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Discussing the origin of "hotspot" volcanism

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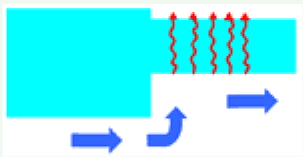
Hydration weakening



Continental lithospheric thinning results from hydration weakening, not "delamination", and is a special consequence of plate tectonics

Yaoling Niu

Durham University, Durham DH1 3LE, UK,

For Discussion of this page, click here.

1. Terminology and concepts

In recent years, the term "delamination" [Ed: see Lithosphere thinning pages, and also Continental delamination and the Colorado Plateau by P. Bird, for an explanation of what delamination is and isn't] has been developed into a model whereby the basal portions of locally or regionally thickened continental mantle lithosphere, and possibly also lower crust, sink into the deeper mantle. Most recently, lithosphere delamination has been suggested to cause continental volcanism. My objective in this webpage is to encourage interested readers to take away the following Q-and-A messages and to remain skeptical of the proposed mechanism and deduced consequences of continental lithosphere "delamination".

Q: Can subcontinental lithosphere be thinned?
A: It is difficult, but it happens in some places.

Q: Can it happen by "delamination"?
A: It is possible, but extremely difficult and perhaps unlikely.

Q: Why is it difficult?
A: Because the lithosphere is too buoyant to sink into the dense asthenosphere.

Q: How then could the lithosphere be thinned?
A: Its basal portions can be transformed into convecting asthenosphere.

Q: How?
A: By hydration-weakening.

Q: Where does the water come from?
A: It comes from recently subducted oceanic lithosphere. Thus, this method of lithosphere thinning is a special consequence of plate tectonics.

Compared with the young (< 200 Ma) ocean crust, the continental crust is rather old, on average > ~ 2.5 Ga. This is because the continental crust is protected by the similarly old continental lithospheric mantle (CLM) from the underlying convective asthenospheric mantle (CAM). Since its inception, much of the CLM (in contrast to oceanic lithosphere) has been isolated from mantle convection. The protective power of the CLM arises from its depleted composition (high Mg/Fe and low Al_2O_3) and physical buoyancy relative to the CAM. It is physically buoyant because it comprises light minerals with high Mg/Fe, lacking dense garnet due to low Al_2O_3 etc. It is true that the CAM is hot, whereas the CLM is cold. However, because of the negligibly small thermal expansion coefficient (~ 3×10^{-5} K^{-1} of mantle peridotites), the density contrast due to the compositional differences (~1%) cannot be overcome without cooling the CLM by ~ 300 K. In other words, in order to reduce the buoyancy contrast so that the CLM may sink into the CAM, the CAM must be additionally > 300K hotter. This is impossible, and therefore, the CLM cannot delaminate and sink into the dense CAM. Straightforward arguments of this kind must be considered when evaluating the likelihood of physical models.

2. Hydration-weakening and the best example

There is evidence that the CLM has indeed been thinned in some places. One of the best examples is eastern China in general and the North China Craton (NCC) in particular. There is every reason why the CLM root of ancient cratons should be stable indefinitely, but this is not the case beneath the NCC. The existence of Paleozoic diamondiferous kimberlites in the NCC indicates that the eastern China lithosphere must have been ~ 200 km thick in the Palaeozoic. However, petrologic studies of Cenozoic volcanism and mantle xenoliths, as well as seismic studies, show convincingly that the present-day CLM beneath eastern China is no more than 80 km thick. Thus, the lithosphere beneath eastern China must have lost more than 120 km of its original thickness, probably in the Mesozoic. “Delamination”, “large scale extension and stretching” and “thermal erosion by mantle plumes” have been suggested as the cause. As explained above, however, the “delamination” process is physically unlikely. Evidence for extension exists, but it is inadequate to explain the observations. As a final resort, mantle plumes were invoked to explain the lithosphere thinning in eastern China and the intra-plate volcanism there in the Mesozoic and Cenozoic. However, there is no evidence of any kind in favor of mantle plumes in the region. Alternatives are needed. I offered an alternative interpretation [1], where I suggest that the Mesozoic lithosphere thinning and Mesozoic/Cenozoic basaltic volcanism in eastern China are a special consequence of plate tectonics.

Mesozoic lithosphere thinning in eastern China is best explained by a process that “transformed” the basal portion of the lithosphere into convective asthenosphere by hydration (Figure 1). The water required may have come from dehydration of subducted Pacific (or predecessor) oceanic lithosphere that is presently lying horizontally in the transition zone beneath eastern Chinese continent, where it is detected by seismic tomography [2]. The Mesozoic volcanism may be genetically associated with the lithospheric thinning because the basaltic source is ancient isotopically enriched ($\varepsilon Nd < 0$; [3]) lithosphere being converted into asthenosphere (Figure 1).

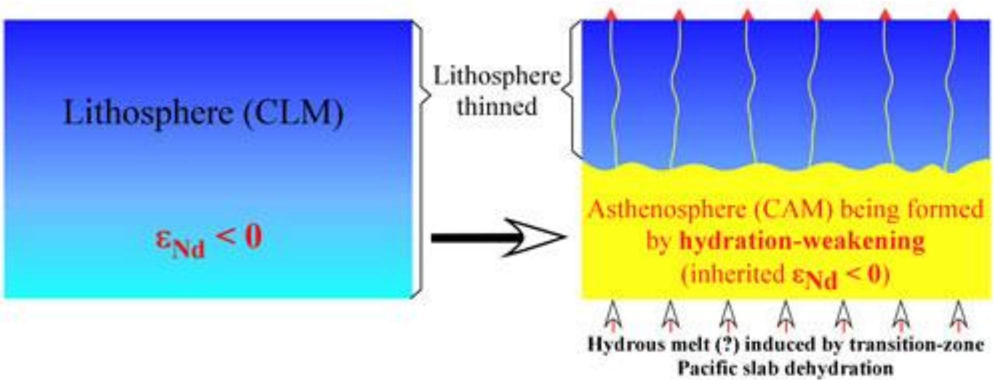


Figure 1: Cartoon illustrating the concept that continental lithosphere can be thinned through “hydration-weakening” at its base [1]. That is, the basal portion of the lithosphere can be transformed into “asthenosphere” by water-induced viscosity reduction. In the case of eastern China, the water may originate from dehydration of subducted Pacific plate that lies horizontally in the transition zone [2]. The water probably rises in the form of hydrous melt although the exact form is

unconstrained. The associated basaltic volcanism would probably have an isotopically enriched signature (i.e., εNd < 0) that is inherited from ancient metasomatized lithosphere that is being transformed into "asthenosphere". In this figure, "Continental lithospheric mantle" is considered to be "cold", rigid, strong, highly viscous/elastic and isolated from convection. "Asthenosphere" is considered to be "hot", soft, weak, less viscous and part of the convection system.

The NNE-SSW Great Gradient Line (GGL; Figure 2) marked by sharp altitude, gravity, crustal thickness and mantle seismic velocity changes from the plateau in the west to the hilly plains of eastern China reflects the variation in lithospheric thickness from probably > 150-200 km thick beneath the plateaus in the west to probably < 80 km thick beneath eastern China (Figure 2). The "remote" western Pacific subduction system "wedge suction" [1] induces asthenospheric flow from beneath eastern China towards the subduction zones, which in turn requires asthenospheric material replenishment from beneath the western plateaus to eastern China (Figure 3). As a result, such eastward asthenospheric flow experiences upwelling and decompression as it passes from beneath thickened to thinned lithosphere, which causes it to partially melt and fuel Cenozoic eastern China basaltic volcanism (Figure 3). Such volcanism may have begun at the end of the Mesozoic lithosphere thinning in the late Cretaceous [4].

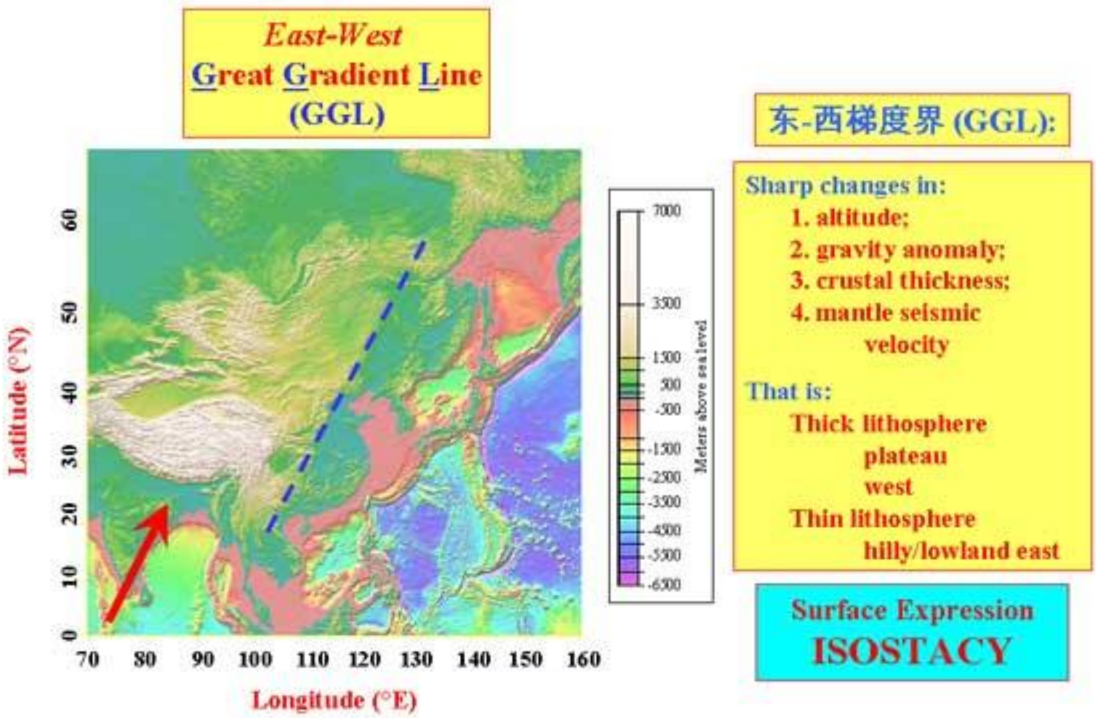


Figure 2: (a) Topographic map showing a sharp altitude contrast in continental China as indicated by the blue dashed line. This line is called the Great Gradient Line (GGL) [1] as this altitude contrast coincides with contrasts in mantle seismic velocity (higher in the west than in the east) at 100-150 km depth, (2) Bouguer gravity anomaly (lower in the west than in the east), and crustal thickness (higher in the west than in the east). These consistent/coincident east-west contrasts are interpreted as the expression of isostacy – reflecting thin lithosphere in the east and thickened lithosphere in the west [1]. Lithosphere thinning in eastern China is generally accepted to have taken place in the Mesozoic (see Figure 1), but lithosphere thickening in western China (plateaus) is interpreted as being genetically associated with the Indian-Asian collision since the Cenozoic [1].

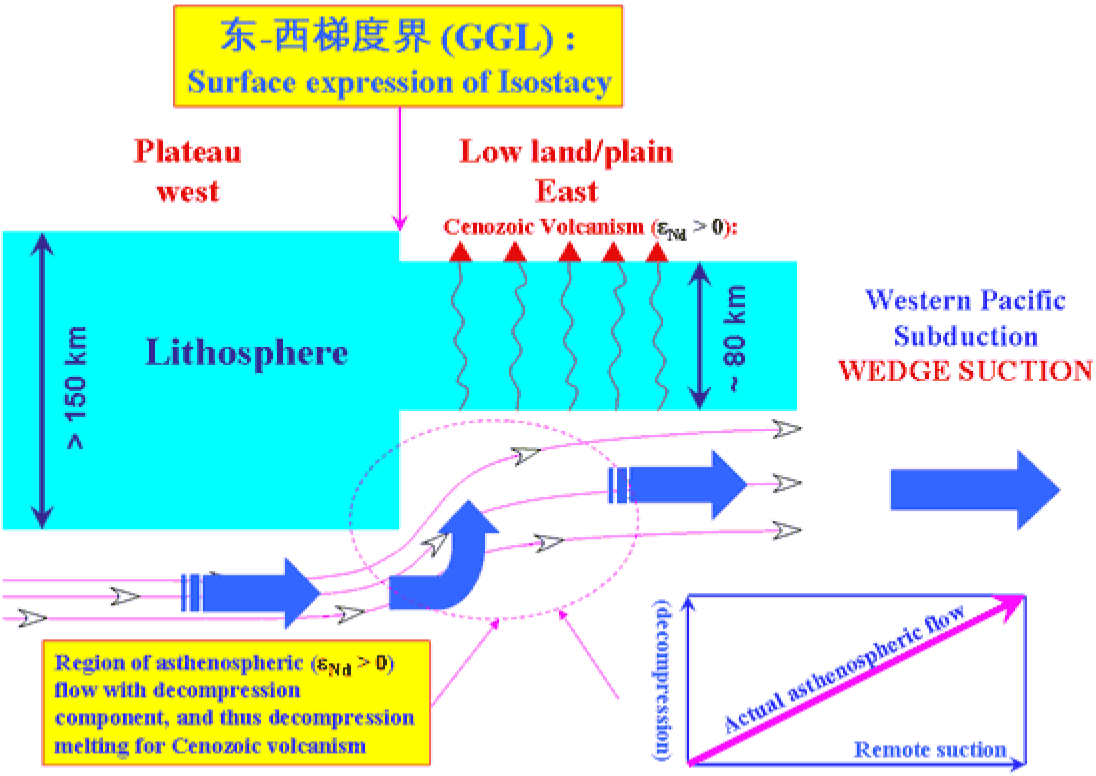


Figure 3: Cartoon showing asthenospheric flow and Cenozoic volcanism in eastern China. The lithosphere is thick beneath high plateaus in western China and thin beneath eastern China (see Figure 2) across the Great Gradient Line (GGL). Western-Pacific-subduction-induced "corner-flow" requires asthenosphere replenishment from the west [1]. In response, the eastward flow of asthenosphere beneath eastern China requires replenishment from the west beneath the plateaus. The latter flow experiences decompression of > 50 km vertically, which will result in decompression melting and Cenozoic volcanism in eastern China. As the source is the asthenosphere, this model explains the isotopic depletion of Cenozoic volcanism (i.e., εNd > 0). Note, the asthenosphere flow is driven by a "wedge-suction"-induced pressure gradient [1], and it is NOT the same as "edge" convection.

This hypothesis, which requires further testing, is consistent with available observations and complies with straightforward physics. The proposed mechanism of lithosphere thinning thus:

1. does not require hot mantle plumes beneath eastern China; the horizontally lying transition-zone slabs [2]act as a cold thermal boundary layer that absorbs heat from above and below, thus preventing hot mantle plumes from rising from the lower mantle and traversing the upper mantle [1];
2. does not require lithospheric "delamination", which suggests that deep portions of the buoyant cratonic lithosphere sink into the dense asthenosphere – a scenario that is physically unlikely;
3. does not require lithospheric extension/stretching the scale of which was limited in the Mesozoic;
4. explains the lithosphere thinning beneath all of eastern China, not just the NCC; and thus
5. questions the significance of South China continental subduction as a cause of lithosphere thinning beneath the NCC.

The suggested mechanisms for Mesozoic/Cenozoic volcanism in eastern China are consistent with the geochemistry of the basalts [3], physical scenarios of mantle melting [1] and geophysical observations [1,2]. The latter principles and observations:

1. do not favor a hot mantle plume origin for eastern China volcanism;

2. do not support the suggestion of oceanic-ridge-like passive mantle upwelling and decompression melting because there is no unambiguous evidence for large-scale rifting or lithosphere separation in eastern China since the Mesozoic;
3. argue that the eastern China Mesozoic/Cenozoic basins may not comprise evidence for continental extension and rifting. These basins may be an isostatic response [1] to horizontally lying dense slab materials in the transition zone.

Important points to note are:

1. the NNE-SSW GGL (Figure 2) [1] is probably a young feature that results from Indian-Asian collision since the early Tertiary;
2. subduction-zone dehydration is necessarily incomplete [1,5] because of formation of stable hydrous phases in subducting slabs. For example, in the subducting crust, lawsonite forms. It can contain ~ 11 wt % H_2O, and is stable up to 11 GPa [6], much deeper than expected subduction-zone dehydration. Importantly, serpentines within subducting lithospheric mantle [5] contains up to 13 wt % H_2O, and is stable up to 7 GPa [7] before being transformed to dense hydrous magnesium silicate phases that are stable at even greater pressures (~ 5 to 50 GPa [6,8]). This allows water transport to great depths in the mantle [9]. All these hydrous phases tend to decompose and form new and less hydrous phases (e.g., Wadsleyite, < 3.0 wt% H_2O; Ringwoodite, < ~ 2.2 wt% H_2O; Mg_2SiO_4-spinel is essentially anhydrous) as the temperature increases [1,6]. The horizontal slabs in the transition zone beneath eastern China [1,5] experience isobaric (horizontal movement) heating with time, and will thus lose water accordingly. The water so released would form hydrous melts that migrate upwards and weaken the deep portions of the lithosphere (hydration-weakening) and transform them into asthenosphere. This gives rise to the process of lithosphere thinning [1];
3. mantle wedge suction, while less strong than ridge suction [10], is an important driving force for asthenospheric flow;
4. more recent lithosphere accretion beneath the NCC is a straightforward consequence of conductive cooling of the asthenospheric mantle. However, the suggestion that "new lithosphere replaces old lithosphere" should be avoided if it is intended to emphasize processes or physical mechanism because it is misleading.

3. Any other examples?

A literature search readily reveals that wherever the concept of "lithosphere delamination" is invoked, oceanic lithosphere subduction was ongoing either simultaneously or shortly beforehand. Other examples include the southern Andes, the western USA, the western Mediterranean and Tibet. On the other hand, mantle plumes have been proposed to have impinged or to underlie the African lithosphere, yet the lithosphere thinning there has only occurred on limited scale and been associated with active rift zones or ancient sutures. This suggests that

1. thermal erosion, if thermal mantle plumes did indeed exist beneath Africa, is ineffective in thinning the lithosphere, and
2. the role of water or hydration-weakening is indeed the key mechanism – no oceanic lithosphere subduction is currently ongoing or occurred in the recent past beneath the African plate. The closest plate boundaries to the African plate are ocean ridges, the south Mid-Atlantic Ridge, the Southwest Indian Ridge, the Central Indian Ridge and the Read sea spreading centers.

A full paper describing these ideas is presently in preparation, but the basic concept and discussion can be found in reference [1].

4. *Acknowledgement*

I thank Gillian Foulger for inviting this contribution.

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Discussion

28th May, 2006, Don Anderson

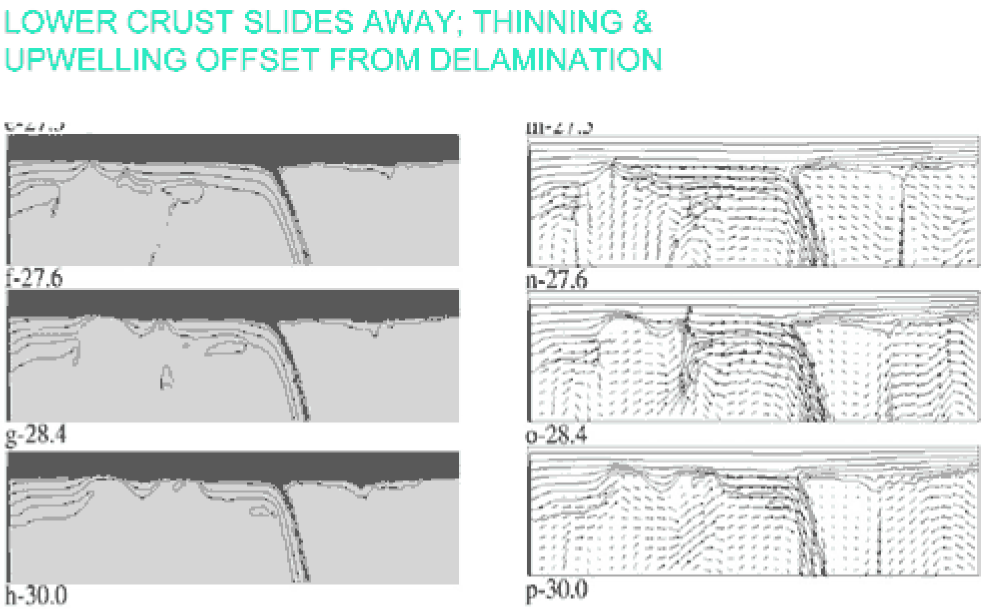
The term 'delamination' has been widely used for the gravitational removal of the continental lithosphere. There have been objections to this usage of the term and it has even been questioned whether it is possible. The term 'foundering' has also been used. There are other ways to remove or thin lithosphere that involve lateral flow or detachments. Over-thickened continental crust can also be removed by mechanisms that do not involve a Rayleigh-Taylor instability. The term 'delamination' does not imply gravitational removal, or lithosphere removal. To avoid confusion, the term 'crustal delamination' should be used for the removal of lower continental crust, by whatever mechanism. Gravitational instability or Rayleigh-Taylor instability or foundering should be used if a specific mechanism is being treated.

Lower crustal delamination is quite different from continental lithosphere removal described by Yaoling Niu in this page. It is difficult to remove buoyant cratonic peridotite (SCLM) for the reasons described. It is not only buoyant; it is strong and has high viscosity, when cold and dry. Weak or wet peridotite can be removed by lateral flow. But mafic overthickened arc and convergent belt lower crust is a different story (Anderson, 2005). The use of the term gravitational instability or Rayleigh-Taylor instability is misleading. The lower crust can be removed by a variety of mechanisms and delamination is a better and more descriptive term. A laminated solid can be delaminated by peeling, scraping, bending, faulting, rubbing, erosion or soaking off the laminations. It is more likely to be a band-aide removal or Velcro type operation than a gravitational instability as in fluid dynamics. It is aided by water from an underlying slab and it is most likely to occur in convergent belts and in arcs and is therefore related to subduction, but it is not the same as subduction.

The removal of dense lower crust should not be confused with, or equated to, continental lithosphere removal or a fluid dynamic Rayleigh-Taylor or density instability. There is probably a buoyant refractory peridotite layer in the shallow mantle (the perisphere), of which the long-lived subcontinental cratonic root (Archon) is part but it likely spreads laterally when heated or fluxed, rather than delaminating or sinking. This depleted layer or region may be the FOZO source of high $^3He/^4He$ ratios (because of the low U and Th content). The lower crustal (>50-km) garnet pyroxenite, "eclogite" or piclogite mafic root is more likely to sink, because of its intrinsically high density.

There are two schools of thought. Many people think in terms of Rayleigh-Taylor instabilities and gravitational instabilities and it is fine to remove delamination from their lexicon so it can be used more appropriately. Much of the so-called delamination literature also involves lithosphere rather than crust. [Ed: Click here to visit a webpage that clarifies terms]. Kay, R. W., and S. M. Kay (1993, Delamination and delamination magmatism, Tectonophysics, 219, 177-189) first started the lower continental crust delamination story and this is how others think about it. It may not be a gravity or fluid dynamic instability, as modeled by some workers.
So, there are two issues; lower crust (garnet pyroxenite) vs ‘lithosphere’, or shallow mantle layer (intrinsically buoyant but cold peridotite) and gravity instability vs tectonic removal (erosion, scraping, faulting, detaching, peeling, unzipping). Confusion concerning these terms is widespread.

I suggest that ‘crustal delamination’ or ‘delamination’ be used in the sense of Kay and Kay (1993) for removal, by whatever mechanism, of the lower continental crust. Discussions of the removal or thinning of the mantle part of the section usually involves a specific mechanism that does not fit into most definitions of the word ‘delamination’ (see Google and Google Images, for ‘delamination’). I have avoided using the word ‘lithosphere’ in this paragraph until now because ‘lithosphere’ means ‘strong shell’ and has no density or chemical connotation. The term ’perisphere’ was introduced for the refractory buoyant mantle layer; it has no connotation of strength. ‘Archon’ is the long-lived mantle root of cratons; it probably survives because it is cold, strong, buoyant and hav not been exposed to high stresses.



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