Collisional Processes and Links to Episodic Changes in Subduction Zones

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Continental collision is commonly accompanied by a sequence of several plate–mantle interactions, including accretion of buoyant features, pulses of slab rollback, slab break-off, formation of slab windows, and lithosphere delamination. Using the combined insight from seismic and dynamical modelling studies, we illustrate how these processes and their characteristic rates and timescales played an important role in shaping the Mediterranean and how they dominated the closure of the Tethyan oceans. Older collisions such as the one that formed the Norwegian Caledonites probably experienced similarly complex plate-mantle interaction, but direct evidence of the associated mantle dynamics is absent.

INTRODUCTION

Subduction zones are intrinsically not steady state features. Magmatism and tectonics related to convergence zone processes, for example, show significant temporal variation (deSilva, this issue). Influences from variation in subducting plate's age, density, local (pre-existing) plate weaknesses, accumulation of slab material at depth, or a large-scale plate reorganisation may lead to time-dependent plate dynamics, while intrinsic timescales of local processes such as magma accumulation and the development of gravitational instabilities can result in periodic or episodic events. Notably, such processes can be triggered by a significant change in the subduction environment, such as the transition from oceanic to continental subduction.

Continental collision is often depicted as a single event, marking the end of the Wilson cycle. But the closure of large ocean basins often involves a range of different mantle processes. Docking of small continental blocks, obduction of oceanic terranes, or accretion of intraoceanic arcs (e.g. the present-day western margin of North America) commonly precede the final collision of two large continents and the ultimate closure of the basin. Such events may lead to temporary changes in convergence rate, slab dip, and mantle flow (Moresi et al. 2014). In extensional settings, such as the Mediterranean, local onset of collision causes back-arc extension adjacent to a region of collision, inducing dramatic rotation and curvature of the subduction zone (e.g. Wallace et al. 2009; Moresi 2015 this issue). The mantle structure underneath changes accordingly: slabs detach or tear, change dip, and buckle. The formation of gaps or tears in the slab, commonly referred to as "slab windows," dramatically affects mantle flow, which facilitates additional reorganisation of the slabs and overriding plate deformation. These events may cause complicated patterns of magmatism (e.g. Rosenbaum et al. 2008). After an oceanic basin closes, continued convergence between the continents results in compression and regional shortening (e.g. the collisions of India and Arabia with Eurasia). Magmatic activity might still take place

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tens of My after the collision due to the dynamics of the mantle wedge that remains hydrated.

Here, we illustrate how continental collisions trigger a range of mantle processes that are likely to influence each other. None of these processes necessarily recur during the collision event, but, together, they may exhibit a succession of events on a range of time and length scales. We use the mantle dynamics associated with the Central Mediterranean and the closure of the Neo-Tethys Ocean (FIG. 1) to illustrate the complexity of the mantle–lithosphere system during continental collision.

GEOLOGICAL AND SEISMOLOGICAL OBSERVATIONS

BRIEF TECTONIC HISTORY

The present-day orogenic belt that extends from the European Alps, through the Zagros Mountains and the Himalayas to south-east Asia is the result of closing the Paleo-Tethys and Neo-Tethys oceans (e.g. Hafkenscheid et al. 2006; FIG. 1). These oceans were separated by terranes aligned roughly east–west, blocks of which form (parts of) present-day Iran, Afghanistan, and South Tibet. These terranes were accreted to Eurasia during the closure of the Paleo-Tethys Ocean; also, and related to the opening of the Atlantic Ocean, several relatively small back-arc basins formed during the Late Jurassic or Early Cretaceous. South of the Cimmerian blocks (Asia), intraoceanic arcs separated the Neo-Tethys from the Semail Sea and the Shyok Sea back-arc basins (FIG. 1; Hafkenscheid et al. 2006; Bouilhol et al. 2013). These arcs were located near the future collisions of Arabia and Greater India with Eurasia, respectively. Greater India rapidly moved northward to collide with the intraoceanic arc systems and Eurasia between 50–40 Ma. Despite this initial collision, there is ongoing northward convergence at 3–4 cm/y even today. During the Late Eocene or Oligocene, Arabia separated from Africa and collided with Eurasia. In between these collisions, the last surviving part of the Neo-Tethys Ocean continues to subduct today.

Further west, many blocks collided with Eurasia in the eastern Mediterranean during the Tertiary to form the Alpine–Carpathian orogeny. The heterogeneous structure of the plates in the central Mediterranean is a result of the complex, episodic nature of the region's subduction history (e.g. Maliverno and Ryan 1986; Faccenna et al. 2004; Rosenbaum and Lister 2004; Miller and Piana Agostinetti 2012). This caused the overriding plate to have variable composition, thickness, and internal layering.

Several episodes of back-arc basin formation occurred since the Africa and Arabia plate collision with Eurasia around 35–30 Ma (Faccenna et al. 2004). First, the western Mediterranean opened (30–16 Ma) and caused the Corsica–Sardinia block to rotate counterclockwise into roughly its present-day position (FIG. 2). After a magmatic and tectonic lull of 3–5 My, the Tyrrhenian Sea opened (FIG. 2;Rosenbaum and Lister 2004; Faccenna et al. 2005). The variable composition and morphology of both the overriding and subducting plates are likely to contribute to the dramatic and complicated patterns in the surface geology, lithospheric assembly, mantle structure, as well as tectonic history.

SEISMIC MAPPING OF UNDERLYING MANTLE STRUCTURE

For recent subduction or collision events, seismic tomography is used to map mantle thermal and compositional structures, which are useful for constraining the related surface processes. The mantle structure of the central Mediterranean is complex, because Cenozoic subduction history was episodic in nature. Evidence of the cold subducting Calabrian slab can be seen via fast-velocity perturbations in seismic tomography (e.g. Wortel and Spakman 2000; Giacomuzzi et al. 2011) and by seismicity in the Benioff zone seismicity, which extends down to ~500 km (Chiarabba et al. 2005). The cusps of the Calabrian arc are composed of continental material and appear to be hindering subduction (Fig. 2A). Beneath the northern Apennines (Italy), tomographic images show a continuous region of fast-velocity material from the near-surface to the lower mantle (Wortel and Spakman 2000; Giacomuzzi et al. 2011; Fig. 2). However, beneath the central Apennines there are no fast-velocity perturbations in the uppermost mantle (<250 km); nor are there subcrustal earthquakes. But there are zones of fast seismic velocities, which represent a deeper (>250 km), detached portion of the slab. Figure 2 shows a regional seismic tomography model (Giacomuzzi et al. 2011) that resolves the local absence or presence of fast velocities (blue in Fig. 2) and which represents the subducted lithosphere. The local absence of the subducted slab is called a “slab window,” and its potential importance in tectonic and magmatic tempos in the Mediterranean will be discussed below.

Seismic anisotropy inferred from shear wave splitting is used to infer mantle flow (i.e. Russo and Silver 1994). These measurements can be used to identify flow around the edges of subducted oceanic lithosphere and may help image slab windows. For the Calabrian slab, flow around the edges has been hypothesized (Faccenna et al. 2005; Baccheschi et al. 2011).

Further east, in the Zagros and Himalaya regions, the continental collision of Eurasia with Arabia and India was still recent enough for seismic tomography to be useful. High seismic velocity anomalies in the upper and lower mantle – interpreted as slab remnants – are clearly recognized in a large area underneath the two sutures (Hafkenscheid et al. 2006). The depth and geographical location of these seismic anomalies provide information about the timing and location of the subducted slabs and contribute to the debate on the location through time of the intraoceanic arc between the Neo-Tethys Ocean and the Semail and Shyok back-arc basins (Hafkenscheid et al. 2006; Bouilhol et al. 2013; Fig. 1).

MANTLE PROCESSES DURING CONTINENTAL COLLISION

The geodynamic models presented next illustrate how continental collisions induce a range of different mantle processes, such as slab break-off, back-arc spreading, and local convective instabilities, each with own typical timescale.

LARGE-SCALE CONVERGENCE AND CONTINENTAL SUBDUCTION

When continents start colliding, continental crust, being buoyant, tends to slow the convergence rates, in some cases episodically. While convergence rates across a suture typically reduce substantially over a few My, regional shortening often continues over prolonged periods, despite the apparent absence of direct driving forces. Various internal and external factors are likely to contribute to the variable duration of a continental collision event. Often, continental collision is not a single event, but involves a series of collisions between arcs and small continental blocks, which may lead to several decelerating convergence events. Prolonged convergence after the onset of continental collision might be caused by different external forcings, such as the local presence of slab-pull from neighbouring slabs, or a mantle-driven flow and lubrication by a hot mantle upwelling. It may also be caused by rheological differences in the subducting continental block, leading to an absence or presence of crustal delamination during subduction. Such delamination removes (part of) the buoyancy from the subducting continent, allows for prolonged subduction, and typically leads to slab rollback. Without such delamination, convergence rates diminish more rapidly, and commonly lead to an advancing trench.

A textbook example is the collision between India and Eurasia, where several factors are likely to contribute to a prolonged period of convergence that accelerates and decelerates episodically (van Hinsbergen et al. 2011). The collision of India with an island arc that separated the Shyok Sea from the Neo-Tethys Ocean at 50 Ma (Bouilhol et al. 2013; FIG. 1) corresponds to the first drop in the India–Eurasia convergence rate. The final India–Eurasia collision occurred at 40 Ma (Bouilhol et al. 2013) and corresponds to another significant decrease in convergence rate. Yet significant convergence of ~4–5 cm/y is still ongoing today. For the India–Eurasia collision, the local presence of slab-pull from neighbouring slabs is generally thought to be insignificant; instead, a mantle-driven flow with lubrication from a hot mantle upwelling is more important (van Hinsbergen et al. 2011). A more recent convergence slowdown at ~20–10 Ma is attributed to increased compression from mantle lithosphere delamination (Molnar and Stock 2009).

SLAB BREAK-OFF AND LATERAL TEAR PROPAGATION

A reduction in convergence rate after the onset of collision allows more time for slabs to warm up and weaken. The contrasting buoyancies between previously subducted oceanic lithosphere and continental crust lead to significant tensile stresses around the ocean–continent transition in the slab. This combination is likely to result in slab break-off, a process whereby the dense oceanic lithosphere is decoupled from the trailing continental lithosphere and sinks into the deep mantle, and the buoyant continental material is allowed to rebound, or “educt” back towards the surface. Numerical modelling shows that the delay time between first collision and final slab necking or break-off can be 2–20 My (Duretz et al. 2011; van Hunen and Allen 2011). Weak or young lithosphere might break almost immediately when entering the trench, in which case the break-off is early and shallow. Older, and therefore colder and stronger slabs might initially be too strong to break: they can be dragged down deep into the mantle until isostatic equilibrium prevents further sinking. In such a case, the cold slab heats up and becomes weaker over time until slab break-off eventually occurs. In 2-D settings, extensional stresses in the slab are mostly vertical. But the often arcuate shapes of subduction zones require subducted slabs to stretch horizontally to accommodate any rollback of the subduction system. In such a rollback scenario, the additional horizontal stresses could speed up tearing of the slab.

In the Mediterranean and Neo-Tethys area, the subducting oceanic lithosphere is Jurassic in age. Being old, cold and strong, it is not expected to undergo a tearing or necking event immediately after subduction. One might expect a significant delay of perhaps 10–20 My between the first collision and the final slab break-off. The collision between Arabia and Eurasia probably started during or before the Oligocene Partial slab break-off, inferred from seismic tomography in eastern Turkey, may be the reason for the Late Miocene plate tectonic reorganisation that initiated the North Anatolian Fault and uplifted the Turkish–Iranian plateau (Faccenna et al. 2006). This suggests a delay time of 15–20 My between first collision and slab break-off, which agrees with the numerical modelling of older subducting ocean basins. In the Himalaya, underthrusting of Indian lithosphere, with no associated mantle wedge, has been inferred from the appearance of inherited zircon grains of Indian origin into the magmatic sources at ~30 Ma. This underthrusting may be due to local slab break-off (Bouilhol et al. 2013), which in turn would suggest a collision–break-off delay time of ~20 My since the first collision of Greater India with the intraoceanic arc at around 50 Ma (Bouilhol et al. 2013).

In a 3-D setting, a slab tear is likely to initiate at a point of locally decreased strength (e.g. preexisting lithospheric faults) or increased tensile stress (e.g. at the lateral transition between subducting oceanic and continental material), and will subsequently propagate along the suture. Numerical modelling shows that lateral propagation rates for a slab tear typically range from ~10 cm/y for old, strong slabs, to possibly several times this speed for younger slabs (van Hunen and Allen 2011).

The opening of the Tyrrhenian Sea by the rollback of the Calabrian slab in the Central Mediterranean occurred in a series of rapid spreading events. Calabrian slab rollback requires slab tears to propagate both to the east (along the southern Apennines) and to the south (northern Tunisia), so tearing the slab from the continental lithosphere on either side (Magni et al. 2014; FIGS. 2 and 3). Local topographic basins might form below such slab tear (Wortel and Spakman 2000) as a result of locally concentrating slab pull forces; these basins are, thus, expected to migrate with the underlying propagating slab tear. Mean rates of Pliocene–Quaternary lateral migration of basins observed in southern Italy are 12–14 cm/y (Ascione et al. 2012).

-BACK-ARC BASIN AND SLAB WINDOW FORMATION

Locally opposing buoyancy forces, such as near subducting passive margins or aseismic ridges, lead to stress concentrations (Magni et al. 2014; Moresi et al. 2014), and may result in back-arc basins (Wallace et al. 2009). This model also applies to the Mediterranean, where collision of the trench with the edge of Adria, to the east, and North Africa, to the south, led to a temporary slowdown of subduction. According to this scenario, opening of the Tyrrhenian back-arc basin from ~10 Ma allowed for further oceanic subduction, while the flanking continental blocks resisted subduction. Numerical models show that such partial collision concentrates stress and deformation near the ocean–continent boundary, where a back-arc may start forming soon after initial collision and may mature in the next ~10 My (Magni et al. 2014; FIG. 3, see also the Supplementary movie S1). At that stage, the trench resumes significant rollback rates. Formation of local back-arc basins requires significant deformation of the trench and stretching of the subducting slab underneath. In order for such deformation to continue, formation of strike-slip fault systems at the surface and slab windows at depth will eventually be required (FIG. 4). Modelling shows that such lateral slab tearing and opening of a slab window typically occurs 5–10 My after initial back-arc basin formation (FIG. 3, Supplementary movie_S1), and that a minimum oceanic basin width on the order of ~1000 km is required to provide the necessary slab pull force to drive these tectonics (Magni et al. 2014). Toroidal flow in laboratory experiments (e.g. Kincaid and Griffiths 2003), and numerical models (e.g. Piromallo et al. 2006) illustrate how mantle material can flow around narrow pieces of subducted oceanic lithosphere. The location, orientation and scale of such slab windows correspond fairly well with those observed under central Italy (FIG. 2), and shear wave splitting results (e.g. Baccheschi et al. 2011) illustrate how material flows into the mantle wedge underneath the Tyrrhenian Sea.

MANTLE WEDGE DYNAMICS AND RELATED MAGMATISM

The water released from subducting oceanic lithosphere can migrate upwards to hydrate the local mantle wedge (see Fig. 1 of Jicha and Jagoutz 2015 this issue): this is generally accepted as the primary cause for arc magmatism. If, after collision, significant mantle-derived magmatism still occurs, the magma composition is often more alkaline than calc-alkaline, and the magma distribution in space and time is more random. These trends suggest that mantle-wedge processes change after the onset of continental collision, which could be due to a number of factors. Petrologically, the subduction and dehydration of relatively wet continental material, with or without associated sediment or crustal melting, will add water to the mantle wedge and likely affect the melt composition. However, slower subduction of drier slabs reduces water supply. Geodynamically, slab motion is an important driver of mantle wedge flow during subduction, but after collision, local convective instabilities may become more important.

Shallow slab break-off can suddenly expose the (perhaps still partly hydrated) overriding plate to hot asthenospheric conditions, and this would cause a partial melting event (Davies and von Blanckenburg 1995). Such an event would have a characteristic signature of being localised and relatively sudden, and if observed would allow us to actually recognise a slab break-off event. In and around southern Tuscany, for example, spatial and temporal patterns of local magmatism could indicate underlying slab tear faults (Rosenbaum et al. 2008). This mechanism, originally proposed for post-collisional magmatism in the Alps (Davies and von Blanckenburg 1995) has also been proposed to have operated elsewhere, e.g. in the Zagros area (van Hunen and Allen 2011). Often, the magmatism is spatially and temporally distributed (Kaislaniemi et al. 2014), which suggests that the relationship between slab break-off and magmatism can be complex.

Slab windows allow the mantle to flow through local gaps in the slab towards the mantle wedge region. This could create new, compositionally distinct magmas by the interaction of fertile mantle with a still partly hydrated mantle wedge. Combined seismic, geological, and geodynamical studies illustrate how such flow of mantle material around the Calabrian slab probably affects Mount Etna (Italy) and may explain why magma compositions vary in the central Mediterranean (e.g. Faccenna et al. 2005; Rosenbaum et al. 2008). Mantle flow through a slab window (FIG. 2) may have led to alkaline magmatism gradually replacing calc-alkaline magmatism around 5–4 Ma between Tunisia and Sicily (Faccenna et al. 2005).

Local gravitational instabilities might be another cause for postcollisional magmatism. Previous hydration of the overriding plate, collisional shortening, and changes in the mantle-wedge flow regime after collision may increase the density of the overriding mantle lithosphere, making it weak enough to delaminate and sink into the mantle wedge. Large-scale delamination of the mantle lithosphere (Molnar and Stock 2009) would result in significant regional uplift and mantle magmatism (from decompression melting in the upwelling return flow) or crustal melting (due to sudden heating at the base of the crust). More subtle amounts of magmatism can be expected from small-scale sublithospheric convection (SSC), in which local gravitational instabilities result in “dripping" of mantle lithosphere and concomitant upwelling of asthenospheric mantle (as return flow) which gives small degrees of partial melting. This concept was originally proposed to explain the Cenozoic Turkish–Iranian Plateau magmatism (Kaislaniemi et al. 2014). The nature of SSC instabilities is rather random in space and time: associated magmatism tends to have a spacing of ~200 km and a recurrence time of ~5–20 My. The intrinsically episodic nature of SSC may explain some seemingly random or chaotic postcollisional magmatism (FIG. 4; see also Supplementary movie S2) and the rather random distribution of magmatism in Central Italy (e.g. Rosenbaum et al. 2008). Similar to the SSC downwellings from the overriding plate, SSC upwellings might form along the surface of the subducting slab. Locally buoyant sedimentary or crustal material might also become weak enough to randomly rise through the mantle wedge (Zhu et al. 2009).

CONTINENTAL COLLISION TIMESCALES AND WIDER IMPLICATIONS

Numerical modelling combined with observations from the well-studied Mediterranean, Zagros and Himalaya collision zones provides insight in the tempo of various processes that probably occur shortly before, during, and after the onset of continental collision. Trench migration, local back-arc basin formation, and magmatism in collision zones are the surface expressions of slab tearing, slab break-off and rollback, and mantle wedge dynamics occurring at depth (FIG. 4). Slowing the rate of subduction reduces the volatile supply, which in turn affects the amount and nature of magmatism almost immediately. Regional convergence, however, might continue long after collision, leading to shortening and thickening, which in turn might trigger gravitational instabilities that may provide episodic magmatism long after collision. The warming and weakening of stalled slabs could lead to slab break-off 10–20 My after initial collision (for the closure of old basins), but might be much faster for younger, weaker slabs.

Present-day and geologically recent continental collisions may provide insight into older collisions. Wallace et al. (2009) illustrate that the collision of continental terranes has always been common and that the associated rotation of fore-arcs and the formation of nearby back-arc basins probably also occurred. The complex dynamics of the Mediterranean situation may appear to be unique today, but similar scenarios are likely to have occurred in past. For example, closure of the Paleo-Tethys Ocean involved the collision of several continental blocks and the opening of several back-arc basins (Hafkenscheid et al. 2006). This created the tectonically and magmatically complex suture zone that runs through the south of Eurasia today.

Direct observations of mantle dynamics at older collision zones are absent, but the geological record suggests analogous complexity. For example, the Norwegian Caledonides formed ~420 Ma by the rather complex final collision primarily between Baltica and Laurentia (Bottrill et al. 2014). Not only did continental blocks and island arc fragments collide with Laurentia before the arrival of Baltica, but the final collision was also diachronous, starting in the south and propagating northward, causing Baltica to be rotated relative to Laurentia. The Western Gneiss Complex in southern Norway experienced much more metamorphism and subsequent exhumation (and therefore a different collision history) than further north (Bottrill et al. 2014). These variations suggest a collision event of a complexity similar to its more recent analogues.

Throughout Earth's history, continental collision zones have been key sites for the net production of continental crust. And although magma production is significantly reduced during the transition from subduction to collision, magmatic products that were formed just before, during or after a collision are protected inside newly amalgamated (super)continents (Hawkesworth et al., 2010). This significantly increases their preservation potential. By realizing that collisional processes may have been similarly complex in the deep past, the remaining geological record may be re-examined to gain more insight in the mantle dynamics of ancient collisional settings.

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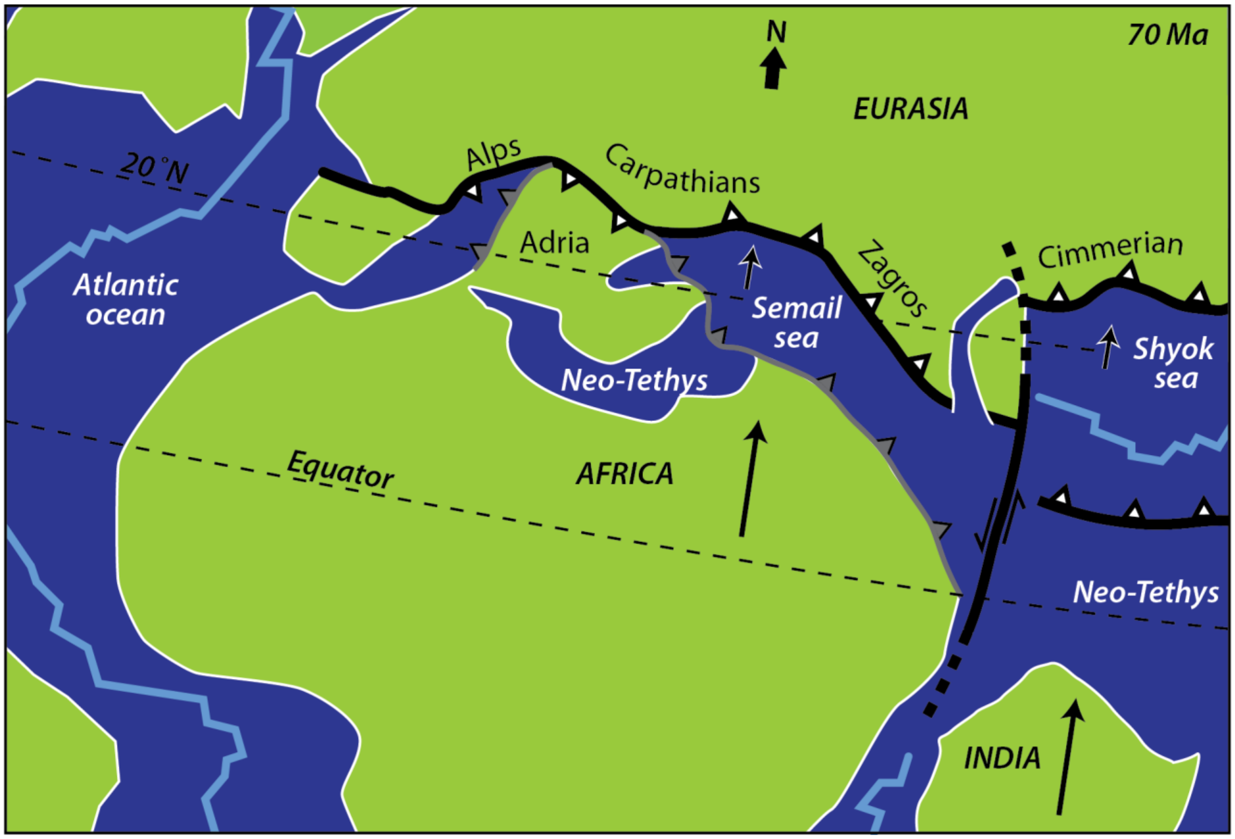
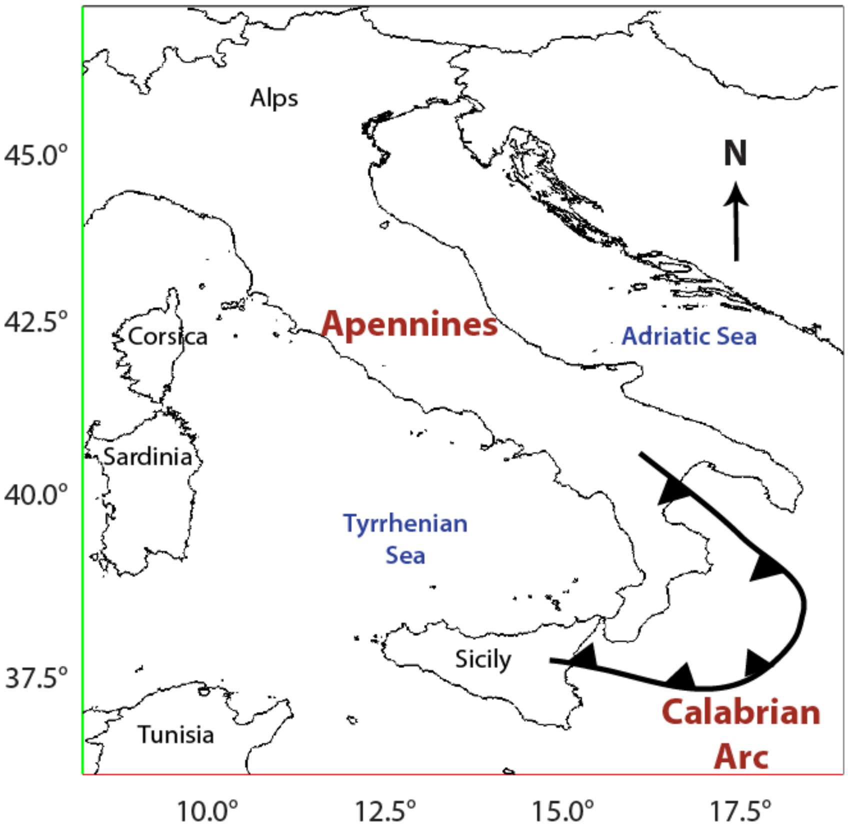


FIGURE 1 Simplified tectonic reconstruction of the Neotethys region at 70 Ma. Modified after Stampfli and Borel (2004).


Alps
45.0°
42.5°
40.0°
37.5°
N
Corsica
Apennines
Adriatic Sea
Sardinia
Tyrrhenian Sea
Sicily
Calabrian Arc
Tunisia
10.0°
12.5°
15.0°
17.5°

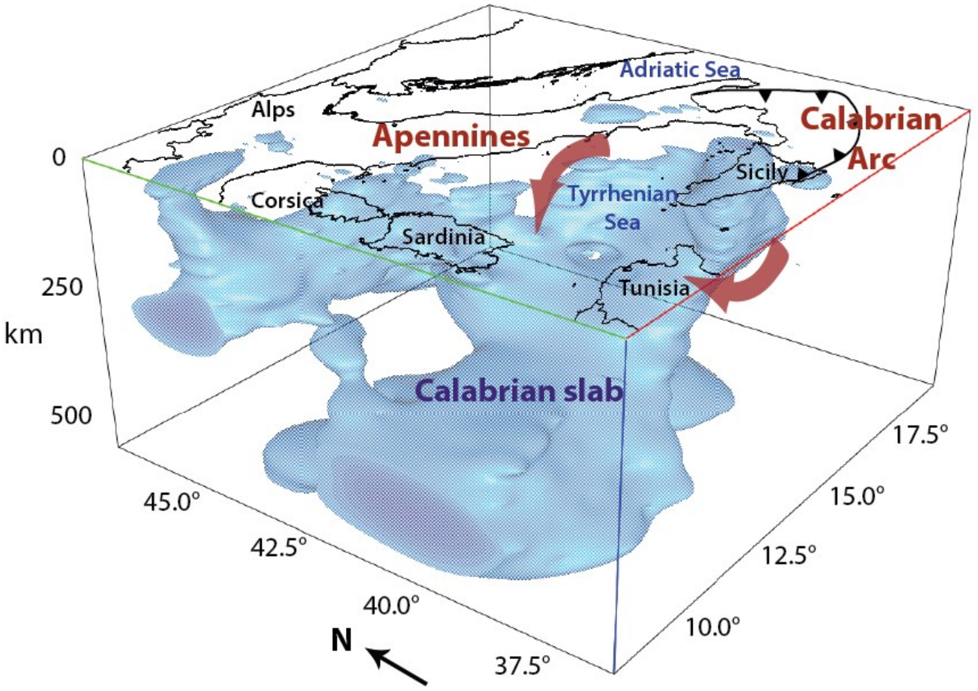

Adriatic Sea
Alps
Apennines
Calabrian Arc
0
Corsica
Tyrrhenian Sea
Sicily
Sardinia
250
km
Tunisia
500
Calabrian slab
17.5°
15.0°
12.5°
10.0°
45.0°
42.5°
40.0°
37.5°
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FIGURE 2 **A.** Map of the model area with labels showing the geographic locations. **B.** Seismic tomography from Giacomuzzi et al. (2011) viewed from the SW. Fast velocity perturbations >1.5% faster than the reference model are shown in blue and the rest are removed in order to show the fragmented subducted lithosphere within the upper mantle and the slab windows beneath the Central Apennines and the edges of the Calabrian slab. Red arrows depict mantle flow patterns through the slab windows around the Calabrian slab and the black line with teeth indicating the location of the Calabrian arc. Labels show the geographic locations as in A) at the surface and slab at depth.

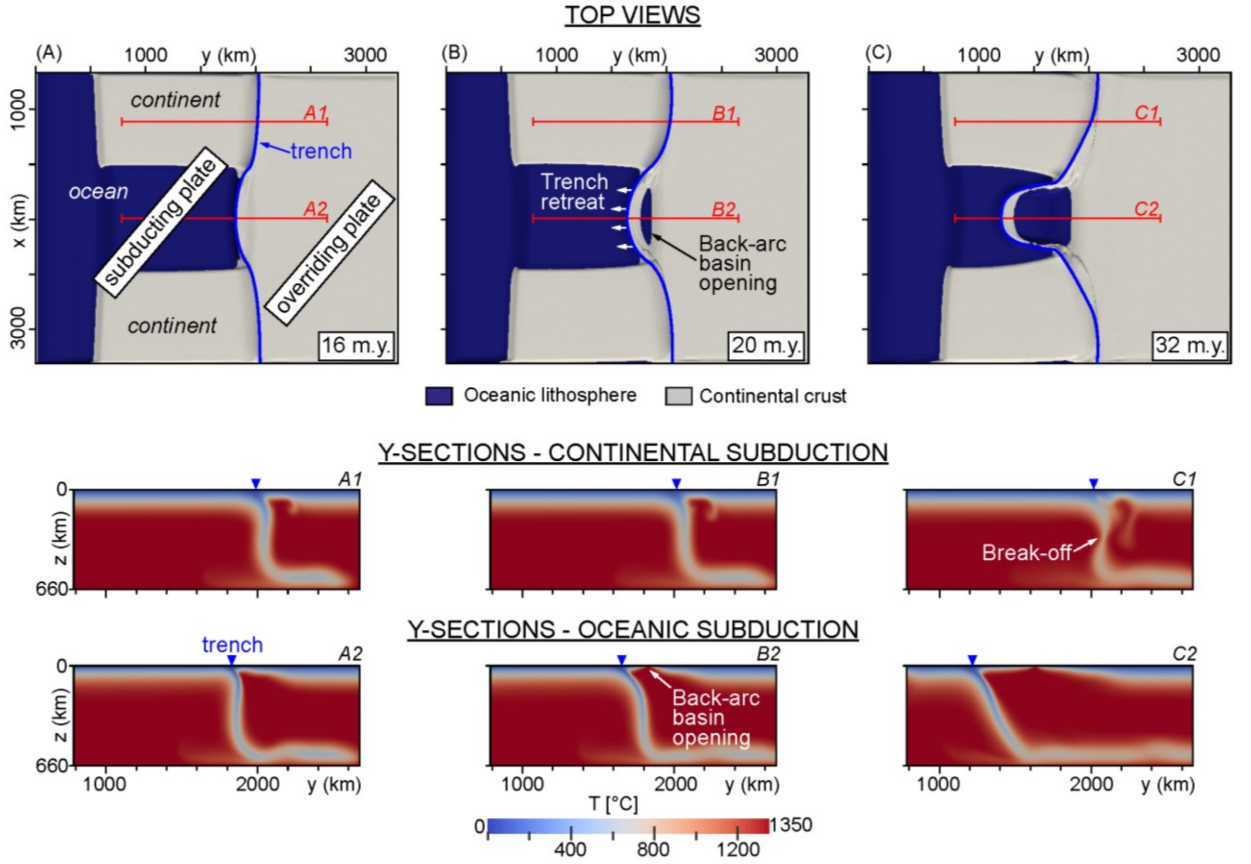

FIGURE 3 Three-dimensional numerical model calculation of the development of a back-arc basin for **(A)** 16 My, **(B)** 20 My, and **(C)** 32 My after the start of the model calculation. Top plots show the plan view of the subduction-collision zone, with white and blue areas representing continental and oceanic lithosphere, respectively. Red lines are locations of the vertical cross sections of the temperature field below. An animation illustrating the 3-D time evolution is shown in the Supplementary movie S1. Modified from Magni et al. (2014)

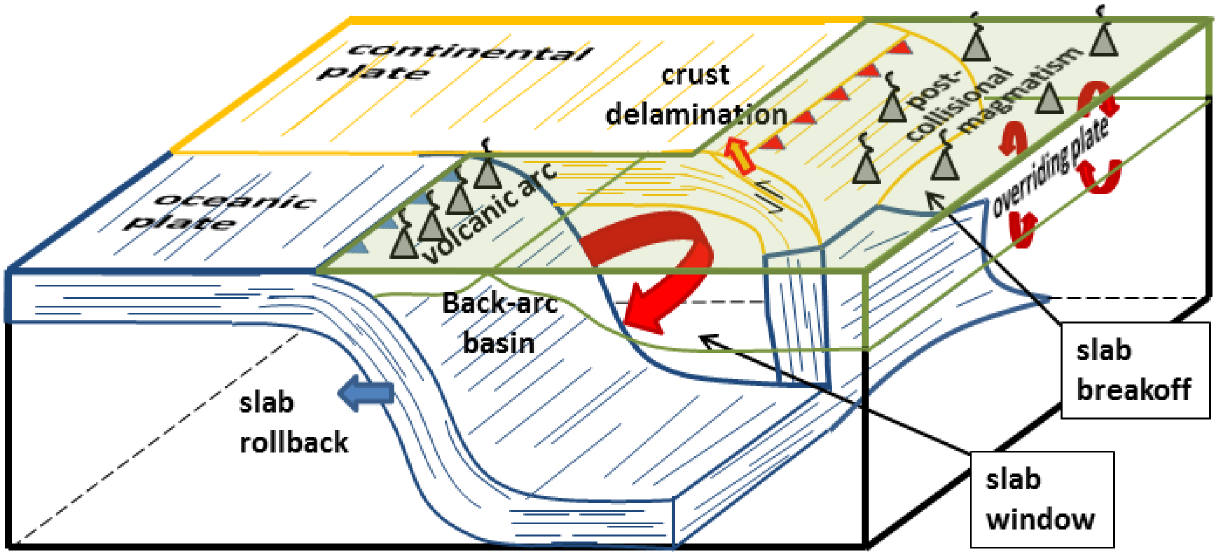

FIGURE 4 Schematic representation of some of the most important geodynamical processes during continental collision. Oceanic subduction gives continued slab rollback, whereas continental subduction results in a stagnant trench position. The differential trench motion leads to slab tearing and the opening of a slab window at depth. Slower convergence after continental collision results in slab weakening and break-off. Post-collisional lithospheric instabilities in the overriding plate leads to small-scale convection and associated magmatism.