Eastern China continental lithosphere thinning is a consequence of paleo-Pacific plate subduction: A review and new perspectives

Pu Sun\textsuperscript{a,b,*}, Pengyuan Guo\textsuperscript{a,b}, Yaoling Niu\textsuperscript{b,c,d,**}

\textsuperscript{a} Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
\textsuperscript{b} Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China
\textsuperscript{c} Department of Earth Sciences, Durham University, Durham DH1 3LE, UK
\textsuperscript{d} School of Earth Science and Resources, China University of Geosciences, Beijing 100083, China

** Correspondence to: Y. Niu, Department of Earth Sciences, Durham University, Durham DH1 3LE, UK.
E-mail addresses: pu.sun@qdio.ac.cn (P. Sun), yaoling.niu@durham.ac.uk (Y. Niu).

1. Introduction

Continents, especially stable cratons, are ancient (Archean or Proterozoic), thick (~ 200 km) and cold (~ 45 mW/m\textsuperscript{2}) with a refractory and dry sub-continental lithospheric mantle (SCLM) (Boyd and Nixon, 1975; Griffin et al., 1999; Lee et al., 2011). Compared with the rheologically weak convective asthenosphere, the SCLM is rigid with conductive geotherms (McKenzie and Bickle, 1988). It is geochemically depleted (low CaO, FeO, and Al\textsubscript{2}O\textsubscript{3} but high MgO) with low density and is thus buoyant and isolated from the convective asthenosphere, which

Abstract

Understanding the processes that lead to the lithosphere thinning is a key aspect of continental geology research. In this paper, we present essential observations and summarize our understandings on the lithosphere thinning and accompanying magmatism in eastern continental China since the Mesozoic as a straightforward consequence of plate tectonics. We show that the lithosphere thinning in the Mesozoic resulted from basal hydration weakening with the water coming from dehydration of the paleo-Pacific plate in the mantle transition zone. The weakening effect is to convert the basal lithosphere into asthenosphere by reducing its viscosity, having thus thinned the lithosphere while triggering mantle melting and crustal magmatism marked by the widespread Mesozoic basalts and granitoids in space and time. These observations and logical reasoning require the existence and effect of subducted paleo-Pacific plate in the mantle transition zone, whose active subduction ended at ~ 90 Ma with the suture located off the continental China marked by the arc-shaped southeast coastline. As a result, the thinned lithosphere began a 40-Myr period (i.e., ~ 90 to ~ 50 Ma) of basal accretion manifested by compositional systematics of basalts erupted in this period. The initiation of the present-day western Pacific subduction at ~ 50 Ma and its eastward retreat caused eastward drift of continental China, leaving the older portions of the present-day Pacific slab stagnant in the mantle transition zone with resumed water supply in the form of hydrous melt to maintain the thinned lithosphere, which is the same as creating and maintaining the oceanic-type seismic low velocity zone (LVZ) beneath eastern China, responsible for the Cenozoic alkali basalt volcanism in the region. That is, the present-day lithosphere-asthenosphere boundary (LAB) beneath eastern China is a petrological boundary, either as an amphibole dehydration solidus or water-saturated solidus. As predicted, the Cenozoic alkali basalts in eastern China demonstrate that lithosphere thickness (i.e., the LAB depth) controls the compositions of mantle melts, i.e., the lid effect. The latter further confirms the LAB beneath eastern China as a solidus, below which decompression melting happens, and above which melt solidifies or ascends rapidly to the surface.

Our studies thus lead us to the unavoidable conclusion that the lithosphere thinning in the Mesozoic, the present-day LAB, the seismic LVZ and the widespread Mesozoic-Cenozoic magmatism in eastern China are all consequences of plate tectonics in response to paleo-Pacific plate subduction, which is of global significance for understanding intra-continental magmatism at present and in Earth’s histories.
ensures the stability of continents over billion-year timescales (O’Reilly et al., 2009). However, several continental regions are known to have experienced lithospheric thinning in the Phanerozoic, accompanied by intense intra-continental deformation and magmatism (e.g., western and central Europe, eastern Australia, western USA and eastern China). To understand the lithospheric thinning is thus significant for understanding the evolution history of the continents we live on and the origin of intra-continental magmatism.

The widespread Mesozoic-Cenozoic magmatism in eastern China makes this vast region an ideal place to study what may have actually caused the lithosphere thinning (Fig. 1). The existence of Paleozoic diamondiferous kimberlites in eastern China indicates a thick (~ 200 km) lithosphere in the Paleozoic (Griffin et al., 1998; Li et al., 2011; Lu et al., 1995), in contrast with the thin (~ 60–100 km) present-day lithosphere to the east of the Great Gradient Line (GGL) which marks a sharp contrast between western and eastern China in topography, gravity anomaly, heat flow, crust thickness and the SCLM thickness (Chen et al., 2008; Niu, 2005; Xu, 2007) (Fig. 2). These observations indicate that the mantle lithosphere of eastern China to the east of the GGL must have been thinned, which is inferred to have happened in the Mesozoic from the widespread Mesozoic tectonomagmatic activities in the vast region (Fan et al., 2000; Gao et al., 2002, 2004; Griffin et al., 1998; Li et al., 2019; Liu et al., 2019; Menzies et al., 1993; Suo et al., 2020; Wang et al., 2021; Wu et al., 2019; Xu, 2001; Zhang et al., 2017).

With the removal of the thick, cold and depleted Archean lithospheric mantle, the present-day mantle lithosphere is thin and is perceived to be newly accreted with the properties of being hot and compositionally more fertile (Chu et al., 2009; Fan et al., 2000; Menzies et al., 2007; Wu et al., 2003; Ying et al., 2006; Zheng et al., 2006).

In this paper, we present essential geological observations and summarize our understandings on the lithosphere thinning and the accompanying magmatism in eastern continental China since the Mesozoic. We illustrate that the lithosphere thinning in the Mesozoic, the present-day lithosphere-asthenosphere boundary (LAB), the oceanic-type seismic low velocity zone (LVZ) and the widespread Mesozoic-Cenozoic magmatism in eastern China are straightforward consequences of plate tectonics (Niu, 2005).

2. Geological background of eastern China

The continental China achieved its final amalgamation in the late Triassic as the result of continental collision of the Yangtze craton against the North China Craton (NCC), forming the Qinling-Dabie orogenic belt in east-central China (Dong et al., 2011) (Fig. 1). Since the early Jurassic, the paleo-Pacific plate started to subduct beneath eastern China (Engebretson et al., 1985). Extensive basaltic and granitic magmatism happened in eastern China during the Jurassic to early Cretaceous period (Fig. 1). However, magmatism is essentially absent during ~90–50 Ma, and only a few volumetrically small basaltic eruptions of this age are scattered in the vast region (Kuang et al., 2012b; Lu et al., 2012; Wang et al., 2006; Xu et al., 2012a; Yan et al., 2005). The alkaline basaltic volcanism began widespread in eastern China since ~50 Ma, clearly after the initiation of the present-day western Pacific subduction at ~50 Ma (Moberly, 1972). These Cenozoic basalts are spatially associated with regional faults (Fig. 1) and contain abundant mantle xenoliths and clinopyroxene megacrysts of high-pressure origin (Song et al., 1990; Sun et al., 2018, 2020; Zhi et al., 1990).

3. Lithosphere thinning in the late Mesozoic

Many models have been proposed to explain the lithosphere thinning in the late Mesozoic, e.g., large-scale delamination of lithospheric mantle (Gao et al., 1998, 2004; Wu et al., 2005) and thermal-mechanical erosion by underlying asthenospheric mantle or mantle plumes (Deng et al., 2004; Griffin et al., 1998; Xu, 2001). Both models have been popular and may still be convenient for many, but Niu (2005, 2006) pointed out that these models are geologically and physically flawed. The “delamination” model suggests the foundering of the eclogitic lower crust together with the underlying lithospheric mantle (Gao et al., 1998, 2004). However, because ancient subcontinental lithospheric mantle is compositionally depleted (high MgO, low FeO and Al₂O₃ and physically buoyant (Jordan, 1978, 1986), it is physically difficult for the buoyant lithosphere to “delaminate” and sink into the underlying dense asthenosphere (Niu, 2005, 2006). The “thermal-mechanical erosion” model also fails because there is no evidence of thermal anomalies (e.g., excess heat from upwelling mantle plume) existing in the asthenospheric...
mantle beneath eastern China in the Mesozoic (Wu et al., 2019). Even if there were mantle plumes, their thermal-mechanical erosion may have limited effect in thinning the lithosphere (Wang et al., 2015a, 2015b). For example, mantle plumes have been proposed to have impinged on or underlain the African lithosphere, yet the lithosphere there is essentially intact except for weakening on limited scales associated with active rift zones or ancient sutures (Niu, 2006, 2009). A literature search readily reveals that wherever the idea of “lithosphere delamination” is invoked, oceanic lithosphere subduction is ongoing either simultaneously or shortly beforehand, such as the southern Andes, the western USA, the western Mediterranean and Tibet, suggesting the potential effect of water supplied via seafloor subduction. The logical reasoning is that the African lithosphere could be “delaminated” if there were water introduced, but its closest plate boundaries are ocean ridges, not subduction zones that can supply needed water to thin the lithosphere. This understanding and the recognition of the older portions of the present-day Pacific plate stagnant in the mantle transition zones beneath eastern China (Káraason and Hilst, 2000) convinced Niu (2005) the significance of water in facilitating lithosphere weakening and thinning. While there is no present-day evidence for the existence of seafloor slabs in the mantle transition zone beneath eastern China in the Mesozoic, its existence is in fact required by the widespread Mesozoic granitoids in space and time (Niu et al., 2015; see below). The above analysis led to, among all the possibilities, the most logical hypothesis of basal hydration weakening as an effective mechanism to have caused the lithosphere thinning by means of converting the basal portions of the lithosphere into asthenosphere in its physical properties (i.e., the reduced viscosity and thus weakened strength) as elaborated below (Hirth and Kohlstedt, 1996, 2004; Karato, 2010; Niu, 2005, 2006, 2014; Niu et al., 2015).

Fig. 2. Sharp contrast between eastern and western China across the Great Gradient Line (GGL) as indicted by the arrowed black dashed line in topography (a), crust thickness (b), Bouguer gravity anomaly (c) and lithosphere thickness (d). Compared with western China, eastern China has lower elevation, thinner crust, higher Bouguer gravity anomaly and thinner lithosphere. Fig. 2a, b and d are made using GMT (Wessel et al., 2013) and models of global ocean and land terrain (http://www.gebco.net/), crustal 1.0 (Laske et al., 2013) and CAM2016Litho (Priestley et al., 2019), respectively. The model data of crust and lithosphere thickness are downloaded from IRIS Earth Model Collaboration (EMC) (https://ds.iris.edu/ds/products/emc/). Fig. 2c is made using the WGM2012 model (Balmino et al., 2012) online (http://bgi.obs-mip.fr/data-products/outils/wgm2012-maps-visualizationextraction/).
3.1. “Basal hydration weakening” caused the lithosphere thinning

Ancient continental lithospheric mantle is physically cold, rigid and dry with high viscosity, in contrast to the hot, plastic and less viscous asthenospheric mantle (Jordan, 1978; Lee et al., 2011; Peslier et al., 2010). Therefore, lithosphere thinning can be achieved by converting the basal lithosphere into asthenosphere by reducing the viscosity (Fig. 3a). Two probable methods can theoretically achieve such conversion: (1) the less effective basal heating (see above) and (2) the more effective basal hydration (Niu, 2005). Seismic tomography shows that the subducted paleo-Pacific plate lies horizontally in the mantle transition zone (i.e., 410–660 km) beneath eastern China with its western end

![Diagram](image-url)

**Fig. 3.** (a) Cartoon illustrating the model of “basal hydration weakening” to cause the lithosphere thinning (Niu, 2005). Modified from Niu (2014). (b) Calculated effective viscosities of the upper mantle at varying olivine H$_2$O contents versus depths, using a shear stress of 0.3 MPa and a cratonic geotherm (40 mW/m$^2$). The pink shaded area shows the effective viscosities of the asthenospheric mantle (Craig and McKenzie, 1986; Hirth and Kohlstedt, 1996, 2004; Pollitz et al., 1998), with the average viscosity ($\sim 5 \times 10^8$ Pa S) indicated by the vertical red line. The black arrow indicates that adding small amount (e.g., $\sim$ 100 ppm) of H$_2$O into olivine of the dry lithosphere can adequately change it into less viscous asthenosphere, resulting in lithosphere thinning. (c) Calculated effective viscosities of the upper mantle at varying olivine H$_2$O contents versus depths, using a shear stress of 0.3 MPa and a steeper Cenozoic geotherm (80 mW/m$^2$; Menzies et al., 2007). Once the water content in the asthenosphere reduces with no continuous water supply, the viscosity of the uppermost asthenosphere will increase as indicated by the purple arrow and thus cause lithosphere thickening by basal accretion of asthenospheric materials, i.e., the reverse of lithosphere thinning by basal hydration weakening. The mantle viscosities at various H$_2$O conditions were calculated using the equations and parameters in Liu et al. (2008a, 2008b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
reaching the GGL (Káraón and Hilst, 2000; Li et al., 2008a, 2008b; Liu et al., 2017a, 2017b; Zhao, 2004; Zhao and Ohtani, 2009). The presence of this cold slab in the mantle transition zone prevents any hot mantle plume arising from the lower mantle into the upper mantle beneath eastern China. Also, this slab is cold and is a heat sink, not heat source, hence providing no excess heat to thin the lithosphere by “basal heating” (Niu, 2005).

Subduction zone dehydration is likely incomplete as revealed by studies of subduction zone metamorphic rocks of sedimentary and basaltic protoliths (Niu, 2004; Sheng et al., 2007; Xia et al., 2005; Xiao et al., 2013). In addition, serpentinitized peridotites atop the oceanic lithospheric mantle contain up to 13 wt% H$_2$O and are stable up to 7.5 GPa (Ulmer and Trommsdorff, 1995) before their transformation into dense hydrous magnesium silicates at higher pressures. Therefore, the stagnant paleo-Pacific plate in the mantle transition zone is predicted to be an important H$_2$O reservoir (Niu, 2005, 2014; Xia et al., 2019). Indeed, studies of the eastern China basalts suggest significant contribution of H$_2$O from the hydrous mantle transition zone (Chen et al., 2015, 2017; Geng et al., 2019; Liu et al., 2015, 2017; Liu et al., 2017a, 2017b; Xia et al., 2019). Water released from this cold slab because of thermal equilibrium with the ambient mantle can migrate upward as H$_2$O-rich silicate melts, and they will weaken the base of lithospheric mantle and convert it into asthenosphere by reducing its viscosity (Li et al., 2008a, 2008b; Liao et al., 2017; Niu, 2005; Wang et al., 2014a, 2014b) (Fig. 3a). Fig. 3b illustrates that with a cratonic geotherm (~ 40 mW/m$^2$), adding ~100 ppm H$_2$O to olivine of the dry lithospheric mantle can reduce its viscosity by more than 1 order of magnitude, and addition of ~200 ppm H$_2$O can effectively reduce the viscosity by 2 orders of magnitude without even considering the weakening effect on between-grain deformation. Therefore, addition of H$_2$O can readily convert the

![Fig. 4. Comparison between >110 Ma and <110 Ma basalts in eastern China in terms of Sr-Nd isotopes (a & b), [Nb/Th]$_{P}$ (primitive mantle normalized Nb/Th) (c) and Pb/Pb* (d). For comparison, the Sr-Nd isotope compositions of the mantle xenoliths in Paleozoic diamondiferous kimberlites and those in early Cretaceous basaltic rocks (indicated by the blue filled area) are also plotted. The basalt data used in these and following diagrams are in Supplementary Tables.](image)

Data source: > 110 Ma basalts (Fan et al., 2004; Gao et al., 2008; Guo et al., 2007; Liu et al., 2014; Liu et al., 2008a; Ma et al., 2014, 2016; Wang et al., 2005; Yang et al., 2004; Yang and Li, 2008; Zhang et al., 2002, 2003), < 110 Ma basalts (Basu et al., 1991; Chen and Peng, 1988; Chen et al., 2007; Chu et al., 2017; Dostal et al., 1991; Fan and Hooper, 1991; Guo et al., 2005; Guo et al., 2016, 2020; Ho et al., 2003; Huang et al., 2013; Kuang et al., 2012a, 2012b; Lee et al., 2006; Li et al., 2017a; Liu et al., 1992, 1994; Lu et al., 2012; Ma and Xu, 2004; Meng et al., 2006; Pang et al., 2019; Peng et al., 1986; Qi et al., 1994; Sakuyama et al., 2013; Sun et al., 2017, 2020; Wang et al., 2006, 2007; Wang et al., 2011a, 2015b; Wang et al., 2011; Xie et al., 1990; Xu et al., 2012a; Xu et al., 2012b; Yan et al., 2003, 2005; Yang et al., 2012; Yang and Li, 2008; Zhang et al., 2003; Zhang et al., 2006; Zhang and Zheng, 2003; Zhao and Ohtani, 2009), mantle xenoliths (Wu et al., 2006; Xu et al., 2013; Zhang et al., 2007, 2008b; Zheng and Lu, 1999). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
highly viscous (strong) lithosphere into less viscous (weak) asthenosphere, resulting in lithosphere thinning.

3.2. Geochemical characteristics of the Jurassic-early Cretaceous (>110 Ma) volcanic rocks suggest partial melting of the lithospheric mantle

The lithosphere thinning in the Mesozoic was accompanied by widespread volcanic activities (Fig. 1). These volcanic rocks show compositional distinction between those erupted before and after ~110 Ma (Liu et al., 2008b; Meng et al., 2015; Xu et al., 2004). The >110 Ma volcanic rocks show generally enriched Sr-Nd isotope compositions with $\varepsilon_{\text{Nd}} < 0$, in contrast to the isotopically depleted <110 Ma basaltic volcanism with $\varepsilon_{\text{Nd}} > 0$ (Fig. 4a & b). Such age-dependent compositional difference of the eastern China basalts is evident with minor exceptions. For example, some ~120 Ma lamprophyres in the Jiaodong Peninsula show depleted Sr-Nd isotope compositions with $\varepsilon_{\text{Nd}} > 0$ (Ma et al., 2014, 2016), and some <110 Ma volcanic rocks from Zhucheng and Laiyang Basin (also in the Jiaodong Peninsula) show enriched Sr-Nd isotope compositions with $\varepsilon_{\text{Nd}} < 0$ (Guo et al., 2005; Meng et al., 2006) (Fig. 4b).

The Sr-Nd isotope compositions of >110 Ma basalts resemble those of mantle xenoliths (peridotites and pyroxenites) associated with the Paleozoic diamondiferous kimberlites and the early Cretaceous basaltic rocks (Fig. 4a), which represent the lithospheric mantle materials before/during the lithosphere thinning. These basalts are thus best understood as originating from the ancient isotopically enriched lithospheric mantle (Guo et al., 2014; Liu et al., 2019; Niu, 2005; Xu, 2001; Zhang et al., 2002). Furthermore, these basalts show “Arc-like” trace element characteristics with negative anomalies of high field strength elements (HFSEs; e.g., Nb, Ta and Ti) and positive Pb anomaly, which were also observed in the mantle xenoliths representing ancient lithospheric mantle (Wu et al., 2006; Xu et al., 2010; Zhang et al., 2008a; Zheng et al., 2001). This is shown in Fig. 4c & d with >110 Ma basalts

Fig. 5. The global upper mantle seismic tomography at 100 km and 150 km depths with the Great Gradient Line (GGL) crossing the Chinese continent shown by the black dashed arrow. To the east of the GGL, the upper mantle beneath the Chinese continent shows seismic low velocity that resembles the seismic structure of the upper mantle beneath young ocean floors. The tomographic maps are made using the model of S362ANI (Kustowski et al., 2008) and the Horizontal Slice Viewer of IRIS EMC (https://ds.iris.edu/dms/products/emc/horizontalslice.html).
having \([\text{Nb/Th}]_N\) (primitive mantle normalized Nb/Th) generally <1 and high \(\text{Pb/Pb}^*\) \((-2 \times \text{Pb}_{N}/[\text{Cen} + \text{Pn}])\). Therefore, the lithospheric mantle source of these basalts must have experienced subduction related melt/fluid enrichment in its histories, certainly long before the major melting event. The geochemical affinity between >110 Ma basalts and the ancient lithospheric mantle indicates a genetic link that these basalts originated from melting of the lithospheric mantle, and that the melting and thinning of the lithosphere are the two aspects of the same process, i.e., the very process of converting the lithosphere into the asthenosphere in response to the basal hydration weakening we envision (Niu, 2005; Niu et al., 2015). The sharp compositional change of the Mesozoic basalts at ~110 Ma indicates that the lithosphere thinning was largely completed at ~110 Ma (Liu et al., 2019; Liu et al., 2008b; Meng et al., 2015; Wu et al., 2019).

3.3. Experimental petrology constraint on the Mesozoic lithosphere thinning

Seismic tomography shows that the uppermost asthenospheric mantle at depth range of 100–150 km beneath eastern China is characterized by an oceanic-type seismic low velocity zone (LVZ), which is also observed in continental regions with a thinned lithosphere (e.g., western USA and eastern Australia) (Fig. 5). Therefore, the thin lithosphere beneath these continental regions is very likely the product of LVZ formation. The formation of LVZ requires the presence of a small fraction of melt enriched in volatile components (e.g., \(\text{H}_2\text{O}\) and \(\text{CO}_2\)) in the asthenospheric mantle (Green et al., 2010; Green and Liebermann, 1976; Kawakatsu et al., 2009; Niu and O’Hara, 2003; Niu et al., 2011; Sakamaki et al., 2013; Schmerr, 2012). Beneath eastern China, water released from the stagnant paleo-Pacific plate in the mantle transition zone can hydrate the overlying asthenospheric and lithospheric mantle, lower their solidus, cause incipient melting and form these hydrous melts, generating the LVZ atop the asthenosphere while leading to the Mesozoic lithosphere thinning (Niu, 2014).

Experimental petrology by Green and co-workers (Green, 2015; Green and Liebermann, 1976; Green et al., 2010) provides evidence for the above statement. Fig. 6 illustrates the water-saturated (> 0.2 wt% \(\text{H}_2\text{O}\)) mantle solidus at >30 kbar and the water-saturated (> 0.4 wt% \(\text{H}_2\text{O}\)) and amphibole (pargasite) dehydration (0.02-0.4 wt% \(\text{H}_2\text{O}\)) solidi at <30 kbar, respectively. Studies of the Mesozoic basalts in eastern China suggest ~1000 ppm \(\text{H}_2\text{O}\) in the Mesozoic lithospheric mantle (Wang et al., 2020; Xia et al., 2013). By assuming this conclusion to be correct, we can infer a water-saturated solidus at >30 kbar and an amphibole dehydration solidus at <30 kbar for the Mesozoic upper mantle beneath eastern China. As discussed above, such high \(\text{H}_2\text{O}\) content can significantly lower the viscosity of the lithospheric mantle, converting its basal portion into convective asthenospheric mantle (Fig. 3). Such conversion will change the thermal state of the lithosphere.

![Fig. 6. A model (modified after Niu and Green, 2018) for the upper mantle beneath eastern continental China. This model is based on experimental petrology determined solidi and associated phase relationships (Green, 2015; Green et al., 2010). The cratonic geotherm (40 mW/m²) does not intersect the mantle solidus and joins the adiabat at greater depths (~250 km). Partial melting begins when the geotherm intersects the water-saturated solidus, and the enlarging partial melting area (the area above the water-saturated solidus and below the geotherm) with progressively steeper geotherm corresponds to progressively higher extent of partial melting. Pargasite is stable under conditions of \(T < 1100 \, ^\circ\text{C}\) and \(P \leq 30\) kbar (~90 km). The present-day geotherm of eastern continental China (~60 mW/m²; Menzies et al., 2007; Xu, 2001) intersects the pargasite dehydration solidus at ~90 km, below which the sub-solidus mantle defines the lithosphere and above which an incipient melt phase is present, defining the seismic low velocity zone (LVZ) beneath eastern China. The continental conductive geotherms were modelled from the surface heat flow values using the method of Pollack and Chapman (1977). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
and result in a progressively steeper (higher $dT/dP$) geotherm beneath eastern China. Once the geotherm intersects the mantle solidus, the ancient lithospheric mantle material (especially those metasomatic dikes/veins with lower solidus temperatures) begins to melt. With the geotherm being progressively steeper, the partial melting area (the area above the water-saturated solidus and below the geotherm) enlarges and the extent of partial melting increases, producing voluminous hydrous melts whose eruption and underplating in the lower crust result in the widespread Mesozoic basaltic and granitic magmatism (Fig. 6).

3.4. Evidence for the existence of stagnant paleo-Pacific plate in the mantle transition zone in the Mesozoic

Jurassic-Cretaceous granitoids are widespread in eastern China (Fig. 1), which span emplacement age from ~190 to ~90 Ma (Fig. 7). They are genetically related to the lithosphere thinning and is ultimately dictated by subduction of the paleo-Pacific plate along the eastern China continental margin in the Mesozoic (Cao et al., 2021; Niu et al., 2015; Wu et al., 2005; Xue et al., 2020; Ying et al., 2011; Zhou et al., 2006; Li et al., 2020). That is, these granitoids were derived from partial melting of lower continental crust caused by underplating of hydrous basaltic melts from the lithospheric mantle (Chen et al., 2013; Gao et al., 2019; He et al., 2010; Hong et al., 2018; Li et al., 2009, 2012; Xie et al., 2008; Yang et al., 2018; Zhao et al., 2016) or for the coastal granitoids in Southeast China near the Mesozoic subduction zone (Niu et al., 2015), from the asthenospheric mantle wedge (Guo et al., 2021; Li et al., 2014; Xue et al., 2020; Zhou and Li, 2000). The mafic dykes commonly seen in the Mesozoic granitoid plutons of similar ages with their host rocks best represent these mantle derived melts (e.g., Kong et al., 2019; Liu et al., 2008a, 2008b; Ma et al., 2016). Therefore, the spatial and temporal distribution of these granitoids manifests the basaltic magmatism in space and time. Fig. 7 shows that the emplacement ages of these granitoids show no systematic variation with their locations (longitude or shortest distance to the GGL), which means that these granitoids are randomly distributed in time (from ~190 to ~90 Ma) and space (a zone in excess of 1000 km wide in eastern China) (Fig. 7b). This indicates an areal distribution of mantle-derived melts beneath eastern China continent in the Mesozoic, thus pointing to an areally widespread stagnant oceanic plate in the mantle transition zone because these melts were genetically associated with the dehydration of the subducted oceanic slab (see above). Therefore, the paleo-Pacific plate must have existed in the Mesozoic mantle transition zone beneath eastern China at least since ~160 Ma (the oldest age of the westmost Mesozoic granitoid magmatism; Fig. 7) as a consequence of fast eastward drift of continental lithosphere in response to the trench retreat of the paleo-Pacific plate subduction in the Mesozoic (Niu, 2014). It should be noted that the Mesozoic volcanic rocks and granitoids are not limited to the east of the GGL, but also extend to the far west of the GGL (Figs. 1 & 7), indicating that the Mesozoic lithospheric thinning is not limited to the east of the GGL (Guo et al., 2014, 2018). We also emphasize that the Mesozoic lithospheric thinning was not limited to the North China Craton (NCC) as widely perceived, but occurred throughout entire eastern China as evidenced by the NNE-SSW GGL across the entire continental China (Li et al., 2015b; Niu, 2005, 2014; Xu, 2007), widespread Mesozoic basaltic and granitic magmatism in entire eastern China (Niu et al., 2015; Wu et al., 2005; Xu et al., 2013; Zhou et al., 2006) (Fig. 1), and young and fertile nature of the lithospheric mantle beneath entire eastern China (Fan et al., 2000; Liu et al., 2012; Tang et al., 2013; Wu et al., 2019; Xu et al., 2000; Zheng et al., 2004).

3.5. Termination of the Mesozoic lithosphere thinning

Because the Mesozoic granitoids in eastern China are products of the lithosphere thinning, the emplacement ages of these granitoids and their intensity reflect the intensity of lithosphere thinning. The histograms of emplacement ages in Fig. 7c indicate that the lithosphere thinning in eastern China began from ~190 Ma, reached a peak at ~140 Ma and terminated at ~90 Ma. The predicted ~90 Ma termination age is somehow younger than the ~110 Ma termination age predicted from the Mesozoic volcanic rocks (Fig. 4), but it should be noted that ~89% of the Mesozoic granitoids are older than 110 Ma, indicating that the lithosphere thinning is essentially completed by this time. The question is what caused the final termination of lithosphere thinning and granitoid magmatism at ~90 Ma?

Because the Mesozoic lithosphere thinning and granitoid magmatism is genetically related with the dehydration of the stagnant paleo-Pacific plate in the mantle transition zone (see above), we can infer with confidence that the dehydration of the mantle transition zone plate ceased at ~90 Ma with no continuous supply of oceanic plate, i.e., the subduction of paleo-Pacific plate must have ceased at ~90 Ma. This inference is consistent with the observation that there is rare or essentially no magmatism in the vast region of west Pacific from ~90 to ~50 Ma. On the other hand, the presence of a few volumetrically small ~90–50 Ma magmatism in eastern China (Kuang et al., 2012b; Lu et al., 2012; Wang et al., 2006; Xu et al., 2012a; Yan et al., 2005) must reflect an anomalously hydrous mantle source beneath these locations, which is confirmed by the recent study on the ~86–78 Ma mafic dykes in eastern China (Liu et al., 2020a, 2020b). Such H2O anomalies in the upper mantle are expected considering that the H2O distribution and the extent of dehydration of the mantle transition zone plate are likely
heterogeneous (Xia et al., 2019). However, it is not straightforward to constrain the exact time of subduction cessation, considering that the last fragments of subducted paleo-Pacific plate would continue to dehydrate in the mantle transition zone for some time. We predict that the subduction cessation at ~90 Ma was caused by trench jam by exotic and unsubductable terranes (e.g., an oceanic plateau or most likely a micro-continent) with the suture located off the continental China marked by the arc-shaped southeast coastline (Niu et al., 2003, 2015), a hypothesis that needs future testing (Niu et al., 2017).

4. Lithosphere evolution of eastern China during ~90–50 Ma

A straightforward consequence of the subduction cessation is that dehydration of the mantle transition zone slab will diminish gradually, and the overlying convective asthenosphere will evolve from the water-saturated state to water-undersaturated or dry state as a result of mantle melting and melt extraction (Niu, 2020). The reduction of water content should be more significant in the uppermost asthenosphere, because the gradually decreasing amount of water released from last fragments of subducted oceanic plate would not be transported to the upper asthenosphere but be absorbed in the deeper asthenosphere (i.e., water-undersaturated with < ~200 ppm H2O) (Green et al., 2010; Kovács et al., 2012). Because of the water reduction and because of the thermal contraction caused by conductive heat loss to the surface (Stein and Stein, 1992), the viscosity of the uppermost asthenosphere will increase (Fig. 3c), and thus the uppermost asthenosphere will become thickening lithosphere through basal accretion, i.e., the reverse of lithosphere thinning caused by basal hydration weakening. Therefore, we infer that after the subduction cessation of the paleo-Pacific plate at ~90 Ma and before the initiation of the present-day western Pacific subduction at ~50 Ma (Moberly, 1972), the lithospheric mantle beneath eastern China should be gradually thickened. This inference is consistent with the discovery of fertile and dry (e.g., < 50 ppm H2O; Li et al., 2015a) mantle peridotite xenoliths representing newly accreted lithospheric materials from the underlying asthenosphere in the 90–50 Ma basalts (Fan et al., 2000; Wu et al., 2003; Yan et al., 2003; Ying et al., 2006; Zhao et al., 2020).

Studies on oceanic and continental intraplate basalts revealed that the lithospheric thickness has significant control on the depth of mantle decompression melting and melt extraction, i.e., the lid effect (Guo et al., 2020; Humphreys and Niu, 2009; Niu et al., 2011; Sun et al., 2017, 2020). Basalts extracted from beneath thick lithosphere show high-pressure signature with high MgO, FeO and low SiO2, Al2O3 and thus low SiO2/MgO, whereas basalts extracted from beneath thin lithosphere show low-pressure signature with low MgO, FeO and high SiO2, Al2O3 and thus high SiO2/MgO. In addition, melts erupted on thick lithosphere are formed by low-degree melting mainly in the garnet peridotite facies, showing prominent “garnet signature” with low abundances of heavy rare earth elements (HREEs; e.g., Yb and Lu) and large fractionation between middle and heavy REEs (e.g., high Sm/Yb or Dy/Yb). Such “garnet signature” will be diluted during continuous decompression melting in the spinel peridotite facies beneath thin lithosphere, producing melts with high abundances of HREEs and low Sm/Yb or Dy/Yb (Fig. 8). Therefore, if the lithospheric mantle of eastern China was gradually thickened during ~90–50 Ma as inferred above, we should observe progressively decreasing SiO2/MgO and more prominent “garnet signature” in the progressively younger mantle-derived melts.

The few volumetrically small basaltic eruptions during ~90–50 Ma in northeast NCC (Kuang et al., 2012b; Lu et al., 2012; Wang et al., 2006; Xu et al., 2012a; Yan et al., 2005) provide a chance to test the above inference. With decreasing ages, these basalts show progressively more depleted Sr-Nd isotope compositions with ϵNd(t) > 0, which suggests

Fig. 8. Schematic illustration of the effect of lithosphere thickness on the compositional variation of intraplate basalts. Decompression melting begins when the adiabatically rising mantle intersects the solidus at Pf and stops when the upwelling melting mantle reaches the lithosphere-asthenosphere boundary (LAB) at Pf. Therefore, the LAB determines the final depth of melt extraction and mantle equilibration, and the melting extent depends on the decompression interval (Pf, Pf). The green layer beneath the LAB represents a melt-rich layer formed by accumulation of upwelling incipient melts as indicated by the green arrowed wavy lines. Modified from Sun et al. (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
progressively higher contribution of depleted asthenosphere matrix in these basalts or progressively decreasing amount of enriched ancient lithospheric component from the asthenosphere. In addition, these basalts show increasing FeO and Dy/Yb and decreasing SiO₂/MgO and HREE (e.g., Lu) with decreasing ages (Fig. 9a-f). Models of varying contributions of source heterogeneities (e.g., recycled oceanic crust and sediments) with time were proposed to explain the compositional variations of these basalts (Liu et al., 2017a, 2017b; Xu, 2014). While we do not deny the possible involvement of these source heterogeneities in the generation of these basalts, the temporal compositional variations of these basalts are to a first order consistent with progressively higher pressures of melt extraction and thus progressively thickened lithosphere during ~90–50 Ma. The temporal compositional variations of these basalts thus confirm our above inference that eastern China must have experienced lithosphere thickening after the subduction cessation of the paleo-Pacific plate at ~90 Ma.

5. Cenozoic volcanism and its implication on the present-day lithosphere-asthenosphere boundary (LAB)

5.1. Geochemical characteristics of the Cenozoic basalts

The Cenozoic basalts in eastern China show depleted Sr-Nd isotope compositions with $\varepsilon_{\text{Nd}(t)} > 0$, suggesting their derivation from the isotopically depleted asthenospheric mantle (Fig. 4a & b). However, these basalts are enriched in incompatible elements with OIB-like trace element characteristics (e.g., high [Nb/Th]N and low Pb/Pb*; Fig. 4c & d), and there is an apparent decoupling (lack of correlation) between incompatible elements and radiogenic Sr-Nd isotopes (Guo et al., 2016; Niu, 2005; Sun et al., 2017). The incompatible element enriched signature reflects that the asthenospheric mantle source must have been metasomatized by a low-degree (low-$F$) melt before the major melting

![Fig. 9. Temporal variation of the compositions of ~90–50 Ma basalts in eastern China. With decreasing ages, these basalts show decreasing $^{87}\text{Sr}/^{86}\text{Sr}$ (a) and increasing $\varepsilon_{\text{Nd}(t)}$ (b), except for those from Daxizhuang in the Jiaodong Peninsula which show higher $\varepsilon_{\text{Nd}(t)}$ than basalts of similar ages. They also show increasing FeO and Dy/Yb and decreasing SiO₂/MgO and HREE content (e.g., Lu) with decreasing ages (c-f), which is consistent with their extraction from beneath a gradually thickening lithosphere. Note that only basalts with Mg# > 0.6 are plotted in Fig. 9c-f in order to avoid the influence of fractional crystallization on the major and trace element compositions of these basalts.](image-url)
event (Niu and O'Hara, 2003; Niu et al., 1996, 2002, 2012) (also see below), and the decoupling between radiogenic isotopes and incompatible elements indicates that this low-F melt metasomatism must happen recently (or currently) with limited time for radiogenic isotopic ingrowth (Guo et al., 2016; Niu, 2005; Sun et al., 2017, 2019).

5.2. Generation of low-F metasomatic melt within the asthenosphere

Since the initiation of the present-day western Pacific subduction at ~50 Ma (Moberly, 1972), the Pacific plate has been subducted to and stagnant in the mantle transition zone beneath eastern China as has been seismically detected (Karaon and Hilst, 2000; Zhao, 2004; Zhao and Ohtani, 2009). The asthenospheric mantle overlying the mantle transition zone is thus hydrated by water released from the stagnant oceanic plate and returned to the water-saturated state (> 200 ppm H₂O). As revealed by the experimental petrology (Green et al., 2010), the 1450 °C adiabat intersects the water-saturated mantle solidus at ~250 km, representing the initiation of mantle incipient melting. On the other hand, the present-day geotherm of eastern continental China (~60 mW/m²; Muenzies et al., 2007; Xu, 2001) intersects the amphibole dehydration solidus at ~90 km, above which an incipient melt is present. This is in fact expected since the amphibole dehydration solidus (pargasite) is stable under conditions of ~90 kbar (~ 90 km) (Fig. 6). The intersection of the oceanic intraplate dehydration solidus at ~90 km, above which an incipient melt is present, reveals that the LAB beneath eastern continental China is an amphibole dehydration solidus at shallower depth (point C in Fig. 6). We therefore conclude that the LAB beneath eastern continental China is petrologically a solidus - a water-saturated solidus or amphibole dehydration solidus in places.

5.4. Lithospheric lid effect on the compositional variation of the Cenozoic basalts

The above inference that the LAB beneath eastern continental China is a solidus suggests that below the LAB a melt phase is present and above the LAB melts freezes or ascends rapidly to the surface. That is, the LAB determines the final depth (pressure) (Pf) of melt extraction or equilibration in the mantle, i.e., the lid effect mentioned above, which has been adequately proved by studies of the oceanic basaltic (Humphreys and Niu, 2009; Niu et al., 2011). However, to test the lid effect in continental settings is not straightforward because compared with the oceanic lithosphere whose thickness (L) can be well estimated from its age (t) using the half-cooling model (HSM) (L = t²/2) (Stein and Stein, 1992), the continental lithosphere thickness at any given location is unknown at the time of volcanism.

The effective way to test the lid effect in continental settings is to use basalts erupted in a region with known varying lithosphere thickness. In eastern China, the Cenozoic basalts erupted on both sides of the GGL with a sharp contrast in lithosphere thickness make it possible to test the lid effect. The basalts in Chifeng-Xilin Hot (rectangle area in Fig. 1) are distributed along a ~ 260 km SE-NW traverse across the GGL with steep gradients in surface topography (~ 500 to 1500 m above the sea level) and lithosphere thickness (~ 80 to 120 km) (Fig. 10a & b) (Guo et al., 2020). Importantly, from the southeast to the northwest, these basalts show decreasing Si₂₇ and increasing Fe₇₂, Ti₇₂, P₇₂, [La/Sm]₁₀ and [Sm/Yb]₀ (Fig. 10c-h). The subcontinent “72” represents melt major elements corrected for the effect of low-pressure fractional crystallization to Mg° = 0.72 (see Niu et al., 1999; Niu and O’Hara, 2008). These spatial trends are the very lid effect, i.e., increasing melt extraction pressures (decreasing Si₂₇ and increasing Fe₇₂), decreasing extent of partial melting (increasing Ti₇₂, P₇₂ and [La/Sm]₁₀) and stronger garnet signature (increasing [Sm/Yb]₀) with increasing lithosphere thickness (Figs. 8 & 10). This finding is fundamentally important because it confirms the significant control of lithosphere thickness (i.e., the LAB depth) on the composition of continental basalts (Guo et al., 2020). This finding further demonstrates that the continental surface elevation is isostatically balanced above a mantle depth that is deeper than the LAB on spatial scale of only ~250 km (Guo et al., 2020).

In addition, given the thinned continental lithosphere and the widespread Cenozoic basaltic volcanism, eastern China is potentially the best test ground to substantiate the lid effect. To test this hypothesis is, however, challenging because, as mentioned above, it is difficult to estimate the LAB depth at the time of volcanism. Assuming the lithosphere thickness remains constant since the volcanism, the seismically detected present-day LAB depth could be used, but the tomographic LAB has low resolution (~ ±10 km) and is to some extent artificial. In this case, we choose to examine Cenozoic basalts in eastern continental China with...
Increasing lithosphere thickness

Fig. 10. Illustration of the effect of lithosphere thickness on the compositional variation of mantle-derived melts in intra-continent settings using basalts erupted on both sides of the Great Gradient Line (GGL) in Chifeng-Xilin Hot region of eastern China (Fig. 1) (a). These basalts are located along a ~ 260 km SE-NW traverse (A-B) with steep gradients in topography (~ 500–1500 m) and lithosphere thickness (~ 80–120 km) (b). Fig. 10a & b were modified from Guo et al. (2020). The X axis in Fig. 10c-h represents the shortest distance to the GGL. These basalts show decreasing Si$_2$ (SiO$_2$ content corrected for the effect of fractional crystallization to Mg$_{72}^f$ in equilibrium with mantle olivine) and increasing Fe$_2$, P$_2$, Ti$_2$, [La/Sm]$_N$ (primitive mantle normalized La/Sm) and [Sm/Yb]$_N$ from the southeast to the northwest. Data are from Guo et al. (2016, 2020), Pang et al. (2019) and Wang et al. (2015a, 2015b).
abundant clinopyroxene (cpx) and rare garnet megacrysts whose equilibrium pressure conditions at the time of the volcanism are estimated to be close to the LAB (Chen et al., 2009; Sun et al., 2020; Yu et al., 2019). Indeed, these megacrysts were most likely crystallized in the melt-rich layer close to the LAB (Fig. 8) which provides a stable and closed environment for generating these compositionally uniform megacrysts (Sun et al., 2020). The equilibrium pressures (or depths) of these megacrysts thus approximate the LAB depths beneath eastern China. If this inference is true and if the lid effect indeed controls the compositions of the Cenozoic basalts in the entire eastern continental China, we should observe significant correlations between the equilibrium pressures of cpx megacrysts and basalt compositions. This is indeed true as shown in Fig. 11, which plots location-averaged compositions of basalts and equilibrium pressures of cpx megacrysts from ten localities throughout eastern China with a north-south spatial coverage of more than 2500 km (Fig. 1) (Sun et al., 2020). With decreasing pressures of cpx megacrysts (decreasing LAB depths), basalts show geochemical variations consistent with decreasing pressure of melt extraction and increasing extent of partial melting (e.g., increasing SiO$_2$, Al$_2$O$_3$ and decreasing FeO, MgO, TiO$_2$) with gradually diluted “garnet signature” (decreasing [Sm/Yb]$_N$) (Figs. 8 & 11).

It should be noted that the demonstration of the lid effect does not negate the effect of other factors such as mantle source heterogeneity on the compositional variation of the Cenozoic basalts in eastern China. In fact, recycled sediment and oceanic crust materials are known to have contributed to these basalts as revealed by radiogenic isotopes (e.g., Sun et al., 2020).

---

**Fig. 11.** Correlation of location-averaged basalt SiO$_2$, Al$_2$O$_3$, FeO, MgO and TiO$_2$ corrected for the effect of fractional crystallization to Mg$_{72}$ (i.e., the subscript 72) (a-e) and [Sm/Yb]$_N$ (primitive mantle normalized Sm/Yb) (f) with location-averaged equilibrium pressures of clinopyroxene (cpx) megacrysts in eastern China (the calculating methods and results of the pressure values are given in Sun et al., 2020). These basalts are from 10 locations of eastern China as indicated in Fig. 1. Each datapoint represents average basalt compositions (Y axis) and average equilibrium pressures (approximating the LAB depth; Sun et al., 2020) of cpx megacrysts (X axis) from a given location with 1sd error bars. The data point labeled with “Dalnor” is off the trend, indicating shallower LAB depth than the equilibrium depths of cpx megacrysts beneath this region. Modified from Sun et al. (2020).
et al., 2017; Xu et al., 2012a, 2012b), oxygen isotope (e.g., Chen et al., 2017; Liu et al., 2015) and non-traditional Mg, Fe and Zn isotopes (e.g., He et al., 2019; Li et al., 2017b; Liu et al., 2016), and these recycled components must have caused varied fertile mantle compositions beneath eastern China. However, despite the importance of these recycled components, their effect on the compositional variation of these basalts must be secondary because their effect does not overshadow the effect of lithosphere thickness variation in Figs. 10 & 11 or else the correlations in these figures would not exist.

We therefore conclude that the lithosphere thickness has significant control on the compositions of continental basalts, and the *lid effect* established on oceanic basalts equally well applies to continental basaltic magmatism. The demonstration of the *lid effect* in eastern China further proves that the LAB beneath the region is a solidus, below which decompression melting occurs, and above which melt solidifies or rises through the lithosphere to the surface.

### 6. Efficacies of the plate tectonics theory in explaining continental magmatism

The theory of plate tectonics established over 50 years ago has revolutionized our understanding of Earth processes. It explicitly explains the seafloor creation at ocean ridges and consumption at subduction zones with associated magmatism along these plate boundaries. However, this theory has long been reckoned as deficient in explaining the tectonomagmatic activity in plate interiors. As we stated above, the lithosphere thinning in the Mesozoic, the Mesozoic-Cenozoic basaltic volcanisms and the ~60–100 km present-day LAB in eastern China are all associated genetically with the subduction of paleo and present-day Pacific plates and their stagnancy in the mantle transition zone. Therefore, the thinning of continental lithosphere and associated continental intraplate volcanism in eastern China are consequences of plate tectonics. We predict that intra-continental basaltic magmatism at present and in Earth’s histories must be widespread and significant in response to seafloor subduction.

![Fig. 12. Timeline cartoon to show the evolution of eastern continental China Since ~190 Ma.](image-url)

(a) ~ 190 Ma

Eastern China continent

Crust

Lithospheric mantle

Asthenosphere

Mantle transition zone

(b) ~ 190-90 Ma

Volcanic eruptions

Newly transformed asthenosphere

Hydrous melts

Dehydration

P. Sun et al.
7. Conclusion

1) We reiterate that the Mesozoic lithosphere thinning is not limited to the North China Craton (NCC) but occurs throughout the entire eastern China including its continental shelf.

2) We illustrate that the subduction initiation of the paleo-Pacific plate at ~190 Ma (Fig. 12a), the stagnancy and dehydration of the subducted paleo-Pacific plate in the mantle transition zone and basal hydration of the lithosphere caused lithosphere thinning by converting the high viscosity lithosphere at its base into the low viscosity asthenosphere (Fig. 12b), i.e., the effect of “basal hydration weakening” advocated 16 years ago (Niu, 2005).

3) The mantle source of the Mesozoic basalts in eastern China changed abruptly from ancient lithospheric mantle to asthenosphere at ~110 Ma, which informs that the lithosphere thinning was largely completed by this time.

4) Water released from the mantle transition zone slab can hydrate the overlying asthenospheric and lithospheric mantle, lower the solidus, cause their partial melting and form voluminous hydrous melts which account for the Mesozoic magmatism and the generation of seismic low velocity zone (LVZ) atop the asthenosphere.

5) The random and widespread distribution of the Mesozoic granitoid plutons in time and space are consistent with a stagnant paleo-Pacific plate present in the Mesozoic mantle transition zone. Partial melting of the lithospheric mantle caused by basal hydration produced hydrous basaltic melts whose underplating beneath and intrusion into the lower crust caused crustal reworking and generation of these Mesozoic granitoids.

6) The termination of granitoid magmatism at ~90 Ma is best understood by subduction cessation of the paleo-Pacific plate. Because of the diminishing water supply from the mantle transition zone slab and because of thermal contraction by conductive heat loss, the lithosphere thickness is inferred to be gradually thickened by basal accretion of asthenosphere after ~90 Ma (Fig. 12c). The geochemical variation of the ~90–50 Ma basalts with decreasing ages is consistent with these basalts extracted from beneath a progressively thickened lithosphere.

7) Since ~50 Ma, the present-day west Pacific subduction initiated, and its eastward retreat caused eastward drift of continental China, leaving the older portions of the present-day Pacific slab stagnant in the mantle transition zone with resumed water supply in the form of hydrous melt to maintain the thinned lithosphere and an oceanic type LVZ beneath eastern continental China, which is responsible for the Cenozoic alkali basalt volcanism in the region (Fig. 12d).

8) The present-day asthenosphere-lithosphere boundary (LAB) beneath eastern continental China is a solidus. The intersection of the geotherm with the amphibole dehydration solidus at ~90 km explains the ~80–100 km LAB depth beneath most regions of eastern continental China. On the other hand, ~60–80 km LAB beneath the regions around the Tanlu fault zone implies a water-saturated upper mantle or a deeper regional geotherm or both.

9) The LAB beneath eastern China as a solidus means that the LAB defines the final pressure of melt extraction and equilibration in the mantle. Therefore, the lithosphere thickness of eastern China is expected to have significant control on the compositional variation of Cenozoic basalts, i.e., the lid effect. This inference is proven by using basalts erupted on both sides of the GGL with highly varied lithosphere thickness and is further substantiated by using basalts and clinopyroxene megacrysts in the entire eastern China.

10) We conclude that the lithosphere thinning in the Mesozoic, the present-day LAB, the seismic LVZ and the Mesozoic-Cenozoic basaltic volcanism in eastern China are consequences of plate tectonics in response to seafloor subduction, which is of global significance for understanding continental lithosphere evolution, including basaltic and granitoid magmatism, at present and likely also over earth’s history.

Declaration of Competing Interest

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

Acknowledgements

This work was supported by the NSFC-Shandong Joint Fund for Marine Science Research Centers (U1606401), the Shandong Provincial Natural Science Foundation (ZR2020MD0029), the National Natural Science Foundation of China (NSFC Grants 41630968, 91014003, 91958215), grants from Qingdao National Laboratory for Marine Science and Technology (2015ASKJ03) and 111 Project (B18048). We are grateful for the invitation by Professor Gillian Foulger and Professor Sanzhong Li. We thank Editor Douwe van Hinsbergen for handling this manuscript and two anonymous reviewers for their constructive comments. Dr. Xiaodong Yang and Dr. Meng Duan are thanked for preparing the diagrams of topography and crust and lithosphere thickness in Fig. 2.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2021.103680.

References


