

# Delamination<sup>☆</sup>

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## What Is Delamination?

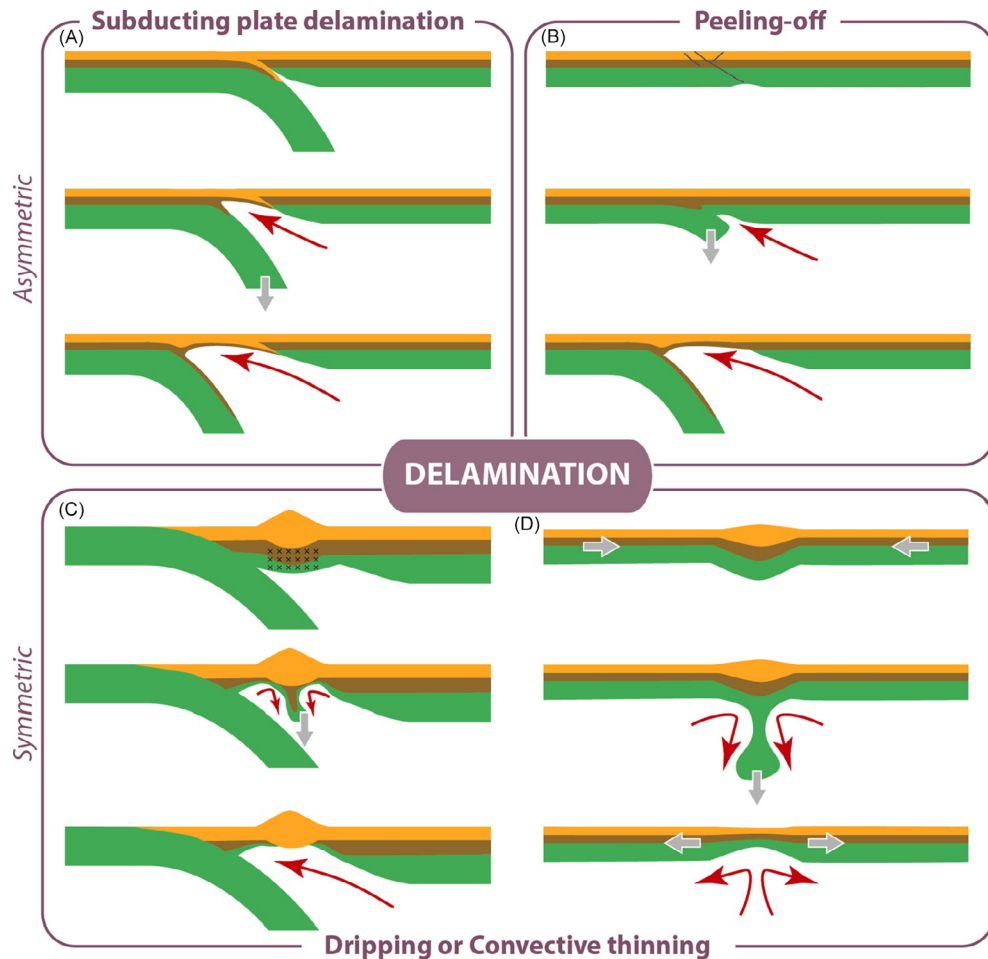
The outer shell of the Earth, the lithosphere, is composed of a shallow layer of buoyant oceanic or continental crust and a denser layer of lithospheric mantle. Delamination is the process in which the bottom part of the lithosphere vertically separates (i.e., delaminates) from the rest of it and sinks into the underlying mantle, allowing the hot asthenosphere to rise to the base of the thinned lithosphere. The change in lithospheric structure and temperature has major consequences on the tectonic, topographic and magmatic evolution of the region in which delamination occurs. Different types of delamination exist and, in the last few decades, many authors used the term “delamination” to describe different processes, which created some confusion around its definition. Here we explain the different types of delamination, their causes, and consequences.

For delamination to occur there needs to be a lithospheric mantle denser than the surrounding material and a region of weakness that allows the dense material to decouple from the rest of the lithosphere. These necessary ingredients can be found in different settings, creating different types of delamination that we can divide into three groups: “subducting plate delamination,” “peeling-off,” and “dripping” (Fig. 1). In the following, we explain the different types of processes called delamination in the literature, emphasizing the differences in physical processes and observables.

## Subducting Plate Delamination

When a subduction zone consumes all the oceanic lithosphere, and the subduction trench reaches a continental lithosphere, the plate resists subducting due to the positive buoyancy of the continental crust. In some cases, the lithospheric mantle and possibly some parts of the continental crust of the subducting plate peels away from the rest of the lithosphere and continues to subduct, leaving only the light continental crust at the surface (Bird, 1978). A weak lower continental crust in between a strong upper crust and a strong mantle lithosphere favors *subducting plate delamination* because it serves as the weak layer needed to decouple the dense lithospheric mantle from the lighter continental crust (Magni et al., 2013). It is hard to tell how weak the lower crust has to be, but this type of delamination is arguably more likely to occur for relatively young continents, which might have a weak, ductile layer at the base of the crust, than for old cratons, which are generally colder and stronger (Burov, 2011). Fluids and melts in the mantle wedge might also play a role in weakening the continent at the time of the collision, allowing the decoupling to occur (Faccenda et al., 2009). In the *subducting plate delamination* scenario, delamination is an asymmetric process that resembles subduction, with the difference that it is not the entire plate sinking into the mantle, but only the lithospheric mantle and possibly part of the lower crust. This type of dynamics results in a delamination front that migrates away from the original suture as the lithospheric mantle slab rolls back and, consequently, in a mantle flow that brings hot mantle material up until the bottom of the continental crust.

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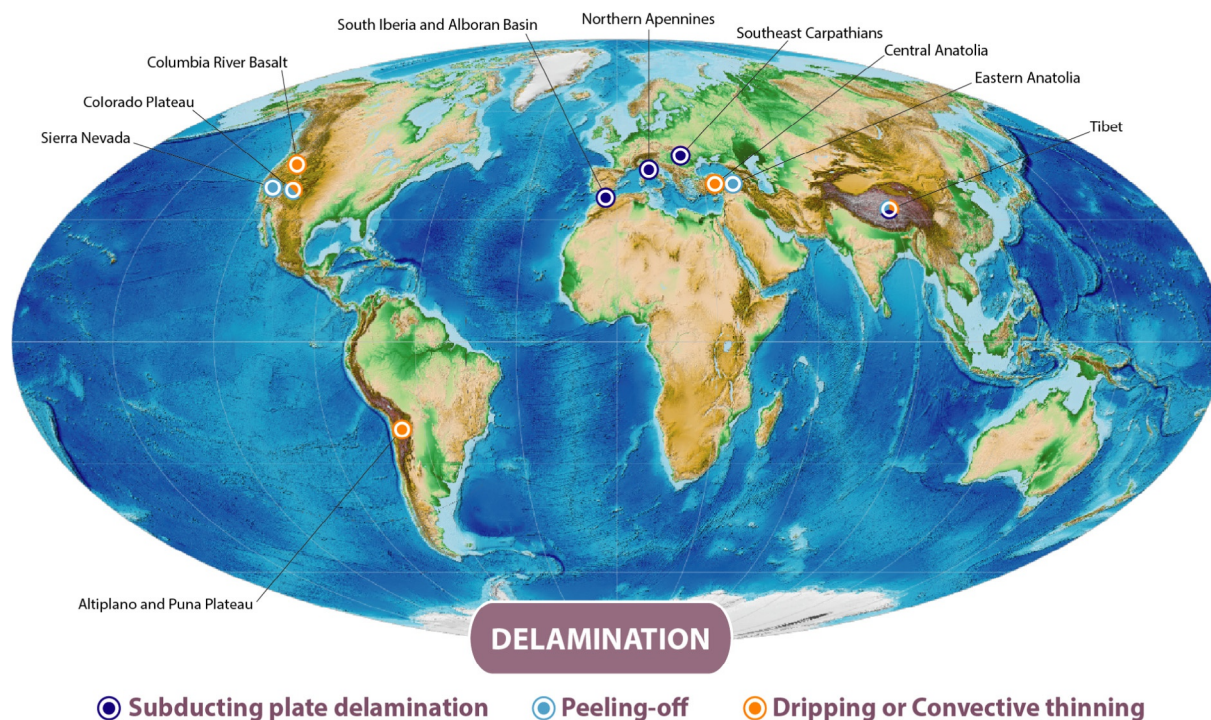
**Fig. 1** Schematic cartoon of the different types of delamination. *Gray arrows* show the main forces acting on the lithosphere (*yellow*: continental upper crust, *brown*: continental lower crust, *green*: lithospheric mantle) and *red arrows* show the mantle flow.

### Consequences and Natural Examples

*Subducting plate delamination* is often associated with a shift from andesitic to basaltic volcanism and migration of the volcanic activity in front of the previous subduction suture zone. Moreover, due to delamination, the tectonic regime quickly changes from compressional to extensional tectonic setting. A migrating topographic signal tracks the location of the delaminating slab, as the slab pull causes subsidence and the delamination of the heavy lithosphere results in uplift. The descending slab induces an asthenospheric return flow, similar to that of in subduction zones, which produces temperature increase and vertical stresses at the bottom of the remained crust. This process has been proposed in several sections of the Mediterranean (Fig. 2), from the Alboran basin to the Southeast Carpathians.

#### *South Iberia and Alboran Basin*

In the Western Mediterranean, subduction has been an active process at least since the Middle Miocene, resulting in the opening of the Alboran Basin. Recently, it has been proposed that the subducting slab has started to delaminate from the crust at the margins of the Alboran Sea. This has been revealed by the analysis of the location of earthquake hypocenters, combined with P-wave seismic tomography and receiver function (RF) analysis that imaged the top of the Alboran slab under the Betics and the central Rif mountains being below the Moho (Turner et al., 2014). This means that the lithospheric mantle is delaminating from the crust at the Moho. Further, an unusually deep Moho is observed in these areas and explained by the load of the descending slab. Basalt thermobarometry gives an independent constraint on understanding the delamination process. Thermobarometry calculations gives information about the thermal and pressure state of the magma source region. Under the Rif mountains, where delamination is occurring, the pressure-temperature equilibration suggests a higher magma temperature and a deeper source than a typical mid-ocean ridge magma, which is interpreted to be the consequence of the asthenospheric upwelling. All the evidence (deeper and hotter magma sources, and characteristic seismicity and slab-like dipping seismic refractors under the Moho) point towards the interpretation of the occurrence of subducting plate delamination at the margins of the Alboran sea at present day.



**Fig. 2** The map shows suggested locations and types of delamination.

### **Northern Apennines**

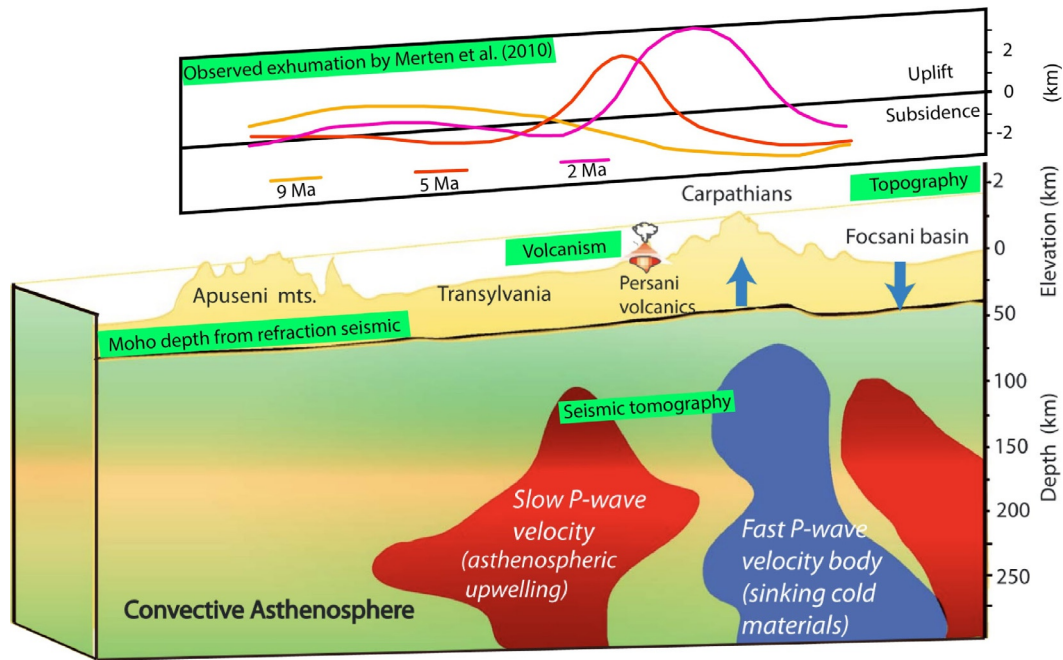
The Apennines mountain chain represents the suture zone of the west-dipping subduction of the Adria microplate (Apennine slab). This subduction zone has been ongoing since ca. 35 Ma, and is still active in its southern segment at the Calabria arc, while the oceanic lithosphere has been completely consumed in the northern part. Here the continental Adria plate progressively reached the subduction trench (from the North to the Central Apennines). However, the Northern-Apennines are still characterized by some subduction like features, such as middle depth (>100 km) earthquakes and fast P-wave anomaly, that images the slab. Receiver function (RF) data clearly image the descending Adriatic Moho from a depth of 40 km below the overriding Apennine Moho. In between them, RF data and active sparse seismicity suggest the presence of an asthenospheric “nose” that is seismically active due to hydration (Chiarabba et al., 2014). The regional stress regime is characterized by extension at the continental collision suture, as well as all the region west of it, while to the East active compression is observed in a narrow zone (Faccenna et al., 2014). Moreover, volcanic evidence suggesting delamination can be found in the Tuscan region. Here, the geochemistry, the age, and the spatial distribution of volcanism show a West to East migration, and two different sources for the metasomatization of the mantle. The first source is suggested to be the old oceanic Ionian lithosphere, while the second group shows signatures of subducted continental crust, suggesting a crustal decoupling during delamination (Serri et al., 1993). From a geodynamic perspective, delamination is consistent with (i) the slower rifting and volcanism migration rate in the Northern-Apennines with respect to the Southern-Apennines (Serri et al., 1993), and (ii) plate reconstruction models, which suggest a larger amount of plate convergence than what could be referred from the total crustal shortening in the area (Le Breton et al., 2017).

### **Southeast Carpathians**

*Subducting plate delamination* has been suggested also for the Southeast-Carpathians by Gîrbacea and Frisch (1998) and Gögüş et al. (2016) (Fig. 3). The Southeast Carpathians is the only corner of the mountain chain where deep seismicity suggests that a slab is still present between 70 and 400 km depth. Similar to the previous examples, delamination causes a migrating pattern in topography, with the occurrence of subsidence (including the opening of the Brasov-basin), followed by uplift and extension. Post-collisional volcanism appears on the suture zone and reveals a change in magma chemistry: shifting from subduction-related andesites to more asthenospheric sourced alkaline magmas (e.g., Harangi et al., 2006). Crustal thickness varies significantly from the Transylvanian Basin and the Carpathian Mountains where delamination removed part of the lithosphere and left a thinned crust (35 km) behind, to the deep Focsani Basin where the crust is thickened (45 km) due to the compressional regime caused by the slab pull.

### **Peeling-off**

Delamination of the continental lithospheric mantle can also happen within the plate interiors, far away from subduction zones, due to some pre-existing weaknesses in the lithospheric mantle (Bird, 1979). Compositional and structural heterogeneities within



**Fig. 3** Observables in the Southeast Carpathians suggesting subducting plate delamination. Figure modified after Göğüş, O. H., Pysklywec, R. N., and Faccenna, C. (2016). Postcollisional lithospheric evolution of the Southeast Carpathians: Comparison of geodynamical models and observations. *Tectonics* **35**(5), 1205–1224.

the continental lithosphere can constitute a sort of “initial flaw,” in which the mantle can percolate through and rise to the Moho, weakening the lower crustal layer. With a weak decoupling layer, the dense lithospheric mantle can peel-off from the crust above. Similar to the previous case, this type of delamination is also asymmetric, with the delamination front moving away from where it originates and sinking into the mantle like a slab. Thus, the *peeling-off* delamination results in a wide area within a continent with anomalously thin lithosphere. Models suggest that the asthenosphere replacing the peeling-off lithospheric mantle can rise with considerably high velocities (up to 24 cm/year; Bird, 1979), which favors basaltic magma production.

### Consequences and Natural Examples

*Peeling-off* delamination has been suggested in several places as a favored process explaining intraplate volcanism, topographic variations, and thinned lithosphere with increased heat flow.

#### Colorado Plateau

The Colorado Plateau is at least 1000 m uplifted with respect to other areas with a similar crustal thickness (42 km). Bird (1979) originally used the model of peeling-off delamination to explain the Tertiary uplift and the igneous activity of the Colorado Plateau. Two phases of volcanism in the Oligocene and late Miocene might be the consequences of two distinct episodes of delamination. The first phase of volcanism with the eruption of the Navajo diatremes at 30 Ma brought up kimberlites and mantle xenoliths. This suggests a deep-mantle magma source with fast rising-speed (Bird, 1979). The second phase comprises the eruption of basaltic magmas at the western and southern margins of the Plateau at ~6 Ma (Roy et al., 2009). This second episode can be also interpreted as the consequence of a dripping-type of delamination (see section *Dripping (or Convective Thinning)*).

Recently, Levander et al. (2011) used receiver function and seismic tomography to image the Moho, LAB and asthenospheric structures. These data reveal the presence of a dipping reflector below the Moho, interpreted as the top of the descending delaminated block. An area of low P- and S-wave velocities and high  $v_P/v_S$  suggests a low-volume of partial melt at the base of the lithosphere. This might have caused an increase in the lithospheric root's density, resulting in dripping/peeling-off delamination.

#### Sierra Nevada

The Sierra Nevada region has experienced multiple phases of volcanic activity. The most recent one (in the Pliocene) is also associated with fast uplift of the southern part of the Sierra Nevada region. Similarly to the Colorado Plateau, it is possible that the previous phases of volcanism created dense lithospheric roots that after >15 Myr of compression peeled-off. This recent volcanism brought up geochemically diverse xenoliths with respect to the ones from the North (Ducea and Saleeby, 1998). The difference in pressure and temperature equilibrium conditions for lower crustal and mantle xenoliths suggest that there has been a change in the compositional and thermal structure below the Sierra Nevadas from the Miocene to the Pliocene. The interpretation of lower crust



and mantle lithosphere delamination is supported by seismic tomography, imaging a slab-like anomaly under the western parts of the area, as well as by the topography evolution of the area, showing first subsidence (with sedimentation) followed by rapid uplift from 3.5 Ma (Le Pourhiet et al., 2006).

### Eastern Anatolia

Peeling-off delamination is also suggested that in the Eastern Anatolia Plateau by Göğüş and Pysklywec (2008). Seismological data shows an isostatically undercompensated crust (i.e., the high plateau topography is not supported by a thick crustal root) and the complete absence of the lithospheric mantle (Gök et al., 2007). Here, the removal of the lithospheric mantle is the cause of the recent (<8 Ma) uplift, increased heat flow, volcanic activity, and synconvergent extension (basins formed during large scale plate convergence tectonics).

### Dripping (or Convective Thinning)

In compressional stress regimes, crustal shortening and thickening can make the base of the lithosphere unstable (i.e., Rayleigh-Taylor instability) and cause sinking plumes of lithospheric mantle material. This *dripping* process can occur (1) at mountain belts when the overriding plate is under compression and the lithosphere thickens more and more until it becomes unstable (Houseman and Molnar, 1997) (also known as *convective thinning*) (Fig. 1D), and (2) at volcanic arcs where the generation of new crust produces a dense residue that composes the arc root which can also become unstable (Kay and Kay, 1993) (Fig. 1C). In any case, this instability causes density-driven foundering of pieces of lithospheric mantle. Differently from the *subducting plate delamination* and *peeling-off*, the *dripping* type of delamination is a more symmetric process, with no migration of the delamination front, and does not necessarily remove the entire lithospheric mantle layer, but only the lower part (Houseman et al., 1981). Thus, *dripping* might not bring hot asthenospheric mantle into direct contact with the bottom of the crust. Although in this case a weak decoupling layer is not strictly necessary for delamination to occur, weak rheology for the part of the lithospheric mantle that drips-off is still required. This weakness can, for instance, be caused by the increase of temperature in the bottom part of the lithosphere as it thickens and reaches greater depths and/or by the presence of fluids and melts.

### Consequences and Natural Examples

The *dripping* process has two main consequences: (1) uplift due to isostatic compensation, as the dense lithospheric mantle is replaced with less dense material and (2) a change in the source of magmatism, as the lithospheric mantle is replaced with hotter and more fertile material. To highlight the effects of *dripping*, we use two case studies: the Altiplano-Puna Plateau in Central Andes (example of foundering of arc roots) and the Central Anatolian Plateau (example of plate thickening due to orocline folding).

If the lower crust has a mafic composition, during crustal thickening it can undergo the basalt-eclogite phase transition at about 50 km depth, which increases the density, thus, makes it unstable and easier to delaminate.

#### Altiplano-Puna Plateau

The Altiplano-Puna Plateau in the Central Andes is one of the highest plateaus in the world, with an average elevation of ~4000 m. It constitutes the back-arc of the Western Cordillera active volcanic arc, which is the result of the ongoing subduction of the Pacific Plate beneath South America. The convergence between these plates created a large amount of shortening that thickened the continental lithosphere of the South American overriding plate, especially in the Central Andes region. The shortening of the Andean Plateau started from 30 Ma, if not before, however, elevation rapidly increased only between 10 and 6 Ma in the North Altiplano and between 7 and 3 Ma in the South Altiplano and Puna Plateau (Garzzone et al., 2008). Thus, although shortening was continuous, uplift happened in discrete and relatively short periods (<5 Myr). However, it is important to keep in mind that there are uncertainties in the computation of uplift ages and other studies suggest that uplift started much earlier (~23 Ma; Scott et al., 2018) and has been continued until today (Jordan et al., 2010). Many authors related the uplift of the Altiplano-Puna Plateau to multiple events of removal of lithospheric mantle material and, at times, of lower crustal material with the process of *dripping*.

The uplift is associated with a change in the regional stress regime that went from a compressional to a more complex strike-slip and extensional regime (Marrett et al., 1994). Along the new strike-slip and extensional faults, a new type of magma was able to rise to the surface and erupt mafic lavas. In the Puna Plateau, previous to the *dripping* events, magmatism was mostly andesitic and dacitic and was related to crustal thickening and melting. During crustal thickening, the lower crust can undergo the basalt-eclogite phase transition at about 50 km depth, which increases the density, thus, makes it unstable and easier to delaminate. Mantle-derived magmatism started when delamination occurred, due to both the lithospheric mantle progressively melting at higher and higher temperatures during foundering and the influx of asthenospheric mantle (Kay et al., 1994; Ducea et al., 2013). Temperature increase at the base of the thinned lithosphere and mafic melts ascending through the crust generate crustal melting, thus a mix of mantle-derived and crustal melts is also possible to occur. Moreover, calc-alkaline lavas have erupted at the margin of the delaminated block, where the lithosphere is slightly thicker, but still affected by the anomalous heat caused by the influx of the asthenosphere. This process likely happened more than once, as these are small scale (<50 km) events that locally change temperature and structure of the lithosphere and result in multiple volcanic fields associated with single drips.

At present-day, evidence that delamination occurred in this region is found in seismic images. For instance, seismic data show that below the Puna Plateau the lithospheric mantle is much thinner than its surroundings, which suggests that a large part of it has been removed (Whitman et al., 1996). In the eastern part of the Altiplano, tomographic images show that warm asthenosphere is present near the base of the crust (Myers et al., 1998). Moreover, Beck and Zandt (2002) noticed a lack of high-velocity lower crust in several regions of the Altiplano-Puna Plateau, which could imply that the mafic lower crust turned into eclogite or that it has been delaminated.

### Central Anatolian Plateau

The Central Anatolian Plateau is an example of *dripping* tectonics as the consequence of shortening, thickening, and folding of an old arc (Göğüş et al., 2017). The compressional tectonic regime and the lithospheric deformation led to the foundering of the arc root and its delamination. *Dripping* might be responsible for more than 1 km of uplift over the Central Anatolian Plateau and for volcanism at the plateau margins since ~10 Ma. Importantly, volcanism is coeval in the north and south margins of the plateau, hence, a symmetric type of delamination, such as *dripping*, is preferred to an asymmetric one. This volcanism is alkaline and is produced by decompressional melting of asthenospheric mantle that is rising at the sides of the lithospheric drip (Varol et al., 2014). During the first stage of *dripping*, when the bottom of the lithosphere starts sinking into the mantle but is still attached to the crust, subsidence can occur due to the pulling force of the heavy drip. This stage is followed by uplift when the removal of the lithospheric mantle is complete. This pattern of the topography evolution during *dripping* is observed in numerical models and seems to fit the elevation history of the Tuz Gölü basin in the Central Anatolian Plateau, although the timing of inversion from subsidence to uplift is not well constrained (Göğüş et al., 2017). Finally, removal of lithospheric roots is consistent with seismic tomography models that show low shear waves velocities below the plateau, with slow anomalies close to the margins and a slightly thicker high velocity body in the center, which could be interpreted to be what is left from the dripping (Fichtner et al., 2013).

## Models and Observations

In the previous paragraphs, we showed how delamination can occur in several settings. However sometimes, in similar settings, delamination is not observed. Thus, the first question one might ask is “what controls the occurrence of delamination”? We already mentioned that a dense lithospheric mantle and a weak region that allows decoupling are necessary ingredients for delamination to occur. In the asymmetric types of delamination (i.e., *subducting plate delamination* and *peeling-off*) the lower continental crust acts as decoupling layer (Fig. 1A and B). For this layer, a viscosity lower than about  $10^{21}$  Pa s seems to be necessary for delamination to occur (e.g., Magni et al., 2013). High Moho temperatures ( $>800$  °C) and the presence of fluids and melts can also weaken the crust and enhance delamination (Göğüş and Ueda, 2018). These factors are also key for the symmetric type of delamination (i.e., *dripping* or *convective thinning*), in which the lithospheric mantle has to weaken in order to delaminate. In the arc region, the abundance of fluids and melts makes it easy for arc roots to become weak and delaminate (Fig. 1C). In the case in which delamination happens due to plate thickening, the temperature-increase at the bottom of the deepening lithosphere is crucial to weaken it and to allow delamination (Fig. 1D). Another possible way to weaken enough the base of the lithosphere is to have a temperature increase (and possible melt formation) by the arrival of a mantle plume. Plume-induced delamination has been suggested by Camp and Hanan (2008) to explain the Columbia River Basalt volcanism and resembles the *dripping* type of delamination described here. In the past (late Archean to early Proterozoic), delamination might have been a more common process than it is today or even the dominant one as temperatures in the Earth’s interior were higher and the lithosphere weaker (Chowdhury et al., 2017).

The next important question is “how can we recognize delamination in geological and geophysical data?” We showed that delamination evolves differently depending on the type and, at times, it resembles other processes (e.g., *subducting plate delamination* and *peeling-off* are very similar to “normal” subduction). It is, therefore, not trivial to distinguish it among other processes, but there are some patterns and common features that we can look for also inferred from geodynamic models.

Numerical models show that during delamination a phase of subsidence is expected, as the dense lithosphere pulls down during sinking. This is immediately followed by a phase of uplift because what is left of the lithosphere after the detachment of the heavy part is overall lighter. Moreover, all the types of delamination are associated with upwelling of mantle material, which can also contribute to the uplift. Thus, a change in topography, from subsidence to uplift is a potential signal of delamination. Basins formation, faults (re-)activation, exhumation, erosion, and sedimentation, are some of the processes that can occur as a consequence of delamination. The magnitude of the topography variation is hard to predict and can vary significantly depending on, but not only, the amount of delaminated material, the thermal structure and elastic thickness of the plate, and the regional stress field. However, the pattern subsidence-to-uplift seems to be common to all delamination types.

Another common feature among all types is the upwelling of hot asthenosphere. In many cases, this results in the appearance of magmatism at the surface or to a shift to a more primitive source of already active magmatism. The location and amount of magmatism due to delamination varies among the different types. Asymmetric delamination is often associated with a migration of the location of volcanism following the roll-back and subduction of the delaminating part of the lithosphere. This is not observed in the symmetric types, in which volcanism remains in the same region where dripping occurs.

Finally, geophysical data can be used to infer crustal and lithospheric thicknesses, which are expected to be anonymously thinner after delamination compared to the surrounding lithosphere. Receiver function seismics are especially useful for imaging the dipping refractors under the (upper) crust and find the location of the decoupling region. Furthermore, seismic tomography allows

finding the delaminated slab and the regions of hot mantle upwelling. It is worthy to note that this is easier to use these methods to identify recent events, for which the lithosphere did not have the time to cool down again yet.

## Summary and Conclusions

Delamination is the process that detaches parts of the continental lithosphere from its shallower and more buoyant part. It can happen in different compressional settings: at subduction zones, volcanic arcs, mountain belts, or away from plate margins in intraplate settings. Delamination needs weak rheology of the decoupling layer, often constituted by the ductile lower continental crust, and/or by high temperatures. The main consequences are (i) a change in topography from subsidence, during the process of delamination, to uplift, right after it has passed, (ii) an increase in magmatic activity and/or a shift to more primitive mantle source, and (iii) a thinned lithosphere. Thus, to identify delamination one must use a multidisciplinary approach, which combines geological, petrological, and geophysical observations and geodynamic model predictions.

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