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Continental collision zones are primary sites for net continental crust growth — A testable hypothesis

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ABSTRACT

The significance of the continental crust (CC) on which we live is self-evident. However, our knowledge remains limited on its origin, its way and rate of growth, and how it has acquired the "andesitic" composition from mantle derived magmas. Compared to rocks formed from mantle derived magmas in all geological environments, volcanic arc rocks associated with seafloor subduction share some common features with the CC; both are relatively depleted in "fluid-insoluble" elements (e.g., Nb, Ta and Ti), but enriched in "fluid-soluble" elements (e.g., U, K and Pb). These chemical characteristics are referred to as the "arc-like signature", and point to a possible link between subduction-zone magmatism and CC formation, thus leading to the "island arc" model widely accepted for the origin of the CC over the past 45 years. However, this "island–arc" model has many difficulties: e.g., (1) the bulk arc crust (AC) is basaltic whereas the bulk CC is andesitic; (2) the AC has variably large Sr excess whereas the CC is weakly Sr deficient; and (3) AC production is mass-balanced by subduction erosion and sediment recycling, thus contributing no net mass to the CC growth, at least in the Phanerozoic. Our recent and ongoing studies on granitoid rocks (both volcanic and intrusive) formed in response to the India–Asia continental collision (~55 ± 10 Ma) show remarkable compositional similarity to the bulk CC with the typical "arc-like signature". Also, these syncollisional granitoid rocks exhibit strong mantle isotopic signatures, meaning that they were recently derived from a mantle source. The petrology and geochemistry of these syncollisional granitoid rocks are most consistent with an origin via partial melting of the upper ocean crust (i.e., last fragments of underthrusting ocean crust upon collision) under amphibolite facies conditions, adding net mantle-derived materials to form juvenile CC mass. This leads to the logical and testable hypothesis that continental collision produces and preserves the juvenile crust, and hence maintains net CC growth.

Importantly, the history of the Greater Tibetan Plateau from the Early Paleozoic to present manifests the history of "super" continent amalgamation through a series of continental collision events with production and preservation of abundant syncollisional granitoids. Plate tectonics in terms of seafloor spreading and subduction is a continuous process on a global scale since its inception (in the early Archean?), whereas continental collision on regional scales and super-continental formation on a global scale are episodic (vs. continuous). Hence, continental collision with juvenile crust formation/preservation and super-continent amalgamation explains the episodic growth of the CC. We are continuing testing and refining this hypothesis by detailed petrological, geochemical and geochronological studies of syncollisional granitoids along older collision zones in central-west China, especially on the northern Tibetan Plateau in a global context.

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"A fact is a simple statement that everyone believes. It is innocent unless found guilty. A hypothesis is a novel suggestion that no one wants to believe. It is guilty until found effective."

[Edward Teller (1908–2003).]

1. Introduction

The significance of the continental crust on which we live is self-evident, yet our knowledge remains limited on its origin, its way and rate of growth, and how it has acquired the "andesitic" composition from mantle derived magmas. The first-order complementarity in incompatible element abundances between continental crust and ocean crust is consistent with the view that the incompatible-element-enriched bulk continental crust represents the extract of a small amount of very low-degree (~1.5% melting) melt from the primitive mantle in Earth's early history (e.g., Hofmann, 1988), which also resulted in an incompatible-element-depleted residue in the upper mantle that became the source of the present-day mid-ocean ridge basalts (MORB; e.g., Gast, 1968; O'Nions et al., 1979; Allègre et al., 1983). This depleted upper mantle has been termed depleted MORB mantle or DMM (Zindler and Hart, 1986). However, in what kind of geological setting and how such very low-degree melting took place in Earth's early history remains unknown, i.e., a hypothesis that cannot yet be tested.

When on Earth the first continental crust (CC) formed/appeared is also uncertain because of the likely preservation problem. The oldest preserved crustal rocks are the Hadean age ~4.0–4.2 Ga tonalitic Acasta Gneiss (Bowring and Housh, 1995; Iizuka et al., 2007) in northern Canada, and granitoid rocks may have actually existed even earlier at ~4.35 Ga as inferred from "granitic" zircons from Jack Hills in western Australia (Cavosie et al., 2004; Harrison et al., 2005). Hadean rocks are rare and the more abundant are Archean age TTG–granite–greenstone belt complexes (see Condie and Aster, 2009; Ernst, 2009). The TTG (tonalite–trondhjemite–granodiorite) assemblages are considered as primary architecture of the continental crust (e.g., Rollinson, 2008; Condie and Aster, 2009). The origin of the TTGs has been extensively studied and discussed over the last decades with ideas including shallow mantle melting and fractional crystallization, partial melting of eclogite/amphibolite, and incipient melting of hydrous, and fertile upper mantle peridotite (see Ernst, 2009 for review). However, the compositional similarity (Fig. 1) between TTGs and the Phanerozoic

subduction-related adakites (e.g., Defant and Drummond, 1990; Castillo, 2006), sanukitoids (e.g., Tatsumi, 2008) or high-Mg andesites (e.g., Kelemen, 1995) has led to the popular acceptance that the TTGs must have formed in Archean-type subduction settings (e.g., Condie, 2005; Martin et al., 2005).

It has long been recognized that the CC is generated through subduction-zone magmatism, i.e., the "island–arc model" proposed by Taylor (1967, 1977), who recognized with wisdom that compared with mantle-derived melts from all tectonic settings, island–arc magmas show remarkable similarity to the bulk CC in incompatible element patterns (Fig. 2), and both must be genetically related. This "island arc model" has been widely accepted as the "standard model" for the origin of the CC. Most studies agreed that the CC continued to grow since the Archean (Fig. 3; see Condie, 2005), while also recognizing that such continuum represents a cumulative growth of a number of magmatic episodes (Fig. 3; McCulloch and Bennett,
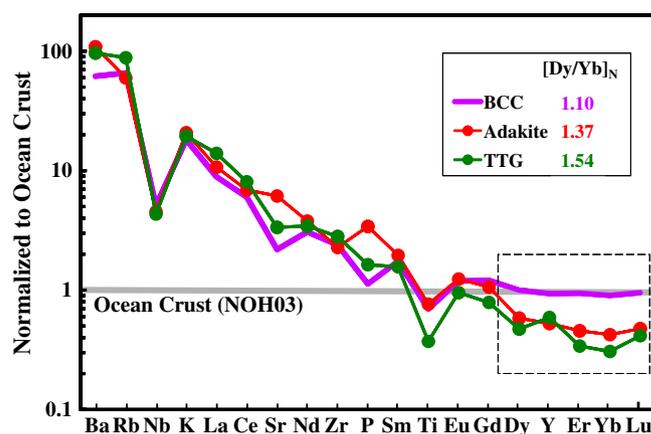
Fig. 1. Multi-element diagram normalized to the mean composition of the ocean crust (Niu and O'Hara, 2003) to show the compositional similarity of the Archean TTGs and the Phanerozoic adakites (data from Martin et al., 2005), both show remarkable depletion of Y and other heavy rare earth elements (HREEs), consistent with the presence of garnet as a residual phase during melting ("garnet signature"). Model bulk continental crust (BCC; Rudnick and Gao, 2003) is also plotted for comparison. Note that the bulk CC shows the same Y and HREE abundances as the ocean crust without the "garnet signature".
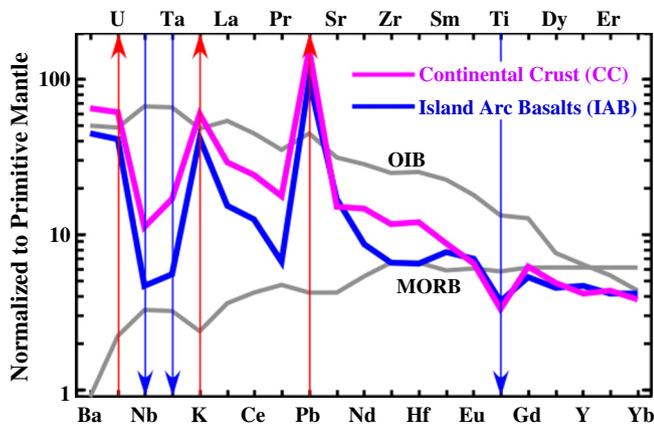
Fig. 2. Multi-element diagram normalized to the primitive mantle to show that compared with mantle derived melts from ocean ridges (MORB) and intra-plate ocean islands (OIB), island arc basalts (IAB, from Elliott, 2003) and the model composition of bulk continental crust (CC; Rudnick and Gao, 2003) show close similarity — both are depleted in "water-insoluble" high field strength elements (e.g., Nb, Ta and Ti) and relatively enriched in "water-soluble" elements (e.g., Ba, U, K, Pb), which is consistent with widely accepted model for arc basalt petrogenesis resulting from subducting slab dehydration induced mantle wedge peridotite melting (e.g., Tatsumi and Eggins, 1995). It is the compositional similarity between bulk CC and IAB that had laid the foundation for the standard "island–arc model" for continental crust formation (Taylor, 1967, 1977).
Data for primitive mantle, MORB and OIB are from Sun and McDonough (1989).

1994; Condie, 1998, 2000), interpreted to have resulted from pulses of mantle derived melts, perhaps in the form of mantle plumes (Stein and Hofmann, 1994; Abbott and Mooney, 1995; Abbott et al., 1997; Albarède, 1998; Polat et al., 1998; Condie, 2000; Kerr, 2003; Niu et al., 2003; Hawkesworth and Kemp, 2006; Kemp et al., 2006; Parman, 2007; Pearson et al., 2007). A more recent study using zircon Hf and O isotopes argues that episodic peaks are not so striking since 3.0 Ga (Dhuine et al., 2012).

In this review article, we do not wish to discuss TTGs nor adakites, but summarize with new thought our novel concept "continental collision zones as primary sites for net continental crust growth" (Niu et al., 2007; Mo et al., 2008; Niu and O'Hara, 2009), which overcomes the shortcomings of the standard island–arc model and abandons the need of mantle plumes for episodic crustal growth. It is our intension

Fig. 3. Histogram of "juvenile" crust with the low-background frequencies interpreted as due to plate tectonic processes whereas the peaks as due to voluminous mantle melting anomalies probably associated with mantle plumes (McCulloch and Bennett, 1994; Stein and Hofmann, 1994; Condie, 2000; Hawkesworth and Kemp, 2006). Selected model curves for continental crust growth: A (Allègre and Rousseau, 1984), B (Kramers and Tolstikhin, 1997; Collerson and Kamber, 1999) and C (Taylor and McLennan, 1995) favor gradual crustal growth over much of the Earth's history whereas D (Armstrong, 1981) suggests that the continental crust reached its present-day volume at ~3.5 Ga. Nevertheless, most models favor continued crustal growth over Earth's history, including the more recent Phanerozoic era seen from the most recent models (Dhuine et al., 2012).

that this review will encourage further discussion and debate on this fundamental Earth problem that has inspired mankind for over a century — the origin and evolution of the continental crust.

2. Shortcomings of the standard "island arc" model and mantle plume supplementary

A new hypothesis becomes necessary if the existing hypotheses or theories are inadequate. As indicated above, the standard island–arc model is based on the similarity in incompatible element abundance patterns between island arc basalts (IAB) and bulk continental crust (CC) (Fig. 2), whereas the mantle plume hypothesis has then been invoked to explain the episodic volumetric growth of the CC as recorded in magmatic rocks (Fig. 3). Because formation of the CC is through magmatism with materials coming from the mantle, any successful model for the bulk CC must be able to explain three basic observations: (1) what kind of processes must have converted mantle derived basaltic melts into the andesitic bulk CC composition; (2) what kind of geological processes must have maintained net bulk CC growth, especially the episodic growth (Fig. 3); and (3) what geological processes must have enabled "intra-oceanic" island arcs and scattered oceanic plateaus amassed to the existing continents for sustained bulk CC growth. The latter may sound naïve, but is important in facilitating our correct understanding of net crustal growth (see below).

2.1. Bulk arc crust is too mafic for the andesitic bulk continental crust

As subduction-zone magmatism largely results from slab-dehydration induced mantle wedge melting (e.g., Gill, 1981; Tatsumi et al., 1986; Pearce and Peate, 1995), the primary magmas there must be basaltic in composition. Indeed, primitive arc melts have high MgO (~10–12 wt.%) and low SiO_2 (~47–49 wt.%) (Nye and Reid, 1986; Eggins, 1993; Bacon et al., 1995). Hence, the bulk island arc crust (AC) is basaltic (e.g., Arculus, 1981; Gill, 1981; Pearcy et al., 1990). This differs markedly from the andesitic bulk CC composition with low MgO (~4–5 wt.%) and high SiO_2 (~57–64 wt.%) (Taylor, 1967, 1977; Taylor and McLennan, 1985, 1995; Wedepohl, 1995; Rudnick and Gao, 2003). To convert bulk AC to bulk CC is not straightforward. Removing the more mafic component from the AC such as the mafic/ultramafic lower AC cumulate beneath an active arc or during orogenesis is a welcome idea (e.g., Kay and Kay, 1993; Rudnick, 1995; Kelemen et al., 2003a; Plank, 2005) to explain why only felsic arc lithologies contribute to continental crust growth, although the perceived physical mechanisms for such removal may be complex (Jull and Kelemen, 2001) or unfeasible because this assumes the absence of lithospheric mantle and free mass exchange between the forming magmatic crust and the melt-producing asthenosphere. An alternative interpretation requires no physical separation of the mafic/ultramafic cumulate from the overlying andesitic lithologies, but argues that the apparent conflict lies in our perception of the felsic crust above the Moho and the mafic/ultramafic cumulate (e.g., chromite-bearing dunite, wehrlite, and amphibole-rich pyroxenites) beneath the Moho in the mantle because the Moho is a seismic, not petrologic, division (Davidson and Arculus, 2006). If this latter interpretation is correct, then the lithospheric mantle immediately beneath the mature continental crust should be dominated by such cumulate assemblages, yet xenolith studies show no evidence for this claim unless they may have been removed subsequently by unknown dislocation processes.

It should be noted that recent seismic studies along the Izu–Bonin–Mariana island arc system allowed the suggestion that the mid-upper AC is characterized by andesitic rocks (e.g., diorite), and is interpreted as convincing evidence for continental crust formation at island arcs (Takahashi et al., 2007; Tatsumi, 2008; Tatsumi et al., 2008). In fact, andesitic (even rhyolitic) rocks are common in island arcs because hydrous basaltic melts have lowered liquidus temperatures and can thus undergo advanced degrees of cooling and evolution to andesitic
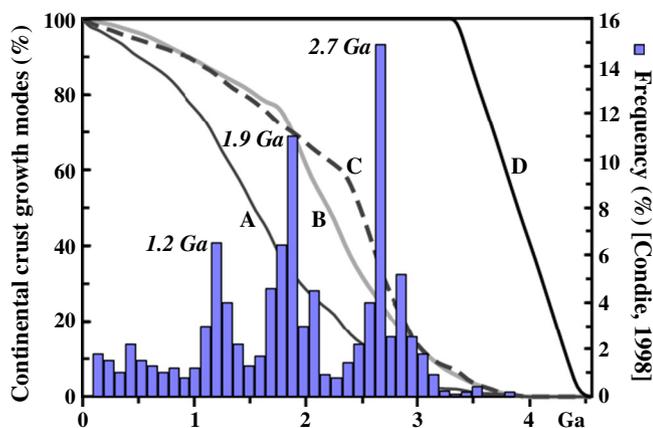
and rhyolitic melts. Furthermore, country (existing arc) rocks of magma chambers can locally melt and produce more felsic melts (Worthington et al., 1999; Tamura et al., 2011). Nevertheless, the bulk AC must be basaltic because they are derived from high extents of hydrous mantle wedge melting (Tatsumi and Eggins, 1995; Niu, 2005). The latter is expectedly consistent with the 3-D seismic investigation at the Mariana arc that the bulk AC is basaltic (Calvert et al., 2008).

2.2. Arc settings have no net crustal addition

If we accept that the CC has been growing over much of the Earth's history (Fig. 3), then globally the rate of new crust production must be greater than the rate of crustal loss to maintain the growth. However, studies have demonstrated that AC production through subduction-zone magmatism (at both island arcs and Andean-type continental arcs; ~2.3 km^3/yr) is mass-balanced by subduction erosion (~1.5 km^3/yr) and sediment recycling (1.0 km^3/yr) (von Huene and Scholl, 1991; Clift and Vannucchi, 2004; Scholl and von Huene, 2007; Stern and Scholl, 2010) on modern Earth, at least in the Phanerozoic (Scholl and von Huene, 2007). Furthermore, isotopic studies suggest that crustal recycling at subduction zones has been important since ~2.0 Ga (Armstrong, 1968; Kramers and Tolstikhin, 1997). This does not mean that no new crust is forming at arcs, but means that no net crust buildup is kept at arcs on a global scale. This observation, together with the fact that the bulk AC is too mafic, demonstrates that active subduction zones are unlikely the sites for net crustal growth, thus contributing no new mass to the growth of the CC (Niu and O'Hara, 2009), at least in the past >500 million years (Scholl and von Huene, 2007).

2.3. Adakites, sanukitoids and high-Mg andesites associated with active seafloor subduction are volumetrically insignificant

In discussing accretion of the continental crust, it is necessary to mention the Archean TTGs (see above) and the widely and hotly studied adakites, high-Mg andesites and sanukitoids in recent years (see Kelemen et al., 2003a; Rollinson and Martin, 2005; Castillo, 2006, 2012; Tatsumi, 2008; Moyen, 2009, 2011). Slab melting and melt–mantle interactions are thought to be an important mechanism to produce these rocks that resemble the bulk CC composition (see Fig. 1). However, formation of these magmas requires not only warm slabs (Defant and Drummond, 1990; Castillo, 2006, 2012; Huang et al., 2010) but also unusually hot mantle wedges that are rare on modern Earth (Tatsumi, 2008). Furthermore, all these magmas/rocks have heavy rare earth element (HREE) depleted "garnet signature" as do the most Archean TTGs, yet the model bulk CC composition does not have such "garnet signature" (Fig. 1). That is, TTGs (plus the Phanerozoic equivalents all together) are volumetrically unimportant in building the present-day bulk CC mass. This is a simple and powerful recognition that places a severe constraint on the validity of any model on continental crust accretion.

2.4. Arc–continent collision is relevant, but again arc crust is too mafic

Following the continental collision model (Niu et al., 2007; Mo et al., 2008; Niu and O'Hara, 2009), others also emphasized the significance of "arc–continent collision" and "preservation" for CC growth (e.g., Hawkesworth et al., 2009, 2010; Condie and Aster, 2010). However, the arc–continent collision models face the same difficulties: (1) while this facilitates lateral growth of the continent, such as the development of the giant *Central Asian Orogenic Belt* (CAOB) (e.g., Kroner et al., 2007; Liu et al., 2012; Xiao et al., 2013), the AC remains too mafic for the andesitic bulk CC (see above); (2) AC melting during arc–continent collision could be invoked to explain juvenile crust addition, but arcs have positive topography, and are too shallow and too cold to melt (see Niu et al., 2003); and (3) even if the AC can melt, its unusually high Sr makes such melt inappropriate for CC (see Fig. 4).
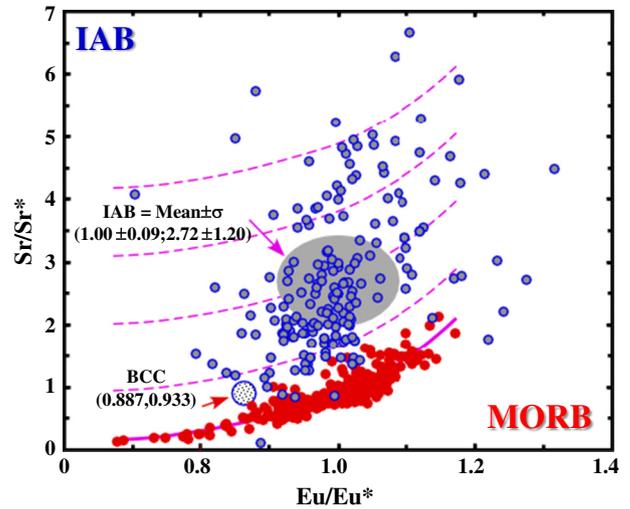

Fig. 4. Comparison of mid-ocean ridge basalts (MORB; Niu and O'Hara, 2009) with island arc basalts (IAB; Elliott, 2003) in Sr/Sr* (2*Sr$_N$/[Pr$_N$ + Nd$_N$]) vs. Eu/Eu* (2*Eu$_N$/[Sm$_N$ + Gd$_N$]) space. The variably large positive Sr anomalies are characteristic of IAB, and are significantly greater than those of MORB. The variably high Sr contents in IAB are consistent with IAB resulting from subducting slab dehydration-induced mantle wedge melting and Sr being an important slab component (Elliott, 2003) originated from altered oceanic crust (Staudigel, 2003). The dashed lines drawn parallel to the data trend defined by MORB are the fractionation trend due to plagioclase only (effect of all other liquidus minerals on Sr is insignificant). Hence, plagioclase fractionation cannot reduce the high Sr/Sr* values in IAB. Therefore, neither IAB nor their evolved derivatives can be candidate for continental crustal material in terms of Sr; continental crust has a weak negative, NOT large positive, Sr anomaly (modified from Niu and O'Hara, 2009).

In brief, arc–continent collision is a common phenomenon in the geological record, and can add CC growth in volume, but cannot contribute to the andesitic bulk CC composition (see above; Niu and O'Hara, 2009). Recently, Condie and Kroner (2013) suggested a major change in the tectonic setting of continental growth at the end of the Archean from "oceanic plateau settings" in the Archean to continental arc settings thereafter. The key argument is that the oceanic arc settings are not primary sites for crustal growth as we have been demonstrating (Niu et al., 2007; Mo et al., 2008; Niu and O'Hara, 2009), and that the continental arc settings are important. But as we argue, arc crust is mass balanced at both oceanic and continental arcs and preservation that is key to net crustal growth requires continental collision (Niu and O'Hara, 2009).

2.5. Mantle plume contributions, if any, are also too mafic

Mantle plumes have been invoked to explain the episodic crustal growth (see Fig. 3 and discussion above). Mantle plume melts, either as flood basalts on land or underplated beneath, are too mafic for the andesitic bulk CC composition. Volumetrically massive oceanic plateaus can be amassed to existing continents, but again they are mafic and difficulties remain on how to convert them to the andesitic composition of the bulk CC material. We can thus conclude that compositionally magmatism associated with mantle plumes is not a major contributor to the CC growth.

3. The new concept

Our recent and ongoing research on syncollisional granitoids from the Greater Tibetan Plateau (Fig. 5) has been inspiring towards the new concept "continental collision zones are primary sites of net continental crustal growth" (Niu et al., 2007; Mo et al., 2008; Niu and O'Hara, 2009; Huang et al., in press). This new concept explains all the above with some aspects that can be further tested and improved. The key elements of this new concept are discussed below.
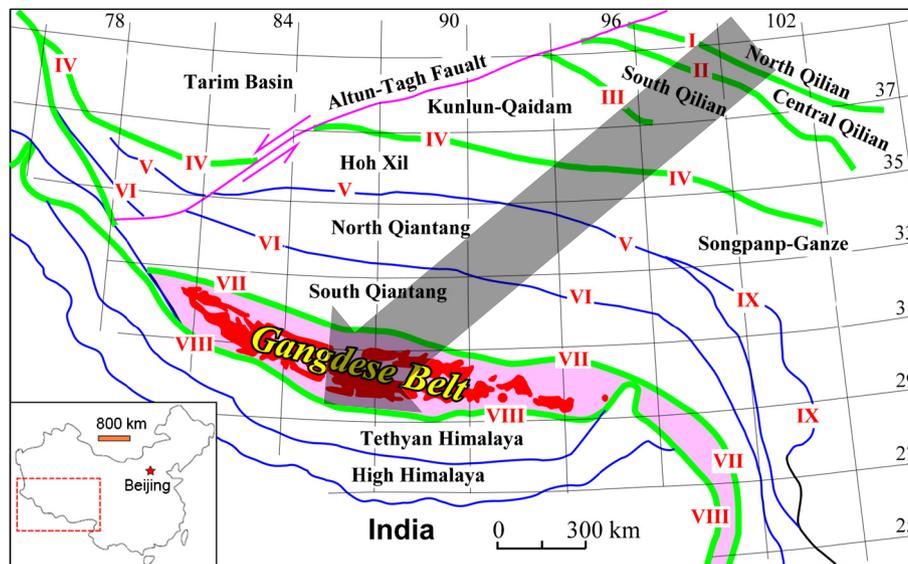
Fig. 5. Outline of the geological framework of the Greater Tibetan Plateau (modified from Pan et al., 2004; Mo et al., 2008), showing that it is a composite terrane amalgamated through a number of continental collision events progressively younger from northeast in the early Paleozoic to southwest in the Cenozoic, as indicated by the gray arrowed band. The lines with Roman numerals indicate collision sutures. Voluminous syncollisional magmatism (batholiths and volcanic rocks) is associated with sutures indicated in thick green. The VIII marks the very suture zone of the India–Asia collision at some ~55 ± 5 Ma. The terrane between VII and VIII is the Lhasa Terrane, also called the Gangdese Magmatic belt, which is best studied in petrology and geochemistry of igneous rocks in the interiors and the syncollisional granitoids in the vicinity of the sutures (Mo et al., 2003, 2005, 2007a,b, 2008; Zhao et al., 2009; Ji et al., 2009; Chung et al., 2005; Zhang et al., 2007; Zhang et al., 2010; Dong et al., 2011; Zhu et al., 2009, 2010, 2011, 2013; Niu et al., in preparation). The Lhasa Terrane is dominated by the South Gangdese Batholith (SGB, ~55 ± 5 Ma, represent the slow cooling age) associated with VIII and the North Gangdese Batholith (~110 ± 5 Ma) associated with VII (pink background). The red patches approximate the spatial distribution of the Linzizong volcanic succession coeval with the SGB. The Linzizong volcanic succession comprises the ~2300 m thick andesitic lower Dianzhong Formation (~65–60 Ma), the ~720 m thick dacitic mid Nianbo Formation (~54 Ma), and the ~2000 m thick rhyolitic upper Pana Formation (~49–44 Ma). We here termed the andesitic lower Dianzhong Formation as *Southern Tibet Syncollisional Andesites* (STSA) that is in time and space genetically associated with the bulk of the SGB. We interpreted the upper younger dacitic Nianbo and rhyolitic Pana formations as resulting from re-melting of the STSA and SGB (Niu et al., in preparation). Studies of syncollisional granitoids from northern collision zones (Sutures I, II, III and IV) are limited (Mo et al., 2007b) and are currently sampled and investigated by Yaoling Niu and his team members (Huang et al., in press; Niu et al., in preparation).

3.1. Continent–continent collisions are necessary for the growth of continental crust

Kroner et al. (2007) concluded that the juvenile crust along the giant Phanerozoic *Central Asian Orogenic Belt* (CAOB) results from many events of collision of the complex Paleo-Asian Ocean "arc-and-backarc" systems with the North China Craton to the south and with the Siberian Craton to the north. Indeed, it is the continental collision that can effectively accomplish continental growth through collaging seafloor geological features with positive topography (e.g., island arcs, scattered ocean islands and oceanic plateaus), which explains why blocks of ocean island basalts can be found in orogenic sutures, why the majority of ophiolites are of island arc origin, and why the CC possesses geochemical signatures of island arc volcanic rocks (Fig. 2) (Niu et al., 2003). However, all these collages are still too mafic to contribute to the andesitic composition of the bulk CC, and additional or different processes must take place.

3.2. Syncollisional partial melting of ocean crust produces andesites of bulk CC composition

Continental collision results from the closure of an ocean basin and thereafter subduction ceases also, but convergence of the "subducting" seafloor may continue for sometime just as the continued underthrusting of the Indian plate beneath Tibet since the onset of the collision about ~60 Ma (Mo et al., 2008). While the Pacific-style subduction beneath American plates to the east and beneath marginal seas in the western Pacific is possible, the scenario in which subduction of a seafloor with a passive margin beneath Andean-type active continental margin is probably more common in explaining many observations in the geological record. This concept is illustrated in Fig. 6, which can effectively explain the origin and petrogenesis of the syncollisional granitoids such as the South Gangdese Batholith (SGB) plus the

southern Tibet syncollisional andesite (STSA) shown in Fig. 5 (Niu et al., 2007; Mo et al., 2008; Niu and O'Hara, 2009). While the timing of the India–Asia collision has been in debate, the well documented geological observations and geochronological data are consistent with the collision beginning at ~ ≥65 Ma and ending at ~45 Ma (e.g., Mo et al., 2002, 2003, 2005, 2007a) with the convergence continuing to this day. Therefore, the SGB (55 ± 5 Ma), STSA (65–60 Ma) and the more felsic volcanic rocks (55–44 Ma) are a magmatic response to the India–Asia collision (Mo et al., 2002, 2005, 2007a; Zhou et al., 2004; also see caption to Fig. 5), and represent products of syncollisional magmatism. Hence, these rocks differ from those associated with intra-oceanic island arcs and continental arcs in space and time, but genetically related to the India–Asia collision (Niu et al., 2007; Mo et al., 2008).

3.2.1. Syncollisional andesites show remarkable compositional similarity to the bulk CC

The ~65–60 Ma syncollisional andesites from southern Tibet (STSA) show remarkable compositional similarity to the bulk CC (Rudnick and Gao, 2003) as seen in Fig. 7. What is more remarkable is the almost identical major and trace element compositions on one-to-one diagram (Fig. 8), and even more remarkable is the essentially identical key element ratios (Fig. 9). These basic observations strongly suggest the presence of a genetic link between formation of the bulk CC and syncollisional andesites as a result of partial melting of the ocean crust (see below). Note that in Fig. 8, the compatible elements (oxide) like MgO, Ni and Cr are significantly lower in the average STSA than in the bulk CC. This is in fact expected because the STSA is the straightforward melt compositions (better than the plutonic SGB rocks with cumulate phases and restite fragments), whereas the bulk CC is the best model estimate that must consider all the lithologies in the crust, including mafic lithologies like ophiolite in orogenic belts and basaltic rocks erupted on land, which are generally
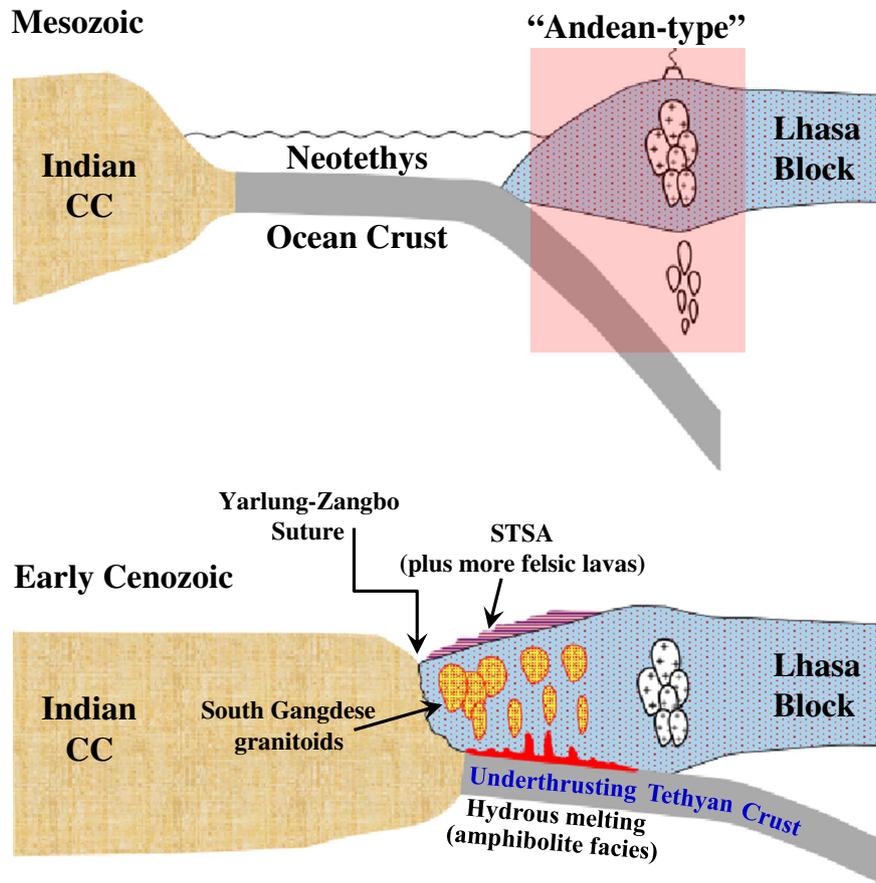
Fig. 6. Top: Cartoon showing the Tethyan Ocean with passive continental margin in Indian plate and Andean-type active volcanic margin at the edge of the Lhasa block (Gangdese Belt) prior to the collision. Bottom: Cartoon illustrating the concept of Tethyan ocean crust melting to produce the syncollisional andesitic melts parental to the STSA and SGB (also see Fig. 5 caption). Modified from Mo et al. (2008).

low in incompatible elements, but strongly enriched in the "mafic" elements like Mg, Cr and Ni.

3.2.2. Syncollisional andesites represent juvenile crust derived from the mantle

Fig. 10 shows that despite the felsic compositions of the STSA, related dacites and rhyolites as well as the SGB, they possess mantle isotopic signatures. Simple mass balance calculations show that isotopically these rocks represent 70–90% mantle contributions with only 10–30% crustal contributions (see Mo et al., 2007a,b, 2008) perhaps due to
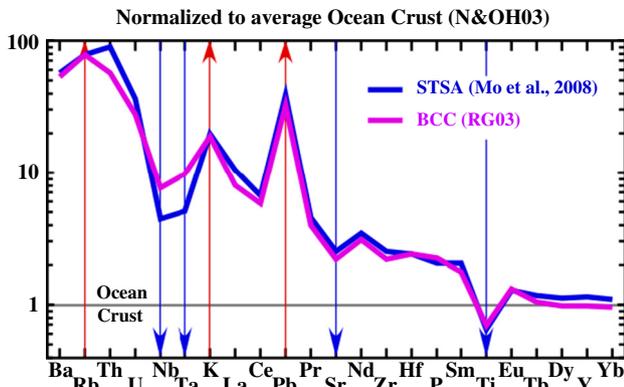
Fig. 7. Multi-element diagram normalized to the mean composition of the ocean crust (Niu and O'Hara, 2003) to show the compositional similarity of the BCC and STSA.
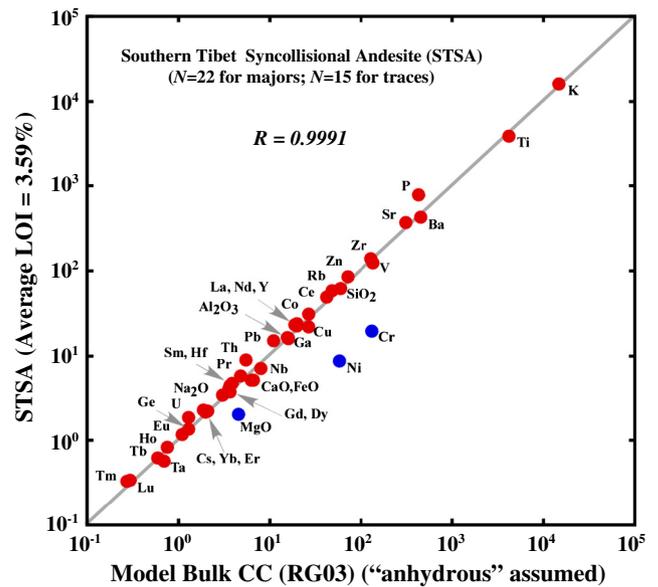
Fig. 8. Average composition of the STSA shows remarkable similarity to the model bulk continental crust composition (CC; Rudnick and Gao, 2003) on one-to-one plot in terms of abundances of all the analyzed major and trace elements with the exception of compatible elements (or oxides) such as MgO, Ni and Cr (see text for discussion). The log scale is used to show all the data with varying abundances (>5 orders of magnitude; the visual deviations are similar in terms of relative error for all abundances levels).
Modified from Mo et al. (2008).

Fig. 9. As in Fig. 8, average composition of the STSA shows remarkable similarity to the model bulk continental crust composition (CC; Rudnick and Gao, 2003) on one-to-one plot in terms of characteristic elemental ratios, including Eu/Eu*, Sr/Sr*, [La/Sm]$_N$ and [Sm/Yb]$_N$ where subscript N refers to normalization against primitive mantle values (Sun and McDonough, 1989). The log scale is used to show all the data with varying values (~3 orders of magnitude).
Modified from Mo et al. (2008).

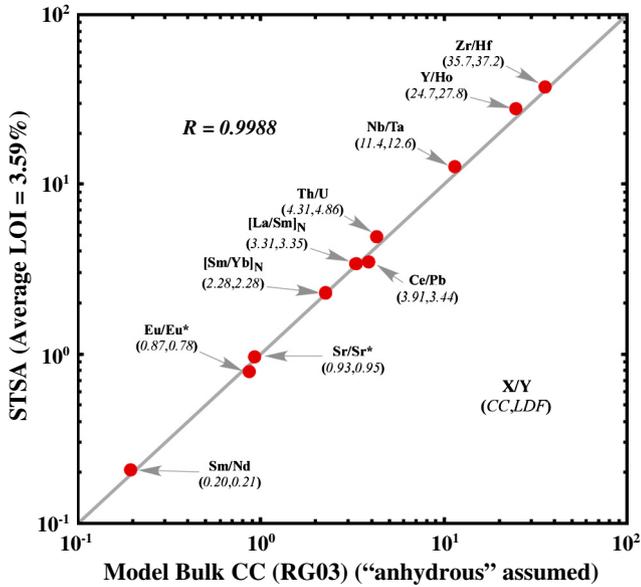magma assimilation in crustal magma chambers or melt contributions from terrigenous sediments as part of the underthrusting ocean crust. Fig. 11 shows the Hf isotopes of zircons from these rocks, especially from rocks of ~65–50 Ma age (syncollisional), mostly having ε$_{Hf(t)}$ >0, emphatically pointing to the dominance of mantle contributions. Hence, these syncollisional rocks make juvenile crust with primary materials coming from the mantle.

3.2.3. "Mantle origin" of the syncollisional andesites — partial melts of the ocean crust

The dominance of mantle isotopic signature of the STSA and related SGB suggests that these rocks must be derived from the mantle. The common interpretation in some of the literature would be partial melting of the mantle peridotite. It is conceptually important to note, however, that melting of wet mantle peridotite could produce high-Mg andesitic melts (O'Hara, 1965; Kushiro et al., 1968; Hirose, 1997), but the amount of melt produced is too tiny (<1% mass fraction) compared to the syncollisional granitoids, which in the case of southern Tibet, can amount to ~350,000 to 500,000 km^3 (Fig. 5; Niu et al., 2007; Mo et al., 2008).

To produce volumetrically significant andesitic melts such as the syncollisional STSA and SGB, the source materials must be basaltic in composition (see Niu, 2005). It is convenient to speculate that to partially melt basaltic AC could produce andesitic melts with inherited "arc signature" (Fig. 2). However, there are two obvious problems with this idea: (1) the AC with positive topography is shallow and is too cold to melt during collision and (2) arc rocks have variably way too much Sr to explain the bulk CC (Fig. 4). Hence, the excess Sr alone is strong evidence against island arc model for the bulk CC. Melting AC will not produce the bulk CC.

The best source candidate in the broad context of Tethyan ocean closing and India–Asia collision is the remaining part of the Tethyan ocean crust (Fig. 6). Partial melting of this ocean crust can produce volumetrically significant andesitic melts (e.g., STSA and SGB). Because the ocean crust was derived from the depleted MORB mantle at an ocean ridge in no distant past, the STSA and SGB will have mantle isotopic signatures inherited from the ocean crust (Figs. 10 and 11).

The question is whether this remaining underthrusting ocean crust is hot enough to melt. The answer is a straightforward "yes" because it is both "wet" enough and "hot" enough to melt. Fig. 11 is a simplified phase diagram, showing that the remaining underthrusting ocean crust takes a high T/P evolution path upon collision and then undergoes hydrous melting under amphibolite facies conditions. This melting produces primary andesitic melts with mantle isotopic signatures, either erupted and fast solidified as andesites (e.g., the STSA) or intruded,
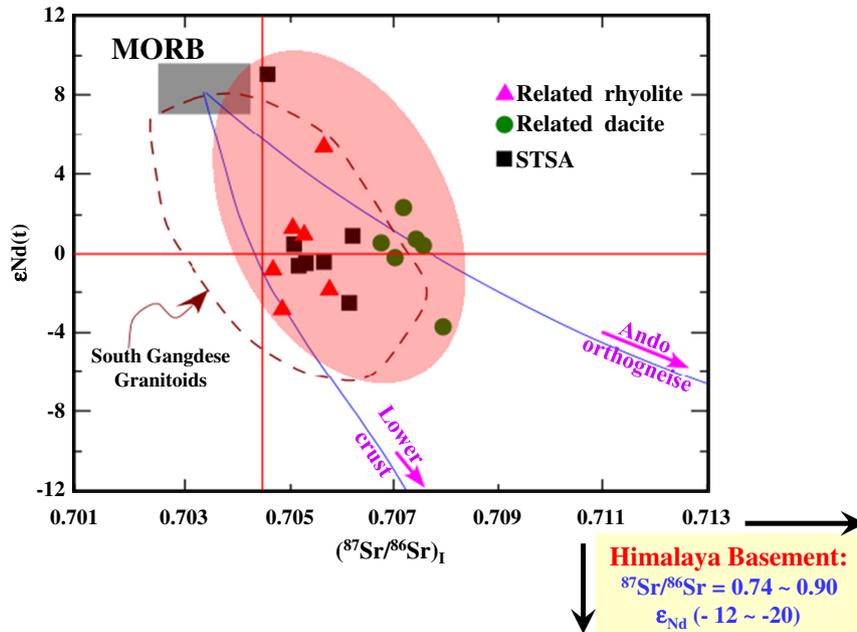
Fig. 10. In ^{87}Sr/^{86}Sr vs. ε$_{Nd(t)}$ space, representative samples from the STSA and the more felsic lavas together with the compositional field of the SGB defined by the literature data (Mo et al., 2007a,b, 2008 and unpublished data by Niu et al., in preparation) are shown to emphasize that despite the more felsic nature of all these rocks, they are isotopically dominated by mantle input (70–90%; see Mo et al., 2007a,b, 2008), and thus represent juvenile crustal material derived from the mantle most likely by melting of the ocean crust (see text for details).

as temperature-dependent viscosity mantle wedge flow models all consistently indicate P–T conditions beneath many active arcs are much hotter (Kelemen et al., 2003b) as indicated by the yellow oval area with dT/dP = ~20–50 °C in Fig. 12.

(3) *Why is the melting taking place under amphibolite facies conditions?* The above analysis indicates that with the high dT/dP path of ~20 °C, the underthrusting ocean crust will enter the amphibolite facies conditions and cross the wet solidus of basaltic rocks in P–T space (Fig. 12). Importantly, this analysis is corroborated by the geochemical data of the STSA (and SGB), which resembles the composition of the bulk CC with no HREE-highly depleted "garnet signature" (Figs. 1 and 7). If the underthrusting ocean crust melted under eclogitic conditions with garnet presence as a residual phase (Fig. 12), the composition of the melt would be similar to adakites (also sanukitoids or high-Mg andesites) and TTGs with highly depleted HREEs (see Fig. 1).
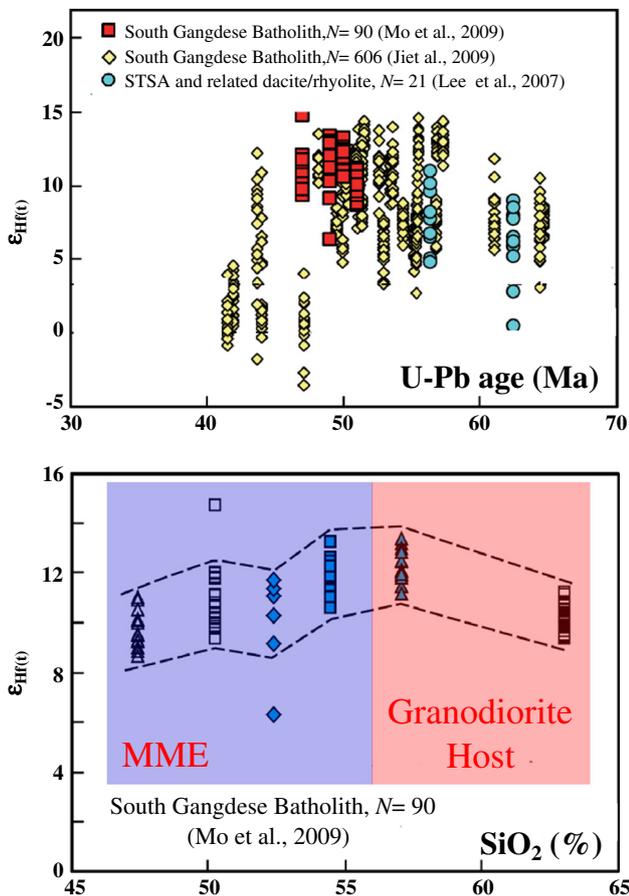
3.2.4. Composition of model partial melts of amphibolite of ocean crust protolith

High degree partial melting of amphibolite of basaltic protolith produces andesitic melts as demonstrated experimentally (Stern et al., 1975; Wyllie and Wolfe, 1993; Wolf and Wyllie, 1994; Rapp, 1995). The pertinent question is whether melting amphibolite of ocean crust (MORB) protolith can produce andesites with trace element systematics that match the STSA or bulk CC (Fig. 7). While well-designed melting experiments are needed, simple calculations demonstrate that an anticipated match is possible (Niu and O'Hara, 2009). The calculations were done by using (1) amphibolite of MORB protolith with modes of ~66.4 wt.% hornblende, ~29.2 wt.% plagioclase (plus minor quartz) and ~4.4 wt.% ilmenite/pseudobrookite (Niu and Lesher, 1991; see photomicrographs in Fig. 13), (2) composition of upper ocean crust (lavas + sheeted dikes) with 75% N-type MORB and 25% E-type MORB

Fig. 11. The mostly highly positive $\varepsilon_{Hf(t)}$ isotope compositions of zircons from the STSA and SAG further corroborate the significant mantle input in the petrogenesis of these rocks in response to the India–Asia collision, giving the zircon crystallization ages of ~65 Ma to 42 Ma (top). Note that the syncollisional granitoids are characteristically containing varying amounts of mafic magmatic enclaves (MMEs; see Fig. 14) that have been interpreted in the literature as resulting from magma mixing of mantle melts (represented by the MMEs) with crustal melts represented by the host granitoids, but the fact that both MMEs and the host granitoids show indistinguishable isotopes (as indicated by the lower panel) and both are dominated by mantle input suggests that the magma mixing interpretation needs revision (see discussion in the text). Data are from Mo et al. (2009), Ji et al. (2009) and Lee et al. (2007).

slowly cooled and solidified as diorites/granodiorites (i.e., the SGB). Three questions need addressing for this concept:

(1) *Why is it wet and hydrous melting?* This is straightforward as the ocean crust is hydrothermally altered during its accretion at ocean ridges and pervasively weathered/hydrated subsequently on the seafloor. This is in fact the premise on which the widely accepted subduction-zone flux-melting for arc magmatism is based (e.g., Gill, 1981; Tatsumi et al., 1986; McCulloch and Gamble, 1991).

(2) *Is it possible that the underthrusting crust would take such a high T/P path?* This is possible and likely because the slab "subduction" becomes retarded (underthrusting) upon collision, and tends to reach thermal equilibrium with the ambience, especially the upper crustal portion. Also, the ambience is hot because it was a hot active continental margin magmatic regime (e.g., the Andean-type) prior to the collision. Importantly, the continued underthrusting upon and during collision means that its induced mantle wedge flow must still have continued (until, perhaps, the slab break-off), which should supply heat and maintain the hot regime for some time (note that the India–Asia convergence continues to this day). In fact, petrologic and seismic data as well

Fig. 12. Simplified phase diagram showing hydrous (H_2O-saturated) solidi of basalts and the more felsic lithologies (granite and tonalite) modified from Niu (2005) using the experimental data of Stern et al. (1975), Wyllie (1977), and Wyllie and Wolfe (1993). The three major metamorphic facies fields (eclogite, amphibolite and granulite) are drawn after Peacock (2003). The two geothermal gradients approximating two extreme subduction zone scenarios are inferred from models of Peacock and Wang (1999). The star and the red solid curve with arrow illustrate the concept of the thermal evolution of the underthrusting Tethyan ocean crust along a high T/P path as a result of retarded subducting and enhanced heating upon and during India–Asia collision. It is expected that the highly hydrated (altered/weathered) ocean crust begins to melt when intersecting the hydrous basaltic solidus under amphibolite facies conditions. Sediments of the more felsic compositions (i.e., granitic or tonalitic) will melt under similar conditions. The yellow oval (labeled "A") indicates P–T conditions, where melting can take place, beneath active arcs constrained by petrologic and seismic observations summarized by Kelemen et al. (2003b). The red rectangle (labeled "B") indicates the likely melting conditions for the syncollisional magmatism.
Modified after Mo et al. (2008).

Fig. 13. Top: Photomicrographs of amphibolite of ocean crust (MORB) protolith with ~66.4 wt.% hornblende, ~29.2 wt.% plagioclase (plus minor quartz) and ~4.4 wt.% ilmenite/pseudobrookite (Niu and Lesher, 1991)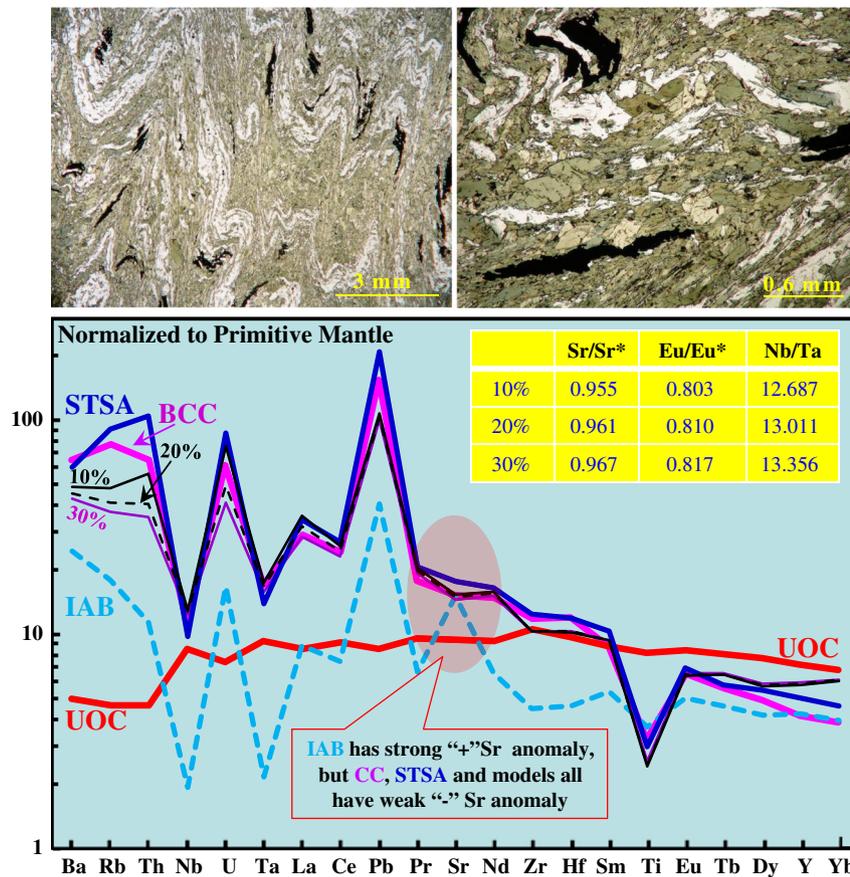. Bottom: Primitive mantle (PM) normalized multi-element diagram to compare compositions of the bulk CC (Rudnick and Gao, 2003), STSA (Mo et al., 2008), upper oceanic crust (UOC) made of 75% N-type MORB and 25% E-type MORB (Niu and O'Hara, 2003, 2008, 2009), and average island arc basalts (IAB; Elliott, 2003). We also show model calculations of aggregated melt compositions of 10%, 20% and 30% accumulated fractional melting of the UOC under amphibolite facies conditions using the mineral modes of amphibolite given above and the relevant partition coefficients in the literature (see Niu and O'Hara, 2009) plus 30% terrigenous of GLASS composition (Plank and Langmuir, 1998) required by the Nd isotope data (Fig. 10). The results capture the overall characteristics of the bull CC and STSA well with the exception of Ba, Rb and Th (see text for details).

(see Niu and O'Hara, 2003), (3) relevant partition coefficients compiled in the literature (see Table 1 of Niu and O'Hara, 2009), and (4) 10% to 30% accumulated fractional melting (similar to equilibrium batch melting in this case). The abundances of the progressively more incompatible elements of the model melts do not well match those of the STSA and bulk CC, but they do capture the key features such as the relative depletion of Nb, Ta and Ti and relative enrichment of Th, U, La and Pb as well as the more sub-chondritic Nb/Ta ratio of <13 (vs. 16.1 of the upper ocean crust and chondritic value of 17.4) characteristic of continental crust (Rudnick and Gao, 2003).

This less-than-perfect match is not ideal, but isotopically, the STSA, though dominated by mantle signatures (i.e., elevated $\varepsilon_{Nd(t)}$ and $\varepsilon_{Hf(t)}$ values; see Figs. 10 and 11 above), requires 10 to 30% input of mature crustal material (Mo et al., 2007a,b, 2008), either assimilated through crustal magma chamber processes or melt contribution of terrigenous sediments as part of the subducting/underthrusting Tethyan ocean crust upon India–Asia collision. While sediment melting experiments have been carried out to illustrate the phase stability (Nichols et al., 1994; Johnson and Plank, 1999), no ideal melting reactions with detailed melting stoichiometry are available to quantify sediment melting. However, for conceptual illustration on the effect of sediment involvement, we can simply add ~30% of the global subducting sediment (GLOSS) (Plank and Langmuir, 1998) to the model amphibolite melts with implicit assumption of total sediment melting (Fig. 13), which captures both the abundances and patterns of the bulk CC reasonably well for all elements with the exception of Ba, Rb Th and U, which are more variable.

Overall, the above exercises (see Table 1 of Niu and O'Hara, 2009), although not yet ideal without adequate experimental data on incongruent melting reactions of amphibolite and sediments, can illustrate the concept that amphibolite melting of MORB protolith with sediment addition can produce the bulk CC composition well. That is, this syncollisional ocean crust melting under amphibolite facies conditions can produce the required "arc-like signature" of the CC (Fig. 2) without invoking active subduction. Note also in Fig. 13 that arc rocks have a strong positive Sr anomaly (also see Fig. 4) while this anomaly does not exist, or if anything, a weak negative one for both STSA and bulk CC, emphasizing that arc rocks themselves or as magma source are inappropriate for contributing to the bulk CC composition (see above).

3.2.5. The mass of the juvenile crust produced by melting of the remaining ocean crust during collision

We mentioned above that the syncollisional granitoids (the SGB and STSA) from southern Tibet amount to ~350,000 to 500,000 km³. The question is whether partial melting of the remaining ocean crust can produce such voluminous juvenile crust during collision. This can be estimated as following Mo et al. (2008).

We consider (1) the STSA and the intrusive SGB are melting product of the underthrusting Tethyan ocean crust; (2) a convergence rate of ~50 mm/yr (or 50 km/Myr) over the ~5 Myr period for the STSA and SGB; (3) only the upper ~3 km basaltic portion of the 7 km ocean crust (i.e., basalts and sheeted dykes vs. lower crustal gabbros and cumulate) is involved in melting (see above); (4) the extent of

melting is 30%; and (5) andesite (and the intrusive granitoids) is about 3% less dense than basalt, then we obtain 5 Myr * 50 km/Myr * 3.0 km * 0.3 * 1.03 = 232 km³ juvenile crust per km strike length produced in this 5 Myr period. That is, the andesitic juvenile crust production rate is ~46 km³ km⁻¹ strike length per Myr. By assuming 30% melting of the upper ~4 km ocean crust, we would get ~62 km³ km⁻¹ strike length per Myr. If we apply this approximate production rate to the entire 1500 km south Gangdese Belt, there would be ~348,000 km³ to 464,000 km³ juvenile andesitic crust. Hence, to produce the observed mass of the juvenile crust is plausible.

4. Discussion

4.1. The advantages of our new concept over the standard "island arc model" with "mantle plume" supplementary

For convenience, we term our new concept as "continental collision zone model" or "collision model" versus the standard island arc model. To objectively assess the two models, we can make the comparison in the form of a score card table (modified from Niu and O'Hara, 2009) as follows (where BCC = bulk continental crust):

	Island-arc model (prevailing standard model)	Collision-zone model (our new concept)
Magma source	Mantle wedge peridotite with slab components	Amphibolite of upper ocean crust (MORB) protolith (with terrigenous sediments)
Primary melt composition relative to BCC	Basaltic ≠ BCC (too mafic)	Andesitic ≈ BCC
Conversion to BCC composition	Required to remove the mafic/ultra-mafic cumulate into the mantle through unknown processes	No need; melting residue that is more mafic/ultra-mafic already in the mantle
Net contribution to BCC growth	No, mass balanced by subduction erosion and sediment recycling	Yes, preserved in continental collision zones as syncollisional andesites and massive granitoids (e.g., those in the vast Greater Tibetan Plateau)
Juvenile crustal material	Yes, but overall mass-balanced	Yes, preserved
Mantle isotopic signature	Yes, from mantle wedge	Yes, inherited from ocean crust
Explanation for BCC signature of Nb–Ta–Ti depletion	Yes	Yes
Explanation for BCC signature of weak Sr depletion relative to Pr and Nd	No, variably high Sr excess	Yes
Explanation for BCC signature of weak Eu depletion relative to Sm and Gd	No	Yes
Explanation for BCC signature of strong sub-chondritic Nb/Ta ratio	No	Yes
Excess Sr and Eu in melting residue	No	Yes, leading to excess Sr and Eu in the mantle
Excess Nb and Ta in melting residue	Unknown (yes in the subducting ocean crust)	Yes, leading to excess Nb and Ta in the mantle

4.2. Continental crust growth is a matter of preservation

Continental crust growth is indeed a matter of preservation (Hawkesworth et al., 2009; Niu and O'Hara, 2009), and is the result of material balance between juvenile crust production (via magmatism) and destruction (subduction erosion, sediment recycling). The crustal mass grows if production/destruction >1. As AC production and destruction at both island arc settings and continental arc settings (the Andean-type active continental margins) are mass balanced (von Huene and Scholl, 1991; Scholl and von Huene, 2007; Stern and Scholl, 2010) on a global scale, volcanic arcs/subduction systems are not sites for net crustal growth, at least in the Phanerozoic. To invoke arc collision as collages against continents can help understand lateral build-up of continents, but because AC is basaltic (too mafic), such arc collages still cannot contribute to the required andesitic material for the bulk CC accretion. Furthermore, it is not straightforward how island arcs can collide with continents without subduction zones in between because collision is a lithospheric action, yet this fundamentally important "subduction-zone" element is missing in most arc–collision models for crustal accretion.

In contrast, syncollisional andesites and granitoids are produced and well preserved as we observe, sample and study. Hence, these represent net contributions of juvenile crust to continental crustal growth. It is important to note that one may argue that continental collision zones and orogenic belts form mountain ranges and will likely experience significant erosion, implying less crustal preservation. However, this is not true as otherwise these juvenile rocks would not have been preserved. While the syncollisional intrusive granitoids are exposed for erosion, the coeval volcanic sequences are well preserved in many sutures (e.g., Sutures III, IV, VII and VIII on the Greater Tibetan Plateau; see Fig. 5), manifesting that erosion ("destruction") is insignificant with production/destruction ≫ 1 for net continental crustal accretion.

4.3. Episodic growth of continental crust reflects super-continental amalgamation

The recognition of episodic growth of continental crust is important (Fig. 3; McCulloch and Bennett, 1994; Condie, 1998, 2000) on a global scale. If continental crust formation were indeed associated with subduction-zone magmatism, and because subduction, as a key element of plate tectonics, must be continuous over Earth's history whenever it began (see Condie et al., 2006; Stern, 2007), it follows that the episodic crustal growth preserved in the geological record must have resulted from some non-plate tectonic process or processes. Mantle plume magmatism has been widely invoked as the cause of such episodic growth. That is, pulses of mantle derived melts in the form of "mantle plumes" as a result of "super mantle avalanche events" (e.g., oceanic plateaus and continental flood basalts) must have contributed episodically to the continental crust mass (Stein and Hofmann, 1994; Abbott and Mooney, 1995; Abbott et al., 1997; Albarède, 1998; Polat et al., 1998; Condie, 2000; Kerr, 2003; Niu et al., 2003; Hawkesworth and Kemp, 2006; Parman, 2007; Pearson et al., 2007). Furthermore, if oceanic plateaus are indeed important for continental growth (e.g., Abbott et al., 1997), continental collision remains essential for crustal mass preservation (Niu et al., 2003). The problem or puzzle with the mantle plume supplementary is several folds: (1) the speculated mantle avalanche resulting from sudden mass exchange between lower and upper mantle is expected to be volumetrically colossal and thermally enormous in causing mantle melting that may contribute to the crustal mass, yet the bulk CC is no more than 0.5 wt.% of the Earth's mass, and its incremental/fractional increase associated with each growth peak (Fig. 3) does not seem to require whole-earth process; (2) mantle plume melts are basaltic and too mafic for the andesitic composition required for the bulk CC; and (3) mantle plume melts do not have the required compositional systematics of the bulk CC (see Fig. 2).

In comparison, our collision-zone model can readily explain the episodic crustal growth. That is, the episodic crustal growth peaks (Fig. 3) may in fact be associated with continental collisions towards the aggregation of supercontinents. For example, the vast Greater Tibetan Plateau is a geological amalgamation formed by several continental collision events since the Early Paleozoic with suture zones and associated syncollisional granitoid batholiths progressively younger towards the south (Fig. 5):

~450 Ma granitoids associated with Suture I, ~420 Ma granitoids with Sutures II and III, ~250 Ma granitoids with Suture IV, ~120 Ma granitoids with Suture VII and the STSA and SGB associated with Suture VIII. Our on-going study explicitly indicates that all these syncollisional granitoid batholiths (dominated by I-type diorites or granodiorites) are net addition of juvenile materials to the continental crust mass. That is, it is the continental collision that produces and preserves the juvenile crustal material, and hence maintains net CC growth.

In this context, it is worth emphasizing conceptually that on a global scale, seafloor spreading/subduction is a continuous process since the inception of plate tectonics, hence, "Island Arc" model cannot explain episodic crustal growth. Continental collision is a consequence of plate tectonics, but it is "episodic", and the syncollisional magmatism can readily explain the episodic crustal growth. Hence, it is logical to state that the growth history of the Greater Tibetan Plateau is the history of sequences of continental collisions, and manifests the history of super-continental formation, during which juvenile crust of andesitic composition (both volcanic and intrusive) is produced and preserved episodically, making net growth of the CC. It is also necessary to emphasize that continental collision can take place on varying regional scales or global scales. As a result, with more and high quality data available on syncollisional granitoids worldwide, the episodic peaks (as seen in Fig. 3) may become less spiking or less regular in time-averaged histograms (e.g., Fig. 3; also see Condie et al., 2009; Dhuine et al., 2012).

4.4. More on the cause of syncollisional ocean crust melting and possible effect of slab break off

We have discussed the petrogenesis of the syncollisional STSA (65–60 Ma) and the bulk of the SAB (55 ± 5 Ma) as a result of the remaining ocean crust melting in response to the India–Asia collision as illustrated in Fig. 12, which can readily explain the volumetrically significant melt production, estimated to be ~350,000 to 500,000 km³ (Fig. 5; see above) without need of any additional processes. However, the ~720 m thick dacitic mid Nianbo Formation (~54 Ma) and the ~2000 m thick rhyolitic upper Pana Formation (~49–44 Ma) overlying the STSA deserve attention, especially the Pana Formation; they are dominated by ignimbrite with abundant quenched glasses with or without phenocrysts, suggesting very high eruption temperatures (super heated?). Importantly, the magnificent columnar jointing locally >80 m high points to voluminous melting and fast eruption/

emplacement of very hot magmas. We propose that these younger, more felsic and hot magmas may have resulted from melting of the earlier emplaced SGB (or deeper equivalent) in response to a hotter source, which may be genetically related to slab break-off and excess heating of ascending asthenospheric mantle. This is a likely possibility to be tested. Slab break-off about 10–20 Myrs after the onset of the collision is theoretically feasible (van Hunen and Allen, 2011).

4.5. The origin of the mafic magmatic enclaves (MMEs)

Fig. 14 shows representative field photos of typical syncollisional granitoids (compositionally dioritic to granodioritic) associated with four suture zones on the Greater Tibetan Plateau (also see Fig. 5). A general feature of the syncollisional granitoids is the presence of mafic magmatic enclaves (MMEs) of varying size dispersed randomly or in certain cases in some group patterns in the granitoid (diorite to granodiorite) host. The origin of the MMEs in the context of the petrogenesis of the (syncollisional) granitoid host has been the subject for over a century since the descriptive work by Phillips (1880). When studying the Sierra Nevada batholith, Pabst (1928) described the MMEs as "autoliths", meaning that the MMEs may be "cogenetic" or part of the same system. This autolith concept is in fact consistent with recent observations (Dodge and Kistler, 1990; Barbarin and Didier, 1992) as summarized by Barbarin (2005): (1) mafic minerals have identical compositions in MME and host, although they vary in modal abundances; (2) although contents of major and trace elements are different in MME and hosts, differences in some major elements (e.g., FeOt, MgO) are relatively constant, and strong correlations exist between variation of major and trace elements; and (3) in each pluton, MME plot along Rb–Sr isochrons is determined using granitoid samples only and does not display significant differences in either ε_{Nd} and ε_{Sr} values with host granitoids. Our recent work (Mo et al., 2005, 2007a,b, 2008, 2009; Niu et al., 2011, in preparation; Huang et al., in press) and ongoing studies in Gangdese, East Kunlun, West Kunlun, South Qilian and North Qilian (see Fig. 5) concur with the above summary. We can further emphasize that Sr–Nd–Hf isotopes between co-existing MME and the host are indistinguishable (Huang et al., in press; also see Fig. 11).

Despite the "autoliths" nature of the MMEs with the host, when interpreting the petrogenesis of the MMEs in the context of understanding the petrogenesis of the syncollisional granitoids the most popular interpretation has always been magma mixing between mantle derived

South Gangdese　　**East Kunlun**　　　　**South Qilian**　　**North Qilian**

Fig. 14. Field photos of the syncollisional granitoids with characteristic mafic magmatic enclaves (MMEs) from orogenic belts, taken by Yaoling Niu in 2001 (South Gangdese), 2009 (East Kunlun), 2010 (South Qilian) and 2012 (North Qilian) (see Fig. 5). Traditionally, granodiorite hosts with MMEs have been interpreted as evidence of magma mixing between mantle derived basaltic melt represented by the MMEs and the crust-derived felsic melt represented by the host, but we find this is not the case for all that we have studied and under studying (see text). These MME-bearing characteristics of the syncollisional granitoids offer an additional line of evidence pointing to the mafic andesitic primary magmas originating from ocean crustal melting.

basaltic melt represented by the MMEs and the crust-derived felsic melt represented by the granitoid host, while also arguing that the similar isotopes between the two result from equilibrium or complete isotopic homogenization (see Liu et al., 2004; Barbarin, 2005; Mo et al., 2007b). The latter interpretation is interesting, but it is physically unlikely with isotopes being homogenized whereas major and trace elements are not.

The best interpretation, as "autolith" implies, is that the MMEs represent the earlier cumulate crystallized from the more primitive (primary?) andesitic melts, and the cumulate piles have later been disturbed by the incoming magmas in magma chambers. The major mineralogy of amphibole + plagioclase(+biotite) is consistent with the parental/primary magmas being mafic andesitic melt resulting from melting of the ocean crust under the amphibolite facies conditions (no garnet signature) (Figs. 7 and 12).

4.6. About the "Daly gap"

The issue is less relevant here, but in case the reviewer's view represents the general opinion in the Earth science community, we feel it is necessary to discuss it briefly. The reviewer stresses that andesites (and diorites) are extremely rare in orogens, and especially in accretionary orogens, a feature long ago recognized (i.e., the Daly gap). We discuss below the observations, concepts and our perspectives.

4.6.1. The observation

The syncollisional granitoids that we discuss are dominated by diorites/granodiorites (normally termed I-type granitoids of andesitic composition) not only from the India–Asia collision zones, but also from all collision zones throughout the Greater Tibetan Plateau as indicated in Fig. 5 as well as from the giant West Qinling orogenic belt in central China. We have sampled most of these belts, and are in the process of detailed petrological, geochemical and geochronological investigations to test the hypothesis given in the title of the paper. As for the abundance of erupted andesites, it is again a matter of preservation and exposure. For example, in the southern Tibet (the youngest orogenic belt), the volumetrically significant syncollisional andesites are well-preserved and exposed. This is also true for parts of the older (260–240 Ma) Kunlun orogenic belt (Suture IV in Fig. 5). In brief, diorites and granodiorites of andesitic composition are abundant and dominate syncollisional granitoids along all the orogenic belts we have sampled.

4.6.2. The concept

It should be noted that the "Daly Gap" (Daly, 1925) was recognized based on the assumption that basaltic magma evolution is dominated by fractional crystallization that is a continuous process and should produce melts of a compositional continuum from basalt through andesite to the more felsic compositions. Both mafic and felsic volcanic rocks are abundant, but the intermediate andesitic rocks are rare, hence the missing-andesite puzzle or the "Daly Gap". Readers should note that the syncollisional granitoids (diorites and granodiorites of andesitic compositions) that we discuss are NOT products of simple basaltic magma evolution, but partial melting of the basaltic ocean crust (with varying amounts of terrigenous sediment addition; see Figs. 6, 12, 13).

4.6.3. Our perspectives on the "Daly Gap"

Bimodal distribution of igneous rocks is a common phenomenon, one mode being basalt and the other felsic magmas, which well illustrates the concept of the "Daly gap" (see above and also Chayes, 1963; Cann, 1968; Clague, 1978; Bonnefoi et al., 1995). We think the origin of the "Daly Gap" may actually be straightforward in terms of magma generation and evolution these two end-member processes.

The magma generation origin. Intrusion of mantle derived basaltic magma into the continental crust will cause crustal melting. As total melting is unlikely (see Niu, 2005), partial melting of the crust will produce the more felsic (than the andesitic continental crust) melts like dacite/rhyolite. The mixture of the two melts would be broadly andesitic, but inadequate mixing would result in rare andesite, but coexistence of volumetrically significant mantle-derived basaltic melt and crust-derived felsic melt in space and time. This simple process explains the bimodal distribution of volcanic rocks and hence the "Daly Gap".

The magma evolution origin. Fractional crystallization of basaltic magma is anticipated to produce residual liquids with a compositional continuum, which is the very concept of the liquid lines of descent (LLDs; Bowen, 1928). However, it should be noted that the amount of melt produced for a given portion of the compositional continuum is not necessarily the same. In fact, the andesitic melt produced is volumetrically less significant and the "Daly Gap" is a straightforward consequence of basaltic magma evolution. This is because at a later stage of basaltic magma evolution at about $T \approx 1100\,°C$ (e.g., in the case of mid-ocean ridge basalts; Niu, 2005; Niu et al., 2002), Ti–Fe oxides become on the liquidus to crystallize. Because Ti–Fe oxides contain little SiO_2 and their crystallization leads to rapid increase of SiO_2 in the residual melt (basaltic–andesite stage) towards high SiO_2 melts if continued crystallization is permitted (without drastic cooling and solidification). As a result, the system produces abundant basalts and the more evolved high SiO_2 rocks (dacitic/rhyolitic) with limited amount of andesite.

5. Summary

1. The standard "island arc" model for continental crust growth has major difficulties: (1) the primary arc magmas or the bulk arc crust is basaltic whereas the bulk continental crust is andesitic; (2) the arc crust production is mass balanced by subduction erosion and sediments recycling, thus contributing no net mass to continental crust growth; and (3) the arc crust is highly enriched in Sr, and is thus inappropriate for the continental crust that is relatively Sr deficient.

2. Our "collision model" is a testable hypothesis that overcomes the major difficulties the "island arc model" faces with. It states that continental collision zones are primary sites for net continental crustal growth.

3. Upon continental collision, seafloor subduction stops, but convergence continues for some time, during which the last fragments of the underthrusting ocean crust (hydrothermally altered at ridges and weathered/hydrated subsequently on the seafloor) will melt under amphibolite facies conditions, producing andesitic melts, which we call "syncollisional andesites", whose major and trace element compositions are essentially identical to the model bulk continental crust.

4. The "syncollisional andesites" are isotopically dominated by mantle signatures inherited from the ocean crust that was derived in no distant past from the mantle at ocean ridges. Hence, the "syncollisional andesites" are genuinely juvenile continental crust materials. That is, continental collision produces and preserves the juvenile crust, maintaining continental crust growth.

5. The greater Tibetan Plateau is the ideal test ground for this hypothesis because its history from the Early Paleozoic to present manifests the history of "super" continent amalgamation through a series of continental collision events with production and preservation of abundant syncollisional granitoids.

6. Plate tectonics in terms of seafloor spreading and subduction is a continuous process on a global scale since its inception, whereas continental collision on various regional scales and super-continental formations on a global scale are episodic (vs. continuous). Hence, continental collision with juvenile crust formation/preservation and super-continent amalgamation explains the episodic growth of the continental crust.

7. We are continuing testing and refining this hypothesis by detailed petrological, geochemical and geochronological studies of syncollisional granitoids along many more collision zones on the Greater Tibetan Plateau in a global context.

8. One of the key tasks of our testing effort is to carry out well-designed and well-controlled melting experiments of amphibolite of MORB protolith as well as terrigenous sediments (1) to acquire incongruent melting reactions for quantitative modeling and (2) to quantify trace element budgets.

Acknowledgments

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