Mountains of Russia, in (the Bergen Arcs of) the Scandinavian Caledonides in western Norway, and in the Dabie-Shan in eastern China (e.g. [5–7]). In these locations, eclogite occurs alongside unreacted rocks that experienced the same *P–T–t* paths, so eclogitization must be controlled by some factor other than pressure or temperature. Fig. 1 shows the extent of reaction in gabbros to blueschist- and eclogite-facies assemblages indicating that eclogitization is not necessarily complete at equilibrium *P–T* conditions. The uneclogitized amphibolite, gabbro, and granulite rocks were metastable at eclogite-facies conditions and only an influx of fluids allowed eclogitization reactions to proceed along a fluid front or along conduits such as fractures. It is possible that some of the mineralization in the Maksyutov Complex of the south Urals occurred along fluid fronts; strong layering of quartz-, mica-, glaucophane-, and garnet-rich zones that have been interpreted as compositional variations [9] may instead be areas of localized fluid infiltration. The assumption that incomplete eclogitization is a result of a short residence time at depth followed by rapid exhumation falls short of the complete story; the rate and extent of eclogite formation is much more a function of the availability of fluids at depth and, to some extent, the deformation of the rocks [5,8].

Although few experimental data exist on eclogite-facies reactions, studies [10] show that H_2O has a major effect on reaction rate. Deformation experiments have been performed on dry albite rocks under eclogite-facies conditions (600–800°C and 1.0–2.0 GPa) produced no jadeite [8,10]. However, the addition of just 1 wt% H_2O produced partial reaction in these undeformed samples at temperatures as low as 600°C. While deformation is an important factor in eclogitization reactions, the focus of this paper is on the role of fluids in the transformation kinetics. Implications from these experiments are that the transformation to eclogite may be suppressed to higher temperatures and that as little as 1–2% fluid can have a profound effect on reactions [8]. The volume of fluid is important to consider in these reactions; it is important to note that eclogite transformations do not require the involvement of large amounts of fluids and these fluids may even only be present in the system temporarily [5].

2.2. Dehydration reactions in subducting slabs

Fluid content decreases in metamorphic rocks with increased pressure and temperature (Fig. 2). The transition from blueschist-facies metabasalts (which contain up to 6.0 wt% H_2O) to eclogite-facies metabasalts (0.8–0.0 wt% H_2O) releases significant amounts of H_2O in the subduction zone [8,13]. In subduction zones, it is the relatively wet mafic crust and serpentinized peridotite that generate most of the volatiles in the subduction system [13]; some of these volatiles will undoubtedly migrate back up the subduction zone while only some infiltrate the quartzofeldspathic rocks. Relatively large amounts (up to $\sim$6%) of H_2O should be released from subducting mafic crust as the rocks pass from blueschist-facies to eclogite-facies, due to the breakdown of lawsonite, clinozoisite, epidote, chlorite, and amphibole. The H_2O released from these dehydration reactions may be readsorbed by adjacent ‘dry’ rocks in hydration reactions [13].

In subduction zones where large blocks of continental crust are subducted, as in the Urals, much less water is available from the subducting slab than there would be if an oceanic slab was being subducted [15]. The minor amounts of fluid that are present in the sialic/felsic continental crust are locked up in micas such as phengite (see [15]), which are stable to considerably higher pressures than mafic minerals (e.g. amphibole). The lack of evolved fluid may cause micaceous mafic rocks or quartzofeldspathic rocks to transform incom-

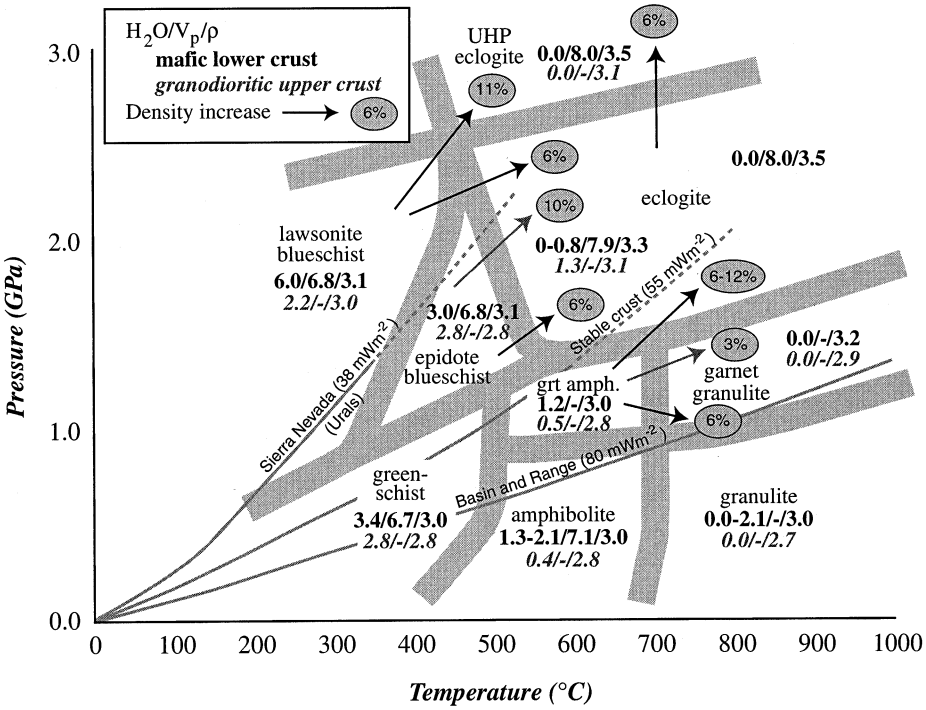

Fig. 2. Pressure–temperature diagram showing stable metamorphic facies. Average estimated maximum fluid contents, seismic velocities, and densities for granodiorite and basaltic bulk composition are included to illustrate buoyancy and H_2O evolution relationships (values are listed as vol%, km s^{-1}, and g cm^{-3}, respectively; figure based on [8,11–13]). Arrows show density increases for various metamorphic transformations. Conductive temperature profiles for the Sierra Nevada, a stable reference crust, and the Basin and Range are included with average heat flow measurements [14].

pletely or not at all to eclogitic or UHP assemblages.

Many UHP subduction zone complexes are dominated by quartzofeldspathic rocks and lack large volumes of mafic rocks; for example, the Western Gneiss Region and the Maksyutov Complex contain only about 5% and 3% mafic rock, respectively [16,17]. If the total volume of H_2O evolved during the transformation of, say, lawsonite blueschist to phengite eclogite is as much as 5% (see Fig. 2), the total volume of fluid released in these dehydration reactions is still very small.

3. Conditions for orogenic collapse

Processes at the base of the crust, namely eclogitization and/or delamination of the crustal root, ultimately control whether a mountain belt collapses. Causes for crustal delamination are thermal, compositional, and due to phase (i.e. density) changes [18]. As discussed in the previous section, while the correct *P–T* conditions must obtain, the metamorphism at the base of the crust necessary to invoke a delamination model requires fluid for the reactions to proceed; thermal considerations for eclogitization are subsidiary. The timing and location of fluid influx in the crust relative to orogenic evolution must also be considered.

3.1. Crust–mantle boundary vs. seismic Moho

The recrystallization of mafic lower crust to eclogite coincides with a large density increase (from about 3.0 g m^{-3} to about 3.3–3.5 g m^{-3}) and a corresponding increase in seismic velocities (see Fig. 2). This transformation requires the growth of high-density, high-seismic velocity minerals like garnet and clinopyroxene at the expense

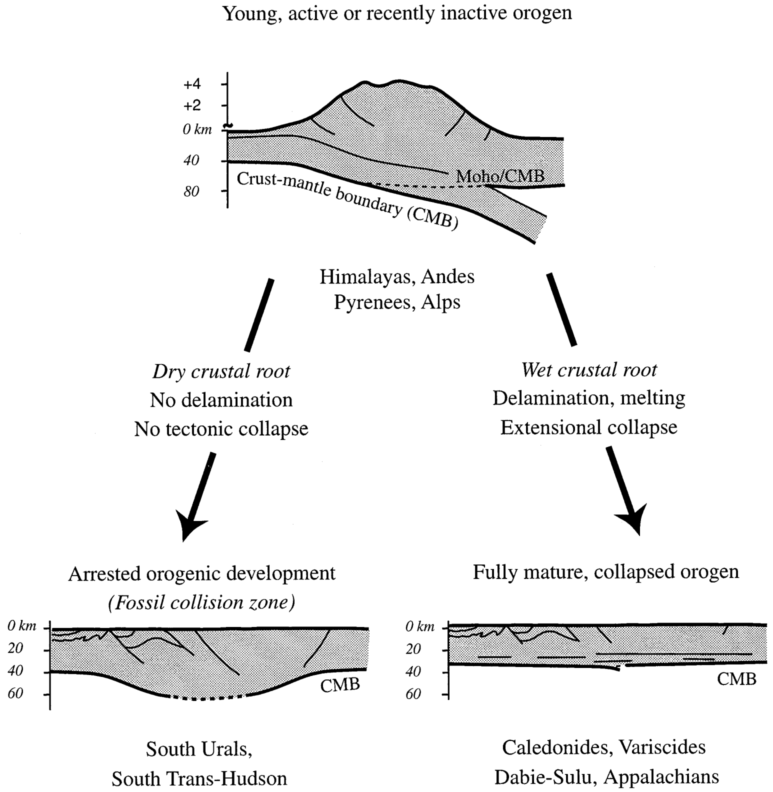

Fig. 3. Model seismic cross-sections of orogens showing the evolution from a young, active continental collision to either a fossil collision zone under dry conditions, or through to completion of the orogenic process due to post-collisional extensional collapse under relatively wet lower crustal conditions. Cartoons are true-scale except topography is vertically exaggerated.

of low-density minerals like plagioclase. Eclogites have seismic velocities (V_p) of at least 8.0 km s^{-1} and are therefore placed below the Moho by seismologists [19]. The process of eclogitization at the base of the crust may be a gradual reaction with the eclogitization 'front' close to the seismic Moho; this transition may appear as a diffuse Moho boundary.

3.2. Delamination of the crustal root

The eclogitization process induces transformation weakening and in that sense, eclogites are weaker (i.e. deform more readily) than their protoliths [16]. In zones of high strain, eclogites are foliated and ductilely deformed; these rheologically weak rocks have a further enhanced deformability when water is present. Metamorphic reactions enhance ductility through grain-size reduction, metamorphic fluid production, and transformation plasticity [8]; eclogitization in turn reduces the strength of the crust [5]. The large density increase forced by eclogitization combined with the weak boundary layer between eclogite and the rocks above the transition zone, destabilizes the crustal root and provides a mode by which the crustal roots detach; the eclogite adds to the negative buoyancy of the 'mantle lid' and leads to the removal of the lower crust [1], specifically, delaminating the dense, mafic lower crustal root.

There is evidence that the metamorphic transition to eclogite is a rapid process that might produce sudden density changes that could trigger delamination; pseudotachylytes from western Norway suggest that co-seismic faulting occurs during eclogitization [20]. Metamorphism begins in subducted dry crust when fluid infiltration be-

Table 1
Comparison of attributes of different mountain belts in various stages of the orogenic process

Orogen	Age	Moho depth (km)	Moho character	Eclogitized root	Delaminated root	Extensional collapse	Melting, late intrusion	Current heat flow ($mW\ m^{-2}$)	Elevation (km)
Young or active collision zones									
Himalayas	Cz	75	Poor refl., imbricated	Yes?	No	Minor	Yes?	60–90	5.5
Western Alps	Mz–Cz	45–51	Poor refl., imbricated	–	No	–	–	–	2.5
Pyrenees	Cz	39–45	Poor refl., imbricated	–	No	–	–	–	2.5–3.5
Andes	Cz	70–74	–	–	Yes?	–	Yes?	–	3.0–4.0
Arrested orogenic development									
South Ural Mountains	Pz	55	Poor reflectivity	Partial?	No	No	No	35	< 1.0
Southern THO	pC	50	Poor reflectivity	Partial?	No	No	No	21–42	< 0.5
Fully mature, collapsed orogens									
Variscides (Northern France)	Pz	30–35	Sharp refl., flat	No root	Yes	Yes	Yes	60–70	< 0.5
Norwegian Caledonides	Pz	35	Well-defined, flat	No root	Yes	Yes	Minor	Low	1.5–2.5
Southern Appalachians	Pz	35–40	Sharp refl., flat	No root	Yes	Yes	–	31–42	1.0–2.0
Dabie-Sulu belt	Mz	35–41	Well-defined, flat	No root	Yes	Yes	Yes	58–87	< 1.0
Northern THO	pC	42	Sharp refl., flat	No root	Yes	Yes	–	42	< 0.5

Data for individual orogens are summarized from: the Himalayas [18,21–24]; the Alps [1,22,25,26]; the Pyrenees [1,25]; the Andes [18,24]; the Urals [2,27–30]; the THO [19,31–34]; the Variscides [1,24]; the Caledonides [26,35]; the Appalachians [1,14]; and the Dabie-Sulu belt [36]. Abbreviations are: Precambrian (pC); Paleozoic (Pz); Mesozoic (Mz); and Cenozoic (Cz). Divide heat flow values by three to approximate geothermal gradients.

gins; if sufficient fluid is introduced into the system, and if the *P–T* conditions are within the eclogite stability zone, reaction will proceed rapidly and the volume of the rock will be reduced by 10–15% [20]. The volume change will allow further fluid infiltration creating conditions that would enhance metamorphic reactions and may induce delamination. Collisional orogens all pass through a stage similar to that currently seen in the Himalayas or Andes, or preserved in only recently terminated collisions such as the Alps or Pyrenees (see Fig. 3). Table 1 compares specific crustal and geological characteristics of different mountain belts displaying various stages of orogenic evolution. In the final stages of development of an orogen, mountain belts characteristically undergo uplift and/or exhumation, plutonism, and tectonic collapse [1,37], arguably caused by eclogitization and the subsequent delamination of the crustal root. Conventionally, if the lower crust is cold ($< 500°C$) and cannot flow rapidly, erosion will play an important role in the degradation of a mountain belt; conversely, if the lower crust is hot ($> 700°C$), mechanical extension will predominate because the lower crust will be eclogitized, allowing it to flow more easily and delaminate [1]. In contrast, I argue that delamination is controlled by the amount of water available for the metamorphism-controlled density changes deformation.

The influence of H_2O in the process of eclogitization and subsequent delamination of an eclogitized crustal root is much more important than temperature alone. Based on the field occurrences of partially eclogitized rocks mentioned above and on the small amount of existing experimental data, one must conclude that in H_2O-absent conditions eclogitization is severely limited and the crustal root will be preserved. The rocks at the base of a dry crust will remain metastable for an indefinite period. Terranes can be dry for extended periods (i.e. hundreds of millions of years) and H_2O-present conditions can be short-lived; it is during this potentially short fluid-present stage that reactions and deformation occur [38]. This proposed model for eclogitization and delamination of the crustal root is different from previous suggestions because it requires fluid rather than T to drive the processes in the lower crust.

4. Overview of the Urals: a stalled collisional orogen

The Ural Mountains formed in the Late Devonian to Permian as a result of the collision between the East European platform, microcontinental blocks to the east, and the intervening Magnitogorsk island arc. The Main Uralian fault suture zone extends the 2000 km along the entire axis of the 400–450 km-wide orogen [39,40]. The south Ural Mountains preserve its collisional structure and show no evidence for post-orogenic tectonic collapse [2,27,29,37]. The development of the south Urals has stalled since the late Paleozoic retaining its collisional structure with a deep crustal root, low topography (< 1600 m), and a lack of post-orogenic extensional collapse.

Seismic reflection data suggest the south Uralian Moho is at about 55 km depth [2,27–29]. The Moho definition under the central axis of the Urals is diffuse; this diffuse character may result from an eclogitized root or from metamorphic phase changes at depth [2]. However, wide-angle stacked images show a well-defined, undulating Moho [28]. The undulatory nature of the Moho can be attributed to significant re-equilibration [28] or possibly to strong lateral velocity variations correlating to major tectonic unit boundaries.

The low surface topography and deep crustal root are preserved along the length of the Urals; the depth of the Moho in the polar and middle Ural Mountains is 50 km and 60 km, respectively [2]. The middle Urals preserve both collisional structures and minor late- to post-orogenic extension [41]. This partial collapse in the middle Urals is probably related to the development of the West Siberian basin and minor normal movement on the Main Uralian fault in the Early Mesozoic [2]; further, structural variations in the middle Urals may have resulted from collision involving a promontory on the East European platform. Whereas the orogenic evolution of the Urals varied somewhat along strike, the continuity of surface topography and the depth of the crustal root indicate that the Urals as a whole have preserved their collisional structure from the late Paleozoic.

5. Comparison of the Urals with the Trans-Hudson orogen (THO)

The preserved collisional structure of the Ural Mountains is similar to the Precambrian THO of North America where there is also little evidence for extensional collapse and where a deep crustal root is still preserved. This collisional structure contrasts sharply with Paleozoic orogens like the Variscides, Caledonides, and Appalachians, and Proterozoic orogens such as the Svecofennides where the orogenic process has gone to completion and the delamination of crustal roots was followed by post-collisional extensional collapse (Fig. 3, Table 1).

The characteristics of the Ural Mountains and the THO vary along strike. The Urals apparently maintain a 50–60 km crustal root for the entire 2000 km length. However in the middle Urals, as in the northern region of the THO, there is evidence for extension at the surface [31]. The middle Urals show only a minor amount of extension while retaining a deep crustal root, whereas the northern THO has collapsed tectonically, lost its deep root, and now displays a flat Moho with strong reflectivity [31,34,41]. The south Urals and the south THO are stalled at an intermediate stage of orogenic evolution; both orogens retain a 50–55 km crustal root and share a characteristically diffuse Moho beneath the deepest part of the crust (e.g. [2]). In the case of the southern THO, subsidence in the overlying Williston Basin is due to eclogitization of a mafic subcrustal body [32]. Because the overall structural character of the Urals seems to be maintained along its length, the partially eclogitized rocks in the Marun-Keu Complex in the polar Urals and evidence for a lack of fluid in the south Uralian crust may indicate that the entire mountain belt lacks fluid at the base of its crust. In contrast, the THO varies dramatically from north to south and these variations may indicate the availability of metamorphic fluid in the north (Table 1). A diffuse Moho in the south THO and in the south Urals probably indicates partial eclogite formation in a deeper crustal body; extensive eclogitization would likely cause delamination and the development of a new, well-defined Moho. Because crustal roots are preserved in the Urals and the south THO, there may never have been sufficient H_2O to allow widespread eclogitization of the base of the crust (i.e. never more than $\sim 1\%$ fluid based on experimental data). Without extensive eclogitization of the base of the crust, there can be no delamination or post-orogenic extensional collapse; it is the eclogitization and removal of these root zones that has a direct and significant impact on orogenic collapse and the evolution of mountain belts. The major difference between these stalled orogens and those that have gone to completion is a lack of fluid at the base of the crust.

6. Buoyancy-controlled exhumation of UHP rocks

A striking difference between the south Urals and many other orogens is the presence of a UHP subduction complex [3,42–44]. The mechanisms responsible for exhumation of UHP terranes must also in part help to preserve UHP index minerals. For example, in the Scandinavian Caledonides of western Norway and in the Dabie-Sulu belt of eastern China, UHP coesite and diamond are preserved and the orogen has undergone post-orogenic extension and lost its crustal root [35,45]. The extensional structures related to collapse in the Dabie-Sulu belt likely played a role in the exhumation of the UHP rocks and operated at a sufficiently fast rate and/or under dry conditions to preserve UHP mineralogy.

The Maksyutov Complex lies in the footwall of the Main Uralian suture zone in the south Urals, but extension on the Main Uralian fault did not play a significant role in the late-stage exhumation of the complex [17] and there is little or no structural evidence of extensional movement on the Main Uralian fault in the south Urals. In contrast to the Dabie-Shan, the lack of a major extensional feature related to the Maksyutov Complex suggests that there must be another mechanism by which UHP rocks can return to the surface.

While extensional faulting and buoyancy-driven exhumation are not mutually exclusive concepts, the Maksyutov Complex provides a plausible test case for dominantly buoyant exhumation of subduction blocks [3,46]. As previously discussed, eclogitization dramatically changes the density structure of the lower crust (Fig. 2) and partially eclogitized crust produces an ideal situation for buoyancy-related vertical movements. Less dense, unreacted, and felsic material may rise from root zones while dense eclogite descends into the mantle [5]; this model for buoyant exhumation can explain the observation that UHP terranes are partially eclogitized or dominantly felsic.

The total volume of mafic rocks in the Maksyutov Complex is small (ca. 3%) compared to the volume of quartzofeldspathic rocks. This results in a subducted block that is significantly more buoyant than the surrounding lower crust and upper mantle; additionally, the presence of a serpentinite mélange likely provided a weakened zone aid the buoyant exhumation process. The Maksyutov Complex underwent significant retrograde metamorphism; the UHP history of the complex is only known from diamond and coesite pseudomorphs rather than diamond or coesite themselves, and calculated exhumation rates are slow compared to other UHP orogens, allowing retrogression [17,42,43].

Density contrasts in the basalt-to-eclogite transition are a driving force in subduction zone systems [47]. The introduction of an amphibolitizing fluid (derived from dehydration reactions in the subducting block) may also be an effective way of exhuming eclogitized crust from subduction zones and continental root zones. The back-reaction of eclogites to less dense lithologies like blueschist and amphibolite could help exhume deep-seated rocks by increasing their buoyancy; therefore, retrograde metamorphism may also play a significant role in the buoyant exhumation of UHP terranes. The broader implication for UHP tectonics is that buoyancy may play a more important role in exhumation of UHP rocks than previously thought.

7. Conclusions

Fluids, not temperature, control eclogitization, delamination, and the ultimate tectonic collapse of mountain belts. Most orogens collapse, but at least two – the Urals and the THO – did not. One may speculate why all UHP orogens are dry. Possibly continued convergence and continental subduction after consumption of oceanic crust generate a dry orogen, and if so the future fate of the Himalaya may be similar to the Urals. This proposed fluid-induced mechanism for the evolution of orogens has consequences for the exhumation of UHP terranes; the lack of post-orogenic extensional collapse in the south Urals indicates that buoyancy plays a much more important role in the exhumation of UHP terranes than previously thought.

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