GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G47717.1

Manuscript received 4 April 2020
Revised manuscript received 7 June 2020
Manuscript accepted 9 June 2020

The life cycle of subcontinental peridotites: From rifted continental margins to mountains via subduction processes

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ABSTRACT

Serpentinization greatly affects the physical and chemical properties of lithospheric mantle. Here we address the fate of serpentinized peridotites and their influence over an entire Wilson cycle. We document the near-surface journey of serpentinized subcontinental peridotites exhumed during rifting and continental breakup, reactivated as buoyant material during subduction, and ultimately emplaced as "ophiolite-like" fragments within orogenic belts. This life cycle is particularly well documented in former Tethys margins, where recent studies describe the ongoing incorporation of Mesozoic serpentinized subcontinental peridotites that diapirically rise from a subducting lower plate's mantle to be emplaced into the accretionary prism in front of a continental arc. This newly recognized mode of subduction-linked serpentine diapirism from the downgoing lithospheric slab is consistent with the origin of some exhumed serpentinized subcontinental peridotites in the Apennines (Italy), these assemblages reaching their present locations during Alpine orogenesis. Transfer of serpentinized subcontinental peridotites from the downgoing to the overriding plate motivates the concept of a potentially "leaky" subduction channel. Weak serpentine bodies may in fact rise into, preferentially migrate within, and eventually leave the intraplate shear zone, leading to strong lateral heterogeneities in its composition and mechanical strength.

INTRODUCTION

Serpentinized peridotites are weaker than other mantle rocks, with an internal friction coefficient, μ_I, of ~0.3 (versus ~0.6), and therefore commonly promote strain localization (Hirth and Guillot, 2013). Serpentinite is also considerably lower in density (ρ ~2.4–2.5 g/cm^3 for 100% serpentinized peridotites) than most rocks (Christensen, 2004). Its buoyancy can often mobilize upwelling masses and aid exhumation (Fryer, 2002). Serpentinized peridotites therefore influence the evolution of tectonic plate boundaries: their presence enhances shear processes, and serpentinite-hosted faults can evolve into zones of permanent lithospheric weakness to be reactivated during different tectonic phases. Fault reactivation also provides paths for fluid infiltration that can generate additional serpentinization (Deschamps et al., 2013) and the upward remobilization of serpentinized peridotites that diapirically interact with overlying rocks (Fryer, 1996; Guillot et al., 2001).

Serpentinized peridotites have long been proposed to control tectonic processes during rifting, continental breakup, and the development of an ocean basin (Pérez-Gussinyé et al., 2001). They also form and exhume at mid-ocean ridges (Cannat, 1993; Deschamps et al., 2013) and transform zones (Fryer, 2002). At the other end of the Wilson cycle, they can also play a significant role during subduction of the oceanic lithosphere and the evolution of orogenic belts (Guillot et al., 2001; Ranero et al., 2003; Deschamps et al., 2013). Previously, these roles have been assessed in the framework of each specific tectonic setting. Here we describe the evolution of exhumed subcontinental serpentinized peridotites (SPs) within a complete Wilson cycle.

EXHUMED SUBCONTINENTAL LITHOSPHERIC MANTLE DURING RIFTING AND CONTINENTAL BREAKUP

Widespread serpentinization and exhumation of subcontinental mantle rocks to the seafloor is commonly seen at magma-poor rifted margins. At the Iberian margin, geophysical images, ocean drilling, and submersible dives identified the Galicia Ridge (offshore western Spain), an uplifted partially serpentinized subcontinental peridotite, as the structure marking the ocean-continent transition (OCT) (Fig. 1A) (Boillot et al., 1995; Dean et al., 2000). Here serpentinization is correlated with crustal normal faults, implying that hydration of the upper mantle occurs during fault activity associated with crustal thinning (Pérez-Gussinyé et al., 2001; Bayrakci et al., 2016). Sheared and serpentinized mantle rocks crop out with basalt, mylonitized underplated gabbro, and upper continental crust rocks—the latter considered to rest on a detachment fault (Boillot et al., 1995). SPs are also locally overlain by a layer of brecciated serpentinites and intercalated with sedimentary rocks (Sawyer et al., 1994).

Seismic images in the Porcupine Basin (offshore western Ireland) suggest the occurrence of serpentinite bodies associated with crustal normal faults created during rifting (Watremez et al., 2018) (Fig. 1A). Finally, serpentinization also occurs at transform continental margins (Turner and Wilson, 2009).

Many of the above modern examples have been used to interpret fragments of exhumed subcontinental lithospheric mantle emplaced in orogenic belts (boxes B and D in Fig. 1A). In the region of the former Tethys, outcrops of SPs ornament both the internal and external domains of the Betic-Maghrebide (Rif-Kabylian, Morocco and Algeria) belt (Fig. 1A). In particular, the Beni Malek massif is regarded as a fossil analogue to the Galicia Ridge (Figs. 1B and 2A) incorporated in the thrust pile of the Iberia-Africa collisional belt (Michard et al., 1992). The Beni Malek massif is a 400-m-thick, 2-km-long lens of serpentinized spinel lherzolite.

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CITATION: Vannucchi, P., Morgan, J.P., Polonia, A., and Molli, G., 2020, The life cycle of subcontinental peridotites: From rifted continental margins to mountains via subduction processes: Geology, v. 48, p. 1154–1158, https://doi.org/10.1130/G47717.1

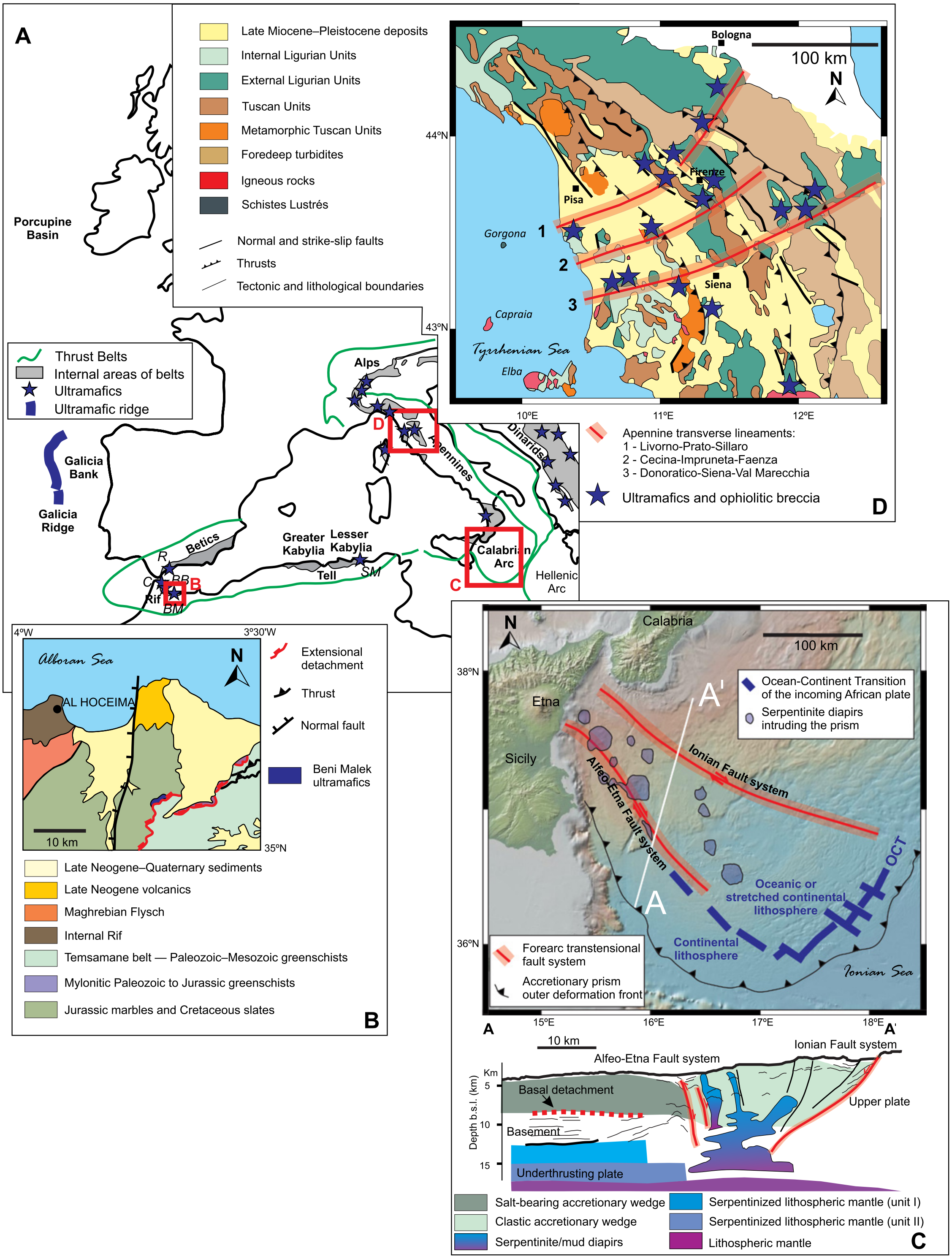

Figure 1. (A) Late Cenozoic tectonic framework of the western Mediterranean (modified from Royden and Faccenna, 2018). R—Ronda, C—Ceuta, BB—Beni Boussera, BM—Beni Malek, SM—Sidi Mohammed. (B) Simplified geological map of area surrounding the Beni Malek ultramafic massif in the Eastern Rif orogenic system (Morocco; modified from Azdimousa et al., 2019). (C) Cartoon cross section across the western Calabrian arc subduction complex (offshore southern Italy) shows tectonic setting and distribution of tectonically controlled serpentinite diapirs (modified from Polonia et al., 2017). Cross section is based on interpretation of multichannel seismic lines, and shows the margin structure where lithospheric transtensive faults trigger upwelling of serpentinite material from the lower plate. The presence of two distinct serpentinite units is taken from D'Alessandro et al. (2016). OCT—ocean-continent transition. (D) Simplified geological map of the southwestern portion of the northern Apennines showing its distribution of ophiolitic blocks and tectonic lineaments (modified from Nirta et al., 2007).

Vestiges of a foliation associated with a stretching lineation of lamellar orthopyroxene crystals have been interpreted to reflect early extensional deformation at mantle depths (Michard et al., 1992). Serpentinization is characterized by chrysotile, lizardite, and polygonal serpentine, with antigorite replacing chrysotile within shear zones (Vázquez et al., 2013). These serpentinite assemblages indicate the occurrence of low- to medium-grade metamorphism affecting previously cooled peridotites. The massif lies in stratigraphic contact with low- grade marine metasediment of Late Jurassic–Early Cretaceous age (ca. 160–140 Ma) (Michard et al., 1992; Vázquez et al., 2013). The absence of basalt and gabbro in the Beni Malek massif, except for limited reworked elements, suggests that significant extensional processes and serpentinization drove the exhumation of the subcontinental mantle peridotites to seafloor conditions (Fig. 2A). Exhumation occurred in the Late Jurassic–Early Cretaceous through normal faults that allowed seawater percolation while uplifting ultramafic footwall rocks.

REACTIVATION OF SUBCONTINENTAL MANTLE PERIDOTITES DURING SUBDUCTION

In subduction zones, uplifted and exhumed serpentinite peridotites are typically associated

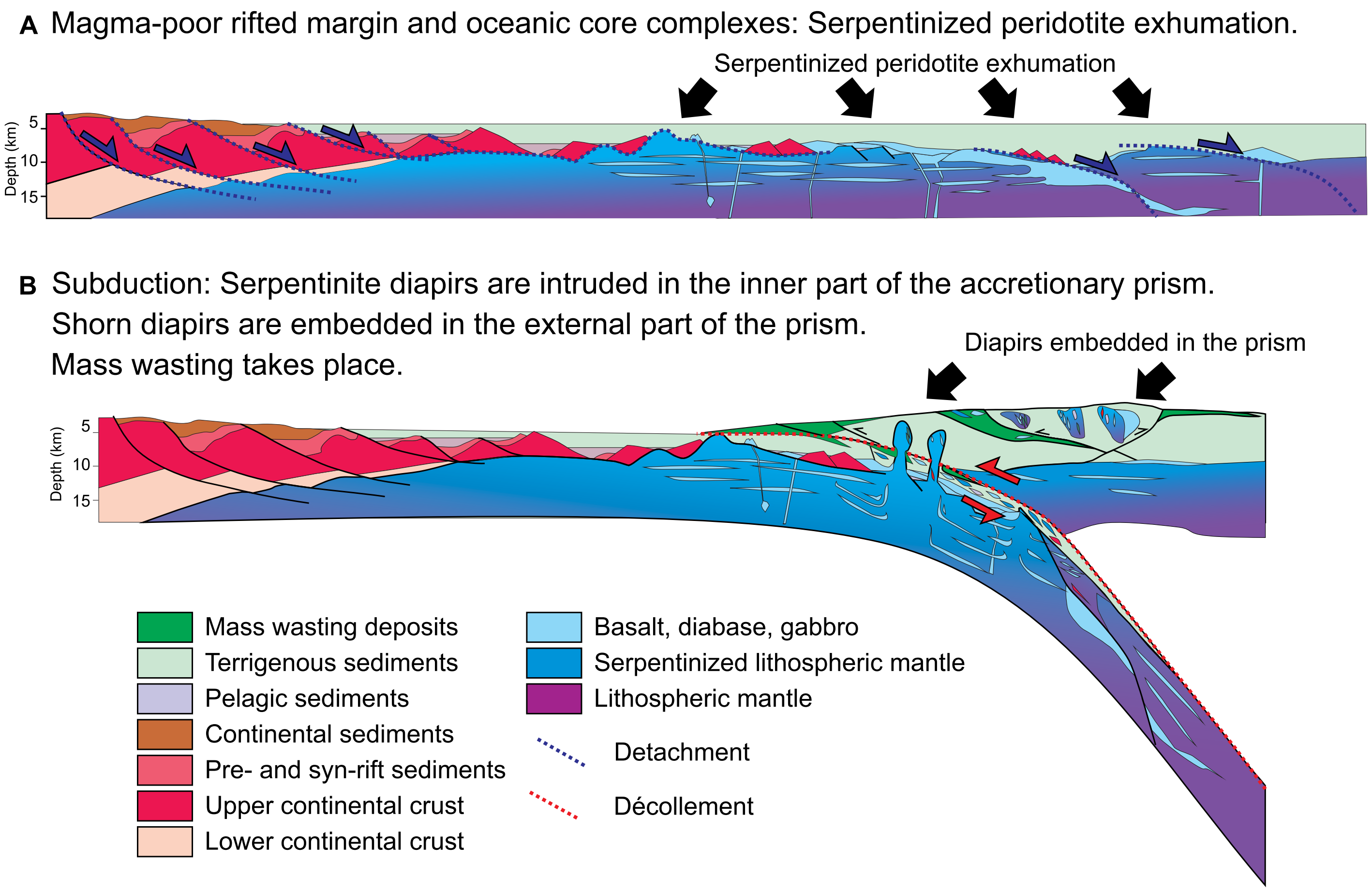

Figure 2. Model of structure and evolution of the exhumation and diapirism of serpentinized peridotites from rifting to subduction. (A) Evolved structure at magma-poor hyperextended margin, adapted from the Galicia margin example (offshore western Spain; modified from Boillot et al. 1995) and slow-spreading rifted margin environment reconstructed from the western Alps and Corsica for the western Tethys (modified from Lagabrielle et al., 2015). (B) Subduction complex with active emplacement of serpentinite diapirs in the inner forearc, embedded shorn diapiric masses in the external part of the prism, and possible mass wasting (marked as dark green units) that reworks some blocks, either as they are emplaced or post-emplacement.

with the serpentinite mud volcanoes that occur in the forearc of the Mariana Trench, interpreted to be a result of mantle wedge hydration caused by dewatering of the subducting slab, which leaves geochemical fingerprints (Fryer, 1996). Recently, a new category of serpentine diapirs has been identified in the forearc of the Calabrian arc (offshore southern Italy), where the African plate subducts beneath Eurasia (Fig. 1C) (Polonia et al., 2017). Here, geophysical data show buried subcircular diapiric structures aligned along major transtensional lithospheric faults (Polonia et al., 2017), the latter linked to slab rollback and responsible for the approximately northwest-southeast margin segmentation (Gutscher et al., 2016, and references therein). In contrast to the Mariana Trench example where the forearc is formed by igneous rocks of arc, ocean island, and ocean ridge affinity (Fryer, 1996), the Calabrian forearc has grown a 10–30-km-thick, 300-km-long accretionary prism in front of its continental lithosphere (Polonia et al., 2016). Diapirs are emplaced into the inner wedge of the accretionary prism in an area where only thin and discontinuous salt-bearing complexes were deposited during the Messinian salinity crisis (Polonia et al., 2016). Furthermore, deformation of deep reflectors associated with the diapirs suggests that their source lies well below the Messinian salt layer, even deeper than the décollement at the base of the prism. Their spatial correlation with positive magnetic anomalies and low heat flow implies that these diapirs correspond to partially serpentinized peridotites, with their Vp/Vs values implying serpentinization of as much as 68%–75% (Polonia et al., 2017).

The three-dimensional reconstruction of the Calabrian subduction interface beneath the inner accretionary wedge implies that the diapirs rose from a shallowly dipping slab (~4°) far from the mantle wedge that therefore cannot be the origin of these bodies (Neri et al., 2009). Instead, seismic-velocity models show that the subducting Ionian Sea lithosphere, pertaining to the Mesozoic Tethys (Dannowski et al., 2019), has been partially serpentinized (Polonia et al., 2017, and references therein). Its proximity to the African foreland suggests that the portion now subducting below the Calabrian arc could have formed part of the Tethyan OCT, with serpentinization inherited from Mesozoic crustal thinning (Polonia et al., 2017). As noted above, widespread SPs in the Betic-Maghrebide (Rif-Kabylian) belt support a view of the Tethys margin having been a magma-poor rifted margin with frequent exhumation of sublithospheric mantle.

Based on the geophysical characteristics and tectonic setting of the Calabrian arc diapirs, Polonia et al. (2017) interpreted that the diapirs are reactivated sublithospheric serpentinite peridotites of the incoming plate that were already exhumed near the seafloor and emplaced adjacent to continental crustal rocks during Tethyan rifting and breakup (Fig. 2B). The transfer of the SPs by recent/ongoing diapirism to the modern subduction-accretion system is facilitated along tear faults (Fig. 1C). These faults cut through the forearc as transtensional features, dissect the subducting Tethyan lithospheric slab, and displace the Tethyan OCT, suggesting that they are transform faults and fracture zone–like structures inherited from Tethyan rifting.

SHORN SERPENTINITE DIAPIRS INTERMIXED WITH UPPER PLATE SEDIMENTS DURING SUBDUCTION AND MOUNTAIN BUILDING

With this diverse suite of modes of serpentine reactivation in mind, we can also reassess the origin of several pervasive yet commonly enigmatic ophiolitic bodies that crop out in the northern Apennines (Fig. 1D). Here, ophiolitic blocks are embedded within the External Ligurian units, which consist of Upper Cretaceous–middle Eocene oceanic sediments deformed within an accretionary prism built during subduction of the Mesozoic western Tethys (Vannucchi and Bettelli, 2002). These ophiolitic blocks are mostly formed of Late Jurassic (Marroni et al., 1998; Nirta et al., 2007) serpentinites, gabbros, and basalts, both as massive and as brecciated masses with subordinate oceanic sediments. SPs are prevalent, followed by basalt. Outcrop areas of single blocks can reach ~0.3 km^2. These ophiolitic blocks are in some cases associated with older lower and upper continental crust rocks, i.e., Paleozoic mafic and felsic granulites and granitoids (Marroni et al., 1998). The peridotites are predominantly fertile spinel lherzolites representative of subcontinental mantle lithosphere exhumed during the Jurassic rifting phase of the western Tethys (Rampone et al., 1995), while basalts are typically of the type inferred to be produced by limited and relatively deep (garnet residual phase) partial melting from a depleted MORB mantle source (Saccani et al., 2015). Petrologic, stratigraphic, and structural data imply that these blocks are derived from a broad (>150 km) OCT domain where exhumation to the seafloor of subcontinental mantle and lower crust occurred in the framework of a magma-poor rifted margin (Marroni et al., 1998). The western Tethys ocean floor was also characterized by extensive exposure of mantle ultramafics with minor effusive magmas indicative of a slow-spreading ridge environment (Fig. 2A) (Lagabrielle and Cannat, 1990), combined with transform fault zones (Abbate et al., 1980). The resulting scenario, with its highly irregular continental margins and rough ocean floor relief, has led to interpretations of the emplacement of these blocks as a byproduct of mass wasting within the accretionary wedge from reactivated fault scarps, thrust fronts, or backthrust systems (Marroni et al., 2002). However, the ophiolitic blocks in the External Ligurian units of the southwestern portion of the northern Apennines rarely preserve stratigraphic relationships with their embedding sediments. Where preserved, these blocks characterize the upper boundary, while the lower boundary is usually faulted (Nirta et al., 2005, and references therein). Moreover, in the southwestern portion of the northern Apennines, ophiolitic blocks crop out along well-defined tectonic lineaments that orthogonally cut the entire Apennine orogenic pile from the Tyrrhenian to the Adriatic Sea (Fig. 1D) (Nirta et al., 2007). These transverse tectonic lineaments appear to have been long-lived lithospheric discontinuities: in the Late Cretaceous, they accommodated the early Apennine convergence by transpression (Nirta et al., 2007); in the Neogene, they controlled the lateral non-cylindricity of the thrust system as well as the segmentation of the sedimentary basins in the Tyrrhenian side of the northern Apennines (Fazzini and Gelmini, 1984; Rosenbaum and Agostinetti, 2015). Like the Alfeo-Etna fault system of the Calabrian arc, these lineaments have been interpreted as Mesozoic structures of the passive continental margin that were reactivated during subduction rollback of the Adriatic-Ionian lithosphere (Royden et al., 1987).

In this scenario, during the early phase of subduction in the southwestern portion of the northern Apennines, the External Ligurian units' accretionary prism could have been intruded by buoyant SPs present on the subducting slab in a mode similar to the modern Calabrian arc situation. Progressive convergence would then have detached the diapirs from their feeding system, leaving them as unrooted blocks of debris (Fig. 2B). Associated steepening of the slab could then have promoted further gravitational instability of the prism with additional mass wasting.

CONCLUSIONS

Serpentinized subcontinental peridotites are known to be uplifted and exhumed to the seafloor during rifting and continental breakup (Fig. 2A). When exhumed SPs subduct, they can be reactivated as diapirs that intrude into the overlying forearc, which is later involved in mountain building processes (Fig. 2B). In this way, SPs can evolve across the diverse tectonic environments that form within the Wilson cycle of a passive continental margin, creating echoes in their rheological and geochemical processes. While here we show well-preserved Tethyan examples, these processes should apply to all margins that form during continental rifting.

This proposed life cycle of SPs provides an alternative explanation as to why the ophiolitic rocks found within fossil accretionary prisms are mostly represented by serpentinite and subordinate basalt, very rarely comprising gabbro and sheeted dikes, and also why these rocks typically have such a wide range of ages and origins (Wakabayashi and Dilek, 2003). In particular, the peridotites and basaltic rocks found in subduction/collisional complexes need not be solely the byproduct of the offscraped tops of subducting seamounts or mass wasting into an oceanic basin.

Finally, dynamic and fluid-flow models of a supra-subduction environment should account for the potential reactivation of SPs from the downgoing plate. This process may be especially frequent during early collisional phases when subduction is thought to be primarily driven by negative buoyancy of the lithospheric slab (Royden and Faccenna, 2018). In this environment, subduction channels have the potential to be "leaky", with downgoing plate material both rising through the channel into the overriding plate and migrating into and along the channel itself. This would induce sudden lateral changes in the subduction channel's composition, rheology, and seismic characteristics.

ACKNOWLEDGMENTS

We thank E. Bonatti, J. Duarte, K. Hattori, M. Godard, and two anonymous reviewers for their insightful comments on previous versions of the paper.

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Printed in USA