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Make subductions diverse again

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ABSTRACT

In the original plate-tectonic centric framework for Earth evolution as proposed in the 1960s, the term 'subduction' was initially applied to the down thrusting of oceanic lithosphere below a continental or oceanic upper plate, delineated by a Wadati-Benioff zone of earthquake foci. Over time, the use of the term has broadened and its meaning weakened by its application to the diversity of mechanisms accommodating lithospheric convergence, foundering and recycling. This has led to complex and sterile debates regarding the tectonic processes in orogens, the initiation of (modern) plate tectonics, or the tectonic regime on other planets, hampering a clear and concise discussion of those problems. We discuss three instances where the use of the ill-defined term "subduction" or even "proto-subduction", through biases and polysemism, has hampered scientific discourse, namely (i) the Cenozoic subduction of the Western Tethys leading to the formation of the European Alps; (ii) the initiation of (modern) "subduction" in the (eo)Archean; and, (iii) lithospheric recycling on Venus. We highlight that Benioff-type subduction is only one of a spectrum of mechanisms that have operated through time (Archean to present) for the foundering and recycling of lithosphere into the mantle. We propose a framework that summarizes the various end-member modes of foundering by focussing on two parameters (i) the type of lithosphere being foundered into the mantle and (ii) the mechanical driver of the foundering process, which might predominantly control convergence and recycling.

1. Introduction

Lithosphere foundering refers to the range of processes whereby material belonging to the uppermost layer of the Earth plunges into the asthenospheric mantle and its chemical components are recycled into the planetary interior. This process is one of the essential cornerstones of the plate tectonics paradigm, which requires that as new oceanic lithosphere (crust and upper mantle) is created at mid-ocean ridges, older lithosphere is destroyed at convergent plate boundaries, thus maintaining a constant surface area. On the modern Earth, subduction is by far the dominant mode of lithospheric foundering and recycling. The recognition of sea-floor spreading and the concomitant recycling of oceanic lithosphere back to the mantle at deep-sea trenches along Wadati-Benioff zones, delineated by earthquake foci (Wadati, 1935; Benioff, 1949; Vine and Matthews, 1963; Heezen and Tharp, 1965; Le Pichon, 1968; Isacks and Molnar, 1969), has been one of the most revolutionary scientific discoveries of the 20th century, paving the way for modern Earth and planetary sciences. It has profoundly shaped the way Earth scientists conceptualize orogenic cycles, continental drift, the formation of continental crust, the flux of heat and matter between solid (mantle and crust) and surficial (atmosphere, hydrosphere, biosphere) reservoirs, including the formation of mineral resources on which our society relies.

The concept of lithospheric foundering (see definitions in Section 2) dates back to Ampferer and Hammer (1911) who describe "Verschluckung" (translated to "downsucking") in the European Alps. Over the first half of the 20th century, similar lithospheric foundering processes have episodically been discussed under a range of descriptive terms (e.g., Holmes, 1931; White et al., 1970). The term 'subduction' was first coined by Amstutz (1955) to describe the under-thrusting of rock masses below others. Although initially developed from geological observation of the Alps, it soon provided a plausible explanation for the dipping Wadati-Benioff zone of earthquake hypocenters around the Pacific Ocean. As the theory of plate tectonics was being formalized in

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the late 1960s, the popularity of this descriptive term increased as it was free "*from genetic implication*" and independent "*of possibly unwarranted inferences about associated seismic, topographic, or bathymetric features*" (White et al., 1970, p. 3431).

During the subsequent decade, several seminal works demonstrated the relevance of foundering cold oceanic lithosphere on mantle convection, plate motions and deformation, establishing subduction as the central paradigm for the plate tectonics and planetary regimes. Reconciling thermal regimes of island arcs and subduction zones at depth revealed the deep thermal structures of slabs, and the role their mass anomaly has for plate motions and continental collision (McKenzie, 1969). This was later established as the fundamental engine of plate motions (Forsyth and Uyeda, 1975) and an integral part of mantle convection (Minear and Toksöz, 1970). The advent of numerical modelling contributed to the establishment of subduction of cold lithosphere in the mantle as a key process of the coupled plate tectonic and mantle convection system (Hager and O'Connell, 1981). The implications for the heat flow and surface mobility over geological times have been demonstrated to be far reaching, illustrating the relevance of global tectonic regimes for the Archean (Christensen, 1985) as well as for (Wilson) cycles of continent assembly and dispersal (Gurnis, 1988).

Other conceptual models have proposed that density contrasts between oceanic lithosphere and the asthenosphere are of a second order importance compared to convective currents exerting drag forces on the base of the lithosphere (e.g., Doglioni, 1991; Ziegler, 1992). Such geodynamic models propose that the general westward drift of lithosphere compared to the eastward movement of the mantle plays a key role on the asymmetrical evolution of lithosphere, such as deformation (compression and extension) of the overriding plate, formation of back-arc systems and changes in slab dip, and are due to different orientations of subducting oceanic slabs with respect to the convective mantle (e.g., Moore, 1973; Uyeda and Kanamori, 1979; Doglioni, 1991; Doglioni et al., 1999; Carminati and Doglioni, 2012 as well as Doglioni and Panza, 2015 for a detailed overview). Moreover, Varga et al. (2012) on the basis of global patterns of earthquakes proposed that the rotation of the Earth (e.g., tidal drag) exerts a long-term control on plate tectonic dynamics (c.f. Doglioni and Panza, 2015). Yet, such hypotheses currently largely lack a thorough quantitative assessment (Ficini et al., 2017) and rely on the hypothetical existence of an Earth-scale eastward directed "mantle wind" for which evidences are disputed (e.g., Schellart, 2009) *We* note that external celestial forcing mechanisms such as gravitational pull is thought to have an important influence on mantle dynamics and magmatism on satellites (e.g., Io) orbiting Jupiter for example (Peale et al., 1979; De Pater et al., 2020).

Nevertheless, the success of an Earth-scale plate-tectonic framework (e.g., Wilson, 1966, 1968) where-by rigid body-plate motion is primarily controlled by subduction of oceanic lithosphere (i.e., Benioff-type subduction; e.g., Carlson et al., 1983; Conrad and Lithgow-Bertelloni, 2002; Schellart, 2004), has largely overshadowed other mechanisms of lithosphere foundering among most sub-communities of Earth scientists. In fact, the original descriptive and versatile nature of the term 'subduction' has progressively grown heavier with a geodynamics component to end up referring almost exclusively to Benioff-type subduction, being currently accepted as the harbinger of plate tectonics. This semantic evolution has conversely been accompanied by the proposal, subdivision and refinement of a large range of models of lithosphere foundering that could equality qualify to the original term 'subduction' sensu Amstutz (1955).

Here, we present some key examples highlighting the need to (re-) define the meaning of the term 'subduction'. Further, we present a qualitative framework underscoring the great diversity of modes of lithosphere foundering. We also provide examples of known or suggested type localities throughout Earth history that document end-member modes of lithosphere foundering. We do not attempt to fully review the large body of studies across Earth and time that have already highlighted in greater details the peculiarity and complexities of individual lithosphere recycling systems. While modes of lithosphere recycling are ultimately controlled by physico-chemical parameters, a more 'geological' approach is warranted here. Our primary intention is to provide a first order framework to invite colleagues to be explicit in the exact type of lithosphere foundering mode that is invoked and to more clearly scrutinize the evidence for it.

2. Definitions regarding lithospheric foundering

In the following paragraphs we define some fundamental terms that will be used in this paper, in order to avoid the pitfalls and polysemism associated with some of them.

Benioff-type subduction (or B-type or Pacific-type subduction) is most commonly referred to as 'subduction' only. It describes the foundering of a slab of oceanic lithosphere previously formed at a mid-ocean ridge (e.g., Carlson et al., 1983: Cloos, 1993), beneath oceanic or continental upper plates. The negative buoyancy of the sinking lithosphere (being denser that the underlying asthenosphere) results in slab pull (Forsyth and Uyeda, 1975; Cloos, 1993; Ueda et al., 2008; Ganguly et al., 2009; Boonma et al., 2019) that is thought to be one of the dominant driving forces of plate motions. Subduction zones feature one or two planar zone (s) of seismicity in the downgoing slab (the Wadati-Benioff plane) (Benioff, 1949; Hasegawa et al., 1978), which may reach the mantle transition zone depth (~660 km). Slab dehydration is further responsible for fluid flux melting within the overlying mantle wedge and the generation of hydrous arc magmatism (e.g., Gill, 1981; Tatsumi et al., 1983). Benioff-type subduction is thought to require three fundamental conditions (cf., Stern, 2018) (i) lithospheric weaknesses along narrow interfaces allowing the development of plates and new margins; (ii) oceanic lithosphere that becomes less buoyant than the underlying upper mantle (asthenosphere); (iii) wide domain of subducting rigid oceanic lithosphere, which can develop a "slab-pull" effect.

Plate tectonics and continental tectonics: Plate tectonics refers to a model that describes the global interaction and kinematics of the lithosphere on the modern Earth whereby rigid tectonic plates made of oceanic and/or continental lithosphere move relative to each other. In this framework, relatively narrow, linear mid-ocean ridges represent divergent plate boundaries where new ocean lithosphere is created. In turn, older oceanic lithosphere is recycled into the asthenospheric mantle at convergent plate boundaries through Benioff-type subduction processes (cf., Stern, 2018). As opposed to the rigid-body motion of large tectonic plates, *continental tectonics* refers to tectonic processes in the continental interior that may be diffused over deformation zones up to thousands of kilometres in width segmented into smaller blocks (Molnar, 1988; Dewey et al., 1986; Mattauer, 1986). Continental tectonic processes include extensional, compressional and transform dynamics all of which may be associated with crustal and/or mantle derived magmatism. In contrast to the dense and rigid oceanic lithosphere, the continental lithosphere is buoyant and has lower yield strength, such that it accommodates convergent and extensional dynamics by crustal thickening and crustal thinning (up to exhumation of the subcontinental lithospheric mantle), respectively, both of which can further be associated with continental-scale crustal flow (e.g., Vanderhaeghe and Teyssier, 2001; Whitney et al., 2004; Medvedev and Beaumont, 2006).

Ampferer-type subduction (or A-type subduction) refers to the "Verschluckung", or downsucking of continental crust and is based on "missing" continental crust in the Alpine orogen (European Alps) (Ampferer and Hammer, 1911). This term was discarded and superseded by Benioff-type subduction with the advent of plate tectonics (cf., Trümpy, 2001). McCarthy et al. (2018, 2020) reinterpreted this mechanism of lithospheric recycling in the Pyrenees and the Western and Central Alps in light of new understanding of hyper-extended basins and passive margins. McCarthy et al. (2020) proposed that Ampferer-type subduction can be defined as the amagmatic closure of hyper-extended basins. These basins are formed by hyperextension of continental lithosphere, exhumation of (subcontinental) mantle and might reach the stage of (magma poor) embryonic oceans with active mid-ocean ridges. In these circumstances, the hyper-thinned nature of the continental lithosphere and mechanically weak serpentinised mantle act as a focus for the initiation of convergence and down-thrusting of "oceanic" material along passive margins (e.g., Zanchetta et al., 2012; Tugend et al., 2014; McCarthy et al., 2020; Auzemery et al., 2022). Consequently, only dry lithospheric mantle is subducted, whereas hydrated lithologies from the downgoing plate (hydrated mantle rocks, sedimentary deposits) are sequentially accreted into a nascent orogenic wedge, leading to amagmatic convergence (i.e., Alpine-type orogen; cf., Ernst, 2005; Mohn et al., 2014).

Delamination: Over time, cold, dense lower crust and residual mantle is likely to be convectively removed and recycled into the warm convective upper mantle, either as wholesale events or as gradual removal of fragments (Bird, 1979; Kay and Kay, 1993; Platt and England, 1994). Such a process of lithospheric recycling is, for example, invoked to account for the differentiation of continental crust through the recycling of primitive and dense mafic cumulates derived from the fractionation of hydrous magmas in arc settings (e.g., Rudnick, 1995; Kelemen, 1995; Müntener et al., 2001; Saleeby et al., 2003). The removal of lithospheric blocks may have operated similarly in the early Earth, providing a context for crustal differentiation (Chowdhury et al., 2017).

Drip and dripduction: Conditions of hotter Earth, likely in the Archean, lead to the lithosphere having distinct rheological properties. Under such conditions the dense granulitic to eclogitic lithosphere may drip into the asthenospheric mantle. Higher mantle temperatures in the early Earth imply a thinner lithospheric mantle and a weaker crust, thereby allowing the formation of downwelling (Rayleigh-Taylor instabilities) where crust drips in the underlying mantle. A drip is a short-wavelength downwelling of a hotter, weaker lithosphere, whereas delamination is the large-scale removal of coherent, rigid blocks into the asthenosphere (Houseman et al., 1981; van Thienen et al., 2004; Fischer and Gerya, 2016). A variant of recycling through drips is called dripduction, and involves a steep subduction-like geometry, whereby the tip of the soft and weak mafic plate systematically drips upon foundering and eclogitization (Moyen and van Hunen, 2012; Sizova et al., 2015). Likely, the difference between these drip-like instabilities is due to the convective vigour of the mantle (Rayleigh number): the more vigorous convection of a hotter mantle deflects effectively the thinner drips, whereas the opposite occurs in a warm mantle, where the lithospheric drips are thicker and the convection less vigorous. Although such processes have not been observed and are essentially based on physically-grounded geodynamic models, they are compatible with some geological observations of Archean terranes (e.g., Moyen and van Hunen, 2012; Moyen and Laurent, 2018).

Subcretion: This mechanism implies the accretion of lithosphere by underthrusting at a craton margin (Cooper et al., 2006; Bédard, 2013; Harris and Bédard, 2015; Bédard, 2018). Zones of lithospheric convergence would therefore act as the loci of cratonic blocks overriding weak thinner lithosphere leading to a gradual thickening. Note that in the case of Archean "dripduction" and "subcretion", the foundered lithosphere is likely to involve thick mafic crust (> 20 km thick; Sleep and Windley, 1982; Herzberg and Rudnick, 2012) and unlike "oceanic plate" sensu stricto that applies to Benioff-type subduction. Furthermore, it differs from Benioff-type flat subduction in that the underthrusted lithosphere is subsequently accreted to the cratonic margin while flat subduction implies continuous subduction.

3. Polysemism and confirmation bias: Abusing the word "subduction"

Cognitive and social psychologists have, in the last 50 years, produced a significant body of work explaining how human beings confidently and tenaciously favour an (apparently) unwarranted hypothesis, termed "hypothesis preservation" or "confirmation bias" (Klayman, 1995; Nickerson, 1998). "Confirmation bias" is a motivational bias that may have numerous definitions including i) the tendency to test hypotheses and search for what is expected/known, also defined as *positive hypothesis testing* (Klayman and Ha, 1987); or ii) an inclination to retain, or a disinclination to abandon, a currently favoured hypothesis (Klayman, 1995) or paradigm, sensu Kuhn (1962). In both cases, this bias may be conscious but is more often subconscious and a consequence of social or peer pressure or contextual components. It is not our intentions to use these terms in a negative connotation and a more neutral approach is warranted, whereby *confirmation bias* implies the natural tendency of human beings to search for information, and interpret evidence, in a manner that favours and maintains their current belief system. This bias can sometimes lead to call upon an unfalsifiable ad hoc hypothesis (that may be right or wrong), to explain contradictory evidences, and ultimately to reinforce the initial hypothesis or belief. Earth scientists, like any human being, are prone to such bias (e.g., Bowden, 2004; Bond et al., 2007; Shipton et al., 2019). Therefore, it can be expected that data or arguments potentially questioning a paradigm such as plate tectonics, would likely be neglected or that an ad hoc hypothesis may be called upon to maintain the paradigm (Suppe, 1998). Below, we will highlight some examples where such biases probably limited the adjustment of the plate tectonic paradigm in the collective consciousness of Earth Scientists to conflicting evidence. Specifically, we are concerned with the adoption of Benioff-type subduction for a wide range of possible modes of lithospheric foundering and recycling.

For most Earth scientists, the word "subduction" is used as a synonym for "foundering", and pictured according to the canonical Benioff-type subduction system (e.g., Fig. 1). Based on a variety of geological, petrological, geochemical, geochronological, or geophysical studies throughout orogenic belts and Earth history it is, if not directly stated, implicitly assumed in most geodynamic cartoons that stages of Benioff-type subduction are involved at some point in the region's past history. However, over the past 50 years, the original descriptive nature of the word 'subduction' has been merged with the genetic attributes of processes involved into the single Benioff-type of subduction. This responds to the need of an explanation of the role of the subduction force balance for the Earth's dynamics, as opposed to the description of the lithospheric descent's kinematics. Today, the polysemic nature of this word is such that its descriptive (lithospheric foundering; sensu Amstutz) and genetic (i.e., Benioff-type subduction in a plate tectonic framework) meanings are too often equated. Moreover, because of the strict dependence of modern plate tectonics on subduction, the inference is often stretched to the implications for the global regime of the planet. Yet, the equivalence between subduction kinematics and the dynamics is not warranted. This has led to artificial debates or the proposal of Benioff-type subduction models on the basis of elusive or non-conclusive geological data and/or unstated model assumptions. Below, we outline three such examples (among many others) to highlight that semantics has been a catalyst for biases that, we think, have negatively impacting scientific research.

3.1. Lithosphere foundering in the Western and Central Alps

The tectonic framework of the European Alps is classically ascribed to Benioff-type subduction of cold, rigid oceanic lithosphere prior to continental collision (e.g., Dietrich, 1976; Stampfli and Marthaler, 1990; Stampfli et al., 1998; Agard et al., 2009; Handy et al., 2010, 2014) (Fig. 1). Different authors relying on a variety of methods propose a number of oceanic slabs subducted into the convective upper mantle (one, two or three) (e.g., Stampfli et al., 1998; Handy et al., 2010; Weber et al., 2015). Three separate lines of evidence for *lithospheric foundering* have been used to infer *a Benioff-type subduction* framework for the Alpine orogen: 1) UHP/LT metamorphism of continental and oceanic rocks (Chopin, 1984; Reinecke, 1991), 2) remnants of ophiolites proposed to represent a pre-existing oceanic crust (Holway, 1904; Lagabrielle and Cannat, 1990), and 3) a geophysically imaged slab at depth

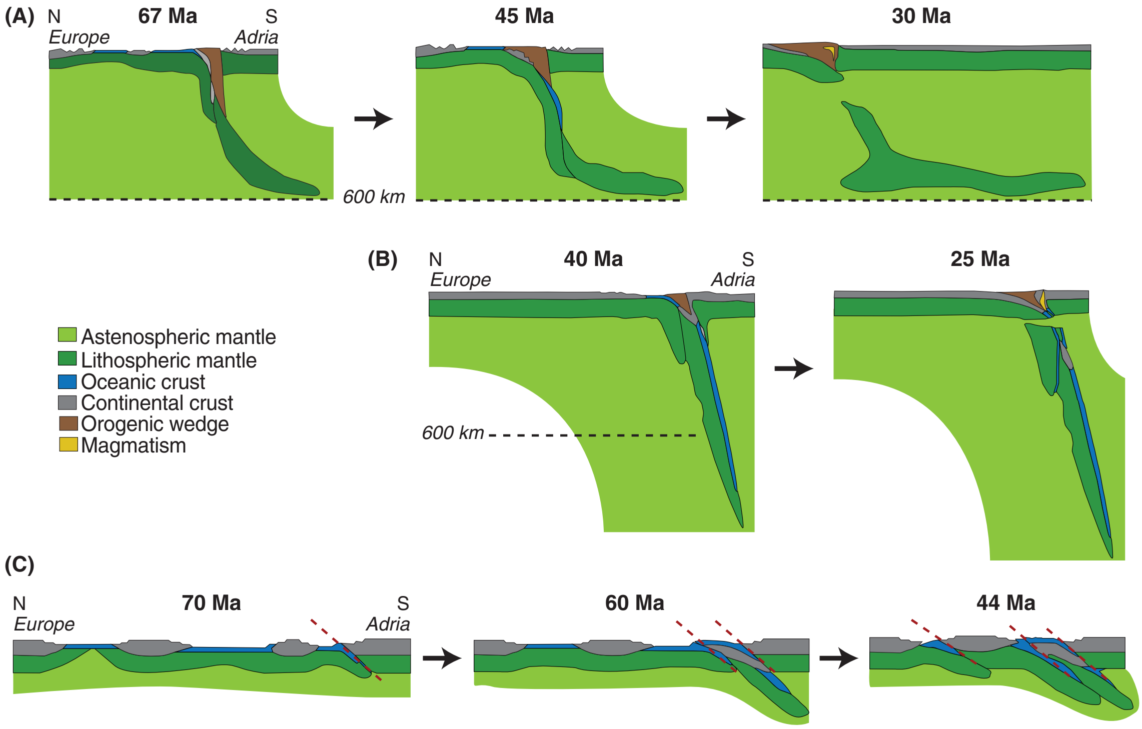


Fig. 1. Proposed Benioff-type subductions in the Western and Central Alps: (A) One subducting oceanic slab (Handy et al., 2010, 2014); (B) Two subducted oceanic slabs (Stampfli et al., 1998); (C) Three subducted oceanic slabs separated by "micro-continents" (Weber et al., 2015). Development of new subduction zones is thought to result from the collision of individual micro-continents with the trench (Stampfli et al., 1998; Weber et al., 2015). Note that for (A) and (B), a slab break-off is required to explain collisional magmatism as well as the lack of geophysically imaged 1000 km-long slab in the upper mantle.

(Lippitsch et al., 2003). However, none of these features are exclusive to Benioff-type subduction zones and can unequivocally differentiate it from alternative processes of lithosphere foundering that could be equally consistent with these observations. Unfortunately, weaknesses of the Benioff-type subduction model for the Alps (discussed below), as highlighted by some authors (Trümpy, 1975; Stampfli and Marthaler, 1990), have been disregarded or overlooked. Garzanti et al. (2018) illustrate this problem by focusing on the mechanism of slab break-off in the Alps. Their review highlights that this mechanism lacks observable and quantifiable geological evidence that can clearly and uniquely point to its occurrence at a specific interval in time. Nevertheless, this hypothetical mechanism has been implicitly accepted by large portions of the geological and geodynamics communities in order to accept a plate tectonic paradigm of the Alps. The argument is generally structured as follow: (1) a uniformitarian Benioff-type subduction model requires a large slab of previously subducted oceanic lithosphere beneath the Alps; (2) however, geophysical imaging only identifies a relatively small high-velocity slab-like anomaly directly attached to the Alpine orogen at shallow depth (< 400 km depth; e.g., Lippitsch et al., 2003); (3) therefore, part of the subducted slab must have broken-off and foundered; a slab foundering event generally linked to a large geophysical anomaly identified at ca. 600 km depth below the Alps (Piromallo and Faccenna, 2004; Spakman and Wortel, 2004; Handy et al., 2010, 2014); and (4) this slab break-off model is subsequently called upon to explain short-term and localised magmatism (thus, implicitly acknowledging the lack of magmatism during subduction; Dietrich, 1976; Davies and von Blanckenburg, 1995), rapid exhumation rates (e.g. Fox et al., 2015), and changes in subduction zone polarity (e.g. Handy et al., 2014).

Alternatively, the Alpine orogen could be considered from a continental tectonic perspective (Molnar, 1988) whereby this orogen resulted primarily from significant internal deformation (hyper-extension followed by compression) of the continental lithosphere without significant subduction of oceanic lithosphere (Mohn et al., 2014; McCarthy et al., 2018, 2020). In this view, the Alps result from the closure of narrow hyper-extended basins and embryonic ocean lithosphere, or Ampferer-type continental subduction. Such a view is in accordance with the narrow width of the Western Tethys, which, along its widest section, varies between 300 and 670 km (Vissers et al., 2013; Pfiffner, 2016) with the widest (sub)basin (Piemonte-Liguria basin/ocean) reaching a width of only ca. 200–300 km (e.g., Manzotti et al., 2014). In such a case, the architecture of the Western Tethys, instead of being formed of a wide oceanic domain separating Adria from Europe, represents a large-scale pinch-and-swell architecture formed of hyper-extended continental rift-basins locally reaching embryonic (ultra-)slow spreading oceanic lithosphere (Mohn et al., 2014; Schenker et al., 2015; McCarthy et al., 2020 and references therein).

Why is such a distinction important? Is such a discussion between "Benioff" and "Ampferer" subduction merely a semantic issue? Constraining the nature of the downgoing plate is crucial in order to identify what specific processes (e.g., plate driving forces) are involved in the growth of an orogen. Two endmember scenarios can therefore be envisioned in the Alps: i) subduction of a (simpler) oceanic architecture (ocean crust) of the Western Tethys leads to the formation of a complex architecture of the Alpine Orogen as a consequence of convergence and the subduction of the majority of the oceanic lithosphere and sedimentary cover (Agard et al., 2009; Agard and Handy, 2021)., or ii) a complex downgoing plate (rift basins) which is then sequentially accreted to a growing orogenic wedge (inverted rift-basins, Mohn et al., 2014; McCarthy et al., 2021).

On the one hand scenario (i), processes is associated with Benioff-type subductions, which imply efficient subduction of an oceanic slab and the control of slab dynamics on the evolution of convergent margins, are thus applied to explain the formation of the Western and Central Alps. For example, the evolution of the Alpine subduction and formation of the Alpine orogen is classically interpreted as a consequence of the gravitation pull of the slab, or slab roll-back as well as slab break-offs. Note that both an oceanic crust slab roll-back during oceanic subduction and *syn*-collisional slab roll-back following a slab break-off are typically envisioned (e.g., Stampfli et al., 1998; Schlunegger and Kissling, 2015; Kissling and Schlunegger, 2018). Syn-collisional magmatism in the Alps is typically explained as a consequence of particular slab dynamics, such as slab tears, slab stretching, slab break-offs or steepening of the slab upon collision (Dietrich, 1976; Davies and von Blanckenburg, 1995; Stampfli et al., 1998; Bergomi et al., 2015; Ji et al., 2019). Moreover, the rapid exhumation of (ultra-)high pressure rocks in the Alps are in certain cases explained as a consequence of slab break-off mechanisms, leading to transient variations in slab-pull forces, promoting rapid ascent of buoyant lithospheric fragments at ca 24–45 *Ma* (e.g., Boutelier and Cruden, 2018). Additionally, progressive slab tears are thought to have also induced the rapid exhumation of the Western Alps more recently, at ca. 2 *Ma* (Fox et al., 2015).

In the second scenario (ii), convergence is not a consequence on internal factors (i.e., internal to the Alpine domain) such as density-driven foundering of an Alpine oceanic slab. Farther afield, external forces, such as northward movement of Africa, lead to a state of compression (e.g., Rosenbaum and Lister, 2005). This state of compression leads to subduction initiation at weak passive margins (e.g., Zanchetta et al., 2012) and the forced down-thrusting of hyper-extended continental (crust and mantle) lithosphere (McCarthy et al., 2020). The heterogeneous lithosphere of the Alpine Tethys, formed of rifted continental blocks and exhumed mantle, is essentially incorporated, albeit variably deformed, into the Alpine orogen (Mohn et al., 2014; Beltrando et al., 2014; Lagabrielle and Cannat, 1990; Pantet et al., 2020). Consequently, the small, subductable domain, primarily consisting of dry lithospheric mantle, acts, at least in the initial stages of convergence, as a passive force (McCarthy et al., 2021) This model does not require slab break-off events (c.f. Garzanti et al., 2018) because there was no wide subductable oceanic domain, thereby solving the conundrums of i) a small geophysically imaged slab at depth, ii) the salient lack of arc magmatism for ca. 40–50 Myr, and iii) the lack of typical (magmatic) subduction-initiation signatures. This implies that, alternative interpretations regarding pre- to syn-collisional magmatism (e.g., Müntener et al., 2021) or the origins of (ultra-)high pressure metamorphism (e.g., Luisier et al., 2019; Tajčmanova et al., 2021), among others, might be worth exploring.

A working hypothesis that the Alpine slab is a rather small and passive actor, and not a driver of plate convergence, subduction and continental collision might not be altogether surprising. One of the characteristic features of the geodynamic evolution of the western Mediterranean from the Cretaceous to Cenozoic is the abundance of rather small subduction zones unlike the scale of circum-Pacific subduction zones as well as the subduction of buoyant continental lithosphere (e.g., Adria margin along the Apennines) (Doglioni, 1991; Carminati and Doglioni, 2012). A mantle-driven conceptual framework (see introduction), whereby mantle convection acts as a main control on the evolution of the architecture of convergent margins has been developed partly on the basis of the distinct asymmetry and contrasting geodynamic evolution of Western and Central Alps compared to the Apennines (e.g., Doglioni, 1991; Doglioni et al., 1999; Carminati and Doglioni, 2012). Additionally, vigorous small-scale convection and mantle flow around small oceanic slabs, as well a dynamic mantle convection (dynamic topography, cf. Flament et al., 2013) have been proposed to control the evolution of orogenic belts and basins throughout wide areas of the Mediterranean (e.g., Faccenna et al., 2010; Carminati and Doglioni, 2012; Faccenna et al., 2014). However, it should be noted that the specific interplay between mantle dynamics (e.g., torroidal flow, global and/or small-scale mantle convection) and lithospheric dynamics (density-driven foundering and lithospheric recycling, evolution of convergent margins, etc.) becomes hard to assess and difficult to untangle (cf. Schellart, 2007; Doglioni et al., 2007). This dichotomy between mantle-driven and slab-driven concepts was questioned in Coltice et al. (2019) who has supported a self-consistent system where both act on each other.

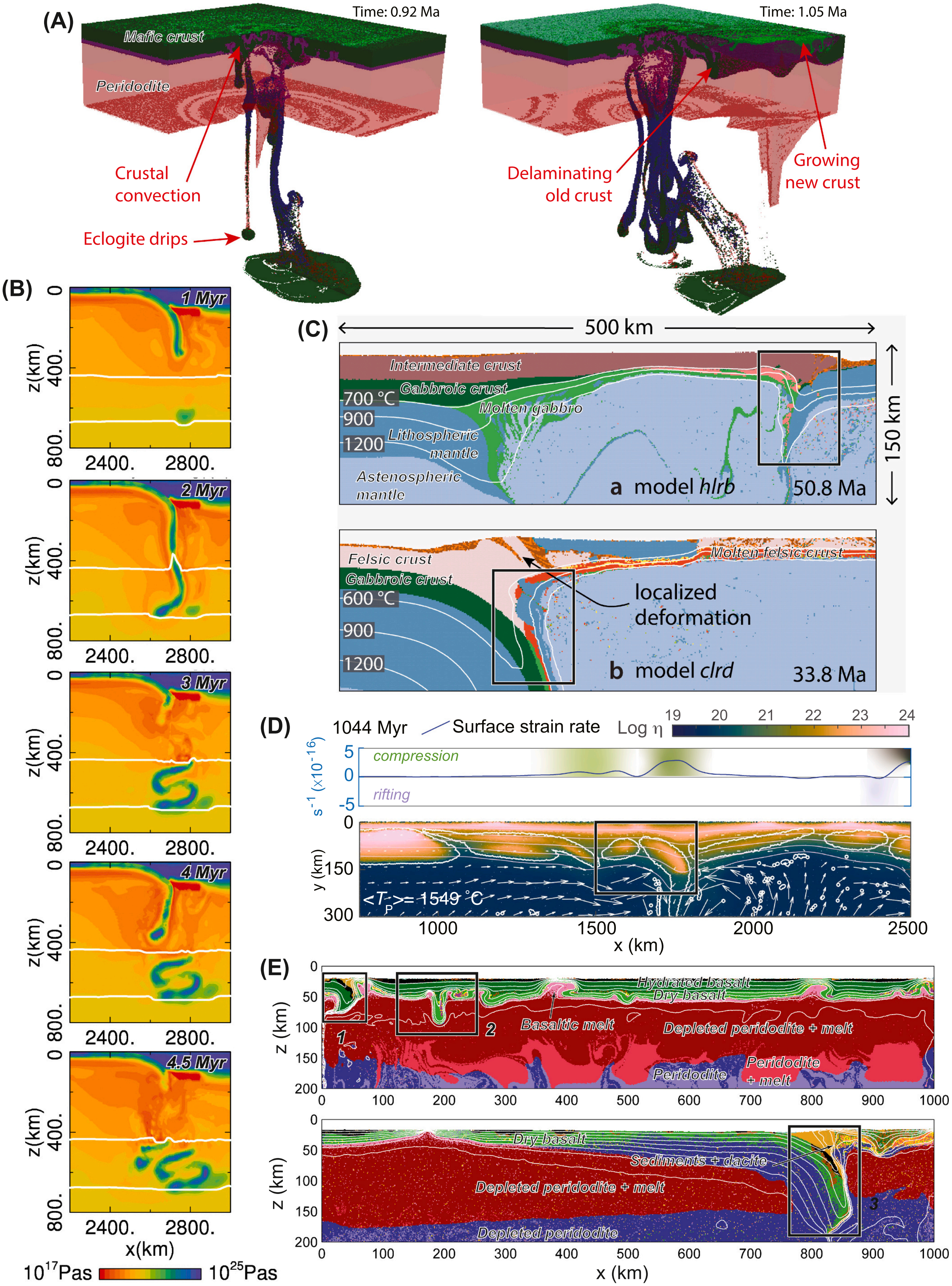
3.2. The beginning of subduction and plate tectonics on Earth

The distinct geological record of the Archean eon (4–2.5 *Ga*) compared to the post-Archean has fostered the emergence of a wide spectrum of suggested modes of lithospheric foundering on the early Earth. This dichotomy between the Archean and Phanerozoic geological record has led to one of the most controversial and persistent question of Earth Sciences: When did plate tectonics begin on Earth? With the implicit assumption that plate tectonics is fully defined by the presence of subduction, such that the presence of one implies the existence of the other. Depending on distinct arrays of evidence this timing has been variably estimated from 4.4 *Ga* (Turner et al., 2014) to less than 1 *Ga* (Stern, 2018).

Critical examination of the evidence, however, reveals that these estimates rely on different data that are often considered in isolation from the other data, and are based on distinct implicit definitions of subduction (Cawood et al., 2018; Brown et al., 2020; Palin et al., 2020; Hawkesworth et al., 2020). Further, these definitions are seldom explicated. "Early" subduction (i.e., older than ca. 3.0 *Ga* or so) is generally proposed on the basis of geochemical evidences for lithosphere recycling, for instance "*[...] global lithospheric recycling in a manner that, if consistent with slab subduction and plume/ridge return flow, would reveal when plate tectonics began.*" (Shirey et al., 2008, p. 2). Conversely, "late" subduction models are based on a requirement of subduction zones similar in all features to modern Pacific-type (Benioff-type) subductions; e.g., "*[...] indicators of modern-style subduction, including complete ophiolite sections, lawsonite eclogites, voluminous accretionary-wedge polymict and broken-formation mélange, rock assemblages comparable to modern ones, and ultra-high-pressure domains of subducted and exhumed continental crust [...]*" (Hamilton, 2011, p. 17). It is clear from these two quotations that "subduction" is used in two different meanings, one being "recycling of lithosphere into the mantle" and the other "Benioff-type subduction". This dual definition is very similar to the issue we describe for modern times, where the description of "arc-like" magmatism is often taken as univocal evidence for Benioff-type subduction, even though it actually points only to lithosphere recycling driving fluid-flux melting in some form.

Large portions of the discussion on the onset of plate tectonics on Earth rely on a chain of assumptions under which lithosphere foundering (kinematic constraints) or recycling (geochemical constraint) imply subduction, which in turn implies global, planetary-scale plate tectonics. Unfortunately, neither of these two logical links are true (cf., Cawood et al., 2018; Brown et al., 2020). A range of evidence for lithosphere foundering and/or recycling has been preserved since the early Archean based on geochemical (e.g., "arc-like" magmatism; Shirey et al., 2008; Hopkins et al., 2008; Moyen and Laurent, 2018), petrological (relatively high-pressure / low-temperature metamorphism, Moyen et al., 2006), paired metamorphic belts (Brown, 2006), perhaps to structural and paleomagnetic (juxtaposition of terrains with different geographic origin, Percival et al., 2012; Cawood et al., 2006, 2018). However, none of these necessarily involve Benioff-type subduction processes. Several recent studies, either conceptual (Moyen and Laurent, 2018; Stern, 2018; Bédard, 2018) or based on numerical modelling of geodynamic processes (Sizova et al., 2015; Fischer and Gerya, 2016; Chowdhury et al., 2017; Capitanio et al., 2019a) all illustrate how lithosphere foundering and recycling can operate without Benioff-type subduction, in a range of settings that might be described as "subcretion", "dripduction", "asymmetric drips", "delamination", etc. (Fig. 2). However, we note that the whole range and diversity of these processes, as well as their distinctive geological footprints (if any) still need to be fully and critically evaluated.

A large body of geochemical evidence suggests that lithosphere recycling operated very early in the Archean, perhaps as early as 4.1 *Ga* (Hopkins et al., 2008); and that blocs in relative horizontal motion were present at least by the neoArchaean (2.7 *Ga*) (Percival et al., 2012; Harris and Bédard, 2015), possibly earlier in some parts of the planet,



(caption on next page)

Fig. 2. Numerical models for Archaean geodynamics, focussing on foundering modes. Note that most of these models are in 2D. In such cross-sectional views, it is actually difficult to visualize the differences between foundering modes, as a key difference is the lateral (along strike) extent of the structures. The reader is referred to the original publications for interpretation of colour code: A, C and E are coded according to lithological types, B and D by viscosity. Boxes in C—E outline loci of lithospheric foundering. A). Drips (plume-induced) at the bottom of a thick mafic crust (Fischer and Gerya, 2016). B) Dripduction (van Hunen and van den Berg, 2008) resulting from the subduction of a thicker lithosphere in a hotter mantle, thus with higher strain at the basalt-eclogite transition. C) Subduction and peel-back (delamination) of the mafic lower crust (Chowdhury et al., 2020). D) Imbrication of rigid blocks of depleted lithosphere (subcretion) (Capitanio et al., 2020). E) Model by (Sizova et al., 2015) showing various modes of foundering in the same system: Ampferer-type subduction of an inverted rift (1), Drips of the dense lower crust (2) and onset of a Benioff-type, self-sustained subduction (3).

although the remaining evidence becomes scarce. However, these observations do not provide unequivocal evidence for the presence of Benioff-type subduction, or of the operation of a globally linked system of lithospheric plates in relative motion (i.e., plate tectonics).

3.3. Lithospheric recycling and subduction on Venus

A similar semantic debate among the Venus research community concerns the significance of subduction-like features observed on the planet. Venus shows over 10,000 km of topographic features similar to Earth's deep-sea trenches (Schubert and Sandwell, 1995). They are associated with positive gravity anomalies (Jurdy and Stefanick, 1999; Smrekar and Stofan, 1999), reflecting the presence of dense material at depth, and collectively the evidence points to the foundering of Venusian lithosphere along these arcuate breaks, resembling Earth's subduction zones (Fowler and O'Brien, 1996; Sandwell and Schubert, 1992; Schubert and Sandwell, 1995). Venus also has abundant evidence for stretching of the lithosphere in the form of rift structures (Phillips and Hansen, 1998; Price et al., 1996). However, unlike on Earth, these structures do not form an interconnected network of plate boundaries (Harris and Bédard, 2014), and therefore do not define a system of plate tectonics. Rifting is only short lived and achieves only minor stretching, while overall average strain rates on the surface are 10^{-17}–10^{-18} s^{-1} (Nimmo and McKenzie, 1998), which are 100 to 1000 times smaller than those along plate margins on Earth, ruling out any significant convergence. Therefore, although the foundering is primarily gravity-driven, due to the negative buoyancy of the lithosphere, this does not result in self-sustained, long-term underthrusting of a plate beneath another, and is therefore not akin to Benioff-type subduction.

In the decades following the articulation of the plate tectonics paradigm, early interpretations (e.g., Schubert and Sandwell, 1995) used the name "subduction", emphasizing the similarity with Earth's Benioff-style subduction. However, differences with Earth's subduction zones were also documented, such as its episodic nature (Fowler and O'Brien, 1996; Turcotte, 1993). Later, realizing the implicit (and involuntary) dynamic implications of using the term 'subduction' for Venus, others have applied more generic terms such as "lithosphere recycling" (Phillips and Hansen, 1998), or have tried to devise terms describing the local processes using a terminology that does not imply global plate tectonics: subcretion (Harris and Bédard, 2014, 2015) or delamination (Moore et al., 2017; Reese et al., 2007). Most of the tectonic activity of Venus remains constrained between ~1 and ~ 0.5 *Ga*, time in which the Venusian lithosphere was clearly not static as it underwent almost complete (80%) rapid recycling event, ~1 *Ga* ago (Phillips and Hansen, 1998). Minor recycling (<20%) and negligible strain (Nimmo and McKenzie, 1998) support the idea of a transition to a poorly mobile surface (Solomatov and Moresi, 1996) and the concept of stagnant lid (or its heat-pipe variant) has often been proposed for Venus (Hansen, 2007; Moore et al., 2017; Reese et al., 1999; Turcotte, 1995). However, like subduction, this term is also used in an inappropriate and ill-defined manner.

Again, part of the debate about tectonics on Venus is one of semantics. The unquestionable presence of zones of lithosphere foundering does not imply the presence of Benioff-style subduction; nor does it imply Earth-like plate tectonics. Here again, the debate would benefit from clarification and the use of terms with limited and well-defined meaning.

Returning to the debate about Earth (early Earth, in particular), one may speculate about geological evidence of lithospheric foundering on Venus, and how they would be interpreted if they occurred on Earth. Undoubtedly, they would reveal shortening, thrusting and folding, burial of cold matter in the mantle with associated features such as HP/LT metamorphism, possibly tectonic mélange hosting these metamorphic rocks, probably dehydration of the down-going lithosphere, and associated arc-like magmatism (including the arcuate shape). Yet, on Venus it is clear that these associations do not occur above a Benioff-style subduction (none being present there), nor do they belong to a plate tectonics system.

4. Modes of lithosphere recycling throughout Earth history and illustrated examples

4.1. A conceptual framework

The most commonly used markers of Benioff-type subduction in the geological past involve calc-alkaline igneous rocks, HP/LT metamorphic paths or tectonic/structural observations (e.g., Kaczmarek et al., 2015; Li et al., 2016; Stern, 2018; Brown et al., 2020). However, as highlighted in the examples above, such criteria typically point to lithosphere recycling or foundering rather than Benioff-type subduction. They may ultimately lead to erroneous conclusions regarding the mode of lithosphere foundering with far reaching implications for our understanding of lithospheric processes. Here, we propose a qualitative framework aimed at distinguishing the most commonly encountered or proposed modes of lithosphere foundering. This scheme considers the nature of the lithosphere involved and the locus of the mechanical driver of the foundering process as the first order controls on the modes of lithosphere foundering. This is illustrated in Fig. 3. While we only highlight a few end-members modes and examples, we consider the transitions between these to be continuous. Yet, recasting those geological characteristics into their key physico-chemical parameters would enable clarification of the exact nature of the transitions between these end-members and/or potential boundary conditions. While this would complement to the current approach, it is beyond scope of the present discussion. Further, we want to stress that these few end-members are chosen among possible others that could lie in between them, and that the names we refer them by (all defined in Section 2) should not be seen as a nomenclature and may be freely substituted by synonyms.

The nature of the material that founders and is recycled into the Earth's mantle is generally ascribed to the term "oceanic lithosphere", and thus, generally indirectly implies a "Benioff-type" subduction and a plate-tectonic paradigm (Fig. 1). However, the term "oceanic lithosphere" is a misleading term. Phanerozoic oceanic lithosphere can reflect either Penrose-type fast-spreading ocean crust (Anonymous, 1972), (ultra)-slow spreading crust (e.g., Lagabrielle and Cannat, 1990; Dick et al., 2003; Cannat et al., 2019) or oceanic crust locally thickened by oceanic plateaus and intra-oceanic magmatic arcs (e.g., Burke et al., 1978; Ben-Avraham et al., 1981; Kerr et al., 2000; Andjić et al., 2018). Further, this neglects that lithosphere or part of the lithosphere other than classical "oceanic lithosphere", such as deep crustal eclogites, ocean-continent transition zones or wholesale continental lithosphere may founder and be recycled into the mantle. Such contrasted lithologies have markedly distinct rheological and mechanical characteristics, chemistry and metamorphic behaviour upon changing pressure and

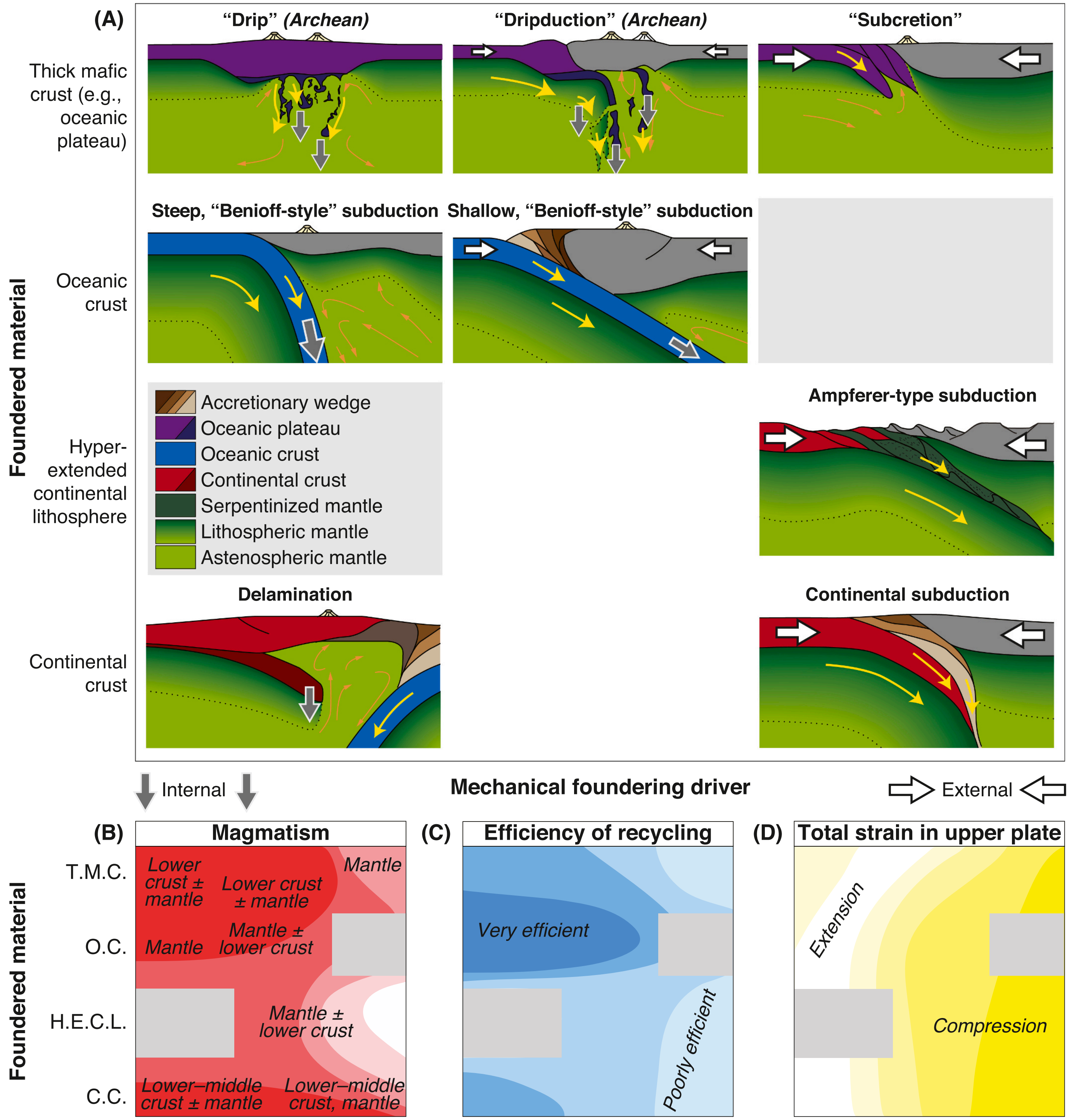


Fig. 3. A) Sketches of some classical modes of lithosphere foundering as a function of the type of foundered lithosphere and of the mechanism of lithospheric foundering. Qualitative impact of the type of foundered lithosphere and of the mechanism of lithospheric foundering on B) magmatic activity, with a highlight the dominant loci of melting and the amount of magma produced (red: abundant; white: no magmatism); C) efficiency of lithosphere recycling into the convective upper mantle (deep blue: very efficient; light blue: poorly efficient); D) Total strain in the upper plate (deep yellow: highly compressive; white: extension). Gray square = no known mechanism of spontaneous/internal subduction for hyper-extended margins or of externally driven oceanic subduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature, all of which can greatly influence the mechanisms of convergence and foundering (e.g., Chenin et al., 2017; McCarthy et al., 2020). For example, the rigid, coherent and dense oceanic lithosphere will undergo dehydration (on its uppermost portion) and eclogitization (of the entire crust) upon subduction, increasing the slab pull mechanism and causing hydrous arc magmatism (Forsyth and Uyeda, 1975; Cloos, 1993; Ganguly et al., 2009; Boonma et al., 2019). In turn, the buoyant continental crust tends to resist foundering, and its dehydration and eclogitization does not lead to large scale slab pull or arc magmatism, but rather promotes accretionary tectonics, crustal thickening and crustal magmatism (Cloos, 1993). For the sake of simplicity and usefulness we have considered four lithospheric endmembers: thick mafic

Table 1

Proposed key characteristics of different types of lithospheric foundering with possible examples. [1] = volume of magmatism is from Jicha and Jagoutz (2015), Arculus (2004) and McCarthy et al. (2020). [2] = Pacific-type and Alpine-type orogens after Ernst (2005).

Name	Main foundering driver	Type of foundered material	Allows to form arc-like magmas[1]	Source of associated magmatism	Metamorphism	Allows compressional belts	Type of orogen[2]	Permits relative horizontal mobility	Can belong to a globally interliked system of plate boundaries	Implies a globally interliked system of plate boundaries	Characteristic features to look for	Possible examples
Steep Benioff-type subduction	Gravitational instability, slab-pull	Penrose-Type ocean crust to (ultra)-slow spreading ocean crust formed at steady-state mid-ocean ridge + occasional large oceanic plateaus	Yes; 20–300 km^3/km/Myr	Lithospheric mantle (± lower crust of the overriding plate and subducted slab?)	High pressure, low temperature metamorphism (blueschists, eclogites)	Some	Long-lived Pacific-type oceanic or continental extensional arc-back arc complex	Yes	Yes	?	*BADR arc magmatic series (Low-FeO, or "calc-alkaline");, oceanic trench and accretionary wedge/prism, subduction mélanges; Subduction initiation characteristics includes tholeiites-boninites-andesites, possible preserved supra-subduction zone ophiolites*	West Pacific subduction zones (Vanuatu, Tonga, Izu-Bonin-Marianas)
Shallow Benioff-type subduction	Gravitational instability, slab-pull and External forces due to relative plate motio	Penrose-Type ocean crust to (ultra)-slow spreading ocean crust formed at steady-state mid-ocean ridge + occasional large oceanic plateaus	Yes; 20–100 km^3/km/Myr	Lithospheric mantle (± lower crust of the overriding plate and subducted slab?)	High pressure, low temperature metamorphism (blueschists, eclogites)	Yes	Long-lived Pacific-type orogens (e.g. Alaskan-type subduction/accretion complex, Andean-type continental magmatic arc)	Yes	Yes	?	*BADR arc magmatic series (Low-FeO, or "calc-alkaline");, oceanic trench and accretionary wedge/prism, subduction mélanges; Subduction initiation characteristics includes tholeiites-boninites-andesites, possible preserved supra-subduction zone ophiolites*	East Pacific subduction zones (Cascades, Andes),
Ampferer-type subduction	External forces due to relative plate motion	Narrow oceanic basins, hyper-extended continental crust: primarily dry subcontinental mantle with possibility of embryonic ultra-slow spreading ocean crust	Yes; 0 to <0.1 km^3/km/Myr	Lithospheric mantle to lower crust	High pressure, low temperature metamorphism (blueschists, eclogites)	Yes	Alpine-type orogen (imbricated sequence of nappes, closure of narrow oceans or wide hyper-extended basins between two contiental blocks)	Yes	Yes	No	*Amagmatic closure of basins, subduction initiation at passive margins, preservation of ocean-continent transition zones and hyper-extended continental crust.*	Pyrenees, European Alps
Continental subduction	External forces due to relative plate motion or far field slab pull	Continental crust	Some	Lower to middle crust ± mantle in some cases	High pressure, low temperature metamorphism of continental rocks (felsic eclogites and "white schists")	Yes	Collisional orogen	Yes	Yes	?	*HP-LT metamorphism of continental crust, anatexia of crust (migmatites), arc-like magmatism*	Himalaya, New Caledonia, European Alps
Subcretion	External forces due to relative plate motion or far field slab pull	Oceanic plateau	Some	Lithospheric mantle	No long-lived crustal thickening; no high-pressure metamorphism	Yes	Dome-and-keel architecture	Yes	Sometimes	No	*?*	Northern Andes
Dripduction	Gravitational instability, slab pull	Amphibolitic to eclogitic lower crust	Yes	Lower crust, lithospheric mantle, oceanic crust	No long-lived crustal thickening; no high-pressure metamorphism	Some	–	Some	Yes	No	*?*	?
Drip	Gravitational instability	Amphibolitic to eclogitic lower crust	Some	Lower to middle crust	No long-lived crustal thickening;	Some	–	No	?	No	*?*	?

(*continued on next page*)

Table 1 (*continued*)

Name	Main foundering driver	Type of foundered material	Allows to form arc-like magmas[1]	Source of associated magmatism	Metamorphism	Allows compressional belts	Type of orogen[2]	Permits relative horizontal mobility	Can belong to a globally interliked system of plate boundaries	Implies a globally interliked system of plate boundaries	Characteristic features to look for	Possible examples
					no high-pressure metamorphism							
(Post-collisional) Delamination	Gravitational instability	Amphibolitic to eclogitic lower crust	Some	Lower to middle crust ± lithospheric mantle,	No	Some	Metamorphic core complex	No	Sometimes	No	*Isostatic rebound? spatial and temporal trends in magmatism? Elevated geotherm?*	Massif Central, Southern Sierra Nevada

crust (e.g., oceanic plateau), oceanic crust (e.g., Penrose-type), hyper-extended continental lithosphere, and continental crust.

The mechanical drivers of lithospheric foundering include buoyancy-driven mechanisms internal to the foundered lithosphere (e.g., delamination of denser material, density-driven foundering of oceanic lithosphere), and far-field external forces transmitted by plate motions, mantle flow or by buoyancy forces arising from distinct types of lithospheres.

End-member modes of lithosphere recycling are represented in Fig. 3, and their respective footprints and implications are detailed in Table 1. The two end-members of Benioff-type subduction are inspired from the circum-Pacific Izu-Bonin-Mariana (IBM) and Andean arcs. The IBM subduction is mostly characterized by an old (125–160 *Ma*), dense and steep oceanic slab (ca. 50–80°; Yokokura, 1981; Ganguly et al., 2009) associated with an overall extensional regime of the overriding crust (Lallemand et al., 2005) such that the foundering of the Pacific plate is dominantly driven by its higher density and further densification upon dehydration (internal slab pull; Forsyth and Uyeda, 1975; Schellart, 2004). In contrast, the central Andean arc is characterized by a relatively young (10–50 *Ma*), moderately dense and shallower oceanic slab dip angle ($< 40°$; Yokokura, 1981; Ganguly et al., 2009), associated with compression and orogenesis along the western margin of South America (Lallemand et al., 2005; Oncken et al., 2006; Horton, 2018). There, in addition to slab pull, large scale mantle flow (drag) probably acts as an important additional driver of the subduction (e.g., Capitanio et al., 2011; Husson et al., 2012; Faccenna et al., 2017; Schellart, 2017; Horton, 2018). Slab density differences apart, it is worth mentioning that the existence of an enigmatic global eastward directed asthenospheric "mantle wind" with respect to the lithosphere has been hypothesized and might impact the dynamics of both eastward and westward directed subduction in opposite ways (e.g., Doglioni et al., 1999; Doglioni and Panza, 2015 and references therein), While this hypothesis could explain subduction angles (e.g., Ficini et al., 2017), its possible role as a foundering driver has not been evaluated quantitatively. Yet, the very existence of such a "mantle wind" has been vigorously questioned (e.g., Schellart, 2009) thereby leaving any study of its possible causes and consequences premature. Both endmembers of Benioff-type subduction are associated with copious hydrous, mantle-derived, calc-alkaline magmatism in the overriding plate with some contribution from the lower crust for the most evolved magmas (e.g., Arculus, 2004; Dufek and Bergantz, 2005; Annen et al., 2006; Jicha and Jagoutz, 2015).

Simple buoyancy principles would preclude continental crust from spontaneously sinking to mantle depth. However, foundering of continental crust may take place in two end-member modes: continental subduction that is driven by far-field forces, and delamination caused by negative buoyancy and sinking (for example if the dense lower crust is decoupled from the buoyant upper crust). Subduction of continental crust usually follows a period of Benioff- or Ampferer-type subduction. In such cases, the driving force of the continental subduction may be a combination of far-field ridge or plume push, pull from the previously subducted slab and/or from laterally continuous subducting oceanic slabs, and basal mantle flow (Ghosh et al., 2006; Capitanio et al., 2010; Becker and Faccenna, 2011; Cande and Stegman, 2011; van Hinsbergen et al., 2011; Sternai et al., 2016; Capitanio, 2020). Yet, the positive buoyancy of the subducted continent can create strong deviatoric stress that have been proposed to cause (i) the detachment of parts of the previously subducted oceanic slab followed by the underplating of the subducted continental crust below the overriding plate (e.g., Negredo et al., 2007; van Hunen and Allen, 2011; Capitanio and Replumaz, 2013; Magni et al., 2017; note that this process is critically discussed by Garzanti et al., 2018), and/or (ii) the decoupling of the subducted continental crust from the subducted subcontinental lithospheric mantle (± lower crust) followed by the rapid exhumation of fragments of the former above the subducting plate along major shear zones (e.g., Capitanio et al., 2010; Gray and Pysklywec, 2012; Magni et al., 2013). While buoyancy constraints and the evolution of far-field forces (e.g., through slab break-off) can lead to subduction blocking and convergence termination (e.g., New Caledonia, European Alps), the Himalayan example highlights that continental convergence can persist in a complex manner over tens of millions of years and is associated with lithospheric thickening rather than continental subduction (e.g., Guillot et al., 2003; Searle, 2019 and references therein). Continental subduction can be associated with a large diversity of magmatism ranging from abundant peraluminous crustal melts (such as the Himalayan or Variscan granites; e.g., France-Lanord and Fort, 1988) or calc-alkaline mantle melts (such as the Alpine tonalites; e.g., Schaltegger et al., 2019).

Internally driven foundering of the lithosphere (or at least the deepest part of it) is probably best exemplified by delamination and break-off of the lower crust and lithospheric mantle. These mechanisms have been proposed as a transient post-collisional process in many orogens (Karsli et al., 2010; Ueda et al., 2012a; Burg, 2012; Laurent et al., 2017) and describe the decoupling, peeling off and sinking of large blocks or slabs of eclogitized lower crust and lithospheric mantle into the asthenosphere (Ueda et al., 2012b; Gray and Pysklywec, 2012). Numerical models highlight that delamination may occur several tens of million years after continental collision and is associated with the lateral propagation of the delamination front (Ueda et al., 2012b; Gray and Pysklywec, 2012). Potential markers of delamination include the rapid development of topography above the upwelling asthenospheric mantle window, high thermal gradient, HT-LP metamorphism and crustal melting, potassic magmatism, migration of coeval crustal, and rejuvenation and refertilization of the lithospheric mantle (Lenoir et al., 2000; Göğüş and Pysklywec, 2008; Ueda et al., 2012b; Puziewicz et al., 2020).

Foundering of hyper-extended continental margins or ocean-continent transitions (OCT) is referred to as Ampferer-type subduction (or OCT-subduction). This transitional lithosphere may be composed of thinned continental crust transitioning to exhumed and serpentinized lithospheric mantle with associated marine sediments. Upon subduction the buoyant upper part of the lithosphere (upper crust or serpentinized mantle + sediments) decouples from the denser lithospheric mantle (± lower crust) becomes accreted to the orogen whereas the denser part subducts into the asthenosphere. The main driver of such subduction likely is external to the subducted material while a minor internal component may be involved if the lower crust is also subducted (Capitanio et al., 2010). The subduction of essentially dry lithologies does not typically allow any significant magmatism as suggested in the case of the European Alps and Pyrenees (McCarthy et al., 2018; McCarthy et al., 2020).

Drips have been proposed as an important process in the evolution of Archean lithosphere (e.g., Van Kranendonk et al., 2007; Van Kranendonk, 2011; Bédard, 2006). Of course, there is no direct observation of this process, and it is hard to describe the key associated geological features that would allow to identify it unequivocally. In general, the underlying model is that the lowermost portion of the (dominantly mafic) protocrust, in granulite or eclogite facies, is denser than the underlying mantle and can detach and sink into the asthenosphere. This requires the absence of a rigid lithosphere under the crust, to permit the sinking of lower crustal fragments. Numerical modelling has no difficulties to form such drips – they form as Rayleigh-Taylor instabilities as a result of a density contrast between the dense upper layer, and the lighter layer beneath (e.g., Johnson et al., 2013). Only recent models however (e.g., Sizova et al., 2015; Chowdhury et al., 2020; Capitanio et al., 2019b) have attempted to combine Rayleigh-Taylor instabilities with other processes, and aim at a better understanding the circumstances under which this process can be dominant, or will be overshadowed by accompanying processes such as shortening. Also, the lack of modern examples has led to a bewildering range of inferred geological footprints, sometimes mutually incompatible, being associated with drips: magmatic manifestations such as melting of the dripping mafic crust (Bédard, 2006); HT/LP metamorphism and pervasive crustal melting, supposedly associated to the removal of the lower crust and the ascent of hot asthenosphere (Kröner et al., 2018); a range of structural features including ascent of domes of partially molten middle or lower crustal rocks (Collins et al., 1998; Van Kranendonk et al., 2004), fold and thrust belts and vertical stretching lineations between these domes (Collins and Van Kranendonk, 1999; Van Kranendonk et al., 2004), and – in more extreme models—down going of upper crustal rocks through the partially molten middle/lower crust, (Bouhallier et al., 1993; Choukroune et al., 1995) possibly connected with the sub-crustal drips (Van Kranendonk, 2011). In fact, almost any structure appears to be reconcilable with drips, casting some doubt on the possibility to devise scientific tests for this process (i.e., to make it “falsifiable” in epistemological sense).

Dripduction is essentially a colloquial term, introduced by Moyen and Laurent (2018) to describe a situation akin to what is modelled by Sizova et al. (2015), van Hunen and van den Berg (2008) and, Moyen and van Hunen (2012) for the early Earth, i.e. an intermediate situation between Benioff-type subduction and drips. A hotter mantle implies thinner lithosphere with lowered buoyancy and rigidity. The foundering of such thin and weak lithospheres is rapidly hampered by diffusion of the thermal, and therefore gravitational, instability. The foundering lithosphere follows its descent as a drip, along an inclined plane (dripduction), laterally swerved by the large convective flow of the hotter early Earth mantle. Once again, no active or recent examples of such processes have been observed. Related geological manifestations would include short-lived, repeated burst of calc-alkaline magmatism (Moyen and van Hunen, 2012), probably akin to modern-day subduction initiation magmatism because a stable subduction is never established (Turner et al., 2014); limited (in time, and in space) burial of crustal material, with related cold geotherms and (relatively) HP/LT metamorphism; compressive, possibly asymmetric (fold and thrust belt) structures.

4.2. *Multimodal orogenic evolution*

In the course of its multimillion-year evolution, a single orogenic domain typically moves within the parameter space of Fig. 3 (type of foundered lithosphere vs mechanical driver of foundering) as the nature of the foundered material is changing and/or as the relative contribution of internal and external foundering drivers is evolving (Fig. 4a). For example, Benioff-type subduction associated with the Mesozoic Andean orogen, probably started in the Jurassic (James, 1971; Oliveros et al., 2006; Boekhout et al., 2012; Maloney et al., 2013). It was likely associated with a steep slab and extensive back-arc extension in the overriding crust until the middle to late Cretaceous, which marks the initiation of the Andean orogeny and the general shallowing of the slab (e.g., Cobbold et al., 2007; Maloney et al., 2013; Schellart, 2017). This transition probably resulted from the opening of the south Atlantic which was associated with a marked increase in the trench-normal absolute overriding plate velocity, horizontal stress and mechanical coupling along the subduction interface (e.g., Silver et al., 1998; Oncken et al., 2006; Husson et al., 2012; Faccenna et al., 2017; Horton, 2018) as well as increased local negative buoyancy of the Nazca plate (Capitanio et al., 2011). Furthermore, the Andean orogeny has been marked by numerous episodes of transient slab flattening locally causing inland migration or cessation of arc magmatism, as well as crustal thickening, oroclinal bending and topographic development (e.g., Ramos and Folguera, 2009; Mamani et al., 2010). Such flat slab episodes have commonly been attributed to the subduction of buoyant oceanic reliefs such as aseismic ridges or oceanic plateau (e.g., Martinod et al., 2010; O’Driscoll et al., 2012) and/or to slab suction induced by the overriding plate advance (e.g., Manea et al., 2012; Schepers et al., 2017). Over its prolonged life, while the nature of the subducted oceanic lithosphere has minimally changed (oceanic lithosphere), the mechanical driver of the subduction has shifted from being essentially internal (slab pull) during the Jurassic and early Cretaceous to progressively include variable proportions of external forces such as mantle drag (blue arrow in

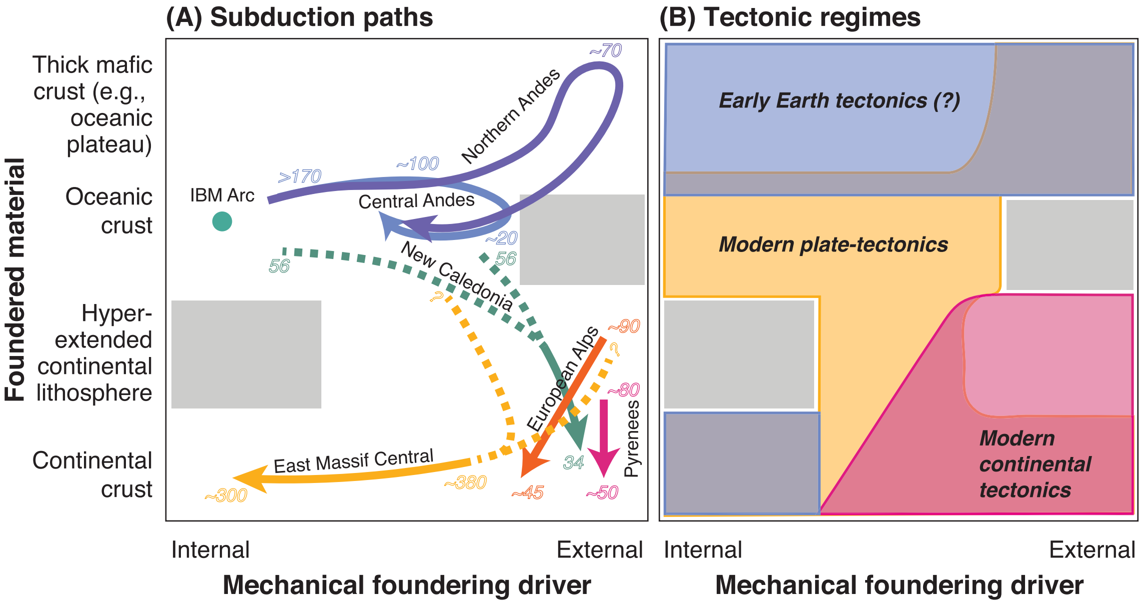


Fig. 4. A) Mechanism of lithospheric foundering versus type of recycled lithosphere with illustrations of subduction/orogenic paths for i) Benioff-type subductions: Izu-Bonin-Mariana arc (IBM arc), Himalayas, Andes and a "classical" Alpine model; ii) Ampferer-type subduction for the Pyrenees and Alps; Field of possible paths of lithospheric recycling for the Variscan is large due to the lack of constraints on the type of recycled lithosphere and the geological record recording the type of lithospheric foundering (source?); B) Proposed fields for different tectonic regimes for i) the Archean (recycling of thick mafic lithosphere); ii) modern plate-tectonics (recycling of rigid ocean crust and continental crust); iii) modern continental-tectonics (recycling of hyper-extended continental lithosphere. Gray square = no known mechanism of spontaneous/internal subduction for hyper-extended margins. It is critical to note that one planet-wide *tectonic regime* includes several distinct modes of *lithosphere foundering*, operating concurrently.

Fig. 4a). In the case of flat slab segments, far field slab pull from normally subducting slab segments (north and south of the flat slab segment) can represent an additional external force. In the northern Andes of Ecuador and Columbia, the scenario is further complicated by the Late Cretaceous to Paleocene accretion (or subcretion in the terminology of Bédard, 2018) of fragments of the Caribbean oceanic plateau followed by a transfer of the subduction zone to the western margin of the newly accreted terrane (Vallejo et al., 2009; Jaillard et al., 2009; purple arrow in Fig. 4a).

Similarly, the Variscan orogen of western Europe has undergone multiple modes of lithospheric foundering throughout its history. It is generally agreed that the Variscan orogeny culminated with the Carboniferous collision between Gondwana, Laurussia and intervening continental terranes (Matte, 2001; Simancas et al., 2005) similar to the Himalayas. In the eastern Massif Central (France), this orogenic phase was followed by a late Carboniferous pulse of granitic magmatism coupled with the extrusion of the Velay granite-migmatite core complex that document the post-collisional delamination of the eclogitic to granulitic lower crustal root (e.g., Laurent et al., 2017; Vanderhaeghe et al., 2020; Fig. 4a). Prior of the continental collision, convergence of the continental masses was accommodated either by Benioff-type subduction of the Rheic and Medio-European oceanic lithosphere (Faure et al., 1997; Nance et al., 2012; Lardeaux et al., 2014) or by the contraction of hyperextended continental crustal domains akin to Ampferer-type subduction processes (Kröner and Romer, 2013; Vanderhaeghe et al., 2020; dashed yellow arrows in Fig. 4a).

In the south east Pacific, the early Eocene marks the end extensional tectonics across the Zealandia continent that resulted in the opening of the Tasman Sea, the Coral Sea and the South Loyalty basin (e.g., Maurizot et al., 2020a and references therein). In north Zealandia, New Caledonia keeps record of the Eocene closure of the South Loyalty basin (from 56 to 34 Ma), that eventually led to continental subduction and obduction of a suprasubduction ophiolite (the Peridotite Nappe; Maurizot et al., 2020b). Most studies concur with the inception of a northeast dipping intraoceanic Benioff-type subduction at 56 *Ma* in the South Loyalty Basin (e.g., Matthews et al., 2015; Maurizot et al., 2020b, 2020c) and was driven by unspecified factors (dashed green arrows in Fig. 4a). In this class of models, the deep (and unexplored) roots of the Loyalty Island represent the remains of the magmatic arc associated with such a subduction zone. Upon consumption of the South Loyalty oceanic lithosphere at around 38 *Ma*, the New Caledonian continental lithosphere was subducted to pressure up to 2.4 GPa (ca. 70 km), rapidly followed by subduction termination and exhumation of the subducted continental ribbon (Maurizot et al., 2020b).

4.3. *Geodynamic implications*

We emphasize that no single criteria can uniquely be used to determine the mode or possible modes of lithosphere recycling have been operating at a studied location. For example, low-temperature and high-pressure metamorphism that is usually thought to characterise Benioff-type subduction may also be encountered for Ampferer-type and continental subduction, and probably in dripduction (Table 1). Similarly, while calc-alkaline magmatism is particularly abundant above Benioff-type subduction zones, all other modes of lithospheric foundering may produce similar magma series (Table 1). Instead, we argue that only a holistic and interdisciplinary approach involving a range of methods and datasets may narrow down the range of permissible options. We also appreciate that during earlier phases of Earth history, the geological record is less complete and the evidence may at best be incomplete, making it difficult to resolve the method of lithospheric foundering.

Further, should the mode of lithospheric foundering be identified at a given place and age, we stress that it cannot be generalized at the global scale for the same age. Numerical models reveal that the transition between tectonic modes is not necessarily sharp and that several modes may coexist for extended periods of time (e.g., Capitanio et al., 2019a). For example, while modern Earth is largely dominated by plate tectonics, continental deformation accommodates a small percentage of the horizontal displacements (Kreemer et al., 2014). Obviously, observations of the current evolution of the Earth's surface showing evidence of continental tectonics cannot be propagated at the planetary scale to disregard plate tectonics (Fig. 4b).

The same appears to be true for other tectonic modes across diverse geologic times and terrestrial-type planets. Diverse processes such as underthrusting, foundering and recycling are documented both on Venus and the early Earth (Harris and Bédard, 2014), yet are not reconciled with a Benioff-type mode of subduction. Such a range of coherent processes reveal the crucial role of recycling mechanisms of lithospheres in planets as well as in early Earth, thereby calling for a deeper understanding of the relation between these processes, lithospheric foundering modes and the global planetary regime.

5. Concluding remarks

We highlight that available data do not currently allow adding more robust quantitative constraints on this proposed conceptual framework presented in Fig. 3, whereby the mode of lithospheric foundering mainly is a function of the type of foundered lithosphere and of the mechanical driver of foundering. Despite the apparently simplicity of this framework, the few end-members that we have highlighted in Fig. 3 and the (sharp or continuous) transition between them are controlled by a suite of physico-chemical parameters of which the relative role and importance remains to be evaluated and which is out of the scope of this paper. A mapping of the physico-chemical parameter space would clarify the relative controls of those on the mode of lithosphere recycling. We hope that it will foster an effort to better quantify these processes and incite colleagues to clarify the mode of lithosphere foundering they mean upon using the way too generic and overused term “subduction”.

It may be useful to remember that such a polysemic problem (description vs interpretation) is far from being exclusive to subduction only but straddles across sciences in general and Earth sciences in particular. In igneous petrology alone, similar semantic debates surround the use the terms ‘calc-alkaline’ and ‘adakitic’ (Arculus, 2003; Moyen, 2009). It seems to be intrinsic to humans to understand the nature of things such that key characteristics and causes are insidiously married into a single word. While it has the merit to ease the dissemination of concepts and ideas, it seems to be often at the expense of accurate communication, and ultimately at the expense of our collective understanding of nature. Should we therefore be more talkative and embrace a culture of detailed description of our thoughts? Probably not as such, but certainly we should maintain awareness that conciseness and accuracy can be opposite forces of which we should strive to maintain a fair balance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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