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Coeval blueschist exhumation along thousands of kilometers: Implications for subduction channel processes

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[1] We herein focus on understanding what controls the detachment and migration of oceanic crustal slices along subduction zones. We provide evidence for the coeval Middle to Late Cretaceous exhumation of oceanic blueschists in the same Neotethyan subduction zone, across more than 3000 km, from depths around 30–40 km, over a short time interval (~ 25 Ma) compared to the duration of subduction (>100 Ma). We stress the importance of such a geodynamic process and suggest that this exhumation was promoted by a regional-scale change in the long-term interplate mechanical coupling. On the basis of geological and geophysical evidence, we propose that the upward migration of oceanic fragments in subduction zones is normally inhibited and only occurs discontinuously, as the subduction channel opens up in response to a major change in plate geodynamics, slab geometry and dynamics, mantle wedge and slab hydration, or a combination of these.

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1. Introduction

[2] Although oceanic lithosphere is doomed to be recycled to the mantle, kilometer-scale fragments metamorphosed to high-pressure low-temperature conditions in subduction zones are found in many orogens [Ernst, 1970; Maruyama *et al.*, 1996]. Understanding what controls the detachment and migration of oceanic crustal slices along subduction zones is thus crucial to constrain exhumation

mechanisms [Platt, 1993; Ring *et al.*, 1999], subduction channel processes [Cloos, 1993; Ernst, 2001; Jolivet *et al.*, 2003] or interplate mechanical coupling [Cailleau and Oncken, 2008]. Two questions are of particular importance: (1) On which time scale and spatial extent do such exhumation events take place? (2) What triggers this exhumation of oceanic material at depth, and what does this tell us in terms of interplate mechanical coupling?



[3] We herein provide evidence for the coeval exhumation of oceanic blueschists (BS) in the same subduction zone, along more than 3000 km, from depths around 30–40 km, over a short time interval (~ 25 Ma). On the basis of available structural, kinematic and geophysical data, we then discuss possible causes for this exhumation and implications for the mechanical behavior of subduction zones.

2. Exhumation of Slab Material Along the Neotethyan Subduction Zone From Turkey to the Himalayas

[4] The final, diachronous closure of the Neotethys (at ~ 55 –30 Ma), after a long-lasting NE dipping subduction history beneath Eurasia [e.g., *Ricou*, 1994; *Dercourt et al.*, 1993, 2000; *Stampfli and Borel*, 2002], led to the formation of an extensive set of collisional belts, from the Alps to the Himalayas [e.g., *Gansser*, 1964; *Ricou*, 1994] (Figure 1a). Despite a protracted subduction history, few blueschists of oceanic affinity are exposed along the suture zone (Figure 1a) [e.g., *Okay*, 1989; *Guillot et al.*, 2008]. Preliminary in situ radiometric ages on phengite revealed that the Zagros BS were exhumed only between ~ 100 –85 Ma [*Agard et al.*, 2006]. This observation was interpreted as a transient process during which the mechanical coupling of the subduction regime was locally modified.

[5] In order to confirm these observations, we provide below (1) new radiometric ages for the Zagros BS performed with an independent technique and (2) a compilation of ages for the Neotethyan blueschists to test whether this conclusion is applicable to other segments of the subduction zone.

2.1. The $^{40}\text{Ar}/^{39}\text{Ar}$ Plateau Constraints on the Exhumation of Zagros Blueschists

[6] Zagros BS crop out as coherent kilometer-scale bodies interleaved with serpentinites (Ashin unit), or as meter-sized BS blocks encased in matrix serpentinite (Seghina unit), which likely promoted their exhumation [e.g., *Guillot et al.*, 2001]. SE Zagros BS represent intermediate to mafic protoliths buried to depths of 30–40 km, with peak P-T estimates around 1.1 GPa and 520–530°C on average, except for the lawsonite-omphacite-bearing BS from Seghina unit (~ 1.7 –1.8 GPa and 500°C). Further information is given by *Agard et al.* [2006].

[7] We performed $^{40}\text{Ar}/^{39}\text{Ar}$ laser probe step-heating dating on isolated single minerals (mainly phengite with the exception of one amphibole) using a procedure described in the auxiliary material.¹ In the Ashin area, plateau ages for twelve samples range from 93.3 ± 1.0 Ma to 105.7 ± 1.1 Ma (see Figure 1b and auxiliary material). These ages are consistent but less scattered than those obtained with the in situ laser technique (82–109 Ma (Figure 1c)) [*Agard et al.*, 2006], probably because the single grain step-heating technique has the capacity to circumvent effects of argon loss, excess argon and contamination by low-potassic minerals such as chlorite. In the Seghina lawsonite blueschists, where higher-pressure conditions are recorded than in Ashin, two phengites provide younger plateau ages of 80.2 ± 0.9 Ma and 85.4 ± 0.9 Ma. Intercept ages in the $^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$ correlation diagrams are consistent with the plateau ages (see auxiliary material).

[8] Given our knowledge of the closure temperature for argon in phengite (~ 400 to 450°C) [e.g., *McDougall and Harrison*, 1999; *Di Vincenzo et al.*, 2001; *Agard et al.*, 2002; *Bosse et al.*, 2005; *Gouzu et al.*, 2006], these ages likely date a cooling stage close to the metamorphic peak or reflect a continuous evolution of cooling-recrystallization processes during early BS exhumation. This interpretation is reinforced by the fact that the dated phengites are highly substituted in all samples ($\text{Si}^{4+} > 3.3$; between 3.5 and 3.7 for Seghina) with few evidence of retrogressive effects, and by the consistency of amphibole and phengite ages in sample IR04-37.

[9] The contrasting modes of occurrences [*Agard et al.*, 2006] and ages of Ashin and Seghina suggest that the two oceanic units could have been buried and exhumed somewhat diachronously (~ 25 Ma) in the Neotethyan subduction zone.

2.2. Exhumation of Blueschists During the Late Cretaceous Along the Neotethyan Suture: Coeval Exhumation of Slab Material

[10] We exhaustively compiled available ages from the literature on oceanic blueschists and eclogites from the Neotethyan suture zone, and compared them to the supposed duration of subduction (Figure 1c). Most of these Rb-Sr, K-Ar and Ar-Ar ages were obtained on high-Si phengite from

¹Auxiliary materials are available in the HTML. doi:10.1029/2009GC002428.

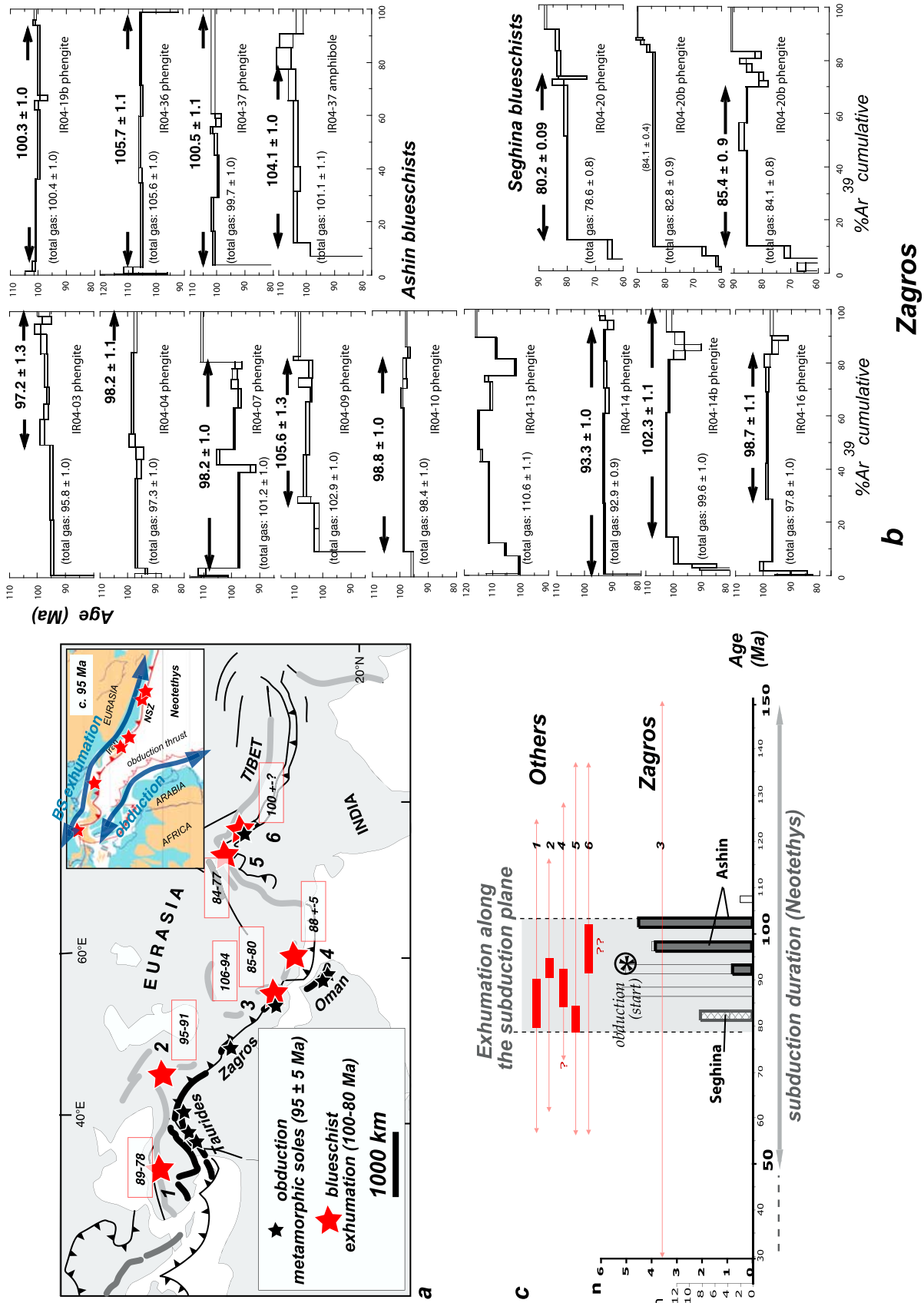


Figure 1



well-preserved high-pressure assemblages with little evidence of retrogression. So far, no more than six blueschist occurrences of oceanic material were reported from Turkey to the Himalayas (Table 1 and Figure 1a). Others correspond to continental margin rocks dragged at depth during obduction or continental subduction (e.g., Tavsanli zone [Okay *et al.*, 1998; Okay, 2002] and Himalayas [Guillot *et al.*, 2008]), or to blueschists returned from distinct subduction zones (e.g., Sistan and Sabzevar oceans [Fotoohi Rad *et al.*, 2005; Tsujimori *et al.*, 2006]).

[11] The few blueschists returned from the long-lived (Jurassic to early Tertiary, on average) Neotethyan subduction provide ages clustering in the restricted time period 105–80 Ma, irrespective of the method used (Figure 1c). Given (1) the P-T paths recorded by these rocks and the closure temperature of the radiometric systems (e.g., on phengite, $\sim 500^{\circ}$ – 550° C for Rb-Sr and 400 – 450° C for Ar/Ar) and (2) the lack of later thermal effects and fluid infiltration (as attested by the good preservation of the blueschists), this age range most probably corresponds to the period of cooling and exhumation immediately following the attainment of peak metamorphic conditions. This suggests that a broadly coeval, Middle to Late Cretaceous short-lived exhumation period occurred all along the suture zone, from Turkey to the Himalayas (>3000 km). This age cluster could also represent a change from a subduction setting dominated by tectonic erosion (thus dragging all blueschists into the mantle) to one dominated by accretionary processes in the subduction channel (hence allowing for the preservation and later

exhumation of these blueschists), as suggested for the Franciscan [Wakabayashi and Dumitru, 2007].

[12] We stress the importance of such a previously unsuspected geodynamic process and note that first, the time scale of exhumation is on the order of 25 Ma. Further data in the various localities are now needed to assess whether this time span (25 Ma) represents a continuous exhumation or discrete exhumation pulses. Second, the material mainly returned from depths around 30–40 km in the subduction zone, either as coherent, kilometer-scale bodies (Ashin, Iran; Stepanavan, Armenia) or as blocks in a melange (Seghina, Iran; Cetmi, Turkey). Third, it coincides with a regional-scale geodynamic reorganization, marked by (1) obduction processes to the south of the Neotethys, encompassing the very same region (Figure 1a) [Nicolas, 1989; Hacker *et al.*, 1996; Parlak and Delaloye, 1999]; (2) kinematic changes and acceleration of convergence [Dercourt *et al.*, 1986; Agard *et al.*, 2007]; (3) the formation of voluminous magmatic arcs (e.g., Kohistan arc [Rolland *et al.*, 2002; Dhuime *et al.*, 2007]); and (4) the development of an echelon, marginal back-arc basins in the upper plate [Arvin and Robinson, 1994; Shojaat *et al.*, 2003; Mahéo *et al.*, 2004; Bagheri and Stampfli, 2008].

3. Geophysical Constraints on Subduction Channel Processes

[13] The data above outline a pulse in upward migration of oceanic slices in a subduction zone and therefore suggest a change along the plate-slab

Figure 1. (a) Neotethyan suture zone from Turkey to the Himalayas. Blueschist ages from the literature and this study are reported. Note the comparable regional-scale extent of obducted ophiolites and blueschist exhumation. The insert shows a reconstruction of the Neotethys at ~ 95 Ma according to Dercourt *et al.* [2000]. (b) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the Ashin and Seghina blueschists. Age spectra are reasonably flat for a large percentage of the argon released, with the exception of marbles IR04-13 and IR04-20b (phengite2) for which no plateau age can be calculated. Significant age discordances are mainly related to the loosely bound argon released during the first heating steps and/or to steps representing a small amount of argon released. Note that intercept ages in the $^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$ correlation diagrams, between 94 to 106 Ma, are consistent with these plateau ages (Table S1 in the auxiliary material). There is a range of intercept ages for the Ashin samples, while a single blueschist from Seghina displays a younger age of 80.3 ± 1.3 Ma. For none of these samples does the initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio indicate the presence of excess argon, which is supported by the age concordance in sample IR04-37 for two minerals with contrasting argon solubility (amphibole and phengite) and by the clustering of the results in the Ashin samples. (c) Blueschist ages from six localities shown in Figure 1a (as large red stars; see Table 1 for references): 1, Biga Peninsula zone; 2, Amassia-Stepanavan zone; 3, SE Zagros; 4, Makran; 5, Shangla; 6, Sapi Sherghol. The arrows indicate the supposed duration of subduction in each locality (thicker portions indicated the exhumation period). Comparison of in situ spot fusion (light, empty histograms) and single grain step-heating laser probe $^{40}\text{Ar}/^{39}\text{Ar}$ ages (thick, filled histograms (this study)) for the SE Zagros blueschists. Single grain step-heating ages are distinguished for Ashin (gray) and Seghina (hatched). Star recalls the inception of obduction at 95 Ma [see Wakabayashi and Dilek, 2003; Agard *et al.*, 2007].



Table 1. Compilation of All Oceanic Blueschists and Eclogites Reported From the Neotethyan Suture Zone With Available P, T, and Age Constraints From the Literature^a

Locality ID	Locality	Age Constraints (Ma)/Method	Maximum P-T Conditions ^b	References
1	Turkey (Cetmi mel., Biga Penins.)	100.3 ± 2.8/Rb-Sr; 99 ± 6.1/Rb-Sr	1.1/510	<i>Okay and Satir</i> [2000]
2	Armenia (Amassia-Stepanavan)	95–91/Ar-Ar	1–1.2/520	<i>Rolland et al.</i> [2008]
3	Iran (SE Zagros)	93–106 (Ashin)/Ar-Ar; 80–85 (Seghina)/Ar-Ar	1.1/520, 1.5–1.8/480	<i>Agard et al.</i> [2006] and this study
4	Iran (Makran)	87.9 ± 5.5/K-Ar	–	<i>Delaloye and Desmons</i> [1980]
5	Pakistan (Indus suture zone)	79.7 ± 0.4/Rb-Sr; 77 ± 0.4/Rb-Sr; 80 ± 2/Ar/Ar; 84 ± 1.7/K-Ar; 83.6 ± 2/Ar-Ar	>0.7/400	<i>Burg et al.</i> [1984], <i>Anczkiewicz et al.</i> [2000], <i>Shams</i> [1980], and <i>Maluski and Matte</i> [1984]
6	India (Sapi-Shergol)	~100/K-Ar (WR + Gln)	0.9–1.1/400	<i>Honegger et al.</i> [1989], <i>Mahéo et al.</i> [2006], and <i>Guillot et al.</i> [2008]

^a See location in Figure 1a. All dating on phengite except locality 6 (WR, whole rock; Gln, glaucophane).

^b Pressure is in GPa; temperature is in °C.

interface. Following *England and Holland* [1979] and *Shreve and Cloos* [1986], most authors envision the plate-slab interface as a subduction channel, in which material may move partly independently from the upper and lower plates. In detail, the structure and dynamic behavior of the subduction channel is still poorly constrained, however [*Gerya et al.*, 2002; *Raimbourg et al.*, 2007; *Yamato et al.*, 2007; *Hilairiet and Reynard*, 2009].

[14] From bottom to top across the plate-slab interface, high-resolution reflection and tomographic imaging of subduction planes shows (1) a composite layer of slab oceanic crust (in places traced down to ~400 km) [*Kawakatsu and Watada*, 2007; *Tonegawa et al.*, 2008], cut into 5–10 km large pieces or less because of large magnitude ruptures, slab bending and/or inherited earlier fracture patterns [*Ammon et al.*, 2008; *Delescluse et al.*, 2008; *Singh et al.*, 2008], underlain by partly hydrated slab mantle [e.g., *Hacker et al.*, 2003; *Syracuse et al.*, 2008]; (2) low-velocity layers, 2–8 km thick, located on top of the slab on several subduction zones [*Abers*, 2005; *Meier et al.*, 2007; *Kopp et al.*, 2008; *Rondenay et al.*, 2008] and interpreted as sediments, serpentinites highly hydrated crustal material or slivers lying along the plate-slab interface (these layers are our best picture so far of what a subduction channel might look like); and (3) a highly hydrated (30–40 vol %) and serpentinitized mantle wedge corner [*Bostock et al.*, 2002; *Hyndman and Peacock*, 2003; *Hilairiet et al.*, 2007]. Across the mantle wedge permeable barrier, whose tip coincides with the downdip limit of the seismic locked zone (at ~40 km) [*Tichelaar and Ruff*, 1993; *Hyndman et al.*, 1997], partial interplate decoupling occurs, while repeated hydrofracturing (and fluid transfer) may be responsible for episodic tremor slip and slow slip events (ETS, SSE [*Rogers and Dragert*, 2003; *Schwartz and Rokosky*, 2007; *Audet et al.*, 2009]).

[15] This overall picture is supported by thermodynamical models of dehydration reactions and plate-slab interface mineralogy accounting for the double seismic zones observed in many subductions [e.g., *Hacker et al.*, 2003, and references therein; *Tonegawa et al.*, 2008].

[16] Oceanic crustal slices thus likely migrate upward along some sort of a channel, but the following questions remain: how do these rocks detach from the sinking slab, at which depth(s), do they circulate in a complex melange zone or as large-



scale imbricated slices? In particular, the extent to which slab- or mantle wedge-derived serpentinites (or sediments) are effectively present in the channel [e.g., *Hilairt and Reynard, 2009*] is extremely important for the upward migration of mafic slices, due to their mechanically weak behavior and high buoyancy [*Hermann et al., 2000; Guillot et al., 2001*]. Note that thermomechanical models of the subduction plane/channel either point to extreme mixing in the subduction channel [*Gerya et al., 2002*] or to movements of individual slices [*Yamato et al., 2007*].

[17] Constraints on the dynamic behavior of the subduction channel are sparse, unfortunately, and rely on very different sources and contrasting time scales, from yearly slip along the slab interface (ETS, SSE) and kinematic/geodetic analysis of subduction plane characteristics [*Lallemand et al., 2005*], to the analytical, numerical and analog modeling designed to encompass millions of years [*Cloos, 1993; Gerya et al., 2002; Raimbourg et al., 2007; Funicello et al., 2008*]. Besides, the time response of the complex subduction zone force balance [*Uyeda and Kanamori, 1979; Scholz and Campos, 1995; Schellart, 2004*] is not known with precision. Convergence velocities, for instance, are regarded as influencing interplate mechanical/seismic coupling [*Le Pichon et al., 1998*] or plate-slab coupling [*Conrad et al., 2004*] on the short term. Modeling suggests that plate velocities will also play a major role on friction and force balance in subduction zones [*Funicello et al., 2008; Arcay et al., 2008*], but extrapolation of seismic coupling to long-term mechanical coupling is at present speculative.

4. Discussion: Implications for Long-Term Mechanical Coupling in Subduction Zones?

[18] This striking coincidence of relatively short-lived BS exhumation from the same subduction zone, across several thousands of km, suggests that the long-term interplate coupling and/or subduction channel processes were modified. This is reminiscent of the exhumation of the oceanic Raspas complex, thought to result from the entrance of an oceanic plateau jamming the Andean subduction zone [*Arculus et al., 1999; Bosch et al., 2002*]. Another example comes from the Franciscan Complex of California where the Cretaceous age of blueschists has to be compared to the long duration of subduction, from about 165 to 25 Ma [e.g.,

Wakabayashi and Dumitru, 2007]. In the case of the Neotethys, however, the exhumation was regional-scale (>3000 km), which calls for mantle-scale processes.

[19] Key, tightly interrelated parameters likely to affect the upward migration of rocks along the plate-slab interface are convergence velocity, slab geometry and the rheological properties of the plate-slab interface. Note that local variations in slab stresses, crustal thickness, incoming hydrous minerals and sediments will also play important roles (as noted by *Peacock et al. [2005]*), but will fail to account for such a large-scale exhumation.

4.1. What Can Impact Subduction Channel Processes to Produce Such Large-Scale Exhumation?

[20] Three end-member mechanisms can tentatively be put forward, which are not mutually incompatible and probably interplay in time and space in subduction zones:

[21] 1. The first mechanism is a change in convergence velocities. The 115–80 Ma plate reorganization and acceleration affecting the Zagros-Oman transect [*Agard et al., 2007*] is an obvious candidate, given the comparable timing and spatial extent of BS exhumation, obduction (Figure 1a, inset) and back-arc formation [*Agard et al., 2006; Bagheri and Stampfli, 2008*]. Viscous resistance of the asthenospheric mantle to faster slab penetration, together with interplate friction and a change in thermal regime, would affect mechanical coupling. Such an example of transient modification of subduction systems in response to kinematic changes was suggested for peri-Pacific subduction zones at 120 Ma [*Vaughan, 1995*].

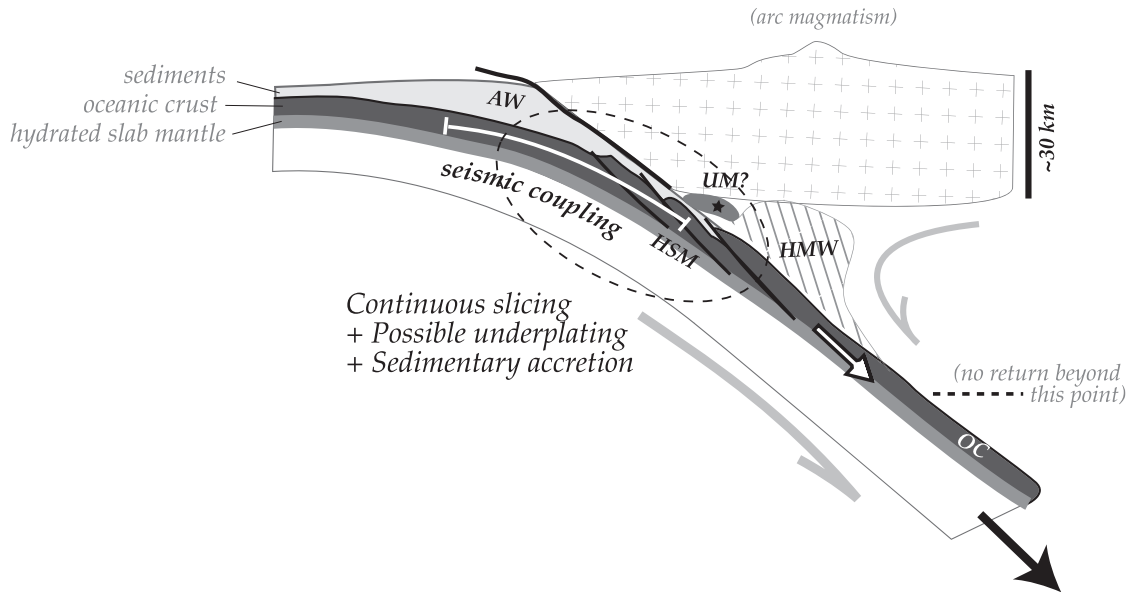
[22] 2. The second mechanism is slab retreat. This will intuitively widen the subduction channel and favor return flow [*Raimbourg et al., 2007*], as proposed by *Brun and Faccenna [2008]*, who relate BS exhumation in the Cycladic subduction zone with the entrance of microcontinents and slab retreat. However, the coeval entrance of microcontinents in the Neotethyan subduction zone, from Turkey to the Himalayas, is unlikely. Similarly, slab widths for effectively retreating slabs are <1500–2000 km [*Schellart et al., 2007*], so that the scale of Neotethyan exhumation may require another mechanism. Plate acceleration (point 1 above) will nevertheless increase the viscosity



contrast between the lithosphere and asthenosphere and promote slab retreat [Funiciello *et al.*, 2008]. Evidence for slab retreat, at least around Central Iran, is indeed provided by the formation of several

back-arc marginal basins (Nain-Baft [Davoudzadeh, 1972; Arvin and Robinson, 1994], Sabzevar [Shojaat *et al.*, 2003; Bagheri and Stampfli, 2008], and possibly Sistan [Tirrul *et al.*, 1983]).

a) 'Steady-state' subduction channel
No exhumation



b) Channel opening (+ enhanced detachment/faulting?)
Short-lived exhumation < 15-20 Myr
From depths ~ 35 km

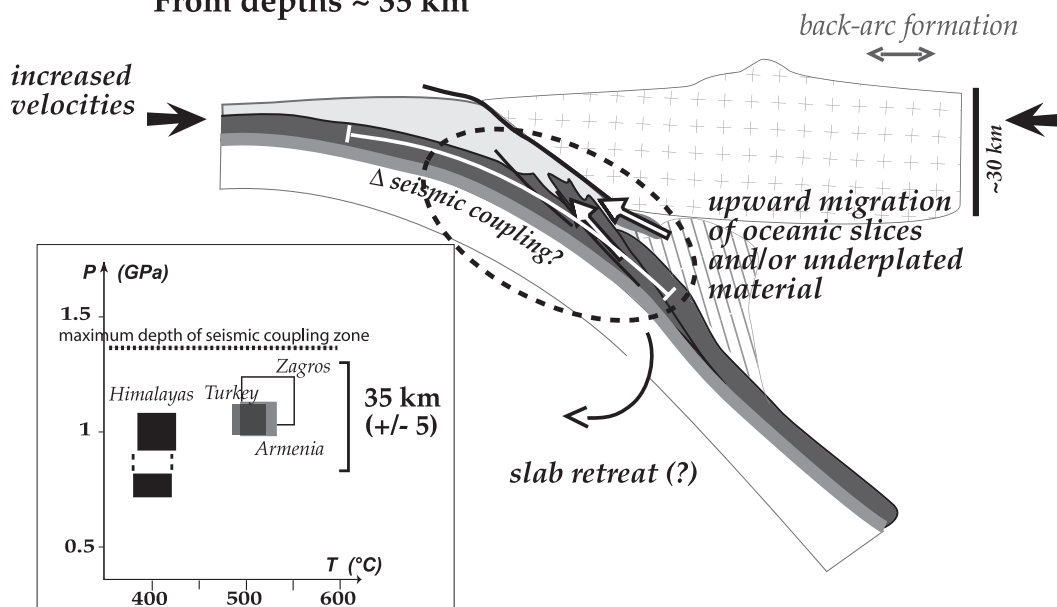


Figure 2



[23] 3. The third mechanism is variation of the extent of mantle wedge hydration and proportion of serpentinites in the blueschist-bearing slices. Indeed, blueschists are exhumed along with serpentinites in present-day subduction zones [Maekawa *et al.*, 1993] and fluid-assisted processes notoriously play a key role [Oncken *et al.*, 2003]. We note that increased velocities should favor steeper slabs, cooler geotherms [Peacock *et al.*, 1994], deeper and more along-slab dehydration [Abers, 2005] and thus increase the downdip limit of the seismic locked zone. Increased mantle wedge circulation [Arcay *et al.*, 2008] may counteract this partly, but the mantle wedge corner proper behaves somewhat independently [Abers *et al.*, 2006].

4.2. Into the Subduction

Channel: Interplate Coupling and the Kinematics and Depth of Slicing

[24] Oceanic BS fragments of the Neotethys originate on average from depths ~ 35 km (section 2). This particular depth range may not be fortuitous and broadly coincides with (Figure 2a) (1) maximum depths of interplate seismic coupling (~ 35 – 50 km) [Peacock and Hyndman, 1999], (2) upper plate Moho depths and depths of possibly underplated material [Oncken *et al.*, 2003], and (3) bottom depths of most accretionary complexes [Brandon *et al.*, 1998]. Singh *et al.* [2008] recently suggested that great earthquakes (recurrence interval $\sim 10^{3-4}$ years) can rupture the oceanic crust as a whole, which, on the long term, suggests that the slicing of oceanic units takes place almost continuously. Continuous slicing of the crust would also be consistent with the link between earthquakes and dehydration reactions [Peacock and Wang, 1999; Hacker *et al.*, 2003] and pseudotachylyte formation deep in subduction zones [Austrheim and Andersen, 2004].

[25] We therefore propose that, in subduction zones (Figure 2b), it is the upward migration (and BS

exhumation) which is fundamentally discontinuous. Upward migration requires an opening of the subduction channel (i.e., a change in long-term mechanical coupling), and is possibly triggered by a major change in plate geodynamics, slab geometry and kinematics, mantle wedge and slab hydration, or a combination of these. More natural data and modeling are needed to better assess this model of intermittent subduction channel opening. As the channel opens up, rocks may probably be returned from variable depths, but in any case < 80 km [Agard *et al.*, 2009]. Our guess is that underplated material [Calvert, 2004; Arroyo *et al.*, 2008; Cailleau and Oncken, 2008] could be mobilized as a result of increased velocities and deeper mechanical coupling (Figure 2b). Although partly obscured by later collisional deformation, a better knowledge of the scale of these blueschist tectonic slices would help constrain the subduction channel mechanical properties.

5. Conclusions

[26] We provide evidence that the few oceanic blueschists returned from the long-lived Neotethyan subduction were exhumed coevally, across more than 3000 km, from depths around 30–40 km, over a short time interval (~ 25 Ma). We stress the importance of such a previously unsuspected geodynamic process and suggest that this exhumation was promoted by a regional-scale change in the long-term mechanical coupling between the upper and lower plates (Figure 2b).

[27] On the basis of geological and geophysical evidence, we propose that the upward migration of oceanic fragments (though probably already fractured at depth) is normally inhibited and only occurs discontinuously as the subduction channel opens up. More data and modeling are now needed in order to understand what controls the opening of the subduction channel and to bridge the gap

Figure 2. (a) Sketch of an idealized subduction zone showing the major features of an oceanic subduction zone: usual depths of seismic coupling along the locked zone (40 ± 5 km) [Peacock and Hyndman, 1999], continuous slicing of the lithosphere, hydration of the mantle wedge and of the slab mantle, and possible underplating at the tip of the mantle wedge. Arc magmatism and the possible formation of an accretionary wedge are also indicated. Maximum depths (70–80 km) correspond to those beyond which oceanic lithosphere is never returned (see the worldwide compilation by Agard *et al.* [2009]). Abbreviations are as follows: AW, accretionary wedge; HSM, hydrated slab mantle; HMW, hydrated mantle wedge; OC, oceanic crust; UM, underplated material. (b) Schematic geodynamic model showing the transient exhumation of blueschists (mainly from depths around 30–35 km, in the Neotethyan case) as the subduction channel opens up in response to a major change in geodynamics, slab dip, mantle wedge hydration, or a combination of these. See text for details.



between the long-term and the seismic mechanical behavior of subduction zones.

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