Geochemistry, Geophysics, Geosystems

AGU ADVANCING EARTH AND SPACE SCIENCE

RESEARCH ARTICLE
10.1029/2020GC009482

Key Points:

- We review insights from observational and numerical modeling studies on plume-induced sinking of lithospheric mantle
- Plume-induced mantle downthrusting within continental interiors and at their rims appears to be much more common than hitherto assumed
- Plausible consequences of intra-continental mantle sinking for the operation of plate tectonics require further investigation

Supporting Information:

- Supporting Information S1

Correspondence to:
S. Cloetingh,
s.a.p.l.cloetingh@uu.nl

Citation:
Cloetingh, S., Koptev, A., Kovács, I., Gerya, T., Beniest, A., Willingshofer, E., et al. (2021). Plume-induced sinking of intra-continental lithospheric mantle: An overlooked mechanism of subduction initiation?. *Geochemistry, Geophysics, Geosystems*, *22*, e2020GC009482. https://doi.org/10.1029/2020GC009482

Received 22 OCT 2020
Accepted 26 DEC 2020

Plume-Induced Sinking of Intracontinental Lithospheric Mantle: An Overlooked Mechanism of Subduction Initiation?

Sierd Cloetingh[1], Alexander Koptev[2], István Kovács[3,4], Taras Gerya[5], Anouk Beniest[6,7], Ernst Willingshofer[1], Todd A. Ehlers[2], Nevena Andrić-Tomašević[2], Svetlana Botsyun[2], Paul R. Eizenhöfer[2], Thomas François[8], and Fred Beekman[1]

[1]Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands, [2]Department of Geosciences, University of Tübingen, Tübingen, Germany, [3]MTA EK Lendület Pannon LitH2Oscope Research Group, Budapest, Hungary, [4]CSFK Geodetic and Geophysical Institute, Sopron, Hungary, [5]Department of Earth Sciences, Institute of Geophysics, ETH-Zurich, Zurich, Switzerland, [6]GEOMAR, Helmholtz Centre for Ocean Research, Kiel, Germany, [7]Department of Geosciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, [8]GEOPS, Université Paris-Sud, CNRS, Université Paris-Saclay, Orsay, France

Abstract Although many different mechanisms for subduction initiation have been proposed, only few of them are viable in terms of consistency with observations and reproducibility in numerical experiments. In particular, it has recently been demonstrated that intra-oceanic subduction triggered by an upwelling mantle plume could greatly contribute to the onset and operation of plate tectonics in the early and, to a lesser degree, modern Earth. On the contrary, the initiation of intra-continental subduction still remains underappreciated. Here we provide an overview of 1) observational evidence for upwelling of hot mantle material flanked by downgoing proto-slabs of sinking continental mantle lithosphere, and 2) previously published and new numerical models of plume-induced subduction initiation. Numerical modeling shows that under the condition of a sufficiently thick (>100 km) continental plate, incipient downthrusting at the level of the lowermost lithospheric mantle can be triggered by plume anomalies of moderate temperatures and without significant strain- and/or melt-related weakening of overlying rocks. This finding is in contrast with the requirements for plume-induced subduction initiation within oceanic or thinner continental lithosphere. As a result, plume-lithosphere interactions within continental interiors of Paleozoic-Proterozoic-(Archean) platforms are the least demanding (and thus potentially very common) mechanism for initiation of subduction-like foundering in the Phanerozoic Earth. Our findings are supported by a growing body of new geophysical data collected in various intra-continental areas. A better understanding of the role of intra-continental mantle downthrusting and foundering in global plate tectonics and, particularly, in the initiation of "classic" ocean-continent subduction will benefit from more detailed follow-up investigations.

Plain Language Summary Subduction zones, areas where tectonic plates sink into the Earth mantle, are a vital component of the plate tectonic cycle and result in the opening and closure of oceans over geologic time. Despite major advances in the study of plate tectonics and geodynamics during the last decades, the causes for triggering subduction are still not well understood. In this paper, we review observations and insights from geodynamic models and show that upwelling inside the mantle (i.e., "mantle plumes or hot spots") offer a viable mechanism that takes lithospheric plates back into the deep mantle, thus initiating subduction. However, subduction initiated by mantle plumes within oceanic tectonic plates has rarely been observed in the Phanerozoic history of Earth (541-0 Ma). In contrast, thick and old continental segments of tectonic plates appear to provide optimal conditions for their participation in plume-induced sinking (subduction) into the interior of modern Earth in a mode detectable by geophysical imaging in different regions (Europe, Asia, North America). The role of such intra-continental mantle sinking in global plate tectonics warrants thorough further examination in forthcoming studies.

10.1029/2020GC009482

1. Introduction

Since the acceptance of the theory of plate tectonics, the subduction process is recognized as a first-order element in the Wilson cycle driving the opening and closure of oceanic basins (Bercovici, 2003; Turcotte & Schubert, 2014; Wilson, 1966). The onset (or initiation) of new subduction zones remains, however, in many aspects an enigma either because of a general lack of direct observations indicating its present-day manifestation or a limited record for past subduction initiation events (Crameri et al., 2020). As a result, possibilities for combining modeling and natural observations to better understand this crucial process are rather limited (see for a review Stern & Gerya (2018) and references therein).

From a traditional plate tectonics perspective (Dewey et al., 1973; Wilson, 1966), ocean-continent transitions at passive margins–like those around the Atlantic Ocean, western Indian Ocean, or Gulf of Mexico—are viewed as the primary sites for subduction initiation. Here, the negative buoyancy of sufficiently old and cold oceanic lithosphere is considered the main reason for the onset of subduction (Davies, 1999; Vlaar & Wortel, 1976). However, the simultaneous increase of lithospheric strength with cooling has been shown to be a considerable obstacle for continental margin collapse (Cloetingh et al, 1982, 1989; Mueller & Phillips, 1991). Strikingly, even though off-ridge oceanic lithosphere and offshore passive margins around the Atlantic Ocean have been subjected to continued ridge-push stress, amplified by sediment loading (Cloetingh et al, 1982, 1984; Regenauer-Lieb et al., 2001) and additional forcing of adjacent continental topography (Marques et al., 2013; Pascal & Cloetingh, 2009), initiation of oceanic lithosphere subduction has not commenced yet. This observation is in line with findings that although tectonic inversion of rifted continental Atlantic-type margins has been widely documented in various opening oceans (Johnson et al., 2008; Lundin & Doré, 2002; Lundin et al., 2013; Vågnes et al., 1998), none of these margins has yet developed into an actual phase of subduction initiation.

Spontaneous collapse along a passive continental margin appears thus to be rare in nature, and most of the recent subduction initiation events are intra-oceanic (e.g., Crameri et al., 2020; Gurnis et al., 2004). In fact, not a single passive margin has actually been converted into an active one during Cenozoic times (e.g., Gurnis et al., 2004). In addition, this process is difficult to reproduce in numerical models, because when adopting realistic parameters for continental crustal and lithospheric thicknesses these preferentially simulate the stable margin mode (see Nikolaeva et al., 2010). As a result, many different alternative scenarios for subduction initiation have been proposed (Stern & Gerya, 2018; and references therein). Most of them are applicable to "classic" ocean-continent subduction or intra-oceanic environments, whereas intra-continental settings are explored relatively scantily in the context of the subduction-like behavior of the mantle lithosphere. With this perspective in mind, we aim to complement previous summaries of subduction initiation processes limited to intra-oceanic and ocean-continent tectonic settings (e.g., Crameri et al., 2020; Gurnis et al., 2004; Stern, 2004; Stern & Gerya, 2018) by providing a closer look into intra-continental environments and analyzing the nature of downthrusting of continental mantle and its subduction-like sinking (or foundering) which could potentially further evolve into a fully established plate-scale subduction of the entire lithosphere (i.e., crust plus mantle lithosphere). This leads us toward a better understanding of lithosphere-scale mechanisms controlling the initiation of this process which, so far, has been overlooked within intra-continental regions on Earth.

We first provide a brief summary of known scenarios of subduction initiation within ocean-continent and intra-oceanic tectonic settings with a particular focus on plume-induced foundering of the lithospheric mantle in order to take into account the possibility that such a mechanism might also be viable in intra-continental settings. We then review observational evidence for intra-continental anomalous mantle structures, which can be interpreted as potential sites where sinking of continental lithosphere has been initiated due to the upwelling of hot mantle material during Cenozoic and recent times. Finally, we compare these data with conclusions drawn from previously published, and newly performed numerical models specifically examining whether the interaction of upper mantle thermal instabilities with the overlying continental lithosphere could provide a reasonable scenario for mantle downthrusting/foundering. We conclude that the onset of large-scale and long-lived sinking of the lowermost lithospheric mantle is likely to be common in continental interiors of Paleozoic-Archean platforms and/or their rims. According to numerical studies, this process does not require any ad hoc assumptions such as preexisting weak zones, external tectonic forcing, extremely positive buoyancy (compositional and/or thermal) of the plume, or an unrealistic reduction of strength of the lithosphere. Its potential role for the initiation of "classic" ocean-continent (i.e., active continental margin) subduction, however, still remains unexplored.

2. Subduction Initiation: A Survey of Mechanisms and Scenarios

2.1. Ocean-Continent Subduction

Passive margin collapse is traditionally thought to be the primary mechanism of subduction initiation due to the aging and increasing negative buoyancy of the oceanic lithosphere. In search of physically sound parameter combinations that would lead to such gravitational instabilities, analog and numerical modeling studies have systematically explored the role of density and strength, and variations thereof (e.g., Auzemery et al., 2020; Faccenna et al., 1999; Goren et al, 2008; Marques et al., 2013; Mart et al., 2005; Nikolaeva et al., 2011, 2010). Nikolaeva et al. (2010) have demonstrated that in the absence of preexisting weak zones spontaneous subduction initiation at a passive margin only occurs when chemically buoyant (depleted) continental lithosphere is anomalously thin and hot. From this point of view, the high heat flow area of the southern Brazilian Atlantic margin (in addition subjected to significant gravitational forcing from high topography—see Marques et al., 2013) is arguably the only viable candidate where subduction initiation is to be expected, whereas other continental margins will remain stable under present-day geodynamic conditions since strengthening of the oceanic plate precludes a gravitationally driven collapse (Nikolaeva et al., 2011).

Apart from this "traditional" (but apparently not viable) mechanism for subduction initiation, at least five other scenarios (directly or indirectly implying pre-existing subduction activity) are thought to trigger subduction in a "classic" ocean-continent context:

1) Subduction initiation induced by suction flow: according to thermo-mechanical numerical modeling by Baes and Sobolev (2017), passive margins (e.g., the western Atlantic) transform into an active ocean-continent convergent boundary when additional forces from mantle flow induced by neighboring subduction zones (e.g., Cascadia and Andean) are present. This mechanism also applies to subduction initiation in an intra-oceanic environment (Baes et al., 2018).
2) Subduction polarity reversal, that is, a change of subduction zone dip when the subducting and overriding plates exchange roles (Stern, 2004). This may occur when buoyant crust (intra-oceanic arc or plateau) of an already subducting plate enters the trench. The natural example of such transition from intra-oceanic to ocean-continent subduction has been detected along Taiwan where break-off of the originally south-dipping Eurasian oceanic slab was likely followed by switching of subduction polarity with establishing the north-dipping subduction of the Philippine Sea plate under the Eurasian continent (Teng et al., 2000). Two other most commonly cited natural examples of this process—the Solomon arc (SW Pacific), which is a result of Miocene collision with the Ontong-Java Plateau (Cooper & Taylor, 1985; Petterson et al., 1999), and the Eastern European Alps, where the downgoing slab reversed from southward to northward during Adria-Europe collision (Handy et al., 2015; Lippitsch et al., 2003) – correspond to a switch of subduction polarity within an intra-oceanic and intra-continental environment, respectively. The NW margin of the India-Asia collision zone (e.g., the Pamir Mountains region) might be another example of intra-continental subduction polarity reversal (Kufner et al., 2016). In numerical experiments, subduction polarity reversals have been reproduced only for intra-continental (Baes et al., 2011b; Faccenda et al., 2008; Pysklywec, 2001) and intra-oceanic (Crameri & Tackley, 2015) collision scenarios, whereas arc-continent collision settings remain to be explored in future studies (Stern & Gerya, 2018).
3) Subduction zone transference (also called "back-stepping of subduction"; Kerr, 2003): when a buoyant crustal block enters the trench, subduction halts locally. However, convergence continues due to the initiation of a new subduction zone with the same dipping direction somewhere else. The new site of subduction is thus transferred away from the collision site, e.g. along-strike of the convergent plate (Stern, 2004). This is another example of subduction initiation due to continued plate convergence that was conceived for ocean-continent interactions. However, the only confirmed natural example of this type of subduction initiation is the Mussau Trench in the Western Pacific that developed within an intra-oceanic setting in response to the collision of the Caroline Ridge with the Yap Trench (Lee, 2004). No single ocean-continent subduction zone has been initiated in Cenozoic times through subduction

10.1029/2020GC009482

zone transference (e.g., the continued collision between India and Eurasia since ∼50 Ma did not develop any new subduction zone along the southern passive margin). This process is also poorly explored by numerical modeling (Stern & Gerya, 2018), which usually reproduces the oceanward trench jumps over continued subduction (Tetreault & Buiter, 2012; Vogt & Gerya, 2014) rather than producing true subduction zone transference scenarios.

4) Compression-induced subduction initiation along inherited weak zones at the edge of a slab (i.e., along so called STEP—Subduction-Transform Edge Propagator—faults; see Govers & Wortel, 2005): coupled thermo-mechanical models by Baes et al. (2011a) postulate that STEP fault-perpendicular convergence leads to the formation of a shear zone dipping toward the continent that has the potential to evolve into a new subduction boundary. According to Baes et al. (2011a), incipient subduction appears to be more feasible for younger oceanic lithosphere due to its lower flexural rigidity. This is in line with previous findings by Cloetingh et al. (1989) on the growing strength of the lithosphere preventing a collapse at a passive margin if the adjacent oceanic plate is older than 20 Ma. In nature, present-day subduction initiation at STEP faults is attributed to the south Tyrrhenian region (Billi et al., 2007; Carminati et al., 1998; Zitellini et al., 2020). Moreover, incipient subduction processes are likely to be expected in future along the following prominent STEP boundaries: 1) the southern end of the New Hebrides subduction zone and the northern end of the Tonga subduction zone (Govers & Wortel, 2005); 2) the northern and southern ends of the Lesser Antilles trench (Wright & Wyld, 2011); and 3) both sides of the Atlantic slab subducting beneath the Scotia plate in the SW Atlantic Ocean (Dalziel et al., 2013; Giner-Robles et al., 2003).
5) Subduction propagation, that is, lateral transmission of subducting plate boundaries from pre-existing intra-oceanic convergent zones along continental margins (reproduced in a recent numerical study by Zhou et al., 2020). Strong slab pull combined with inherent weaknesses at an adjacent passive margin resulted in subduction propagation in multiple regions as 1) demonstrated in a numerical study for the Western Mediterranean (Chertova et al., 2014), 2) derived from the tectonic evolution of the Indonesia subduction zone in the Banda region (Hall, 2012) and Nazca subduction along the Andes (Chen et al., 2019), and 3) is to be expected north of the Lesser Antilles subduction zone (Zhou et al., 2020). In the intra-oceanic setting, a similar scenario of subduction propagation from the point of subduction nucleation along inherent lithospheric weakness was also proposed almost 3 decades ago for the Izu-Bonin-Mariana arc system in the Western Pacific (Stern & Bloomer, 1992). Subduction propagation due to stress transfer from a nearby convergent region along inherited lithospheric weak zones could be closely related to (and even in certain cases undistinguishable from) a *direct migration of subduction zones* (i.e., slab rollback) that likely leads to convergent margins invading an ocean basin as, for example, observed near the Scotia, Lesser-Antilles and Gibraltar arcs (Duarte et al., 2018). Actually, a new subduction zone at the SW margin of Iberia has been proposed to form as a result of the combined impact of 1) an "invasion process" (Duarte et al., 2013) related to the migration of the Gibraltar Arc (Gutscher et al., 2002) and 2) the Africa-Eurasia convergence (Kherroubi et al., 2009), potentially accompanied by 3) the *delamination of oceanic lithosphere* due to internal weakness in serpentinized upper mantle (Duarte et al., 2019). However, interpretations that the Gibraltar Arc is a subducting plate boundary are controversial (e.g., Platt et al., 2003, 2013).

2.2. Ocean-Ocean Subduction

Traditionally, subduction scenarios presume convergence between oceanic and continental lithospheres, but most young subduction zones (i.e., formed in the last 65 Ma) are of intra-oceanic origin (Gurnis et al., 2004). For the initiation of ocean-ocean subduction, four main mechanisms have so far been proposed:

1) Compression-induced conversion of a preexisting fault into subduction (Maffione et al., 2015; Toth & Gurnis, 1998): a weak zone turns into a subduction zone in response to plate motion acceleration (Agard et al., 2007) possibly caused by the push from (super)plumes (Jolivet et al., 2016).
2) Inversion of a spreading ridge (Beaussier et al., 2019; Duretz et al., 2016; Gülcher et al., 2019): intra-oceanic subduction initiated under external compressive forces at or near an intra-oceanic divergent plate margin. A possible example is the Oman ophiolite complex, for which prior to its obduction, intra-oceanic subduction initiated at the locus of the actively spreading Neotethyan ridge in the Late Cretaceous (Agard et al., 2016; Duretz et al., 2016).

3) Collapse of oceanic transform faults, that is, subduction initiation due to a localized lateral buoyancy contrast between juxtaposed oceanic plates of different cooling ages. This concept has been thoroughly investigated and successfully reproduced in numerical (Dymkova & Gerya, 2013; Gerya et al., 2008; Hall et al., 2003; Matsumoto & Tomoda, 1983; Nikolaeva et al., 2008; Zhu et al., 2009) and analog (Boutelier & Beckett, 2018) modeling studies. A proverbial example of oceanic transform fault collapse is the formation of the Izu-Bonin-Mariana subduction zone (Brandl et al., 2017; Stern & Bloomer, 1992) where melt composition changes from MORB-like toleiites to boninites, reflecting an increase in the fluids derived from the sinking slab during the progression of subduction initiation (Reagan et al., 2017). Such a magmatic change, generalized to the "Subduction Initiation Rule" (Whattam & Stern, 2011), has been recently reproduced in geodynamic-petrogenetic models (Leng et al., 2012).
4) Plume-induced subduction initiation involves a sufficiently large and hot plume head that can rupture the overriding plate and flow atop of its broken part, thus providing self-sustained subduction in the adjacent part of the oceanic lithosphere (Ueda et al., 2008; Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b). Originally, given a lack of known present-day analogs, significant weakening of the lithosphere caused by upward migration of the melts extracted from the plume was not thought to be feasible in the Phanerozoic Earth, limiting the applicability of this mechanism to the hotter Archean lithosphere and circular corona structures on Venus (Gerya et al., 2015; Gülcher et al., 2020; Ueda et al., 2008). However, Whattam and Stern (2015) recently provided compelling evidence for plume-induced subduction initiation along the southern margin of the Caribbean and northwestern South America in the Late Cretaceous, thus inspiring new numerical studies to explore this mechanism in the context of modern Earth as well (Baes et al., 2016, 2020a, 2020b).

2.3. Continent-Continent Subduction

Plume-induced subduction initiation within oceanic lithosphere has received significant attention in modern geodynamic research (Ueda et al., 2008; Gerya et al., 2015; Lu et al., 2015; Baes et al., 2016, 2020a, 2020b) unlike a paucity of studies in continental settings. Since the studies by Burov & Cloetingh (2009, 2010), no new attempts have been made to investigate plume-lithosphere interaction as the driving mechanism for subduction-like downward movements of the continental lithosphere. This is still the case despite a growing body of robust geophysical data, including observations from seismic tomography and magneto-telluric sounding in areas such as the Caucasus (Ismail-Zadeh et al., 2020; Koulakov et al., 2012; Zabelina et al., 2016); Central Asia (He & Santosh, 2018); North-East China (Kuritani et al., 2019; Li et al., 2020; Wang et al., 2018; Zhang, 2012); Iberia and its margins (Civiero et al., 2019); the Carpathians (e.g., Wortel & Spakman, 2000; Koulakov et al., 2010; Ismail-Zadeh et al., 2012; Ádám et al., 2017; Petrescu et al., 2019), and the Colorado Plateau (Levander et al., 2011) where upwelling of hot mantle material flanked by downgoing slabs of sinking mantle lithosphere has been recently documented. This makes *plume-induced intra-continental mantle sinking/foundering* a viable and testable mechanism, deserving detailed investigation by means of both modeling and critical analysis of pertinent observations.

3. Joint Occurrence of Upper Mantle Upwelling and Simultaneous Sinking/Foundering of Continental Lithosphere: Observational Evidence

Extensive observational evidence has been reported for deep-rooted mantle upwelling expressed by negative anomalies in seismic velocity and apparent resistivity. In many cases, these deep-rooted upwellings appear to trigger subduction-like sinking of the lower lithospheric mantle manifested in positive seismic velocity and resistivity anomalies, leaving, however, the shallower part of the lithosphere tectonically undisturbed.

A compelling example is given by a ~NNW-SSE oriented seismic cross-section from the Scythian to the Arabian plate through the Caucasus Mountains (Figure 1a; Ismail-Zadeh et al., 2020; see also Koulakov et al., 2012). Beneath the mountain belt, a significant negative seismic velocity anomaly (up to 3%) rooted at depths of ~400 km is interpreted as a zone of hot mantle upwelling/plume emplacement. At the southern and northern flanks of the head of this mantle plume, subduction-like sinking/foundering of mantle lithosphere (high velocity zones) is detected to depths of ~200–300 km. Delaminated lithospheric remnants at deeper levels (~400–500 km) provide evidence for proto-slab(s) break-off/detachment.

10.1029/2020GC009482

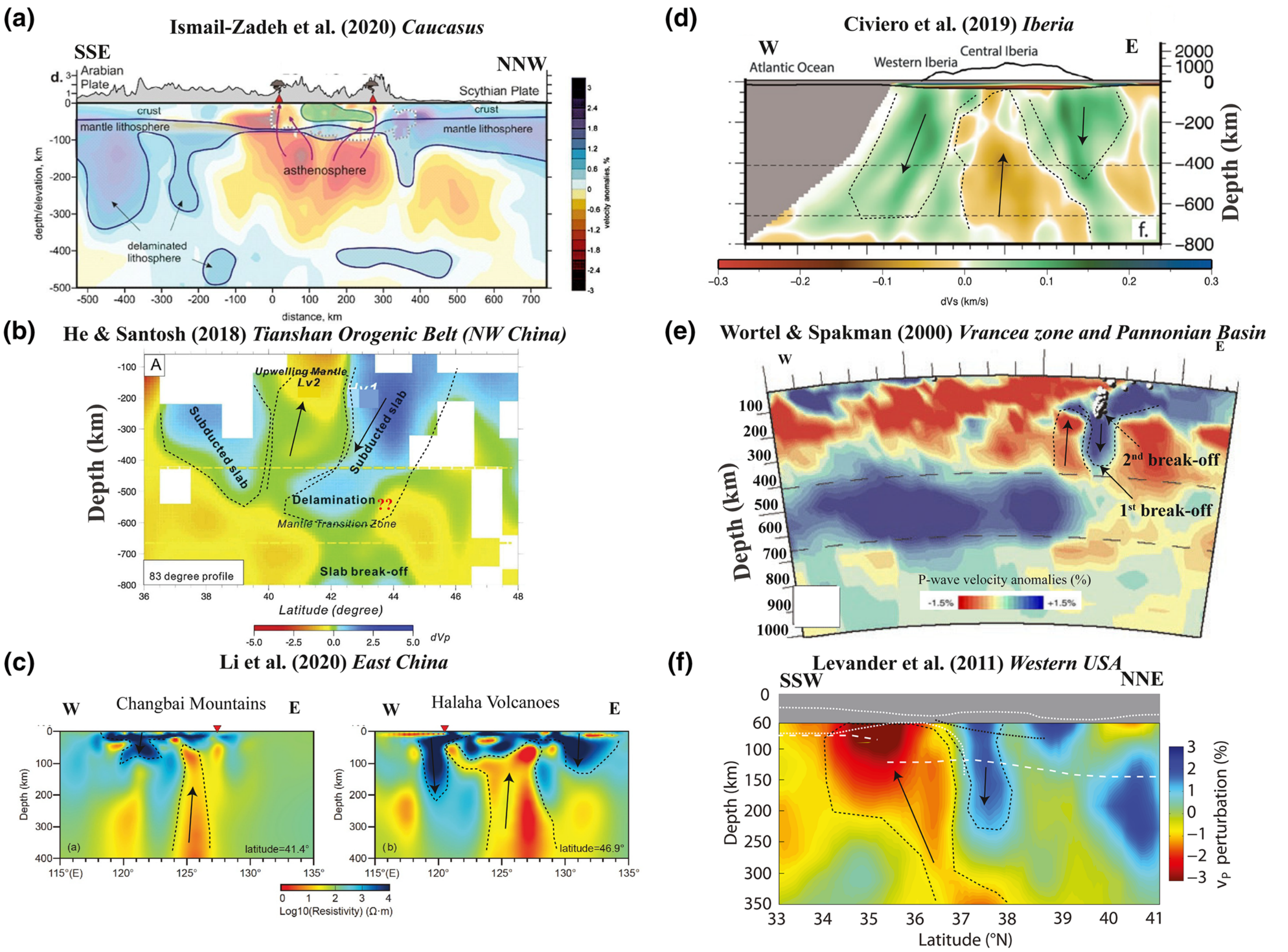

Figure 1. Examples of intra-continental settings with observational evidence for plume-induced sinking/foundering of lithospheric mantle. (a) Combined results of regional and local tomography and interpretation of the Caucasus area. Blue patterns correspond to parts of the mantle lithosphere; green pattern represents the rigid block in the Transcaucasian region. Arrows indicate possible paths of feeding volcanic centers in the Lesser Caucasus and Greater Caucasus belts. Red colors mark areas of upper mantle upwelling rooted at the top of mantle transition zone (Ismail-Zadeh et al., 2020). (b) Tomographic slice parallel to the 83 longitude from the Tibetan Plateau, through the Tianshan orogenic belt to the Junggar Basin (He & Santosh, 2018). (c) Results from magneto-telluric imaging in North-East China. Two cross-sections parallel to the 41.1° (left) and 46.9° (right) latitudes demonstrate deep origins of Cenozoic volcanism (Changbai and Halaha, respectively) as well as downwelling of continental lithosphere in surrounding areas (Li et al., 2020). (d) Seismic tomography below the Iberian Peninsula and its Atlantic passive margin, illustrating subvertical low-velocity upper mantle structure flanked by two zones of positive anomalies (Civiero et al., 2019). (e) Regional tomographic cross-section through the Pannonian Basin/Carpathians arc system showing a wide area with low upper mantle velocities below the Neogene back-arc basin and a slab-like high-velocity body below the arc (Wortel & Spakman, 2000). (f) Seismic tomography beneath the Colorado Plateau revealing a high-velocity downwelling body extending to ~200–250 km depth and adjacent deep-seated low-velocity zone representing plume-like upwelling of upper mantle material (Levander et al., 2011).

A suite of NS and EW oriented seismic profiles across the Chinese Tianshan and the Tarim Basin in western China (He & Santosh, 2018) revealed two positive velocity anomalies dipping in opposite NS directions (Figure 1b). These have been interpreted as remnant slabs, that is, the northward and southward subducted lithosphere of the Tarim and Junggar basins, respectively, reaching depths of ~400 km (see also Koulakov, 2011; Sychev et al., 2018). A shallow (~100–200 km) negative velocity anomaly located beneath the boundary between the Tianshan and the Tarim Basin is thought to reflect upwelling mantle material responsible for extensive magmatism in the region, while the positive velocity anomaly at ~500 km depth beneath the Tianshan may represent delaminated material (He & Santosh, 2018). However, given the well-recorded and prolonged subduction of the Junggar Ocean since the Cambrian (Han et al., 2016; Han & Zhao, 2018), this deep-seated positive anomaly may also be interpreted as the southward continuation of the

Junggar basin lithosphere. Hence, mantle upwelling beneath the Tianshan may have promoted foundering of the Tarim and Junggar continental lithospheres.

Figure 1c shows the results of a magnetotelluric study of North-East China (Li et al., 2020) for two E-W oriented cross-sections through the Changbai and Halaha volcanic areas (left and right sections, respectively). In the centers of both sections, deep-rooted (>400 km) negative resistivity anomalies are visible. Along the Halaha volcano section, the low resistivity zone is flanked by two high resistivity bodies at both the western and eastern sides reaching depths of ∼200 km. On the Changbai volcano section, only one relatively small and shallow (to a depth of ∼100 km) positive resistivity anomaly is observed on the western side of the low resistivity area. The latter can be interpreted as an upwelling mantle plume, whereas high resistivity zones along its edges mark the downward movements of continental lithospheric mantle.

An E-W oriented seismic transect through the center of the Iberian Peninsula and the adjacent passive margin of the Atlantic Ocean clearly displays a negative seismic velocity anomaly under the high intraplate topography of Central Iberia flanked by high velocity bodies on its western and eastern sides (Figure 1d; Civiero et al., 2019). Negative seismic velocity anomalies beneath the Pannonian Basin and a positive velocity anomaly beneath the Carpathian belt at the Vrancea zone are clearly expressed in a seismic tomography profile from the Eastern Alps to the Black Sea (Figure 1e, Wortel & Spakman, 2000). This suggests that mantle upwelling beneath the Pannonian Basin marked by high heat flow (Lenkey et al., 2002) might have played a key role in the detachment/delamination of the Vrancea slab. Although the existence of thermally induced upwelling beneath the Pannonian Basin has been challenged by some recent studies (Harangi et al., 2015; Harangi & Lenkey, 2007), the presence of hydrous plumes from the mantle transition zone (see below) may offer a viable alternative (Kovács et al., 2020).

Figure 1f shows the results of a NNE-SSW oriented seismic cross-section through the Colorado Plateau from the Basin and Range to the Rocky Mountains (Levander et al., 2011) with a sub-vertically aligned narrow high-velocity body extending to ∼200–250 km depth. At the SSW-end, this high velocity body is edged by a slow velocity zone, which reaches considerably deeper levels in the upper mantle (>350 km). In our view, mantle upwelling has probably contributed to the weakening and subsequent foundering of the lower part of the continental lithosphere beneath the Colorado Plateau.

In summary, in several areas in Eurasia (Caucasus, Central Asia, North-East China, Iberia, Central Europe), and North America (Colorado Plateau) subduction-like sinking/foundering of continental lithosphere is associated with upwelling of hot mantle material (see Figure 1). These upwellings are likely to contribute significantly to the weakening and subsequent sinking of the lower continental lithosphere. It is important to note that relatively narrow high velocity (and apparent resistivity) bodies usually extend not deeper than neighboring, deep-rooted low velocity and resistivity anomalies. Therefore, it appears that upper mantle instabilities actually precede initiation of foundering of continental lithosphere instead of the other way around (except of possibly the example of the Pannonian Basin/Carpathian arc system—see below). Another striking feature of these sites is that plumes affect mostly the deep to middle lithospheric mantle and generate only moderate extension of the crust and slightly elevated heat flow at the surface.

While in most of the examples discussed above (Figures 1a–1c and 1e) plume emplacement has preceded subduction-like foundering of the mantle of continental origin, mantle upwelling in the upper mantle in the Neogene back-arc Pannonian Basin associated to lithospheric mantle removal (delamination) beneath the Southeast Carpathians region (Figure 1d) has, in contrast, been triggered by a phase of previously existing oceanic lithosphere subduction zones (Matenco et al., 2007; Göğüş et al., 2016). Subsequent onset of continental subduction/collision along the Carpathian belt has caused a break-off/detachment of the oceanic slab ("1st break-off" on Figure 1d), with detached fragments still residing within the upper mantle transition zone (∼400–600 km). The present-day ongoing slab detachment/delamination in the Vrancea zone at depths of ∼200 km could, however, have a strong causal relationship with the impact of present-day subduction-induced convective instabilities within the upper mantle wedge ("2nd break-off" on Figure 1d). Note also the negative velocity anomalies at both sides of the downgoing Vrancea slab (Figure 1d) indicating that slab break-off could already have been completed in the adjacent segments along-strike the Carpathian arc (Wortel & Spakman, 2000). Lateral tearing of the slab in SE direction is also consistent with the analyses of the Neogene-Quaternary sedimentary (Meulenkamp et al., 1996) and magmatic (Seghedi et al., 2004) records in the area.

In this context, it should be noted that initial mantle instabilities do not only occur as a consequence of thermal perturbations but also as a result from refertilization/rehydration of the upper mantle (i.e., hydrous plumes; Xia et al., 2013; Kuritani et al., 2019) through the subduction of fluid-rich oceanic plates. Alternatively, mantle instabilities may originate from a hydrous transition zone at ∼410–660 km depth. Although the excess of fluids in this zone was commonly attributed to be the graveyard of previously subducted slabs—for example, the Mesozoic slabs under the Carpathian-Pannonian region (Kovács et al., 2020; Wortel & Spakman, 2000; Hetényi et al., 2009), it may not be directly linked to the present-day subduction cycle. Moreover, given the questionable interpretation that slab subduction by itself can bring enough volatiles down to the transition zone (Zheng et al., 2016), some studies have, in contrast, postulated a potentially pristine origin for volatiles in the hydrous transition (e.g., Hier-Majumder & Hirschmann, 2017).

Moreover, subduction initiation by a mantle plume is likely to be a common process operating not only on Earth but also on other Earth-like planets. In particular, recent numerical studies (Gülcher et al., 2020) have demonstrated the importance of plume-induced subduction in the formation of Venus' coronae, long-known circular volcano-tectonic features, often associated with elevated topography and active volcanism (Gerya, 2014; Roberts & Head, 1993; Stofan et al., 1991). These results pave the path for more detailed studies on the possible occurrence of similar, corona-like structures on Earth, in particular within the intraplate areas subjected to mantle upwelling. For example, the plume-assisted east African continental rifts embracing the Tanzanian craton (Koptev et al., 2015, 2016, 2018b) have been shown to bear many features—such as an overall elliptical shape, the presence of a mantle plume (Kenya plume), doming processes (Kenya dome), a central plateau (East African plateau) and volcanism—that are strikingly similar to those of the Venus coronae (Lopez et al., 1997). From a geometric point of view, the Alboran domain and the adjacent Betics and Rif mountains of the Western Mediterranean back-arc system (e.g., Platt et al., 2013) and the Caribbean plate system (Whattam & Stern, 2015) may represent other possible candidates. However, an unambiguous identification of such circular trenches within (intra-continental) subduction settings is more difficult on Earth, because active plate tectonics and erosion continue to reshape and remove the surface expression of past Earth mantle upwelling events.

4. Plume-Induced Initiation of Subduction and Subduction-like Sinking/Foundering: Insights From Numerical Models

According to a commonly used classification proposed by Stern (2004), subduction initiation is subdivided into "induced" (caused by ongoing plate convergence related to far-field tectonic forcing) and "spontaneous" (caused by internal gravitational instability, i.e., by local forces originating in situ). However, when subduction initiates along preexisting structures it can be challenging to discriminate between induced and spontaneous scenarios. Oceanic transform fault collapse, for example, was traditionally thought of as an "induced" mechanism that requires external forces (Hall et al., 2003) as simplified geodynamic models often have difficulties to reproduce this mechanism without using kinematic boundary conditions (Arcay et al., 2020). Yet, lateral buoyancy contrasts between different oceanic plates juxtaposed at oceanic transform faults have proven to be an adequate driving force to trigger subduction spontaneously. A required condition is the efficient reduction of strength along hydrated faults, which may be pre-defined (Gerya et al., 2008; Nikolaeva et al., 2008) or formed due to fluid percolation in a self-consistent solid-fluid model (Dymkova & Gerya, 2013). Similarly, passive continental margins that are considered as potential sites for purely spontaneous gravitationally driven subduction initiation (Davies, 1999; Vlaar & Wortel, 1976), are likely subject to significant amounts of additional forcing originating from topographic gradients (Marques et al., 2013; Pascal & Cloetingh, 2009) and/or mantle suction flow induced by neighboring subduction zones (Baes & Sobolev, 2017). In addition, a recently established database on subduction initiation events suggest that most new subduction zones initiate in oceans in proximity of active trenches: subduction breads subduction (Crameri et al., 2020).

Numerical models exploring the spontaneous mode of subduction initiation (e.g., Arcay et al., 2020; Dymkova & Gerya, 2013; Gerya et al., 2008; Nikolaeva et al., 2010, 2008) inevitably require a pre-defined sufficiently wide lithosphere-scale "weak" zone of hydrated rocks presumably inherited from previous tectonic activity. The presence of such pre-localized weak interfaces (usually characterized by significantly reduced brittle/plastic strength) is compulsory in these models to localize initial deformation and to decouple the plates, thus triggering slab foundering. On the contrary, within originally homogenous lithosphere, self-localized deformation (driven, e.g., by shear heating; Crameri & Kaus, 2010) that can subsequently lead to subduction initiation (Thielmann & Kaus, 2012) always implies the need to employ compressional boundary conditions that mimic externally induced plate convergence.

A radically different conceptual framework for understanding subduction triggering processes has come from studies investigating mantle plume-lithosphere interactions. As shown in 2D (Ueda et al., 2008; Burov & Cloetingh, 2009, 2010) and 3D (Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b) modeling studies, the emplacement of a thermo-(chemical) mantle plume anomaly beneath an oceanic (Ueda et al., 2008; Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b) or continental (Burov & Cloetingh, 2009, 2010) plate appears to trigger self-sustained subduction, even in the absence of both kinematic boundary conditions and initially pre-defined intra-lithospheric heterogeneities/weaknesses. According to the scenario first proposed by Ueda et al. (2008), a hot and positively buoyant plume rises to the oceanic lithosphere (Figure 2a1) and then quickly passes through it, ultimately leading to crustal break-up (Figure 2a2). Partially molten plume material, initially uplifted along a narrow central wedge, then starts to spread laterally atop of the broken plate, while at the same time pushing the ends of two newly created lithospheric segments downwards (Figure 2a3). Continuous downward movement of these proto-slabs eventually evolves into self-sustained subduction on both sides of the newly formed oceanic lithosphere that developed above the site of initial plume emplacement (Figure 2a4).

Following up on the pioneering study by Ueda et al. (2008, Figure 2a), intra-oceanic subduction initiation has been further investigated considering 1) the mantle plume itself (Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b) or 2) horizontal flow in the asthenosphere induced by a remote thermal upwelling (Lu et al., 2015) as the driving force. All these studies have postulated that the interaction of the oceanic lithosphere with upper mantle thermal instabilities is a very efficient mechanism to break plates and initiate subduction. Natural observations of this process, however, are notoriously rare. Despite numerous intra-oceanic "hotspots" (Courtillot et al., 2003), only one of them has triggered subduction around the Caribbean plate in the Late Cretaceous (Whattam, 2018; Whattam & Stern, 2015), whereas in all other cases no proven hot spot-related ocean-ocean subduction has been detected so far. One of the most prominent "negative" examples is the North Atlantic Igneous Province (Saunders et al., 1997) associated with the Iceland plume that 1) produces melt during most of the past 60 Myr (e.g., Kerr, 2003), thus contributing to melt-induced magmatic weakening of the overlying plate, which is typically the most important condition for plume-induced subduction (Ueda et al., 2008, Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b); 2) has presumably triggered the opening of the North Atlantic Ocean at ~60 Ma (Beniest et al., 2017b) and caused the active spreading axis to jump from the Aegir ridge to the Kolbeinsey ridge at ~30–35 Ma (Koptev et al., 2017), thus attesting a sufficiently high buoyancy of the plume to overcome the strength of not only oceanic but even continental lithosphere; 3) channeled along the thin-lithosphere corridors underneath continental lithosphere and the mid-oceanic ridges (Steinberger et al., 2019); 4) presently extends not only along the mid-oceanic ridge but also in perpendicular directions (see seismic tomography by Rickers et al., 2013 and laboratory and numerical experiments by Schoonman et al., 2017 and Koptev et al., 2017, respectively), thus impinging oceanic lithosphere of ages older than 20 Ma as required for the formation of stable subduction zones in numerical experiments (Baes et al., 2016; Lu et al., 2015). For these reasons, the Iceland plume seems to satisfy all principal model prerequisites for the initiation of stable subduction within the North Atlantic oceanic lithosphere: 1) intensive plume-induced magmatism likely lowering the strength of the overlying plate, 2) sufficient buoyancy of the thermo-(chemical) plume anomaly, and 3) interaction with oceanic lithosphere of ages exceeding 20 Ma. However, the North Atlantic region still remains a subduction-free area. This apparent contradiction between numerical model predictions and observations can likely be traced to the adoption of not well known values for model parameters controlling magmatism-induced lithospheric weakening (e.g., brittle/plastic strength reduced by a factor of $\sim10^{-2}$–10^{-4}; Gerya et al., 2015) and/or mantle plume buoyancy (e.g., buoyancy flux of ~0.15 kg $\times$ m^{-1} $\times$ s^{-1}; Lu et al., 2015). Both of these assumptions are likely not typical for present-day Earth conditions, making this scenario of plume-induced intra-oceanic subduction more feasible in a Venus-like environment (Gülcher et al., 2020) and/or in the hotter and more vigorously convecting early Earth, producing hotter upper mantle thermal instabilities with a higher degree of partial melting (Gerya et al., 2015; Ueda et al., 2008). It is also noteworthy that plume-induced subduction initiation is usually reproduced in the context of tectonically neutral or compressional regimes. The

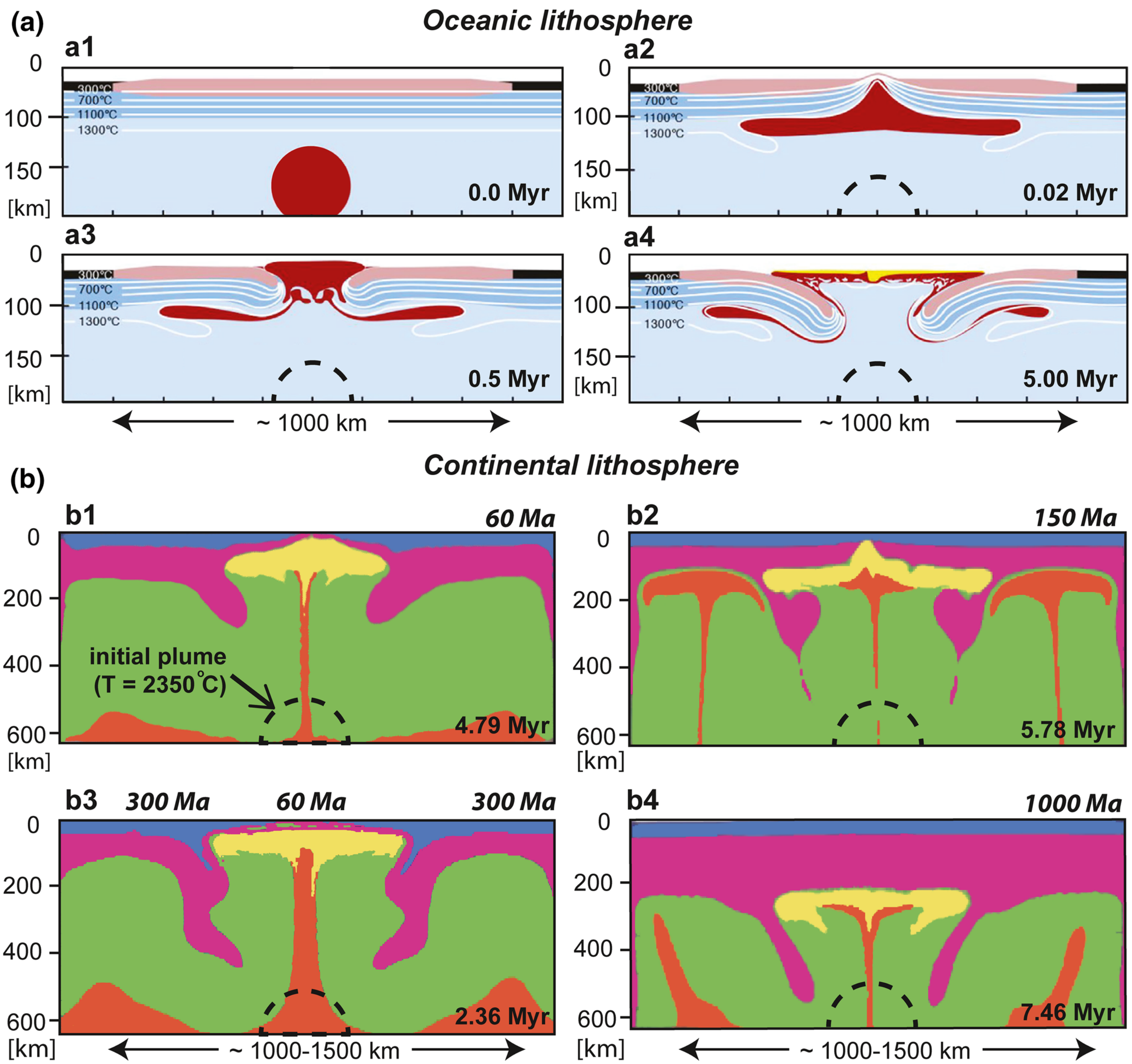

Figure 2. Numerical models of plume-induced subduction initiation in (a) intra-oceanic and (b) intra-continental settings. (a) Temporal evolution of mantle plume induced subduction initiation (model by Ueda et al., 2008; plot modified from Stern & Gerya, 2018). Note the extremely fast (<0.05 Myr) penetration of buoyant thermo-chemical plume material through the overlying oceanic plate, which is subjected to significant weakening due to plume-related magmatic activity. (b) Emplacement of extremely hot (initial temperature of ~2,300°C) plume anomaly initiates downwelling movements in continental lithosphere of different ages (modified from Burov & Cloetingh, 2009, 2010): b1) 60 Ma (Cenozoic lithosphere); b2); 150 Ma (Mesozoic lithosphere); b3) younger (60 Ma; Cenozoic) central block embedded into older (300 Ma; Paleozoic) lithosphere; b4) 1,000 Ma (Proterozoic lithosphere). Note the different vertical levels for horizontal intrusion of the plume head: below the crust (b1 and b2), between upper and lower crust (b3) and within the lowermost lithospheric mantle (b4).

North Atlantic Realm, in contrast, has been under tectonic extension not only since continental break-up in Early Tertiary (Lundin & Doré, 2005) but also during the preceding long-lasting phase of pre-break-up rifting initiated in Permo-Triassic times (Reemst & Cloetingh, 2000; Ziegler & Cloetingh, 2004). The presence of far-field extensional forces could be, therefore, an alternative explanation for the absence of plume-induced subduction in the region.

10.1029/2020GC009482

Plume-induced subduction initiation in the context of a continental overlying plate has been comprehensively explored in studies by Burov & Cloetingh (2009, 2010). Similar to the intra-oceanic tectonic setting (Figure 2a), most scenarios for continental lithosphere invoke strong thermo-mechanical erosion of the lithospheric mantle followed by crustal break-up and incipient oceanization above the plume head (Figures 2b1–2b3). However, in contrast to the oceanic models where plume material always spreads atop of a ruptured plate (Figures 2a3 and 2a4), horizontal intrusion of a hot mantle plume may occur at very different levels of the continental lithosphere depending on its age and internal structure. In particular, when relatively young (60–150 Ma) and homogeneous lithosphere is involved (Figures 2b1 and 2b2), the plume intrudes below the positively buoyant continental crust, pushing the underlying part of denser mantle downward (Figure 2b1). If, on the contrary, the lithosphere is heterogeneous with a younger (60 Ma) central block embedded into older (300 Ma) surroundings, plume material spreads laterally at much shallower levels, decoupling upper crust from the lower crust. The lower crust then remains attached to the mantle of the older segments that are pushed downward by the plume-induced movement (Figure 2b3). The oldest continental plate (1,000 Ma) represents the opposite end-member where the plume underplates the lithosphere, causing downthrusting of only the very lowermost parts of the lithospheric mantle on the extremities of the flattened plume head (Figure 2b4). Importantly, in this last scenario plume-induced mantle downthrusting is not accompanied by vertical penetration of plume material toward the surface, and the overlying plate is thus not ruptured, which is in contrast to all previous models for plume-induced subduction initiation for both oceanic (Figure 2a) and younger continental lithosphere (Figures 2b1–2b3). Note also that the deformation in the lowermost lithospheric mantle primarily occurs in a regime of ductile flow. Different from the commonly known term "thrust" applied in the field of structural geology, usually ascribing the term to deformation under brittle conditions, we adhere here to the terminology adopted in Burov & Cloetingh (2010), attributing the term "(mantle) downthrusting" to initial downward sinking motion of the lowermost lithospheric mantle followed by quasi-vertical foundering of formed proto-slabs.

Different from drastically reduced yield stresses adopted in models for the oceanic lithosphere that is presumably weakened by intense magmatic activity of the plume (Ueda et al., 2008; Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b), the parameters of elastic-ductile-plastic rheology laws for crust and mantle of the continental lithosphere in the study by Burov & Cloetingh (2009, 2010) are based on experimentally derived estimates for the rock mechanical properties (Kirby & Kronenberg, 1987; Kohlstedt et al., 1995), and were not subject to further lowering due to the effects of strain- (Brune & Autin, 2013; Gueydan et al., 2008; Huismans & Beaumont, 2003) and/or melt-related softening (Bahadori & Holt, 2019; Gerya et al., 2015; Gerya & Meilick, 2011; Lavecchia et al., 2016). This means that mantle plume ascent through the entire plate as reproduced in the models for relatively young continents (Figures 2b1 and 2b2) is mostly due to the significantly positive buoyancy of the plume head ($\Delta\rho \sim 100\text{–}120$ kg $\times$ m^{-3}), mainly associated to the high thermal contrast between the plume itself and its surrounding material (up to +1,000°C when emplaced below the lithosphere).

In order to investigate the effects of a more realistic (lower) temperature contrast when a plume encounters the base of the lithosphere ($\Delta T \sim 250\text{–}350$°C; White & McKenzie, 1995; Thompson & Gibson, 2000), we carried out an additional set of modeling experiments (Figure 3), built upon the setups from our previous studies (Beniest et al., 2017a). In these models, we adopt a laterally homogeneous (two-layered continental or one-layered oceanic) crust and lithospheric mantle and free-slip boundary conditions for the left and right vertical edges. The mantle plume anomaly is incorporated as a semi-circle of 100 km-radius seeded at the bottom of the model box. Additional details of the model setup and parameters used are presented in detail in Supporting Information Section S1.

In the models presented in Figure 3, the lower temperatures (1,700°C) assumed for the initial mantle anomaly prevent a penetration of the plume material into the lithosphere with a strength not subjected to weakening. In previously published studies of plume interactions with very young oceanic lithosphere (5–20 Ma), such "plume underplating" (i.e., when plume material spreads below the bottom of the lithosphere) has been considered as "failed subduction initiation" (Baes et al., 2016). This agrees with our model where lithospheric mantle of a "young" (30 Ma) oceanic plate is subjected to extremely shallow (<100 km) downthrusting of a thin layer (Figure 3a1). However, for significantly older (80 Ma) and thicker (115 km) oceanic lithosphere, we identify a different mode of intermediate downthrusting/foundering (to depths of

10.1029/2020GC009482

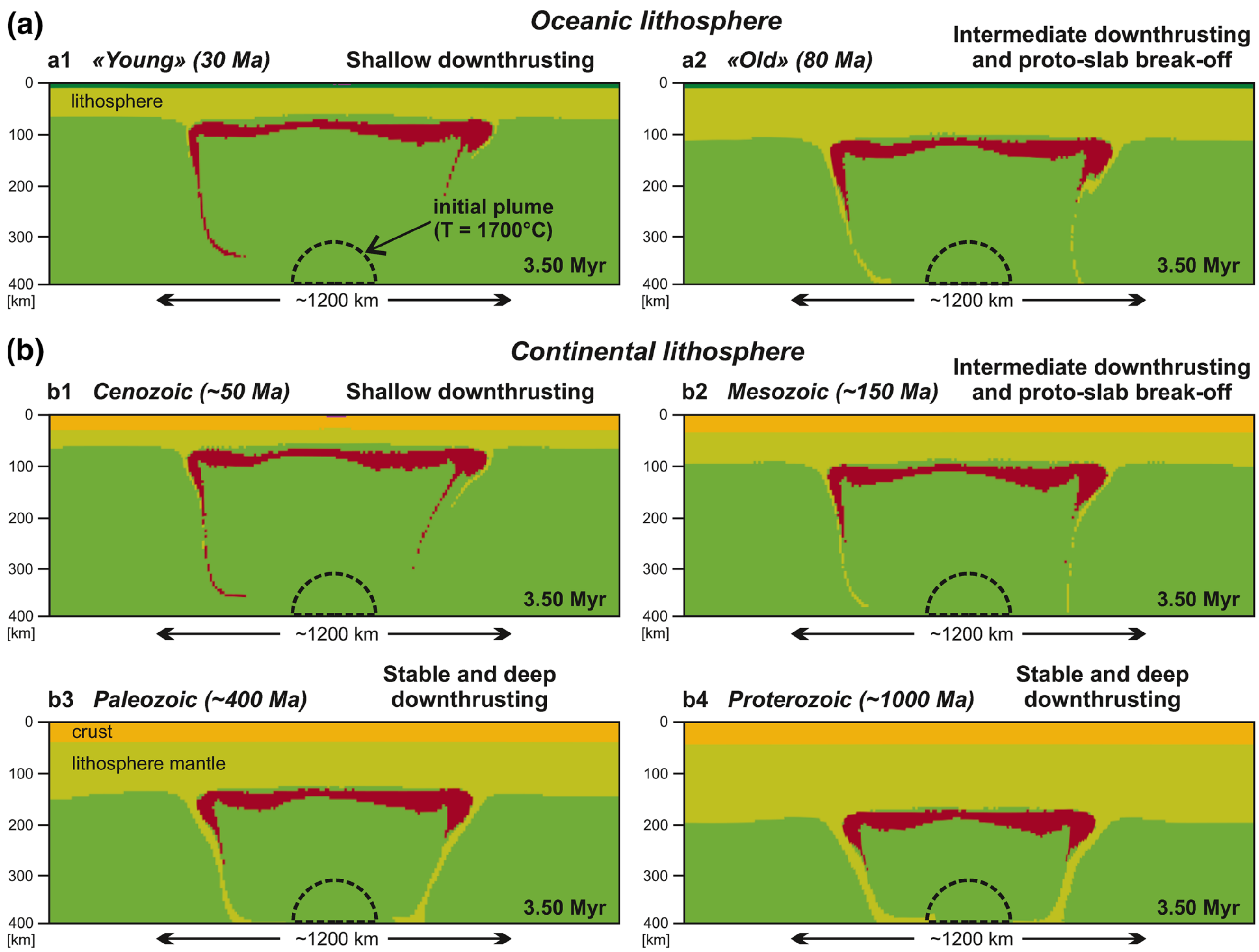

Figure 3. Numerical models of a mantle plume anomaly with a moderate initial temperature (1,700°C) interacting with an overlying oceanic (a) and (b) continental lithosphere of different thermo-tectonic ages. Note that the style of plume-induced downthrusting and sinking/foundering is mainly conditioned by the thermal thickness of the overlying plate. In particular, a deep and stable mode of mantle downward motion only develops under condition of relatively old (>300 Ma) and thick (>100 km) lithosphere.

200–300 km) with subsequent break-off of the foundering proto-slabs (Figure 3a2). Interestingly, the experiments with a lithosphere of similar thicknesses but with a continental structure—either Cenozoic (65 km; Figure 3b1) or Mesozoic (100 km; Figure 3b2)—evolve in the same way as their oceanic counterparts (Figures 3a1 and 3a2, respectively). It thus appears that the system behavior in terms of plume-induced downthrusting and foundering is controlled by the total thermal thickness of the overlying plate, whereas its internal rheological stratification (Burov, 2011; Koptev et al., 2019) is irrelevant. Finally, when a mantle plume anomaly is emplaced below a sufficiently old (>300 Ma) and thick (150–200 km) lithosphere (Figures 3a3 and 3a4), the initiated intra-continental mantle sinking can be regarded as stable and deep since the proto-slabs founder continuously (i.e., not interrupted by detachment), reaching the bottom of the model box at 400 km. It is also noteworthy that downwelling lithospheric material is sufficiently thicker here (thickness is of order of several tens km) than in cases of shallow and intermediate downthrusting characterized by extremely low thicknesses of sinking proto-slabs (not more than 10 km). In the model with a 200 km-thick Proterozoic overlying plate (Figure 4), initial downthrusting of the lowermost lithospheric mantle, which is expressed in the symmetrical descending of the isotherm of 1,300°C by ∼50 km at the flanks of the plume-related thermal anomaly, starts immediately after the plume impinges on the base of the lithosphere (Figure 4a1). Due to negative buoyancy of these relatively cold (<1,300°C) downthrusted segments, which are also subjected to the push of the head of the laterally spreading plume, subduction-like foundering of

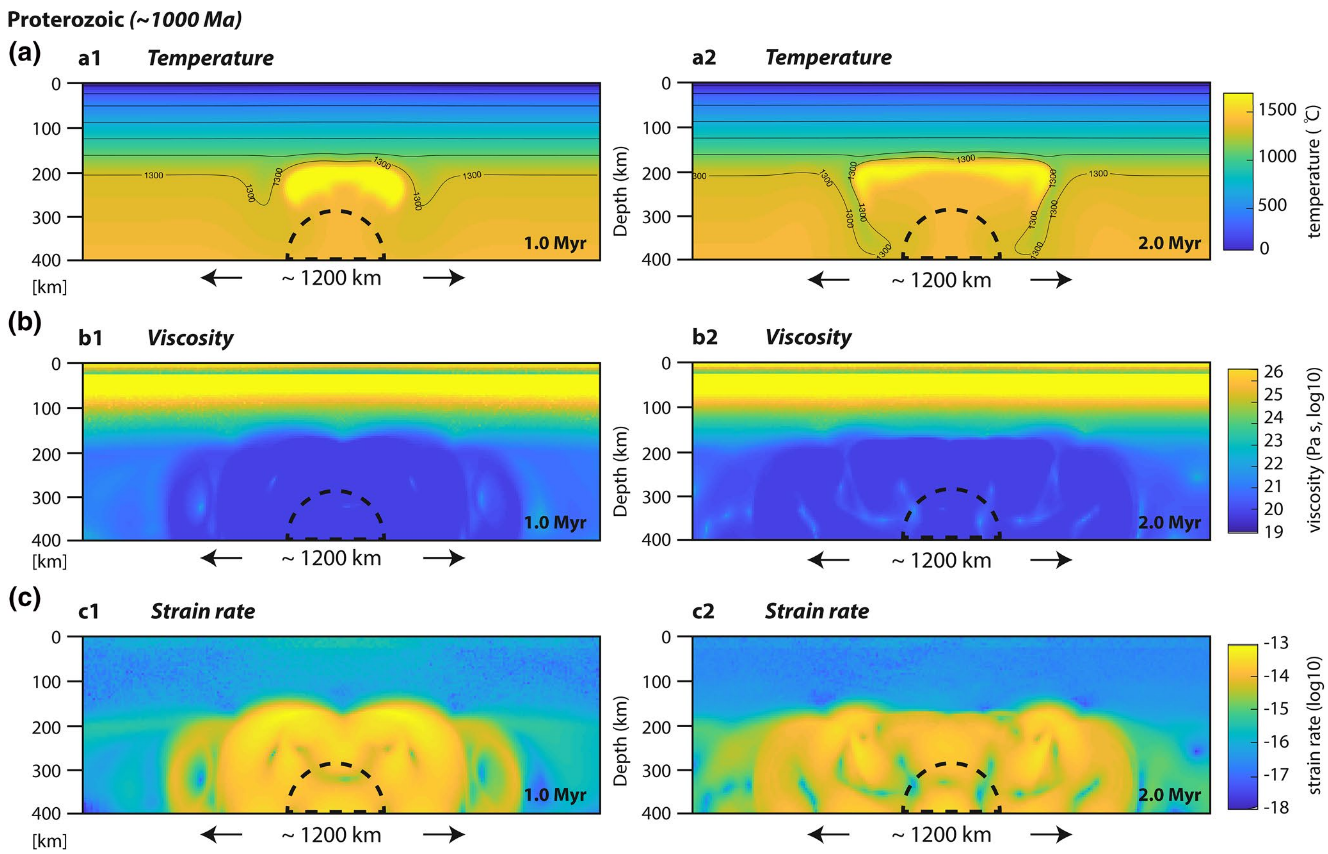

Figure 4. Numerical model of plume-induced subduction-like sinking/foundering in case of the Proterozoic lithosphere (see also Figure 3b4): modeled fields of (a) temperature; (b) viscosity; and (c) strain rate at 1 and 2 Myr.

mantle material continues, reaching 400 km depth at ∼2 Myr after onset of the experiment (i.e., ∼1 Myr after plume emplacement and initiation of mantle downthrusting; see Figure 4a2). Subsequently, sunken proto-slabs remain stable for several Myr (Figure 3d). In the viscosity field (Figure 4b) the proto-slabs are expressed less clearly than in the temperature distributions (Figure 4a). Importantly, modeled strain rates show that deformation occurs only in ductile material of the asthenosphere and lowermost lithosphere, whereas the crust and most of the lithospheric mantle remain nearly undeformed (Figure 4c).

Based on the above results, we conclude that large-scale and long-lived foundering at the level of the lowermost lithospheric mantle can be triggered by mantle anomalies of moderate temperatures and sizes within strong continental interiors of Paleozoic-Proterozoic-(Archean) platforms that are not subject to significant magmatic weakening, thermal erosion or rifting/break-up. Moreover, given the minimal requirements to reproduce this process in the model (without any added kinematic boundary conditions nor pre-localized lithospheric structures nor strength lowering in the lithosphere nor excessive thermo-chemical contrasts in the plume), thick and old continental lithosphere might potentially provide the optimal conditions for mantle downthrusting and subduction-like sinking/foundering into the interior of the Earth. This is in line with numerous natural examples of intra-continental downwelling in the upper mantle detected by different geophysical techniques in various regions over the world, such as the Caucasus (Ismail-Zadeh et al., 2020; Koulakov et al., 2012), North-East China (Kuritani et al., 2019; S. Li et al., 2020), and the Colorado Plateau (Levander et al., 2011) (see Section 3 for details).

As mentioned above, deep-seated mantle downthrusting/foundering in the case of a thick continental lithosphere (Figure 2b4; Figures 3b3 and 3b4) does not require vertical uplift (or emplacement) of plume material up to intermediate/shallow lithospheric levels, nor will they show the associated rifting/break-up processes detectable at the surface. However, we do not exclude that for certain combinations of thermo-mechanical

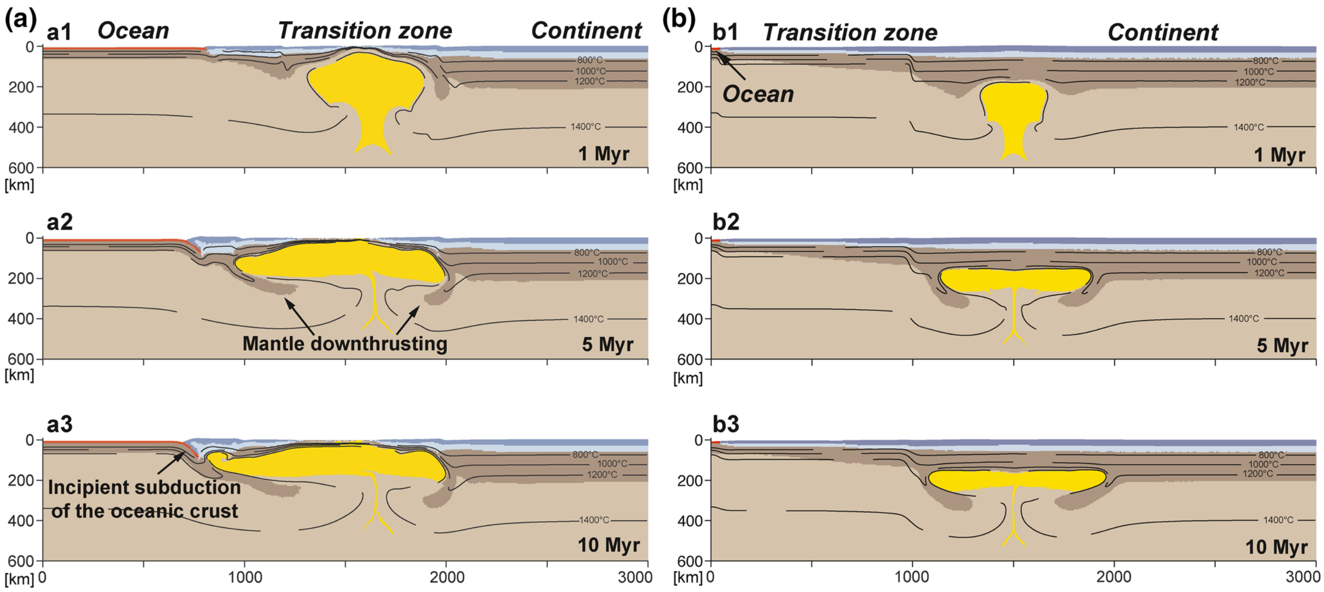

Figure 5. Numerical experiments of plume-lithosphere interaction at passive continental margins (modified from François et al., 2018). (a) A mantle plume emplaced at the transition zone between oceanic and continental lithosphere triggers not only mantle downthrusting on the extremities of the plume but also incipient subduction of the oceanic crust. (b) A mantle plume initially shifted toward the thick continental lithosphere produces intra-continental mantle downthrusting at both ends of the flattened plume head (similar to the fully intra-continental models shown in Figure 2b4 and Figures 3b3 and 3b4).

parameters and boundary conditions such processes may take place at a later stage. For example, in previous studies it was reported that under ultraslow tectonic extension (<5 mm/yr) mantle plume protrusion into the lithosphere might be postponed up to ~100 Myr after initial emplacement at the lithospheric base (Koptev et al., 2018). Delayed rupture of the lithosphere, combined with other possible factors as for example changes in far-field forcing (i.e., tectonic inversion) and/or (re)activation of shear zones in the crust and the uppermost lithospheric mantle, might be important for the transition from initial plume-induced deep-mantle downthrusting/foundering into a fully established process of plate-scale subduction. Present-day observations (see Section 3) seem to detect an intermediate stage of this process when hot plume material already resides at relatively shallow depths—~100 km in the Caucasus area (Ismail-Zadeh et al., 2020; Koulakov et al., 2012), ~80–100 km in North-East China (S. Li et al., 2020), and ~60–80 km in the Colorado Plateau (Levander et al., 2011) – but has not yet reached the crust to complete the rupture of the continental plate (Figure 1). This might indicate that a much longer time period is needed for mantle plumes to penetrate into shallowest lithospheric levels than usually expected in models for oceanic (<0.1 Myr; Figure 2a) and young continental (<5 Myr; Figure 2b1–3) lithosphere, for which plume-induced break-up is mandatory before or during subduction/downthrusting. In nature, however, vertical ascent of plumes through the lithosphere and subsequent break-up (if any) likely postpones the initial phase of downthrusting, especially in the case of a mature overlying plate.

Mantle plume emplacement at the transition zone between oceanic and continental lithosphere might play a key role in the initiation of ocean-continent subduction (e.g., Van der Lee et al., 2008). For example, as shown in a recent study by Stern and Dumitru (2019), the Yellowstone mantle plume emplaced at ~55 Ma below the western coast of North America has likely disrupted an older subduction zone and allowed thermal weakening and lithospheric collapse of the oceanic Farallon plate forming the new east-dipping Cascadia subduction zone. Numerical models of plume-lithosphere interaction at passive continental margins (François et al., 2018) also reveal plume-induced incipient downthrusting of oceanic crust and mantle lithosphere (Figure 5a). Supported by external tectonic compression, such a system might be easily transformed into a self-sustained ocean-continent subduction zone. When the position of the plume is shifted toward the continental interiors, initiated downthrusting is localized at the level of the lowermost mantle of the continental lithosphere (Figure 5b), similar to the results of models that assume a sufficiently thick overlying plate is subjected to the impact of the mantle plume (Figure 2b4; Figures 3b3 and 3b4). In between

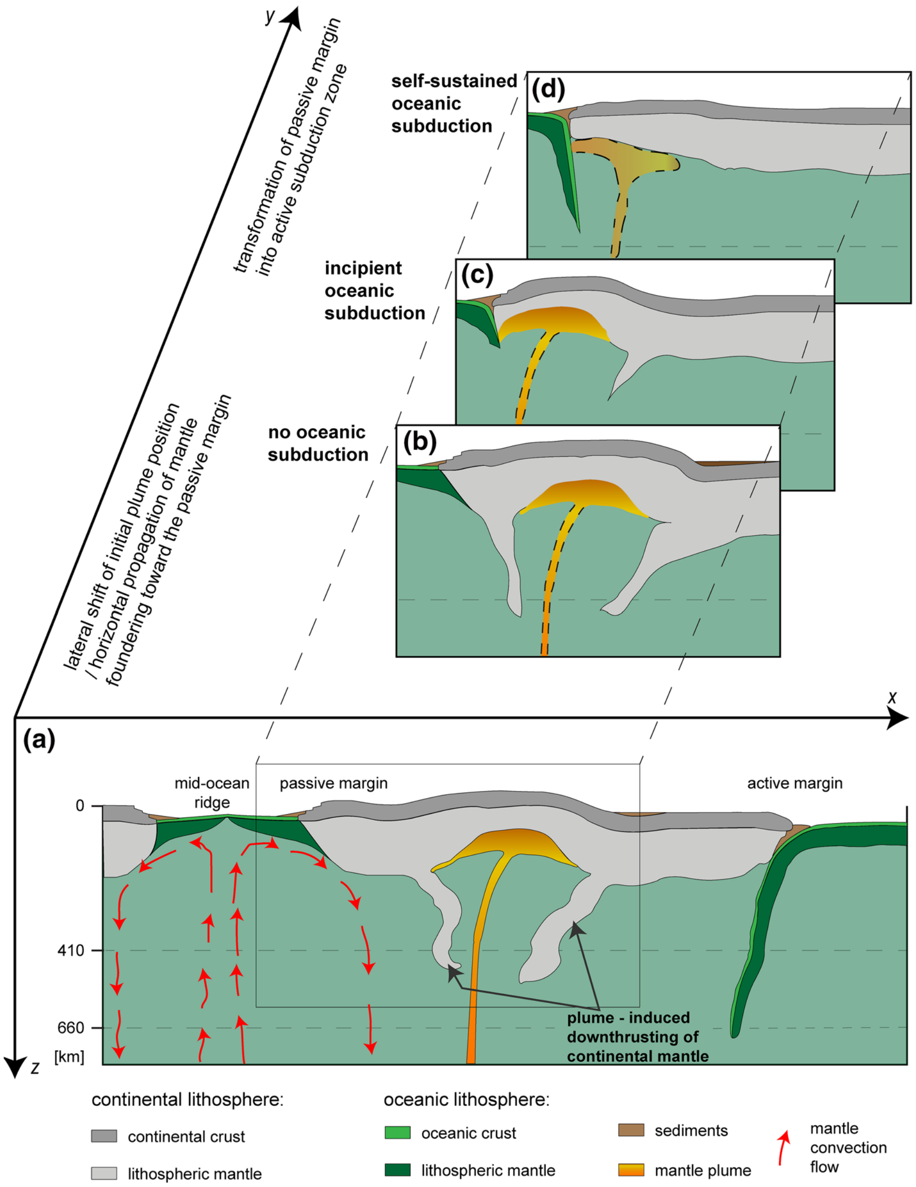

Figure 6. Plume-induced sinking of intra-continental lithosphere and its possible consequences for subduction initiation. (a) interaction of mantle plume with continental mantle as a mechanism for initiation of subduction-like sinking (foundering) of the lowermost lithosphere (see Sections 3-4); (b) shift of original plume location closer to the passive margin or along-strike (in *y*-dimension) lateral migration of plume-induced mantle downthrusting and foundering, for example, along oblique continent-ocean boundary, potentially leading to (c) incipient downthrusting of oceanic lithosphere (see Figure 5a3) passive margin collapse and establishment of self-sustained "classic" ocean-continent subduction.

these end-members (Figures 5a and 5b) a large spectrum of intermediate cases is to be expected for different initial locations of the plume and various widths of the transition zone. Moreover, by analogy with recent, successfully modeled propagation of pre-existing intra-oceanic convergent zones along weakened passive margins (Zhou et al., 2020), lateral migration in the third dimension could also be an efficient mechanism for transmitting incipient intra-continental downthrusting/foundering toward passive continental margins, potentially leading to their collapse (Figure 6). Additional numerical experiments that explore the role of intra-continental mantle foundering in the initiation of "classic" ocean-continent subduction should equally be pursued as the search for potential and hitherto unrecognized examples of this process in nature.

10.1029/2020GC009482

5. Discussion

Subduction zones are the expression of convergent plate margins (Stern, 2002), with a total present-day along strike length of >55,000 km (Lallemand, 1999), almost equal to that of mid-oceanic spreading ridges (Kearey et al., 2009). The initiation of ocean-continent subduction along passive continental margins has remained a controversial problem. As shown by numerical modeling experiments, in the absence of pre-existing weak zones, a passive margin can be spontaneously transformed into an active subduction zone under the following two conditions: 1) unusually thin overriding continental lithosphere (<65–75 km; Nikolaeva et al., 2010) or 2) sufficient mantle downwelling flow just below the passive margin (Baes & Sobolev, 2017). Numerous candidates for future sites of active subduction at present-day passive margins have been proposed including: the mechanically weak southern Brazilian Atlantic margin (Marques et al., 2013; Nikolaeva et al., 2011); the East African margin (Gerya, 2011) which is strongly affected by the thermal anomaly of the African superplume (Mulibo & Nyblade, 2013; Koptev et al., 2015, 2016); and the Argentine Basin and the U.S. East Coast which are both presumably subjected to slab suction from long-lived Andean and Cascadia subduction zones (Baes & Sobolev, 2017). Despite confirmation by numerical models and the identification of promising candidate regions that are expected to develop subduction initiation processes along passive margins, no irrefutable natural example of initiated self-sustained subduction has yet been documented.

The most viable mechanism to trigger ocean-continent subduction appears to be the lateral propagation from pre-existing intra-oceanic convergent zones which onset, in turn, is very common in the Cenozoic (Crameri et al., 2020; Gurnis et al., 2004). This scenario requires the existence of inherited localized weak zones at passive margins (Munch et al., 2020; Zhou et al., 2020), and has been successfully reproduced in numerical models and proposed as a likely future scenario for the Atlantic passive margin to the north of the Lesser Antilles (Zhou et al., 2020). It also appears to apply to well-established subduction in the Sunda Arc where subduction initiation in the Eocene is thought to be due to eastward propagation from the eastern end of two parallel subduction zones north of India, one of which was intra-oceanic (Hall, 2012; Jagoutz et al., 2015). Subduction polarity reversal due to arc-continent collision is another intuitively acceptable mechanism for the transition from ocean-ocean to ocean-continent subduction (Stern, 2004) although both data- and model-driven evidences for this process are limited (Crameri et al., 2020; Stern & Gerya, 2018).

Intra-continental subduction is traditionally thought to be related to oceanic basin closure and subsequent continental collision. In this case, underthrusting of the continent by another block of continental lithosphere is presumably driven by the negative buoyancy of adjacent oceanic lithosphere that already entered the trench. Far-field tectonic forces represent another mechanism driving continental subduction that are usually simulated by a constantly advanced wall/piston in laboratory analog experiments (Regard et al., 2003; Willingshofer et al., 2013), or by a constant velocity applied to the vertical edges of numerical models (e.g., Pysklywec et al., 2010). In this case a precursor oceanic slab is not essential and may be absent, as was reported, for example, for the Dinaric subduction zone that formed during the Paleogene in response to a change in the convergent motion between Africa and Eurasia (Sun et al., 2019). However, such "collisional" intra-continental subduction usually only lasts a few Myr (Yamato et al., 2007) and is succeeded by return flow (exhumation) of buoyant continental crust to the surface (Burov et al., 2001; Burov & Yamato, 2008), slab break-off (Duretz et al., 2014; Li et al., 2013) and/or delamination of the overriding plate lithospheric mantle (François et al., 2014; Li et al., 2016; Ueda et al., 2012).

Another (and potentially much more common) way to initiate a subduction-like process in an intra-continental setting is the interaction of the continental lithosphere with plume-like diapiric mantle instabilities. As demonstrated by numerical experiments, upwelling of hot plume material can produce spontaneous downthrusting/foundering of the mantle part of the overlying continental lithosphere even without any induced convergence or pre-existing localized plate weaknesses. Under the condition that the continent is relatively young (Cenozoic-Mesozoic, LAB <150 km), subduction initiation occurs only when the mantle plume is sufficiently hot (and therefore buoyant) to penetrate through the entire lithosphere, and dragging its broken segments into the mantle with a downward motion (Burov & Cloetingh, 2009, 2010). This mechanism is consistent with findings from numerous studies of intra-oceanic settings (Ueda et al., 2008; Gerya et al., 2015; Baes et al., 2016, 2020a, 2020b), where subduction develops exclusively in combination with preceding break-up of the lithosphere by ultra-fast (<0.1 Myr) uplift of plume material to the surface.

If, however, the strength of oceanic lithosphere above the plume anomaly overcomes its thermal and/or compositional buoyancy, "plume underplating" (i.e., lateral spreading of the plume head beneath the plate) without subduction initiation becomes the dominant mode (e.g., Baes et al., 2016). Thick and strong continental plates of older thermo-tectonic ages (Paleozoic-Proterozoic-Archean, LAB >150 km) prohibit any vertical penetration of the plume material through the lithosphere even if the impinging thermal anomaly is extremely high (up to +1,000°C below the LAB at the moment of the emplacement; Burov & Cloetingh, 2009). However, in contrast to thin plates of oceanic and young continental lithospheres, horizontal propagation of the plume head below a thick continent is shown to initiate downward displacement of the adjacent lowermost lithospheric mantle into the asthenosphere. Once triggered, downthrusting becomes a self-sustaining process leading to sinking of the proto-slabs to depths of at least 400–500 km (Figure 2b4; Burov & Cloetingh, 2009). With newly performed numerical experiments (Figures 3 and 4), we have demonstrated that mantle downthrusting and foundering of old continental lithosphere can be reproduced with thermal anomalies of moderated size (initial radius of 100 km) and of much more moderate temperature contrasts (+250–350°C) than in previous studies (Burov & Cloetingh, 2009, 2010) and in the absence of a compositional stratification of lithospheric mantle (e.g., a highly depleted upper part underlain by a more fertile lowermost segment characterized by a higher proportion of high-density minerals as advocated by Hu et al., 2018). Therefore, lithospheric mantle foundering of a mature continental platform appears to be the least demanding mechanism of plume-induced mantle sinking. It neither requires excessive density contrasts between plume and lithosphere nor significant weakening of the overlying plate that are both necessary conditions for vertical ascendance of plume material to the surface and associated fragmentation of the lithosphere, mandatory precursors of subduction in the scenario for young continental and oceanic lithosphere.

These modeling results are consistent with natural observations. Numerous "hot-spots" within oceanic basins (Courtillot et al., 2003) are associated with the emplacement of long-lived (Jellinek & Manga, 2002) mantle plumes, which are likely rooted at the base of the lower mantle (French & Romanowicz, 2015). In some cases, they result in the formation of thick oceanic plateaus due to very large volumes ($>0.1 \times 10^6$ km^3) of plume-derived magmatic material that erupts onto and intrudes into the oceanic lithosphere (Kerr, 2003, 2015). However, only one of these "hot-spots" (the Late Cretaceous Caribbean plume) has forced the overlying plate into sustained intra-oceanic subduction (Whattam & Stern, 2015). Such scarcity in documented examples of plume-induced subduction within intra-oceanic settings is in line with the modeling studies simulating this process (Baes et al., 2016; Gerya et al., 2015; Ueda et al., 2008), where subduction initiation requires far-going assumptions on the high required buoyancy of the plume, and an overlying lithosphere that needs to be strongly weakened. Both conditions are rarely met in Phanerozoic Earth's history, making this scenario more applicable to the Precambrian Earth and to other Earth-like planets (e.g., Venus, see Ueda et al., 2008; Gerya et al., 2015; Gülcher et al., 2020). In contrast, observations within intra-continental settings provide numerous examples of anomalous mantle structures that can be interpreted as downgoing proto-slabs triggered by a mantle plume upwelling: that is, the Caucasus (Ismail-Zadeh et al., 2020; Koulakov et al., 2012); Central Asia (He & Santosh, 2018); North-East China (Kuritani et al., 2019; Li et al., 2020); Iberia (Civiero et al., 2019); the Carpathians (Ismail-Zadeh et al., 2012; Wortel & Spakman, 2000); and the Colorado Plateau (Levander et al., 2011). Importantly, observed depths of the upper mantle positive thermal anomalies are typically deeper than the maximum depth of the cold downwelling bodies (Wang et al., 2018; Wang & Kusky, 2019). This confirms one of the basic assumptions that upper mantle instabilities precede initiation of downthrusting in continental lithospheric mantle, not vice versa. Other striking observations in the continental realm, such as 1) mantle plumes that never reach the crust or the shallowest levels of the lithospheric mantle, and 2) the lack of evidence for incipient or shortly forthcoming ruptures of the lithosphere, are also in agreement with model predictions that favor initial downthrusting at deep levels of the lithospheric mantle. In this case, no penetration of plume material through the lithosphere occurs and the plate will not break, which would be expected in the case of subduction initiation within oceanic lithosphere under Precambrian Earth conditions (Gerya et al., 2015; Ueda et al., 2008). Apart from thermal plumes, convective movements in the upper mantle generated by adjacent tectonic activity or small-scale (Solomatov, 2004) edge-driven convection (Liu et al., 2018; Wang & Kusky, 2019) may also lead to downthrusting and foundering of the mantle lithosphere. This would explain why subduction-like behavior of the continental lithosphere is more frequently detected along the edges of plate domains.

10.1029/2020GC009482

The increasing number of documented examples of intra-continental foundering together with simple numerical requirements to reproduce this process suggest that it might be common on Earth. It is noteworthy that this mechanism does likely operate not only in the Cenozoic and present-day, but also in deeper Phanerozoic time. For example, a recent study by Hu et al. (2018) postulates plume-triggered foundering and subsequent detachment/delamination of lithospheric keels of the Western Gondwana craton since Mesozoic times. We, thus, conclude that plume-induced downthrusting and sinking of deeper continental lithospheric mantle might be as important to plate tectonics as mid-oceanic spreading ridges and passive/active continental margins (Figure 6).

However, the exact consequences of continental mantle downthrusting/foundering to global tectonics remain unclear. In particular, the question how this foundering could initiate "classic" ocean-continent subduction has never been addressed. Could ongoing continent-continent foundering laterally propagate toward adjacent passive margins? What is the contribution of external tectonic forces to such propagations? What is the role of pre-existing crustal/lithospheric weakness zones and their spatial location with respect to the area of initial plume impingement (e.g., Lavecchia et al., 2017)? How important is the delayed (plume-induced?) break-up of the overriding plate? How relevant are magmatically induced weakening of the continental lithosphere (e.g., Bahadori & Holt, 2019; Sobolev et al., 2011) and the existence of mid-lithospheric discontinuity (e.g., Kovács et al., 2017; Rychert & Shearer, 2009; Selway et al., 2015)? Can hydrous (i.e., compositionally buoyant) plumes trigger similar downthrusting of the mantle lithosphere to thermal plumes (e.g., Kuritani et al., 2019)? What is the role of surface erosion and associated sediment transport and deposition? The last (but not least) question might be particularly important in view of first-order control of erosion and sedimentation on crustal stresses and fault activity (well known for decades—see for example, Burov & Poliakov, 2003; Roy et al., 2016; Ballato et al., 2019) and on the conditions of partial melting (recently discovered by Sternai, 2020). The newly developed numerical techniques allowing thermo-mechanical models to be fully coupled with landscape evolution simulations in 3D (Braun & Yamato, 2010; Collignon et al., 2014; Nettesheim et al., 2018; Thieulot et al., 2014; Ueda et al., 2015) open new perspectives for a hybrid geomorphological-geodynamical modeling quantifying the distinct tectonic and surface processes and their mutual feedbacks on different spatial and temporal scales. The aforementioned fundamental questions, therefore, need to be addressed by the (re)assessment of the geological record and geophysical data combined with these innovative modeling approaches. Given a general lack of viable mechanisms for ocean-continent subduction initiation (see section 2.1), a detailed examination of possible scenarios for the further development of plume-induced foundering of the continental mantle (especially with regard to the spatial-temporal transition to "classic" ocean-continent subduction) is warranted and presents a challenging task to be pursued further.

6. Conclusions

The process of subduction is fundamental to understand the driving forces behind plate tectonics and the tectonic history of Earth. Traditionally, negative buoyancy of sufficiently old oceanic lithosphere has been viewed as a primary cause for gravitationally driven subduction initiation at passive continental margins (Vlaar & Wortel, 1976). However, increasing the strength of the oceanic plate through cooling places serious hurdles toward continental margin collapse (Cloetingh et al., 1982, 1989), even in the presence of additional forcing due to topographic gradients (Marques et al., 2013) and/or sedimentary loading (Cloetingh et al., 1982, 1984). Nevertheless, as summarized by Gurnis et al. (2004), nearly a third of all active subduction zones have been formed during Cenozoic times, implying that subduction initiation must be a routine process in the mode of plate tectonics currently operating on Earth. Intra-oceanic subduction is most likely triggered by mechanical heterogeneities within the oceanic lithosphere that is subjected to forcing from proximate active subduction zones (Crameri et al., 2020). Less frequent (Crameri et al., 2020) initiation of "classic" ocean-continent subduction could be caused by lateral propagation of the trench from a previously existing ocean-ocean subduction zone toward a sufficiently weak continental margin (Zhou et al., 2020). Other scenarios of subduction initiation in an intra-oceanic environment or at the continent-ocean transition zone usually lack independent confirmation through observations and/or self-consistent reproducibility in numerical models (e.g., Stern & Gerya, 2018; Crameri et al., 2020; and references therein).

Continent-continent subduction has been most commonly attributed to the closure stage of an oceanic basin. Preceded by subduction of an adjoining oceanic slab, underthrusting of one continental block by another has, therefore, not been considered as a formation of a new subduction zone. Interaction of a continental plate with a hot mantle plume anomaly provides a fundamentally different framework for the understanding and interpretation of intra-continental subduction-like sinking/foundering since it is initiated without a pre-existing subduction zone, applied far-field tectonic forces or inherited lithospheric-scale heterogeneities and weaknesses (Burov & Cloetingh, 2009, 2010). Numerical experiments reveal that downthrusting at the level of the lowermost mantle of sufficiently thick lithosphere (>100 km) can be triggered by upper mantle instabilities under minimal requirements for thermo-chemical contrasts in the plume of moderate initial radius (100 km) and without magmatism-induced strength lowering in the overlying plate.

Therefore, it appears that continental interiors of thick Paleozoic-Proterozoic-(Archean) platforms provide optimal conditions for initiation of sinking of lithospheric mantle into the underlying asthenosphere. This is in agreement with numerous recent observations of mantle downwelling in intra-continental settings: the Caucasus (Ismail-Zadeh et al., 2020; Koulakov et al., 2012); Central Asia (He & Santosh, 2018) North-East China (Kuritani et al., 2019; Li et al., 2020); Iberia (Civiero et al., 2019); the Carpathians (Ismail-Zadeh et al., 2012; Wortel & Spakman, 2000); and the Colorado Plateau (Levander et al., 2011). In contrast, intra-oceanic subduction initiated by mantle plumes is notoriously rare in the Phanerozoic with only one proven example of subduction initiated in Late Cretaceous times around the Caribbean plate (Whattam & Stern, 2015).

We conclude that continental mantle sinking is a much more common feature than hitherto assumed, detectable by geophysical imaging and easily reproducible in numerical experiments. The role of these intra-continental structures in global plate tectonics deserves to be comprehensively explored in more detail in future research, with a particular focus on their lateral propagation toward passive continental margins and possible subsequent transformation into "classic" ocean-continent subduction zones (Figure 6), in analogy with the recently successfully modeled propagation of intra-oceanic convergent zones (Zhou et al., 2020).

Data Availability Statement

Rheological and thermal data used for the construction of the numerical simulations in this research are summarized in the supporting information file of this paper. The rheological data in there originate from Chopra and Paterson (1984), D'Acremont et al. (2003), and Ranalli (1995). The thermal data are from Artemieva (2006) and Koptev & Ershov (2010, 2011). The FLAMAR software used in this research is based on the FLAC-Para(o)voz computational method (Cundall, 1989; Poliakov et al., 1993) and is described in detail in Burov and Poliakov (2001), Burov and Diament (1995), Le Pourhiet et al. (2004), and Yamato et al. (2008).

Acknowledgments
This study is co-funded by an Alexander von Humboldt Foundation fellowship to A. Koptev and A. Beniest; the Distinguished Guest Scientist Fellowship Program of the Hungarian Academy of Sciences to S. Cloetingh; the MTA CSFK Lendület Pannon LitH2Oscope grant and NN128629 (Topo-Transylvania) grant to I. Kovács; and a German Science Foundation grant to T.A. Ehlers (DFG EH329 23-1). We thank Marzieh Baes and Pietro Sternai for very insightful and constructive reviews.

References

Ádám, A., Szarka, L., Novák, A., & Wesztergom, V. (2017). Key results on deep electrical conductivity anomalies in the Pannonian Basin (PB), and their geodynamic aspects. *Acta Geodaetica et Geophysica*, *52*(2), 205–228.

Agard, P., Jolivet, L., Vrielynck, B., Burov, E., & Monie, P. (2007). Plate acceleration: The obduction trigger?. *Earth and Planetary Science Letters*, *258*(3–4), 428–441.

Agard, P., Yamato, P., Soret, M., Prigent, C., Guillot, S., Plunder, A., & Monié, P. (2016). Plate interface rheological switches during subduction infancy: Control on slab penetration and metamorphic sole formation. *Earth and Planetary Science Letters*, *451*, 208–220.

Arcay, D., Lallemand, S., Abecassis, S., & Garel, F. (2020). Can subduction initiation at a transform fault be spontaneous? *Solid Earth*, *11*(1), 37–62.

Auzemery, A., Willingshofer, E., Yamato, P., Duretz, T., & Sokoutis, D. (2020). Strain localization mechanisms for subduction initiation at passive margins. *Global and Planetary Change*, *195*, 103323.

Baes, M., Gerya, T., & Sobolev, S. V. (2016). 3-D thermo-mechanical modeling of plume-induced subduction initiation. *Earth and Planetary Science Letters*, *453*, 193–203.

Baes, M., Govers, R., & Wortel, R. (2011a). Subduction initiation along the inherited weakness zone at the edge of a slab: Insights from numerical models. *Geophysical Journal International*, *184*(3), 991–1008.

Baes, M., Govers, R., & Wortel, R. (2011b). Switching between alternative responses of the lithosphere to continental collision. *Geophysical Journal International*, *187*(3), 1151–1174.

Baes, M., & Sobolev, S. V. (2017). Mantle flow as a trigger for subduction initiation: A missing element of the Wilson Cycle concept. *Geochemistry, Geophysics, Geosystems*, *18*(12), 4469–4486. https://doi.org/10.1002/2017GC006962

Baes, M., Sobolev, S., Gerya, T., & Brune, S. (2020a). Plume-induced subduction initiation: Single-slab or multi-slab subduction?. *Geochemistry, Geophysics, Geosystems*, *21*(2), e2019GC008663. https://doi.org/10.1029/2019GC008663

Baes, M., Sobolev, S. V., Gerya, T., & Brune, S. (2020b). Subduction initiation by plume-plateau interaction: Insights from numerical models. *Geochemistry, Geophysics, Geosystems*, *21*, e2020GC009119. https://doi.org/10.1029/2020GC009119

Baes, M., Sobolev, S. V., & Quinteros, J. (2018). Subduction initiation in mid-ocean induced by mantle suction flow. *Geophysical Journal International*, *215*(3), 1515–1522.

Bahadori, A., & Holt, W. E. (2019). Geodynamic evolution of southwestern North America since the Late Eocene. *Nature Communications*, *10*(1), 1–18.

Ballato, P., Brune, S., & Strecker, M. R. (2019). Sedimentary loading-unloading cycles and faulting in intermontane basins: Insights from numerical modeling and field observations in the NW Argentine Andes. *Earth and Planetary Science Letters*, *506*, 388–396.

Beaussier, S. J., Gerya, T. V., & Burg, J. P. (2019). Near-ridge initiation of intraoceanic subduction: Effects of inheritance in 3D numerical models of the Wilson Cycle. *Tectonophysics*, *763*, 1–13.

Beniest, A., Koptev, A., & Burov, E. (2017a). Numerical models for continental break-up: Implications for the South Atlantic. *Earth and Planetary Science Letters*, *461*, 176–189.

Beniest, A., Koptev, A., Leroy, S., Sassi, W., & Guichet, X. (2017b). Two-branch break-up systems by a single mantle plume: Insights from numerical modeling. *Geophysical Research Letters*, *44*(19), 9589–9597.

Bercovici, D. (2003). The generation of plate tectonics from mantle convection. *Earth and Planetary Science Letters*, *205*(3–4), 107–121.

Billi, A., Presti, D., Faccenna, C., Neri, G., & Orecchio, B. (2007). Seismotectonics of the Nubia plate compressive margin in the south Tyrrhenian region, Italy: Clues for subduction inception. *Journal of Geophysical Research*, *112*(B8). https://doi.org/10.1029/2006JB004837

Boutelier, D., & Beckett, D. (2018). Initiation of subduction along oceanic transform faults: Insights from three-dimensional analog modeling experiments. *Frontiers of Earth Science*, *6*, 204.

Brandl, P. A., Hamada, M., Arculus, R. J., Johnson, K., Marsaglia, K. M., Savov, I. P., & Li, H. (2017). The arc arises: The links between volcanic output, arc evolution and melt composition. *Earth and Planetary Science Letters*, *461*, 73–84.

Braun, J., & Yamato, P. (2010). Structural evolution of a three-dimensional, finite-width crustal wedge. *Tectonophysics*, *484*, 181–192.

Brune, S., & Autin, J. (2013). The rift to break-up evolution of the Gulf of Aden: Insights from 3D numerical lithospheric-scale modelling. *Tectonophysics*, *607*, 65–79.

Burov, E. B. (2011). Rheology and strength of the lithosphere. *Marine and Petroleum Geology*, *28*(8), 1402–1443.

Burov, E., & Cloetingh, S. (2009). Controls of mantle plumes and lithospheric folding on modes of intraplate continental tectonics: Differences and similarities. *Geophysical Journal International*, *178*(3), 1691–1722.

Burov, E., & Cloetingh, S. (2010). Plume-like upper mantle instabilities drive subduction initiation. *Geophysical Research Letters*, *37*(3). https://doi.org/10.1029/2009GL041535

Burov, E., Jolivet, L., Le Pourhiet, L., & Poliakov, A. (2001). A thermomechanical model of exhumation of high pressure (HP) and ultra-high pressure (UHP) metamorphic rocks in Alpine-type collision belts. *Tectonophysics*, *342*(1–2), 113–136.

Burov, E., & Poliakov, A. (2003). Erosional forcing of basin dynamics: New aspects of syn-and post-rift evolution. In D. A. Nieuwland. *New Insights into Structural Interpretation and Modelling*, Geological Society, London, Special Publications (Vol. 212, pp. 209–223). Geological Society. https://doi.org/10.1144/GSL.SP.2003.212.01.14

Burov, E., & Yamato, P. (2008). Continental plate collision, P-T-t-z conditions and unstable vs. stable plate dynamics: Insights from thermo-mechanical modelling. *Lithos*, *103*(1–2), 178–204.

Carminati, E., Wortel, M. J. R., Spakman, W., & Sabadini, R. (1998). The role of slab detachment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence. *Earth and Planetary Science Letters*, *160*(3–4), 651–665.

Chen, Y. W., Wu, J., & Suppe, J. (2019). Southward propagation of Nazca subduction along the Andes. *Nature*, *565*(7740), 441–447.

Chertova, M. V., Spakman, W., Geenen, T., Van Den Berg, A. P., & Van Hinsbergen, D. J. J. (2014). Underpinning tectonic reconstructions of the western Mediterranean region with dynamic slab evolution from 3-D numerical modeling. *Journal of Geophysical Research: Solid Earth*, *119*, 5876–5902. https://doi.org/10.1002/2014JB011150

Civiero, C., Custódio, S., Rawlinson, N., Strak, V., Silveira, G., Arroucau, P., & Corela, C. (2019). Thermal nature of mantle upwellings below the Ibero-western Maghreb region inferred from teleseismic tomography. *Journal of Geophysical Research: Solid Earth*, *124*, 1781–1801. https://doi.org/10.1029/2018JB016531

Cloetingh, S. A. P. L., Wortel, M. J. R., & Vlaar, N. J. (1982). Evolution of passive continental margins and initiation of subduction zones. *Nature*, *297*(5862), 139–142.

Cloetingh, S. A. P. L., Wortel, M. J. R., & Vlaar, N. J. (1984). Passive margin evolution, initiation of subduction and the Wilson cycle. *Tectonophysics*, *109*(1–2), 147–163.

Cloetingh, S., Wortel, R., & Vlaar, N. J. (1989). On the initiation of subduction zones. In L. J. Ruff, & H. Kanamori (Eds.), *Subduction zones Part II. Pageoph topical volumes* (pp. 7–25). Birkhäuser Basel.

Collignon, M., Kaus, B. J. P., May, D. A., & Fernandez, N. (2014). Influences of surface processes on fold growth during 3-D detachment folding. *Geochemistry, Geophysics, Geosystems*, *15*, 3281–3303. https://doi.org/10.1002/2014GC005450

Cooper, P. A., & Taylor, B. (1985). Polarity reversal in the Solomon Islands arc. *Nature*, *314*(6010), 428–430.

Courtillot, V., Davaille, A., Besse, J., & Stock, J. (2003). Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters*, *205*(3–4), 295–308.

Crameri, F., & Kaus, B. J. (2010). Parameters that control lithospheric-scale thermal localization on terrestrial planets. *Geophysical Research Letters*, *37*(9). https://doi.org/10.1029/2010GL042921

Crameri, F., Magni, V., Domeier, M., Shephard, G. E., Chotalia, K., Cooper, G., & Mulyukova, E. (2020). A transdisciplinary and community-driven database to unravel subduction zone initiation. *Nature Communications*, *11*(1), 3750.

Crameri, F., & Tackley, P. J. (2015). Parameters controlling dynamically self-consistent plate tectonics and single-sided subduction in global models of mantle convection. *Journal of Geophysical Research: Solid Earth*, *120*, 3680–3706. https://doi.org/10.1002/2014JB011664

Dalziel, I. W., Lawver, L. A., Norton, I. O., & Gahagan, L. M. (2013). The Scotia Arc: genesis, evolution, global significance. *Annual Review of Earth and Planetary Sciences*, *41*.

Davies, J. H. (1999). The role of hydraulic fractures and intermediate-depth earthquakes in generating subduction-zone magmatism. *Nature*, *398*(6723), 142–145.

Dewey, J. F., Pitman, W. C., III, Ryan, W. B., & Bonnin, J. (1973). Plate tectonics and the evolution of the Alpine system. *The Geological Society of America Bulletin*, *84*(10), 3137–3180.

Duarte, J., Riel, N., Civiero, C., Rosas, F., Schellart, W., Almeida, J., & Terrinha, P. (2019). Delamination of oceanic lithosphere in SW Iberia: a key for subduction initiation? *Geophysical Research Abstracts*, *21*.

Duarte, J. C., Rosas, F. M., Terrinha, P., Schellart, W. P., Boutelier, D., Gutscher, M. A., & Ribeiro, A. (2013). Are subduction zones invading the Atlantic? Evidence from the southwest Iberia margin. *Geology*, *41*(8), 839–842.

Duarte, J. C., Schellart, W. P., & Rosas, F. M. (2018). The future of Earth's oceans: consequences of subduction initiation in the Atlantic and implications for supercontinent formation. *Geological Magazine*, *155*(1), 45–58.

Duretz, T., Agard, P., Yamato, P., Ducassou, C., Burov, E. B., & Gerya, T. V. (2016). Thermo-mechanical modeling of the obduction process based on the Oman ophiolite case. *Gondwana Research*, *32*, 1–10.

Duretz, T., Gerya, T. V., & Spakman, W. (2014). Slab detachment in laterally varying subduction zones: 3-D numerical modeling. *Geophysical Research Letters*, *41*(6), 1951–1956. https://doi.org/10.1002/2014GL059472

Dymkova, D., & Gerya, T. (2013). Porous fluid flow enables oceanic subduction initiation on Earth. *Geophysical Research Letters*, *40*(21), 5671–5676. https://doi.org/10.1002/2013GL057798

Faccenda, M., Gerya, T. V., & Chakraborty, S. (2008). Styles of post-subduction collisional orogeny: Influence of convergence velocity, crustal rheology and radiogenic heat production. *Lithos*, *103*(1–2), 257–287.

Faccenna, C., Giardini, D., Davy, P., & Argentieri, A. (1999). Initiation of subduction at Atlantic-type margins: Insights from laboratory experiments. *Journal of Geophysical Research*, *104*(B2), 2749–2766.

François, T., Burov, E., Agard, P., & Meyer, B. (2014). Buildup of a dynamically supported orogenic plateau: Numerical modeling of the Zagros/Central Iran case study. *Geochemistry, Geophysics, Geosystems*, *15*(6), 2632–2654. https://doi.org/10.1002/2013GC005223

François, T., Koptev, A., Cloetingh, S., Burov, E., & Gerya, T. (2018). Plume-lithosphere interactions in rifted margin tectonic settings: Inferences from thermo-mechanical modelling. *Tectonophysics*, *746*, 138–154.

French, S. W., & Romanowicz, B. (2015). Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature*, *525*(7567), 95–99.

Gerya, T. (2011). Future directions in subduction modeling. *Journal of Geodynamics*, *52*(5), 344–378.

Gerya, T. V. (2014). Plume-induced crustal convection: 3D thermomechanical model and implications for the origin of novae and coronae on Venus. *Earth and Planetary Science Letters*, *391*, 183–192.

Gerya, T. V., Connolly, J. A., & Yuen, D. A. (2008). Why is terrestrial subduction one-sided? *Geology*, *36*(1), 43–46.

Gerya, T. V., & Meilick, F. I. (2011). Geodynamic regimes of subduction under an active margin: effects of rheological weakening by fluids and melts. *Journal of Metamorphic Geology*, *29*(1), 7–31.

Gerya, T. V., Stern, R. J., Baes, M., Sobolev, S. V., & Whattam, S. A. (2015). Plate tectonics on the Earth triggered by plume-induced subduction initiation. *Nature*, *527*(7577), 221–225.

Giner-Robles, J. L., González-Casado, J. M., Gumiel, P., Martın-Velázquez, S., & Garcıa-Cuevas, C. (2003). A kinematic model of the Scotia plate (SW Atlantic Ocean). *Journal of South American Earth Sciences*, *16*(4), 179–191.

Goren, L., Aharonov, E., Mulugeta, G., Koyi, H. A., & Mart, Y. (2008). Ductile deformation of passive margins: A new mechanism for subduction initiation. *Journal of Geophysical Research*, *113*(B8). https://doi.org/10.1029/2005JB004179

Govers, R., & Wortel, M. J. R. (2005). Lithosphere tearing at STEP faults: Response to edges of subduction zones. *Earth and Planetary Science Letters*, *236*(1–2), 505–523.

Göğüş, O. H., Pysklywec, R. N., & Faccenna, C. (2016). Postcollisional lithospheric evolution of the Southeast Carpathians: Comparison of geodynamical models and observations. *Tectonics*, *35*(5), 1205–1224.

Gueydan, F., Morency, C., & Brun, J. P. (2008). Continental rifting as a function of lithosphere mantle strength. *Tectonophysics*, *460*(1–4), 83–93.

Gülcher, A. J., Beaussier, S. J., & Gerya, T. V. (2019). On the formation of oceanic detachment faults and their influence on intra-oceanic subduction initiation: 3D thermomechanical modeling. *Earth and Planetary Science Letters*, *506*, 195–208.

Gülcher, A. J. P., Gerya, T. V., Montési, L. G. J., & Munch, J. (2020). Corona structures driven by plume-lithosphere interactions and evidence for ongoing plume activity on Venus. *Nature Geoscience*, *13*, 547–554.

Gurnis, M., Hall, C., & Lavier, L. (2004). Evolving force balance during incipient subduction. *Geochemistry, Geophysics, Geosystems*, *5*(7). https://doi.org/10.1029/2003GC000681

Gutscher, M. A., Malod, J., Rehault, J. P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., & Spakman, W. (2002). Evidence for active subduction beneath Gibraltar. *Geology*, *30*(12), 1071–1074.

Hall, R. (2012). Late Jurassic-Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics*, *570*, 1–41.

Hall, C. E., Gurnis, M., Sdrolias, M., Lavier, L. L., & Müller, R. D. (2003). Catastrophic initiation of subduction following forced convergence across fracture zones. *Earth and Planetary Science Letters*, *212*(1–2), 15–30.

Handy, M. R., Ustaszewski, K., & Kissling, E. (2015). Reconstructing the Alps-Carpathians-Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. *International Journal of Earth Sciences*, *104*(1), 1–26.

Han, Y., & Zhao, G. (2018). Final amalgamation of the Tianshan and Junggar orogenic collage in the southwestern Central Asian Orogenic Belt: Constraints on the closure of the Paleo-Asian Ocean. *Earth-Science Reviews*, *186*, 129–152.

Han, Y., Zhao, G., Cawood, P. A., Sun, M., Eizenhöfer, P. R., Hou, W., & Liu, Q. (2016). Tarim and North China cratons linked to northern Gondwana through switching accretionary tectonics and collisional orogenesis. *Geology*, *44*(2), 95–98.

Harangi, S., Jankovics, M. É., Sági, T., Kiss, B., Lukács, R., & Soós, I. (2015). Origin and geodynamic relationships of the Late Miocene to Quaternary alkaline basalt volcanism in the Pannonian basin, eastern-central Europe. *International Journal of Earth Sciences*, *104*(8), 2007–2032.

Harangi, S., & Lenkey, L. (2007). Genesis of the Neogene to Quaternary volcanism in the Carpathian-Pannonian region: Role of subduction, extension, and mantle plume. *Geological Society of America Special Paper*, *418*, 67–92.

He, C., & Santosh, M. (2018). Role of mantle dynamics in rebuilding the Tianshan Orogenic Belt in NW China: A seismic tomographic investigation. *Journal of Geodynamics*, *116*, 37–46.

Hetényi, G., Stuart, G. W., Houseman, G. A., Horváth, F., Hegedűs, E., & Brückl, E. (2009). Anomalously deep mantle transition zone below Central Europe: Evidence of lithospheric instability. *Geophysical Research Letters*, *36*(21). https://doi.org/10.1029/2009GL040171

Hier-Majumder, S., & Hirschmann, M. M. (2017). The origin of volatiles in the Earth's mantle. *Geochemistry, Geophysics, Geosystems*, *18*(8), 3078–3092. https://doi.org/10.1002/2017GC006937

Huismans, R. S., & Beaumont, C. (2003). Symmetric and asymmetric lithospheric extension: Relative effects of frictional-plastic and viscous strain softening. *Journal of Geophysical Research*, *108*(B10). https://doi.org/10.1029/2002JB002026

Hu, J., Liu, L., Faccenda, M., Zhou, Q., Fischer, K. M., Marshak, S., & Lundstrom, C. (2018). Modification of the Western Gondwana craton by plume-lithosphere interaction. *Nature Geoscience*, *11*(3), 203–210.

Ismail-Zadeh, A., Adamia, S., Chabukiani, A., Chelidze, T., Cloetingh, S., Floyd, M., & Soloviev, A. (2020). Geodynamics, seismicity, and seismic hazards of the Caucasus. *Earth-Science Reviews*, 103222.

Ismail-Zadeh, A., Matenco, L., Radulian, M., Cloetingh, S., & Panza, G. (2012). Geodynamics and intermediate-depth seismicity in Vrancea (the south-eastern Carpathians): Current state-of-the art. *Tectonophysics*, *530*, 50–79.

Jagoutz, O., Royden, L., Holt, A. F., & Becker, T. W. (2015). Anomalously fast convergence of India and Eurasia caused by double subduction. *Nature Geoscience*, *8*(6), 475–478.

Jellinek, A. M., & Manga, M. (2002). The influence of a chemical boundary layer on the fixity, spacing and lifetime of mantle plumes. *Nature*, *418*(6899), 760–763.
Johnson, H., Dore, T. G., Gatliff, R., Holdsworth, R. W., Lundin, E. R., & Ritchie, D. (2008). The nature and origin of compression in passive margins. (Vol. *306*, p. 220). Geological Society of London, Special Publications.
Jolivet, L., Faccenna, C., Agard, P., Frizon de Lamotte, D., Menant, A., Sternai, P., & Guillocheau, F. (2016). Neo-Tethys geodynamics and mantle convection: from extension to compression in Africa and a conceptual model for obduction. *Canadian Journal of Earth Sciences*, *53*(11), 1190–1204.
Kearey, P., Klepeis, K. A., & Vine, F. J. (2009). *Global tectonics* (3rd ed.(1–496). Willey-Blackwell.
Kerr, A. (2003). Oceanic plateaus. *Treatise on Geochemistry*, *3*, 537–565.
Kerr, A. C. (2015). Oceanic plateaus. In J. Harff, M. Meschede, S. Petersen, & J. Thiede (Eds.), *Encyclopedia of marine geosciences*. Dordrecht: Springer.
Kherroubi, A., Déverchère, J., Yelles, A., De Lépinay, B. M., Domzig, A., Cattaneo, A., & Graindorge, D. (2009). Recent and active deformation pattern off the easternmost Algerian margin, Western Mediterranean Sea: New evidence for contractional tectonic reactivation. *Marine Geology*, *261*(1–4), 17–32.
Kirby, S. H., & Kronenberg, A. K. (1987). Rheology of the lithosphere: selected topics. *Reviews of Geophysics*, *25*(6), 1219–1244.
Kohlstedt, D. L., Evans, B., & Mackwell, S. J. (1995). Strength of the lithosphere: Constraints imposed by laboratory experiments. *Journal of Geophysical Research*, *100*(B9), 17587–17602.
Koptev, A., Burov, E., Calais, E., Leroy, S., Gerya, T., Guillou-Frottier, L., & Cloetingh, S. (2016). Contrasted continental rifting via plume-craton interaction: Applications to Central East African Rift. *Geoscience Frontiers*, *7*(2), 221–236.
Koptev, A., Burov, E., Gerya, T., Le Pourhiet, L., Leroy, S., Calais, E., & Jolivet, L. (2018). Plume-induced continental rifting and break-up in ultra-slow extension context: Insights from 3D numerical modeling. *Tectonophysics*, *746*, 121–137.
Koptev, A., Calais, E., Burov, E., Leroy, S., & Gerya, T. (2015). Dual continental rift systems generated by plume-lithosphere interaction. *Nature Geoscience*, *8*(5), 388–392.
Koptev, A., Calais, E., Burov, E., Leroy, S., & Gerya, T. (2018b). Along-axis variations of rift width in a coupled lithosphere-mantle system, Application to East Africa. *Geophysical Research Letters*, *45*(11), 5362–5370. https://doi.org/10.1029/2018GL077276
Koptev, A., Cloetingh, S., Burov, E., François, T., & Gerya, T. (2017). Long-distance impact of Iceland plume on Norway's rifted margin. *Scientific Reports*, *7*(1), 1–11.
Koptev, A., Ehlers, T. A., Nettesheim, M., & Whipp, D. M. (2019). Response of a rheologically stratified lithosphere to subduction of an indenter-shaped plate: Insights into localized exhumation at orogen syntaxes. *Tectonics*, *38*(6), 1908–1930.
Koulakov, I. (2011). High-frequency P and S velocity anomalies in the upper mantle beneath Asia from inversion of worldwide traveltime data. *Journal of Geophysical Research*, *116*(B4). https://doi.org/10.1029/2010JB007938
Koulakov, I., Zabelina, I., Amanatashvili, I., & Meskhia, V. (2012). Nature of orogenesis and volcanism in the Caucasus region based on results of regional tomography. *Solid Earth*, *3*(2), 327.
Koulakov, I., Zaharia, B., Enescu, B., Radulian, M., Popa, M., Parolai, S., & Zschau, J. (2010). Delamination or slab detachment beneath Vrancea? New arguments from local earthquake tomography. *Geochemistry, Geophysics, Geosystems*, *11*(3). https://doi.org/10.1029/2009GC002811
Kovács, I., Lenkey, L., Green, D. H., Fancsik, T., Falus, G., Kiss, J., & Vikor, Z. (2017). The role of pargasitic amphibole in the formation of major geophysical discontinuities in the shallow upper mantle. *Acta Geodaetica et Geophysica*, *52*(2), 183–204.
Kovács, I., Patkó, L., Liptai, N., Lange, T. P., Taracsák, Z., Cloetingh, S. A. P. L., et al. (2020). The role of water and compression in the genesis of alkaline basalts: Inferences from the Carpathian-Pannonian region. *Lithos*, *354*, 105323.
Kufner, S. K., Schurr, B., Sippl, C., Yuan, X., Ratschbacher, L., Ischuk, A., & Tilmann, F. (2016). Deep India meets deep Asia: Lithospheric indentation, delamination and break-off under Pamir and Hindu Kush (Central Asia). *Earth and Planetary Science Letters*, *435*, 171–184.
Kuritani, T., Xia, Q. K., Kimura, J. I., Liu, J., Shimizu, K., Ushikubo, T., & Yoshimura, S. (2019). Buoyant hydrous mantle plume from the mantle transition zone. *Scientific Reports*, *9*(1), 1–7.
Lallemand, S. (1999). *La subduction oceanique*. Newark, NY: Gordon and Breach.
Lavecchia, A., Beekman, F., Clark, S. R., & Cloetingh, S. A. P. L. (2016). Thermo-rheological aspects of crustal evolution during continental breakup and melt intrusion: The Main Ethiopian Rift, East Africa. *Tectonophysics*, *686*, 51–62.
Lavecchia, A., Thieulot, C., Beekman, F., Cloetingh, S., & Clark, S. (2017). Lithosphere erosion and continental breakup: Interaction of extension, plume upwelling and melting. *Earth and Planetary Science Letters*, *467*, 89–98.
Lee, S. M. (2004). Deformation from the convergence of oceanic lithosphere into Yap trench and its implications for early-stage subduction. *Journal of Geodynamics*, *37*(1), 83–102.
Leng, W., Gurnis, M., & Asimow, P. (2012). From basalts to boninites: The geodynamics of volcanic expression during induced subduction initiation. *Lithosphere*, *4*(6), 511–523.
Lenkey, L., Dövényi, P., Horváth, F., & Cloetingh, S. A. P. L. (2002). Geothermics of the Pannonian basin and its bearing on the neotectonics (Vol. 3, pp. 29–40). EGU Stephan Mueller Special Publication Series.
Levander, A., Schmandt, B., Miller, M. S., Liu, K., Karlstrom, K. E., Crow, R. S., et al. (2011). Continuing Colorado Plateau uplift by delamination-style convective lithospheric downwelling. *Nature*, *472*(7344), 461–465.
Li, Z. H., Liu, M., & Gerya, T. (2016). Lithosphere delamination in continental collisional orogens: A systematic numerical study. *Journal of Geophysical Research: Solid Earth*, *121*, 5186–5211. https://doi.org/10.1002/2016JB013106
Lippitsch, R., Kissling, E., & Ansorge, J. (2003). Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. *Journal of Geophysical Research*, *108*(B8). https://doi.org/10.1029/2002JB002016
Liu, L., Morgan, J. P., Xu, Y., & Menzies, M. (2018). Craton destruction 1: Cratonic keel delamination along a weak mid-lithospheric discontinuity layer. *Journal of Geophysical Research: Solid Earth*, *123*, 10–040. https://doi.org/10.1029/2017JB015372
Li, S., Weng, A., Li, J., Shan, X., Han, J., Tang, Y., & Wang, X. (2020). The deep origins of Cenozoic volcanoes in Northeast China revealed by 3-D electrical structure. *Science China Earth Sciences*, 1–15.
Li, Z. H., Xu, Z., Gerya, T., & Burg, J. P. (2013). Collision of continental corner from 3-D numerical modeling. *Earth and Planetary Science Letters*, *380*, 98–111.
Lopez, I., Marquez, A., & Oyarzun, R. (1997). Are coronae restricted to Venus? Corona-like tectonovolcanic structures on Earth. *Earth, Moon, and Planets*, *77*(2), 125.
Lu, G., Kaus, B. J., Zhao, L., & Zheng, T. (2015). Self-consistent subduction initiation induced by mantle flow. *Terra Nova*, *27*(2), 130–138.
Lundin, E., & Doré, A. G. (2002). Mid-Cenozoic post-breakup deformation in the "passive" margins bordering the Norwegian-Greenland Sea. *Marine and Petroleum Geology*, *19*(1), 79–93.

Lundin, E. R., & Doré, A. G. (2005). NE Atlantic break-up: A re-examination of the Iceland mantle plume model and the Atlantic-Arctic linkage. *Geological Society, London, Petroleum Geology Conference series*, *6*(1), 739–754.

Lundin, E. R., Doré, A. G., Rønning, K., & Kyrkjebø, R. (2013). Repeated inversion and collapse in the Late Cretaceous-Cenozoic northern Vøring Basin, offshore Norway. *Petroleum Geoscience*, *19*(4), 329–341.

Maffione, M., Thieulot, C., Van Hinsbergen, D. J., Morris, A., Plümper, O., & Spakman, W. (2015). Dynamics of intraoceanic subduction initiation: 1. Oceanic detachment fault inversion and the formation of supra-subduction zone ophiolites. *Geochemistry, Geophysics, Geosystems*, *16*(6), 1753–1770. https://doi.org/10.1002/2015GC005746

Marques, F. O., Nikolaeva, K., Assumpção, M., Gerya, T. V., Bezerra, F. H., do Nascimento, A. F., & Ferreira, J. M. (2013). Testing the influence of far-field topographic forcing on subduction initiation at a passive margin. *Tectonophysics*, *608*, 517–524.

Mart, Y., Aharonov, E., Mulugeta, G., Ryan, W., Tentler, T., & Goren, L. (2005). Analogue modelling of the initiation of subduction. *Geophysical Journal International*, *160*(3), 1081–1091.

Matenco, L., Bertotti, G., Leever, K., Cloetingh, S. A. P. L., Schmid, S. M., Tărăpoancă, M., & Dinu, C. (2007). Large-scale deformation in a locked collisional boundary: Interplay between subsidence and uplift, intraplate stress, and inherited lithospheric structure in the late stage of the SE Carpathians evolution. *Tectonics*, *26*(4).

Matsumoto, T., & Tomoda, Y. (1983). Numerical simulation of the initiation of subduction at the fracture zone. *Journal of Physics of the Earth*, *31*(3), 183–194.

Meulenkamp, J. E., Kováč, M., & Cicha, I. (1996). On Late Oligocene to Pliocene depocentre migrations and the evolution of the Carpathian-Pannonian system. *Tectonophysics*, *266*(1–4), 301–317.

Mueller, S., & Phillips, R. J. (1991). On the initiation of subduction. *Journal of Geophysical Research*, *96*(B1), 651–665.

Munch, J., Gerya, T., & Ueda, K. (2020). Oceanic crust recycling controlled by weakening at slab edges. *Nature Communications*, *11*(1), 2009.

Mulibo, G. D., & Nyblade, A. A. (2013). Mantle transition zone thinning beneath eastern Africa: Evidence for a whole-mantle superplume structure. *Geophysical Research Letters*, *40*(14), 3562–3566.

Nettesheim, M., Ehlers, T. A., Whipp, D. M., & Koptev, A. (2018). The influence of upper-plate advance and erosion on overriding plate deformation in orogen syntaxes. *Solid Earth*, *9*, 1207–1224.

Nikolaeva, K., Gerya, T. V., & Connolly, J. A. (2008). Numerical modelling of crustal growth in intraoceanic volcanic arcs. *Physics of the Earth and Planetary Interiors*, *171*(1–4), 336–356.

Nikolaeva, K., Gerya, T. V., & Marques, F. O. (2010). Subduction initiation at passive margins: Numerical modeling. *Journal of Geophysical Research*, *115*(B3). https://doi.org/10.1029/2009JB006549

Nikolaeva, K., Gerya, T. V., & Marques, F. O. (2011). Numerical analysis of subduction initiation risk along the Atlantic American passive margins. *Geology*, *39*(5), 463–466.

Pascal, C., & Cloetingh, S. A. (2009). Gravitational potential stresses and stress field of passive continental margins: Insights from the south-Norway shelf. *Earth and Planetary Science Letters*, *277*(3–4), 464–473.

Petrescu, L., Stuart, G., Tataru, D., & Grecu, B. (2019). Crustal structure of the Carpathian Orogen in Romania from receiver functions and ambient noise tomography: How craton collision, subduction and detachment affect the crust. *Geophysical Journal International*, *218*(1), 163–178.

Petterson, M. G., Babbs, T., Neal, C. R., Mahoney, J. J., Saunders, A. D., Duncan, R. A., & Natogga, D. (1999). Geological-tectonic framework of Solomon Islands, SW Pacific: Crustal accretion and growth within an intra-oceanic setting. *Tectonophysics*, *301*(1–2), 35–60.

Platt, J. P., Behr, W. M., Johanesen, K., & Williams, J. R. (2013). The Betic-Rif arc and its orogenic hinterland: A review. *Annual Reviews of Earth and Planetary Sciences*, *41*, 313–357.

Platt, J., & Houseman, G. (2003). Evidence for active subduction beneath Gibraltar: Comment. *Geology*, *31*(1), e22.

Pysklywec, R. N. (2001). Evolution of subducting mantle lithosphere at a continental plate boundary. *Geophysical Research Letters*, *28*(23), 4399–4402. https://doi.org/10.1029/2001GL013567

Pysklywec, R. N., Gogus, O., Percival, J., Cruden, A. R., & Beaumont, C. (2010). Insights from geodynamical modeling on possible fates of continental mantle lithosphere: Collision, removal, and overturn. *Canadian Journal of Earth Sciences*, *47*(4), 541–563.

Reagan, M. K., Pearce, J. A., Petronotis, K., Almeev, R. R., Avery, A. J., Carvallo, C., & Heaton, D. E. (2017). Subduction initiation and ophiolite crust: New insights from IODP drilling. *International Geology Review*, *59*(11), 1439–1450.

Reemst, P., & Cloetingh, S. (2000). Polyphase rift evolution of the Vøring margin (mid-Norway): Constraints from forward tectonostratigraphic modeling. *Tectonics*, *19*(2), 225–240.

Regard, V., Faccenna, C., Martinod, J., Bellier, O., & Thomas, J. C. (2003). From subduction to collision: Control of deep processes on the evolution of convergent plate boundary. *Journal of Geophysical Research*, *108*(B4). https://doi.org/10.1029/2002JB001943

Regenauer-Lieb, K., Yuen, D. A., & Branlund, J. (2001). The initiation of subduction: criticality by addition of water? *Science*, *294*(5542), 578–580.

Rickers, F., Fichtner, A., & Trampert, J. (2013). The Iceland-Jan Mayen plume system and its impact on mantle dynamics in the North Atlantic region: Evidence from full-waveform inversion. *Earth and Planetary Science Letters*, *367*, 39–51.

Roberts, K., & Head, J. W. (1993). Large-scale volcanism associated with coronae on Venus: Implications for formation and evolution. *Geophysical Research Letters*, *20*(12), 1111–1114. https://doi.org/10.1029/93GL01484

Roy, S. G., Koons, P. O., Upton, P., & Tucker, G. E. (2016). Dynamic links among rock damage, erosion, and strain during orogenesis. *Geology*, *44*, 583–586.

Rychert, C. A., & Shearer, P. M. (2009). A global view of the lithosphere-asthenosphere boundary. *Science*, *324*(5926), 495–498.

Saunders, A. D., Fitton, J. G., Kerr, A. C., Norry, M. J., & Kent, R. W. (1997). The north Atlantic igneous province (Vol. 100, pp. 45–94). Geophysical Monographs, American Geophysical Union.

Schoonman, C. M., White, N. J., & Pritchard, D. (2017). Radial viscous fingering of hot asthenosphere within the Icelandic plume beneath the North Atlantic Ocean. *Earth and Planetary Science Letters*, *468*, 51–61.

Seghedi, I., Downes, H., Szakács, A., Mason, P. R., Thirlwall, M. F., Roşu, E., & Panaiotu, C. (2004). Neogene-Quaternary magmatism and geodynamics in the Carpathian-Pannonian region: A synthesis. *Lithos*, *72*(3–4), 117–146.

Selway, K., Ford, H., & Kelemen, P. (2015). The seismic mid-lithosphere discontinuity. *Earth and Planetary Science Letters*, *414*, 45–57.

Sobolev, S. V., Sobolev, A. V., Kuzmin, D. V., Krivolutskaya, N. A., Petrunin, A. G., Arndt, N. T., & Vasiliev, Y. R. (2011). Linking mantle plumes, large igneous provinces and environmental catastrophes. *Nature*, *477*(7364), 312–316.

Solomatov, V. S. (2004). Initiation of subduction by small-scale convection. *Journal of Geophysical Research*, *109*(B1). https://doi.org/10.1029/2003JB002628

Steinberger, B., Bredow, E., Lebedev, S., Schaeffer, A., & Torsvik, T. H. (2019). Widespread volcanism in the Greenland–North Atlantic region explained by the Iceland plume. *Nature Geoscience*, *12*(1), 61–68.

Stern, R. J. (2002). Subduction zones. *Reviews of Geophysics*, *40*(4), 3-1-3-38.

Stern, R. J. (2004). Subduction initiation: spontaneous and induced. *Earth and Planetary Science Letters*, *226*(3–4), 275–292.

Sternai, P. (2020). Surface processes forcing on extensional rock melting. *Scientific Reports*, *10*(1), 1–13.

Stern, R. J., & Bloomer, S. H. (1992). Subduction zone infancy: examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs. *Geological Society of America Bulletin*, *104*(12), 1621–1636.

Stern, R. J., & Dumitru, T. A. (2019). Eocene initiation of the Cascadia subduction zone: A second example of plume-induced subduction initiation? *Geosphere*, *15*(3), 659–681.

Stern, R. J., & Gerya, T. (2018). Subduction initiation in nature and models: A review. *Tectonophysics*, *746*, 173–198.

Stofan, E. R., Bindschadler, D. L., Head, J. W., & Parmentier, E. M. (1991). Corona structures on Venus: Models of origin. *Journal of Geophysical Research*, *96*(E4), 20933–20946.

Sun, W., Zhao, L., Malusà, M. G., Guillot, S., & Fu, L. Y. (2019). 3-D Pn tomography reveals continental subduction at the boundaries of the Adriatic microplate in the absence of a precursor oceanic slab. *Earth and Planetary Science Letters*, *510*, 131–141.

Sychev, I. V., Koulakov, I., Sycheva, N. A., Koptev, A., Medved, I., El Khrepy, S., & Al-Arifi, N. (2018). Collisional processes in the crust of the northern Tien Shan inferred from velocity and attenuation tomography studies. *Journal of Geophysical Research: Solid Earth*, *123*, 1752–1769. https://doi.org/10.1002/2017JB014826

Teng, L. S., Lee, C. T., Tsai, Y. B., & Hsiao, L. Y. (2000). Slab breakoff as a mechanism for flipping of subduction polarity in Taiwan. *Geology*, *28*(2), 155–158.

Tetreault, J. Á., & Buiter, S. J. H. (2012). Geodynamic models of terrane accretion: Testing the fate of island arcs, oceanic plateaus, and continental fragments in subduction zones. *Journal of Geophysical Research*, *117*(B8). https://doi.org/10.1029/2012JB009316

Thielmann, M., & Kaus, B. J. (2012). Shear heating induced lithospheric-scale localization: Does it result in subduction? *Earth and Planetary Science Letters*, *359*, 1–13.

Thieulot, C., Steer, P., & Huismans, R. S. (2014). Three-dimensional numerical simulations of crustal systems undergoing orogeny and subjected to surface processes. *Geochemistry, Geophysics, Geosystems*, *15*, 4936–4957. https://doi.org/10.1002/2014GC005490

Thompson, R. N., & Gibson, S. A. (2000). Transient high temperatures in mantle plume heads inferred from magnesian olivines in Phanerozoic picrites. *Nature*, *407*(6803), 502–506.

Toth, J., & Gurnis, M. (1998). Dynamics of subduction initiation at preexisting fault zones. *Journal of Geophysical Research*, *103*(B8), 18053–21806.

Turcotte, D., & Schubert, G. (2014). *Geodynamics*, (1–636). Cambridge University Press.

Ueda, K., Gerya, T. V., & Burg, J. P. (2012). Delamination in collisional orogens: Thermomechanical modeling. *Journal of Geophysical Research*, *117*(B8). https://doi.org/10.1029/2012JB009144

Ueda, K., Gerya, T., & Sobolev, S. V. (2008). Subduction initiation by thermal-chemical plumes: Numerical studies. *Physics of the Earth and Planetary Interiors*, *171*(1–4), 296–312.

Ueda, K., Willett, S. D., Gerya, T., & Ruh, J. (2015). Geomorphological-thermo-mechanical modeling: Application to orogenic wedge dynamics. *Tectonophysics*, *659*, 12–30.

Vågnes, E., Gabrielsen, R. H., & Haremo, P. (1998). Late Cretaceous-Cenozoic intraplate contractional deformation at the Norwegian continental shelf: Timing, magnitude and regional implications. *Tectonophysics*, *300*(1–4), 29–46.

Van der Lee, S., Regenauer-Lieb, K., & Yuen, D. A. (2008). The role of water in connecting past and future episodes of subduction. *Earth and Planetary Science Letters*, *273*(1–2), 15–27.

Vlaar, N. J., & Wortel, M. J. R. (1976). Lithospheric aging, instability and subduction. *Tectonophysics*, *32*(3–4), 331–351.

Vogt, K., & Gerya, T. V. (2014). From oceanic plateaus to allochthonous terranes: Numerical modelling. *Gondwana Research*, *25*(2), 494–508.

Wang, Z., & Kusky, T. M. (2019). The importance of a weak mid-lithospheric layer on the evolution of the cratonic lithosphere. *Earth-Science Reviews*, *190*, 557–569.

Wang, Z., Kusky, T. M., & Capitanio, F. A. (2018). On the role of lower crust and midlithosphere discontinuity for cratonic lithosphere delamination and recycling. *Geophysical Research Letters*, *45*(15), 7425–7433.

Whattam, S. A. (2018). Primitive Magmas in the Early Central American Volcanic Arc System Generated by Plume-Induced Subduction Initiation. *Frontiers of Earth Science*, *6*, 114.

Whattam, S. A., & Stern, R. J. (2011). The "subduction initiation rule": A key for linking ophiolites, intra-oceanic forearcs, and subduction initiation. *Contributions to Mineralogy and Petrology*, *162*(5), 1031–1045.

Whattam, S. A., & Stern, R. J. (2015). Late Cretaceous plume-induced subduction initiation along the southern margin of the Caribbean and NW South America: The first documented example with implications for the onset of plate tectonics. *Gondwana Research*, *27*(1), 38–63.

White, R. S., & McKenzie, D. (1995). Mantle plumes and flood basalts. *Journal of Geophysical Research*, *100*(B9), 17543–17585.

Willingshofer, E., Sokoutis, D., Luth, S. W., Beekman, F., & Cloetingh, S. (2013). Subduction and deformation of the continental lithosphere in response to plate and crust-mantle coupling. *Geology*, *41*(12), 1239–1242.

Wilson, J. T. (1966). Did the Atlantic close and then re-open? *Nature*, *211*(5050), 676–681.

Wortel, M. J. R., & Spakman, W. (2000). Subduction and slab detachment in the Mediterranean-Carpathian region. *Science*, *290*(5498), 1910–1917.

Wright, J. E., & Wyld, S. J. (2011). Late Cretaceous subduction initiation on the eastern margin of the Caribbean-Colombian Oceanic Plateau: One Great Arc of the Caribbean (?). *Geosphere*, *7*(2), 468–493.

Xia, Q. K., Liu, J., Liu, S. C., Kovács, I., Feng, M., & Dang, L. (2013). High water content in Mesozoic primitive basalts of the North China Craton and implications on the destruction of cratonic mantle lithosphere. *Earth and Planetary Science Letters*, *361*, 85–97.

Yamato, P., Agard, P., Burov, E., Le Pourhiet, L., Jolivet, L., & Tiberi, C. (2007). Burial and exhumation in a subduction wedge: Mutual constraints from thermomechanical modeling and natural P-T-t data (Schistes Lustrés, western Alps). *Journal of Geophysical Research*, *112*(B7). https://doi.org/10.1029/2006JB004441

Zabelina, I., Koulakov, I., Amanatashvili, I., El Khrepy, S., & Al-Arifi, N. (2016). Seismic structure of the crust and uppermost mantle beneath Caucasus based on regional earthquake tomography. *Journal of Asian Earth Sciences*, *119*, 87–99.

Zhang, K. J. (2012). Destruction of the North China Craton: Lithosphere folding-induced removal of lithospheric mantle? *Journal of Geodynamics*, *53*, 8–17.

Zheng, Y., Chen, R., Xu, Z., & Zhang, S. (2016). The transport of water in subduction zones. *Science China Earth Sciences*, *59*(4), 651–682.

Zhou, X., Li, Z. H., Gerya, T. V., & Stern, R. J. (2020). Lateral propagation-induced subduction initiation at passive continental margins controlled by preexisting lithospheric weakness. *Science Advances*, *6*(10), eaaz1048.
Zhu, G., Gerya, T. V., Yuen, D. A., Honda, S., Yoshida, T., & Connolly, J. A. (2009). Three-dimensional dynamics of hydrous thermal-chemical plumes in oceanic subduction zones. *Geochemistry, Geophysics, Geosystems*, *10*(11). https://doi.org/10.1029/2009GC002625
Ziegler, P. A., & Cloetingh, S. (2004). Dynamic processes controlling evolution of rifted basins. *Earth-Science Reviews*, *64*(1–2), 1–50.
Zitellini, N., Ranero, C. R., Loreto, M. F., Ligi, M., Pastore, M., D'Oriano, F., & Prada, M. (2020). Recent inversion of the Tyrrhenian Basin. *Geology*, *48*(2), 123–127.

References from the Supporting Information

Artemieva, I. M. (2006). Global 1× 1 thermal model TC1 for the continental lithosphere: implications for lithosphere secular evolution. *Tectonophysics*, *416*(1–4), 245–277. https://doi.org/10.1016/j.tecto.2005.11.022
Burov, E.B., & Diament, M. (1995). The effective elastic thickness (Te) of continental lithosphere: What does it really mean? *Journal of Geophysical Research*, *100*, 3905–3927. https://doi.org/10.1029/94JB02770
Burov, E., & Poliakov, A. (2001). Erosion and rheology controls on synrift and postrift evolution: Verifying old and new ideas using a fully coupled numerical model. *Journal of Geophysical Research*, *106*, 16461–16481. https://doi.org/10.1029/2001JB000433
Byerlee, J. (1978). Friction of rocks. In *Rock friction and earthquake prediction*. Basel: Birkhäuser.
Chopra, P.N., & Paterson, M.S. (1984). The role of water in the deformation of dunite. *Journal of Geophysical Research*, *89*, 7861–7876. https://doi.org/10.1029/JB089iB09p07861
Crameri, F., Schmeling, H., Golabek, G.J., Duretz, T., Orendt, R., Buiter, S.J.H., et al. (2012). A comparison of numerical surface topography calculations in geodynamic modelling: an evolution of the "sticky air" method. *Geophysical Journal International*, *189*, 38–54. https://doi.org/10.1111/j.1365-246X.2012.05388.x
Cundall, P.A. (1989). Numerical experiments on localization in frictional materials. *Ingenieur-Archives*, *59*, 148–159. https://doi.org/10.1007/BF00538368
D'Acremont, E., Leroy, S., & Burov, E.B. (2003). Numerical modelling of a mantle plume: The plume head-lithosphere interaction in the formation of an oceanic large igneous province. *Earth Planetary Science Letters*, *206*, 379–396. https://doi.org/10.1016/S0012-821X(02)01058-0
Koptev, A. I., & Ershov, A. V. (2010). The role of the gravitational potential of the lithosphere in the formation of a global stress field. *Izvestiya, Physics of the Solid Earth*, *46*(12), 1080–1094. https://doi.org/10.1134/S1069351310120050
Koptev, A. I., & Ershov, A. V. (2011). Thermal thickness of the Earth's lithosphere: A numerical model. *Moscow University Geology Bulletin*, *66*(5), 323-330. https://doi.org/10.3103/S014587521105005X
Le Pourhiet, L., Burov, E., & Moretti, I. (2004). Rifting through a stack of inhomogeneous thrusts (the dipping pie concept). *Tectonics*, *23*, 1-14. https://doi.org/10.1029/2003TC001584
Poliakov, A., Podladchikov, Y., & Talbot, C. (1993). Initiation of salt diapirs with frictional overburdens: numerical experiments. *Tectonophysics*, *228*, 199–210. https://doi.org/10.1016/0040-1951(93)90341-G
Ranalli, G., 1995. *Rheology of the Earth*, 2nd ed (1–414). Springer Netherlands.
Turcotte, D., & Schubert, G. (2002). *Geodynamics*, (1–863). Cambridge University Press.
Yamato, P., Burov, E., Agard, P., Le Pourhiet, L., & Jolivet, L. (2008). HP-UHP exhumation during slow continental subduction: Self-consistent thermodynamically and thermomechanically coupled model with application to the Western Alps. *Earth Planetary Science Letters*, *271*, 63–74. https://doi.org/10.1016/j.epsl.2008.03.049