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Resolving the crustal composition paradox by 3.8 billion years of slab failure magmatism and collisional recycling of continental crust

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ABSTRACT

In the standard paradigm, continental crust is formed mainly by arc magmatism, but because the compositions of magma rising from the mantle are basaltic and continental crust is estimated to contain about 60% SiO_2 and much less MgO than basalt, the two do not match. To resolve this paradox, most researchers argue that large amounts of magmatic fractionation produce residual cumulates at the base of the crust, which because arcs are inferred to have magmatically thickened crust, form eclogites that ultimately founder and sink into the mantle. Not only are there problems with the contrasting bulk compositions, but the standard model also fails because prior to collision most modern arcs do not have thick crust, as documented by their eruption close to sea level, and in cases of ancient arc sequences, their intercalation with marine sedimentary rocks.

Our study of Cretaceous batholiths in the North American Cordillera resolves the crustal composition paradox because we find that most are not arc-derived as commonly believed; but instead formed during the waning stages of collision and consequent slab failure. Because the batholiths typically have silica contents > 60% and are derived directly from the mantle, we argue that they are the missing link in the formation of continental crust.

Slab failure magmas worldwide are compositionally similar to tonalite-trondhjemite-granodiorite suites as old as 3.8 Ga, which points to their collective formation by slab failure and long-lived plate tectonics. Our model also provides (1) an alternative solution to interpret compiled detrital zircon arrays, because episodic peaks that coincide with periods of supercontinent amalgamation are easily interpreted to represent collisions with formation of new crust by slab failure; and (2) that models of early whole-earth differentiation are more reasonable than those invoking progressive growth of continental crust.

1. Introduction

How and when continental crust formed are contentious, long-standing issues among geologists. Most geoscientists believe that continental crust formed principally by water-induced melting of the mantle wedge above subduction zones to produce juvenile basaltic melts, which rise into the crust where they fractionate (Rudnick, 1995; Davidson and Arculus, 2006; Hawkesworth and Kemp, 2006; Tatsumi and Stern, 2006; Lee et al., 2007; Stern and Scholl, 2010; Jagoutz and Schmidt, 2012, 2013; Arndt, 2013; Jagoutz and Kelemen, 2015). This paradigm is problematic because geologists estimate the bulk composition of continental crust to be andesitic-dacitic with just over 60% SiO_2 yet magmas rising into the crust within arcs are basaltic (Taylor and McLennan, 1985, 1995; Rudnick and Fountain, 1995; Rudnick and Gao, 2003; Hacker et al., 2011). The contradictory nature of the two concepts creates what is known as the *crustal composition paradox* (Rudnick, 1995).

The paradox is typically resolved with a circular argument that invokes large-scale, lower-crustal foundering of residual material, dominated by pyroxene, amphibole, and garnet cumulates, from the base of magmatically thickened arc crust (Jagoutz and Behn, 2013; Lee and Anderson, 2015). In the arc model, the dense cumulates and restites must exist because most crust is manufactured in arcs, and the estimated amount of fractional crystallization necessary to create rocks with the composition of upper crust from arc basalt is ~86% (Kay and Kay, 1991; Ducea and Saleeby, 1998; Ducea, 2001; Hawkesworth and Kemp, 2006; Jagoutz and Kelemen, 2015; Lee and Anderson, 2015, and references therein) and, based on mantle xenoliths from the Sierra Nevada, along with cross sections of older arcs such as Kohistan, > 2:1 for bulk crust (Ducea, 1998; Ducea and Saleeby, 1998; Jagoutz and

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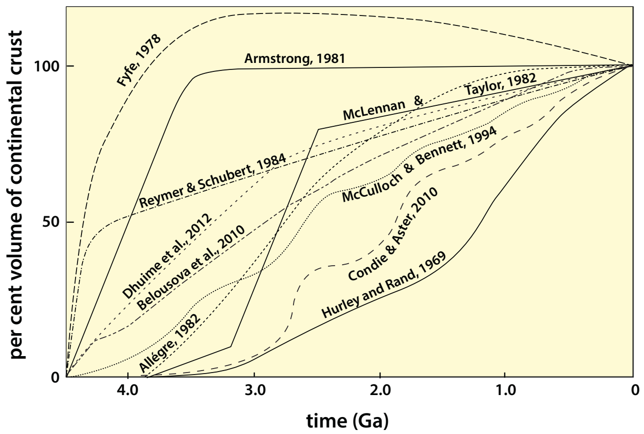

Fig. 1. Crustal growth curves modified from Bowring and Housh (1995); Rino et al. (2004); Hurley and Rand (1969); McLennan and Taylor (1982); Allègre (1982); McCulloch and Bennett (1994); Reymer and Schubert (1984), Armstrong (1981), and Fyfe (1978); McLennan and Taylor (1982); Dhuime et al. (2012); Belousova et al. (2010); Condie and Aster (2010).

Schmidt, 2013). Thus, because the generally accepted model for the bulk of crustal formation is arc magmatism (Rudnick, 1995; Hawkesworth et al., 2009), huge volumes of residue must form in the lower crust, and then be removed – presumably by gravitational foundering (e.g., Lee and Anderson, 2015; Ducea, 2002; Saleeby et al., 2003; Ducea and Barton, 2007; Jagoutz and Behn, 2013; Jagoutz and Schmidt, 2013; Ducea et al., 2015) – as such thick crust is not observed. This observation highlights another difficulty with the arc model, because in order for the inferred mafic residue to founder, it must first be converted to eclogite, which requires pressures typically unattainable in arc crust (Green and Ringwood, 1967; Poli, 1993; Hacker, 1996), as prior to collision, arcs are generally low-standing regions without thick crust (Levi and Aguirre, 1981; Hildebrand and Bowring, 1984; Busby-Spera, 1988; Busby, 2012; Hildebrand and Whalen, 2014b, 2017).

Allied with the problem of how continental crust is formed is a long-standing controversy over when the bulk of this crust was formed (Fig. 1). Since the advent of plate tectonics, most researchers developed crustal growth models in which the cumulative volume of continental crust was derived progressively from the mantle to leave it depleted in crust-forming elements (Hurley and Rand, 1968; O'Nions et al., 1979; Veizer and Jansen, 1979; Allègre, 1982; Allègre and Rousseau, 1984; Reymer and Schubert, 1984; Taylor and McLennan, 1985; McCulloch and Bennett, 1994; Condie, 1998; Rino et al., 2004; Condie et al., 2016). In this model, if continental crust was created progressively by arc magmatism from the mantle, then arc magmatism must have changed composition through time. Workers promoting this hypothesis point to the tonalite-trondhjemite-granodiorite (TTG) suites common to Archean cratons, but believed by many to be absent today (Moorbath, 1977; Jacobsen and Wasserburg, 1981; Martin, 1986; Martin and Moyen, 2002; Jacobsen, 1988; McCulloch and Bennett, 1994; Kamber et al., 2002; Kleinhanns et al., 2003; Arndt, 2013; Hawkesworth et al., 2010; Jagoutz et al., 2011; Laurie et al., 2015), although a few researchers (Drummond and Defant, 1990; Atherton and Petford, 1993) suggested that younger examples exist.

In this contribution, we summarize our detailed studies on the tectonic setting and geochemistry of Cordilleran-type batholiths (Hildebrand and Whalen, 2014a, 2014b, 2017) and conclude that a major crust-forming process has been largely overlooked, in that Cordilleran batholiths appear to be dominated – not by arc magmatism – but by magmas produced during *slab failure*. We argue that this magmatism provides the missing link in the formation of continental crust and so precludes the necessity of large-scale, sub-arc foundering, because the more siliceous compositions of slab failure magmatism "balance" the less siliceous arc basalts. Furthermore, we show that the geochemistry of Phanerozoic slab failure rocks is similar to that of Precambrian TTG suites, which leads us to argue that similar tectonomagmatic processes have been active since at least 3.8 Ga.

Our findings support models in which the volume of continental crust has remained more or less constant over time and that ongoing crustal growth was, and is, balanced by recycling of older continental crust into the mantle (Fyfe, 1978; Armstrong, 1981, 1991; Bowring and Housh, 1995; Hildebrand and Bowring, 1999). We also argue that slab failure magmatism explains the episodic peaks in crystallization ages indicative of magmatic activity (Condie et al., 2017) because the peaks broadly coincide with periods of supercontinental amalgamation (Hawkesworth et al., 2009, 2013, 2016), which involve an increase in the number of collisions and related slab failure.

2. What is slab failure?

Slab failure is the rupture and separation of subducting plates during collisions. It occurs during collisions because continents are buoyant and resist subduction, whereas all but the youngest oceanic lithosphere is negatively buoyant relative to the asthenosphere, so is pulled down into the mantle by gravity (Roeder, 1973; Price and Audley-Charles, 1987; Sacks and Secor, 1990; Davies and von Blanckenburg, 1995; Davies, 2002; Atherton and Ghani, 2002). During slab break-off, oceanic lithosphere, and transitional crust of rifted margins, which, like oceanic crust, is effectively welded to the subjacent mantle. These domains tear off and are subducted into the mantle (Fig. 2). During this process the sedimentary platform-cover sitting atop the buoyant continental crust is "scraped off", jaming the subduction zone (Cloos et al., 2005; Duretz et al., 2011; Bercovici et al., 2015). Following break off, the lower plate rebounds to underplate the arc

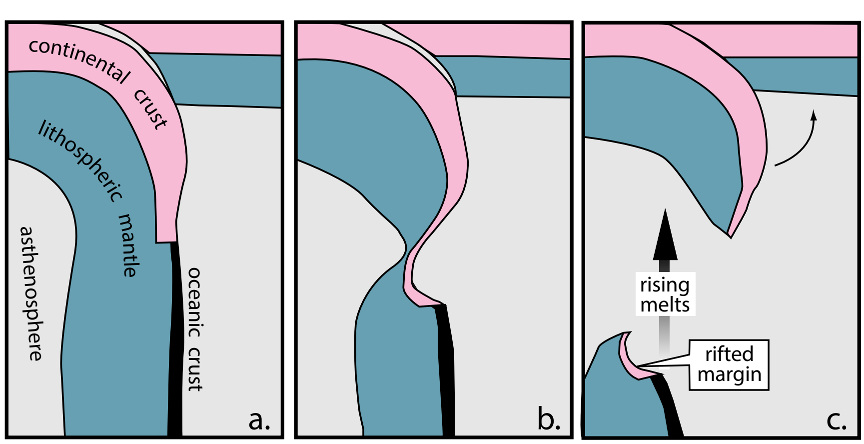

Fig. 2. Sketches illustrating some features of moderately deep slab failure. In (a) the leading edge of the continet is subducted beneath the overriding arc-bearing plate; in (b) we illustrate the tearing of the subducting slab largely by ductile necking; and in (c) we show the possibility of the rifted margin separating from the main continental mass and sinking into the mantle along with the oceanic lithosphere as suggested by Hildebrand and Bowring (1999). In our model magmas are derived from melting of the oceanic crust. Adapted from Freeburn et al. (2017).

(Magni et al., 2017). It is partly this buoyancy-driven rebound that exhumes high and ultra-high pressure (UHP) rocks of the subducted continental margin and drives erosion and extensional collapse of the upper, arc-bearing, plate (for example: Ernst et al., 1997).

Another factor that can contribute to uplift and exhumation of the collision zone depends on the angle of subduction, or slab dip, when tearing occurs. If the slab dip is moderate, then lithospheric mantle is replaced as asthenosphere rises through the newly formed gap in the ruptured plate, which itself can generate a vertical isostatic uplift of several kms to the collision zone (Cloos et al., 2005).

It is commonly believed that hot asthenosphere rising through the gap melts due to decompression or possibly heat from the overlying lithosphere (Davies and von Blanckenburg, 1995; Macera et al., 2008; Hildebrand, 2009, 2013); however, recent numerical models, designed specifically to investigate the conditions required to create slab failure magmatism, suggest that this might only happen in cases of very shallow break-off (Freeburn et al., 2017). When the angle of subduction is steep, as might be the case in the subduction of old, dense oceanic lithosphere, or in deep break-off, then asthenosphere does not necessarily upwell, but instead flows laterally, or even downward, to fill the gap (Fig. 2). In this case, asthenosphere probably would not melt adiabatically and the origin of *syn*- to post-collisional magmatism is more obscure.

3. Slab failure magmatism

We began to characterize slab failure magmatism with examples from collisional orogens in our “home” orogens of Wopmay and the Appalachians (Hildebrand and Bowring, 1999; Whalen et al., 2006) but in 2013 decided to combine our experience and interest to better characterize the magmatism and understand its potential importance in space and time. Initially, we examined the Cretaceous Coastal batholith of Peru (Cobbing et al., 1981; Pitcher et al., 1985) and by using the temporal relations between magmatism and deformation, developed a model in which the bulk of the plutonic rocks that make up the batholith were products of slab failure (Hildebrand and Whalen, 2014a).

3.1. Peninsular Ranges batholith

Our understanding improved when we focused on rocks of the Peninsular Ranges batholith of Southern and Baja California where there are detailed maps, ICP-MS geochemistry, and modern U-Pb dating (Lee et al., 2007; Morton and Miller, 2014). There, we studied the two major suites of magmatism: the ~128–100 Ma Santiago Peak-Alisitos arc and 99–86 Ma La Posta plutons, which sit more or less side by side and have long been recognized to differ in age, trace element and isotope content, opaque mineralogy, depth of emplacement, and crustal thickness (Gastil et al., 1975, 1990; Silver et al., 1979; Gromet and Silver, 1987; Silver and Chappell, 1988; Kimbrough et al., 2001; Tulloch and Kimbrough, 2003). Although all workers agreed that the older Santiago Peak-Alisitos rocks represented a magmatic arc, the tectonic setting of the younger La Posta magmatism was generally inferred by most researchers to represent a continuation of arc magmatism, despite development of numerous models that invoked closure of back-arc basins and collisions just prior to their emplacement (Silver and Chappell, 1988; Gastil et al., 1981; Gromet and Silver, 1987; Todd et al., 1988; Walawender et al., 1990; Busby et al., 1998; Johnson et al., 1999; Kimbrough et al., 2001; Ortega-Rivera, 2003; Schmidt et al., 2014).

Rocks of the Santiago Peak-Alisitos arc comprise mostly weakly to moderately deformed, low-grade, shallow marine, volcanic rocks and associated epizonal plutonic rocks ranging in age from 128 to 100 Ma; whereas to the east, compositionally zoned, mesozonal plutonic complexes of the 99–86 Ma La Posta suite were emplaced into deformed amphibolite grade rocks. Arc magmatism shut down during a period of regional deformation and metamorphism, constrained to be about 100 Ma (Premo and Morton, 2014; Johnson et al., 2002; Alsleben et al., 2008; Schmidt et al., 2009). The metamorphism and deformation coincided with a period of eastward-vergent thrusting (Pubellier et al., 1995) where rocks of the Guerrero superterrane, basement to the 128–100 Ma Santiago Peak-Alisitos arc (Tardy et al., 1994; Dickinson and Lawton, 2001; Centeno-García et al., 2003, 2008, 2011; Schmidt et al., 2014), were placed over a drowned west-facing Albian carbonate platform (Warzeski, 1987; Lawton et al., 2004; LaPierre et al., 1992; Monod et al., 1994, 2000; González-Léon et al., 2008; Martini et al., 2012) and related eastwardly migrating flexural foredeep, comprising upper Albian to Turonian siliciclastic sedimentary rocks (Mack, 1987; González-Léon and Jacques-Ayala, 1988; Monod et al., 2000). The overthrusting of a west-facing marginal platform terrace by the arc terrane is readily interpreted to indicate closure of a marginal basin, known as the Bisbee-Arperos seaway, by westward subduction of marginal basin lithosphere. This was followed by attempted subduction of the leading edge of eastern Mexico beneath the Santiago-Peak-Alisitos arc and its basement during the Oregonian event (Martini et al., 2011, 2014; Hildebrand, 2013; Hildebrand and Whalen, 2014b, 2017).

3.2. Sierra Nevada batholith

The overall temporal and lithological similarities between the Peninsular Ranges and Sierran batholiths have long been noted (Tyrrell, 1929; Daly, 1933); in fact, so much so, that they are commonly assumed to have formed a continuous batholith (Hamilton, 1969; Ducea, 2001), despite their separation by the younger region of Laramide deformation, metamorphism, and plutonism, which passes orthogonally between the two batholiths (Hildebrand, 2015). For our purposes their original spatial relationships are unimportant, because in any case, plutons of the Sierra Nevada batholith are closely comparable to those of the Peninsular Ranges batholith. Cretaceous rocks of the Sierra comprise a western facies consisting of arc supracrustal rocks and associated plutons (Clemens-Knott and Saleeby, 1999), that were deformed at, or just prior to 100 Ma (Saleeby et al., 1990; Memeti et al., 2010; Wood, 1997; Saleeby et al., 2008), and an easterly facies of post-deformational 99–82 Ma tonalitic-granodioritic plutons known as the Sierran Crest magmatic suite (Coleman and Glazner, 1998). A major ~100 Ma east-vergent thrust belt lies farther east (see summary in Hildebrand and Whalen, 2017), but the location of the suture is obscured by younger Basin & Range extension. Magmatism in both the Sierra Nevada and Peninsular Ranges batholiths ceased at 83 ± 1 Ma (Coleman and Glazner, 1998; Saleeby et al., 2008).

3.3. Geochemistry

That magmatic rocks of the Peninsular Ranges and Sierra Nevadan batholiths were both pre- and post-collisional fits all of the existing data, and so we compiled and examined their geochemistry to ascertain if there were attributes that might be used to delineate the two suites in the absence of clear and unequivocal evidence for collision, and to better understand the sources of their magmas. While they are superficially similar, we found consistent major and minor geochemical differences between the two suites (Hildebrand and Whalen, 2014b). For example, most rocks of the La Posta and Sierran Crest magmatic suites contained 60–70% SiO_2 whereas the arc suite displayed a continuous range from basalt to rhyolite. Relative to the arc rocks, members of the La Posta-Sierran Crest suites were generally more enriched in incompatible elements, Na, and Nb, but depleted in Y and Yb (Fig. 3). We exploited those differences to develop several discrimination diagrams (Fig. 4) and tested their reliability with geochemistry from much younger arc and slab failure rocks (Fig. 5) before studying the tectonic setting and geochemistry of other Cordilleran batholiths in western North America and elsewhere (Hildebrand and Whalen, 2017). There, we found that late *syn*- to post-tectonic plutons predominate, were emplaced during exhumation of thickened crust, and are geochemically

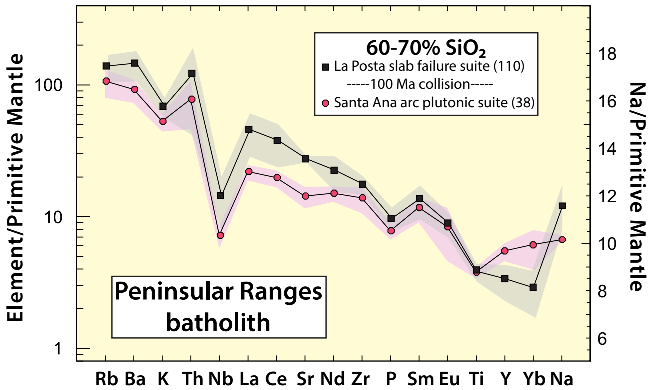

Fig. 3. Primitive mantle–normalized extended element plots for plutonic rocks of Peninsular Ranges batholith showing compositional averages and ranges for plutonic rocks older and younger than 100 Ma with 60–70% SiO_2. Primitive mantle–normalizing values are from Sun and McDonough (1989).

similar to our recognized slab failure rocks (Hildebrand and Whalen, 2017). Although pre-collisional arc rocks exist in some batholith belts, such as the Peninsular Ranges and Sierra Nevada, they are spatially subordinate to slab failure suites. Presumably, this is because arcs and their basement constitute the upper plates of collisional belts and so they are preferentially eroded during collision-related uplift and exhumation.

4. Origin of slab failure magmatism

The transverse compositional asymmetry of Cordilleran batholiths within North America has long been recognized (Lindgren, 1915; Buddington, 1927; Larsen, 1948; Moore, 1959: Moore et al., 1961; Silver and Chappell, 1988), and following the advent of plate tectonics most researchers developed models in which older Cretaceous plutons were emplaced into accreted terranes above an eastwardly dipping subduction zone. In that model, shallowing subduction forced magmatism to prograde eastwardly into the western margin of North America where it interacted with, and assimilated, older cratonic crust (Bateman, 1974; Kistler and Peterman, 1978; Kistler, 1978, 1990; Gastil et al., 1981; Hamilton, 1988; Hill et al., 1988; Saleeby et al., 1990; Walawender et al., 1990; Chen and Tilton, 1991; Johnson et al., 1999; Todd et al., 2003; Grove et al., 2003; Ortega-Rivera, 2003; Ducea and Barton, 2007; Paterson et al., 2014; Schmidt et al., 2014; Cao et al., 2015; Ducea et al., 2015).

4.1. Trace elements

In their pioneering study of rare earth elements (REE) transversely across the Peninsular Ranges batholith, Gromet and Silver (1987) demonstrated the inadequacy of upper crustal differentiation and assimilation processes to explain the differences between the two magmatic groups. They pointed out that the variations in Sr, $\delta^{18}O$, and REE contents between the two suites indicated that, although the western pre-100 Ma rocks were typical arc rocks, the eastern, post-100 Ma rocks were derived from a plagioclase-free, garnet bearing source – most likely eclogite. They suggested that altered oceanic basalts ponded at the base of the crust and thickened it, only to be remelted later to create the post-100 Ma suite; but they were unable to explain how the oceanic basalts might have been emplaced at the base of the arc crust prior to arc magmatism in the east. While certainly attractive, models that involve melting of basalt accumulated at the base of the arc are unsatisfactory because the post-100 Ma rocks are post-tectonic, and at the time of the magmatism, the leading edge of the continental margin had already been subducted beneath the arc, effectively isolating the arc from the mantle. And the switchover happened far too rapidly for accumulations of basalt to build up, as even the youngest arc rocks are intercalated with marine sedimentary rocks in both the Peninsular Ranges (Allison, 1974; Phillips, 1993; Busby et al., 2006) and Sierra Nevada (Nokleberg, 1981; Saleeby et al., 2008; Memeti et al., 2010).

Nevertheless, our compilation of trace elements within the two suites, pre- and post-collisional, supports Gromet and Silver's (1987) general findings that the magmas were derived from two different sources at different depths. In this regard the work of Putirka (1999) is informative. He modeled aggregate melts using polybaric partial melting of mantle rocks from their source to the base of the lithosphere and found that Sm/Yb and Na/Ti ratios increased with depth of melting in peridotite, eclogite, and garnet pyroxenite and also with greater lithospheric thickness. We plotted both arc and slab failure suites on a La/Sm vs Sm/Yb diagram (Fig. 6), and the slab failure suites consistently have higher Sm/Yb than arc suites, indicative of initial melting at greater depths. We believe that the differences between the two suites are sufficiently consistent, and petrologically significant, that the diagram provides, in samples with $< 70\%$ SiO_2, a robust way to discriminate between arc and slab failure suites (Hildebrand and Whalen, 2017).

Another feature noted by Gromet and Silver (1987), and by others more recently in the Coastal batholith of British Columbia (Girardi et al., 2012), that helps to constrain the petrogenesis of slab failure magmas is that they generally have minor to negligable Eu anomalies, which we confirmed as a general case for post-collisional magmas (Hildebrand and Whalen, 2014b, 2017). The lack of a Eu anomaly on chondrite normalized RSS plots suggests the absence of residual plagioclase in the source.

4.2. Oxygen isotopes

Oxygen isotopes also help to constrain the origin of the post collisional magmas. In an important regional overview of $\delta^{18}O$ from zircon, quartz, and whole rocks within Sierran plutons, Lackey et al. (2008), showed that plutons of the post-100 Ma Sierran Crest magmatic suite had $\delta^{18}O_{zircon}$ within, and close to, the range of mantle $\delta^{18}O_{zircon}$ values. For example, Tuolumne plutons have $\delta^{18}O_{zircon}$ ratios of 6.0%–6.6%, Mount Whitney zircons are 5.67%–5.90%, and other plutons emplaced at 96 Ma range as low as 4.21%. The sub-mantle values presumably represent melting of hydrothermally altered rocks that had previously interacted with low $\delta^{18}O$ meteoric water at high temperature (see Bindeman, 2008). Overall, the magmas were dominantly mantle-derived but with some contamination by rocks that had previously interacted with meteoric water.

Plutonic rocks of the post-100 Ma La Posta suite in the Peninsular Ranges batholith have slightly heavier whole rock $\delta^{18}O$ with values between 8 and 11 (Taylor and Silver, 1978), which Gromet and Silver (1987) argued were derived from altered oceanic basalts and/or sedimentary rocks. Deep-seated plutonic rocks and their related gneisses in the southern Sierra have similar $\delta^{18}O$ to those of the Peninsular Ranges and also to Mesozoic pyroxenite xenoliths carried to the surface by Cenozoic magmatism. When coupled with observed $^{87}Sr/^{86}Sr_i$ ~0.705 and positive $\varepsilon Nd_{(0)}$ in the plutons, these observations led Lackey et al. (2005) to argue that relatively young, hydrothermally altered oceanic crust was the most plausible source of the magmatism as hydrothermally altered, oceanic basalt has whole rock $\delta^{18}O$ ~10% (Eiler, 2001; Bindeman et al., 2005). Within the Coast batholith of British Columbia, plutons in the age range 100–85 Ma have relatively primitive Nd, Sr and Pb isotopic ratios but $\delta^{18}O_{qtz}$ values between 7 and 10%, which collectively suggest involvement of mafic rocks that underwent near surface alteration by meteoric water (Wetmore and Ducea, 2009; Girardi et al., 2012).

Mid-Cretaceous mantle xenoliths carried to the surface by Cenozoic basaltic volcanoes in the Sierra Nevada have dominantly mantle $\delta^{18}O$ values as expected (Lackey et al., 2008; Ducea, 1998); but some have negative $\varepsilon Nd_{(0)}$ and $^{87}Sr/^{86}Sr_i > 0.706$ (Fig. 7). When seen in plutonic

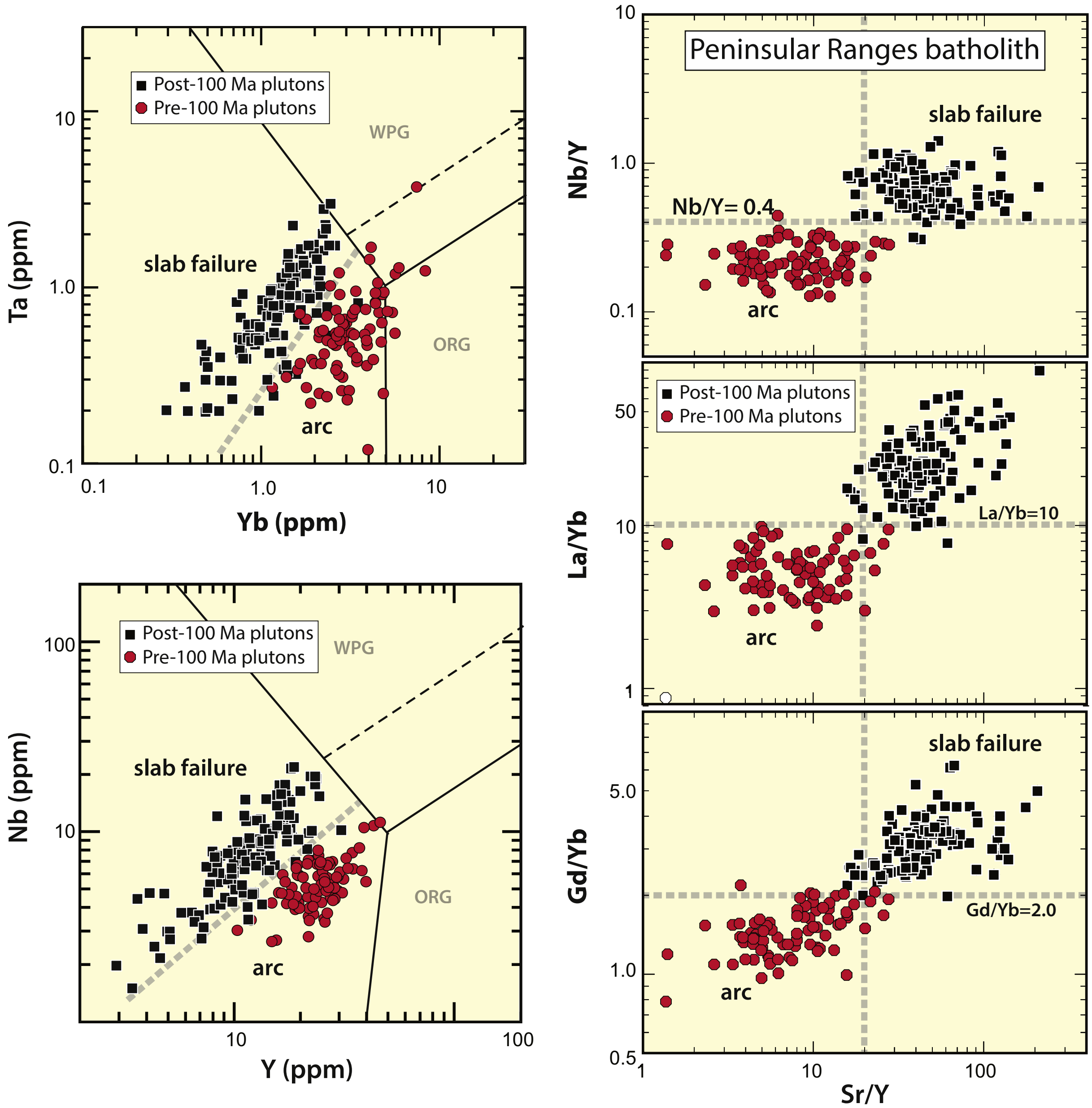

Fig. 4. Samples with $SiO_2 > 60\%$ from the Peninsular Ranges batholith plotted on Nb/Y, La/Yb, and Gd/Yb vs. Sr/Y and on modified Pearce et al. (1984) Nb vs. Y and Ta vs. Yb diagrams. Rocks older than 100 Ma are interpreted to represent arc magmatism, whereas rocks younger than 100 Ma postdate a major deformational event and are best interpreted as slab failure rocks. WPG–within plate granite; ORG–oceanic ridge granite.

rocks these systematics are generally attributed to assimilation of continental crust (Kistler and Peterman, 1978; DePaolo, 1980, 1981; Bateman, 1992; Ducea and Barton, 2007; DeCelles et al., 2009). However, this may not be the case, as the xenoliths, as well as the Sierran Crest plutons, have Nd and Sr isotopic values similar to values from much younger basalts widely erupted in western North America, including those of the < 17 Ma Snake River Plain and the 44–7 Ka Big Pine volcanic field along the eastern Sierran fault scarps (Fig. 7). We now examine the implications of the isotopic similarities between the plutons, xenoliths, and basalts.

4.3. Radiogenic isotopes

Lavas of the Snake River Plain are widely interpreted to represent a mantle "hotspot" that was overridden by North America as it migrated westward (Smith et al., 2009; Yuan and Dueker, 2005; Waite et al., 2006). Because the entire magmatic system—which includes Miocene and younger rocks of the Columbia Plateau, Oregon High Lava Plains, the Snake River Plain, and the Yellowstone Plateau— represents one magmatic system, and because the plume passed beneath exotic terranes and old Precambrian lithosphere as North America moved westward, Pb, Sr, and Nd isotopes from the westernmost (Steens-Imnaha) basalts have plume isotopic signatures, whereas those collected farther east above ancient lithosphere suggest contamination by subcontinental lithospheric mantle (Hanan et al., 2008). Thus, the effects of subcontinental lithospheric mantle and crust on the magmas can be ascertained with high degrees of confidence.

Three-component mixing models, utilizing (1) the oceanic island basalt–like Steens-Imnaha lava, erupted west of the inferred continental edge, to represent the plume component, (2) old lithosphere like that of the Wyoming craton, and (3) younger Paleoproterozoic-like lithosphere, show that > 97% of the variability can be accounted for by

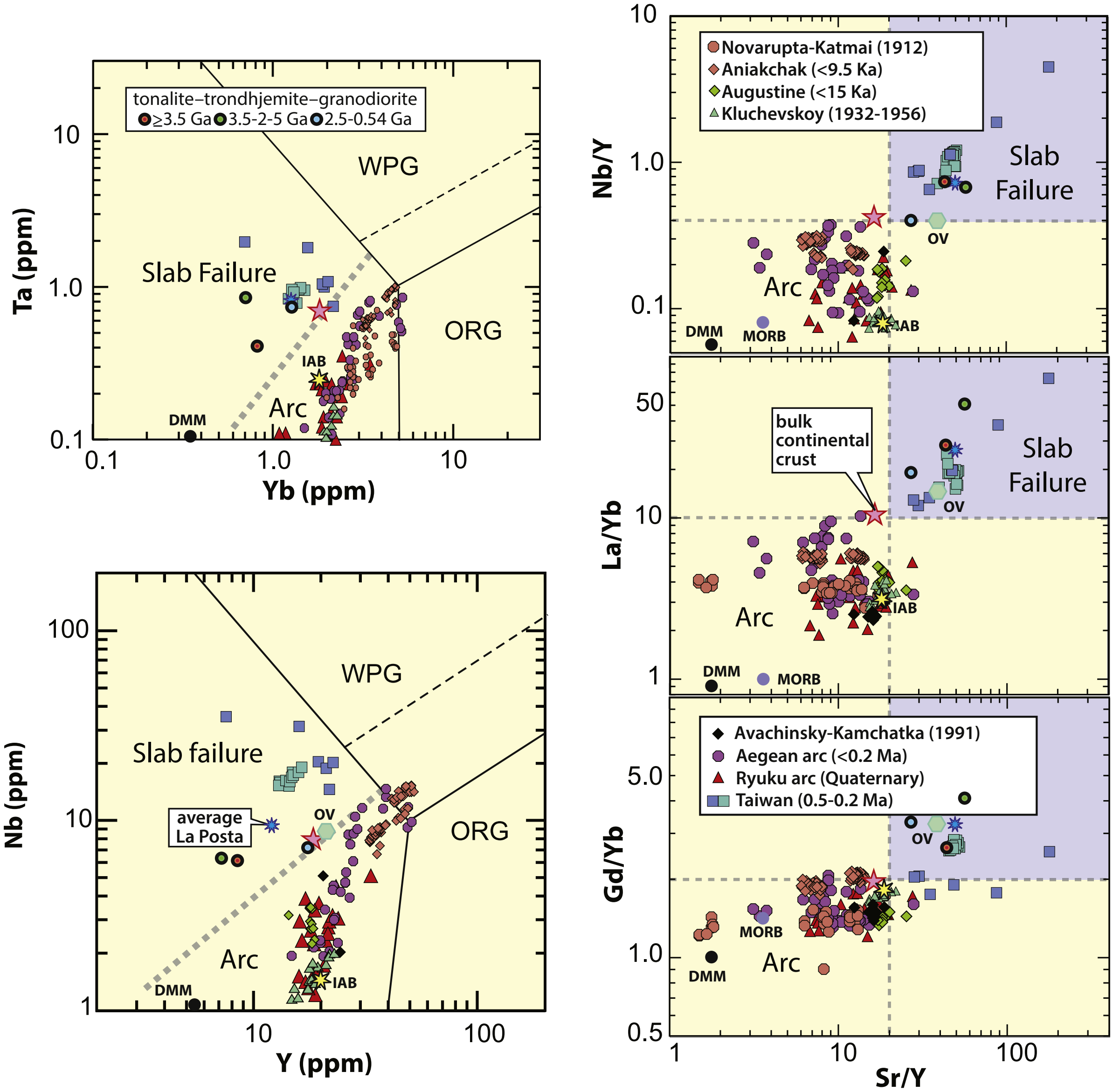

Fig. 5. We tested our discrimination plots with trace elements from young arc and slab failure settings for: (A) Novarupta- Katmai from Hildreth and Fierstein (2012); Aniakchak from Bacon et al. (2014); Augustine from Johnson et al. (1996); Avachinsky from Viccaro et al. (2012); Aegean arc from Bailey et al. (2009); Ryukyu from Shinjo et al. (2000); Kluchevskoy from Dorendorf et al. (2000); postcollisional lavas (Tsaolingshan and Kuanyinshan) of northernmost Taiwan from Wang et al. (2004); average compositions of different-aged tonalite-trondhjemite-granodiorite (TTG) suites (Martin et al., 2005); average compositions for the La Posta suite from Hildebrand and Whalen (2014b); mid-ocean-ridge basalt (MORB), and island-arc basalt (IAB) from Kovalenko et al. (2010). The large stars indicate values for bulk continental crust from Rudnick and Gao (2003). WPG—within-plate granite; ORG—ocean- ridge granite.

progressive incorporation of older subcontinental mantle lithosphere (SCLM) into the plume source as it migrated eastward (Jean et al., 2014). Note that the lower crust beneath the Snake River Plain is old and radiogenic, with $^{87/86}$Sr as high as 0.83 and εNd values ranging from −20 to −50, as deduced from xenoliths (Leeman et al., 1985), and so if the deep mantle melts, which contained very low Rb concentrations (Camp et al., 2003), interacted with the crust in any appreciable way, it would be readily apparent.

Thus, we infer that the Sr and Nd isotopic ratios of the post-100 Ma plutonic rocks of the Sierra Nevada and Peninsular Ranges batholiths were derived from old, enriched SCLM by fractional melting. Other post-collisional suites, such as the 100–85 Ma plutons within the Coast Range batholith of British Columbia have positive εNd and $Sr_i < 0.704$ (Girardi et al., 2012; Wetmore and Ducea, 2009) similar to Steens basalt (Camp and Hanan, 2008), but contain the typical slab failure trace element signatures (Hildebrand and Whalen, 2017), so apparently do not have old, enriched SCLM beneath them. Note that in the case of post-collisional magmatism, the subcontinental mantle typically belongs to the lower plate continental margin and not the arc, as the continental margin is pulled beneath the arc to isolate it from its formerly subjacent mantle. Thus, where old cratonic lithosphere is pulled beneath an arc built on young crust, adjacent arc and slab failure magmas may have very different isotopic ratios simply because the arc magmas rose through young arc lithosphere, whereas the younger slab failure magmas rose through old, enriched lithosphere pulled beneath the arc just prior to slab failure. Likewise, where both upper and lower plates are young, they both should exhibit non-radiogenic isotope ratios.

If continental crust is uninvolved in the genesis of Sierran slab failure melts, as indicated by oxygen isotopes, then this presents a

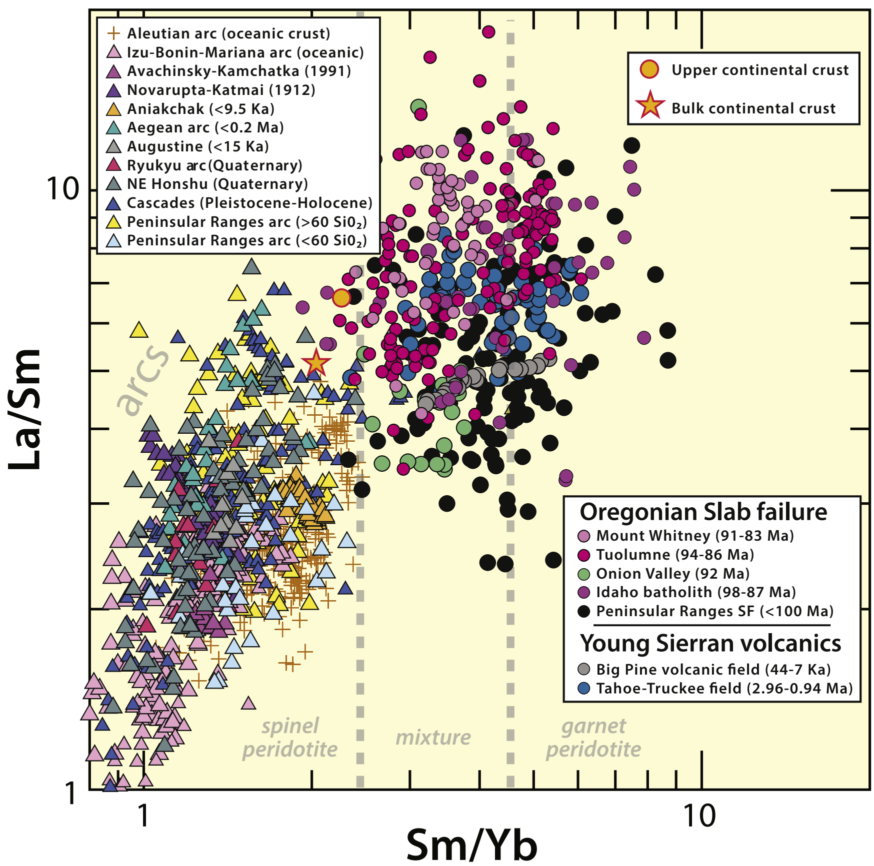

Fig. 6. La/Sm vs. Sm/Yb plot for various arc and slab failure igneous suites, illustrating the differences between various arc suites and Oregonian slab failure suites. Virtually all slab failure rocks have Sm/Yb > 2.5, whereas most arc rocks have Sm/Yb < 2.5. Labeled gray tone subdivisions into different fields that indicate inferred source rocks are derived from the work of Putirka (1999) and based on partial melting models of xenoliths believed to represent sub-Sierran lithospheric mantle. Arc suites are as in Fig. 4 plus samples from GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/) for Izu-Bonin, Marianas, NE Honshu, and Cascades. Aleutians: $n = 411$; other arcs: $n = 750$; Post 100 Ma Oregonian rocks: Mount Whitney (Hirt, 2007); Tuolumne data (Memeti, 2009); Onion Valley data (Sisson et al., 1996); Idaho batholith (Gaschnig, 2015, personal commun.); Peninsular Ranges data (Lee et al., 2007); Big Pine data (Blondes et al., 2008); and Tahoe-Truckee data (Cousens et al., 2011). Estimated compositions of upper and bulk continental crust are from Rudnick and Gao (2003). SF— slab failure.

paradox, for if crustal processing does not create the high SiO_2 concentrations, then it must be a characteristic of the melts arriving in the crust, yet how can melts rising out of the mantle be more siliceous than basalt, especially when partial melts of garnet peridotite yield Ti-enriched basalts (Walter, 1998; Davis et al., 2011)? One has to look to mid-oceanic ridge basalt and its metamorphic equivalents, eclogite, amphibolite, and garnet pyroxenite, for the answer. The main question is where the MORB and metamorphosed equivalents might reside during melting? Likely sources include enriched subcontinental lithosphere, subducted mid-ocean ridge basalt, rift facies continental crust, and perhaps basalts formed during rifting (seaward dipping reflectors–SDRs), or possibly some combination from each environment.

4.4. Experimental work

The early work by Green and Ringwood was fundamental to our understanding of phase relations in metabasalt and its ultimate metamorphism to eclogite, which they suggested could melt to produce granodioritic and quartz dioritic melts (Ringwood and Green, 1966; Green and Ringwood, 1967). Because they established that eclogite was denser than rocks of the mantle, their work has been essential to all those who favor foundering as a method to balance the material flux in and out of arcs. Within our plutonic rocks, the lack of a Eu anomaly suggests that there was no residual plagioclase in the source. In experiments with gabbro, they found that at pressures > 2 GPa and temperatures > 1100 °C, plagioclase did not coexist with garnet and pyroxene (Ringwood and Green, 1966; Green and Ringwood, 1967).

In another set of experiments (Rapp et al., 1991), olivine-normative amphibolite and an alkali-rich basalt yielded minor residual plagioclase at 16 kbar, but exclusively garnet-clinopyroxene-rutile at 22 kbar and above. Thus, at depths of > 100 km, there is unlikely to be plagioclase in eclogite of the descending slab, or metabasalt at the base of, or within, the lower subcontinental lithospheric mantle.

Rapp et al. (1991) also examined the bulk compositions of melts generated by vapor-absent melting of natural olivine-normative amphibolites, three low-K MORB-like rocks, and an alkali basalt. Resultant melts produced by 10%–40% melting were tonalitic-trondhjemitic at all pressures from 8 to 32 kbar and were highly depleted in heavy rare earth elements (HREEs) with La/Yb of 30–50 when garnet was present in the residue.

Additional melting experiments by Rapp and Watson (1995) used four different basaltic starting compositions and they examined changes in the relative proportions of melt and coexisting residue from 1000 °C to 1150 °C, over pressures from 8 to 32 kbar. They found highly siliceous melts of granitic to trondhjemitic composition at 5%–10% partial melting at 8–16 kbar, but the residue contained plagioclase. At 32 kbar and 1100–1150 °C, they found that trondhjemitic-tonalitic, granodioritic, quartz dioritic, and dioritic partial melts resulted from 20%–40% partial melting and left a garnet-clinopyroxene residue. Thus, they showed that magmas with high Sr/Y and La/Yb could be produced by 10%–40% melting of partially hydrated metabasalt in the presence of garnet between 1000 °C and 1100 °C. Although subduction zones are typically too cool to produce these partial melts, melting of hot, young oceanic crust near spreading ridges (Peacock, 1996) or above and adjacent to zones of deep mantle upwelling would satisfy those conditions.

Direct slab melts should interact with mantle peridotite as they ascend, and Rapp et al. (1999) studied this experimentally by allowing oceanic crustal melts to infiltrate and react with peridotite. At nearly 4 GPa and high melt-to-rock ratios, they found that the interaction produced high Mg# adakites (high Sr/Y and La/Yb), but at melt-to-rock ratios close to unity, the melts were completely consumed by reaction with the peridotite. Only when additional heat was added to the system did melt remain. Trace-element abundances in hybrid slab melts were

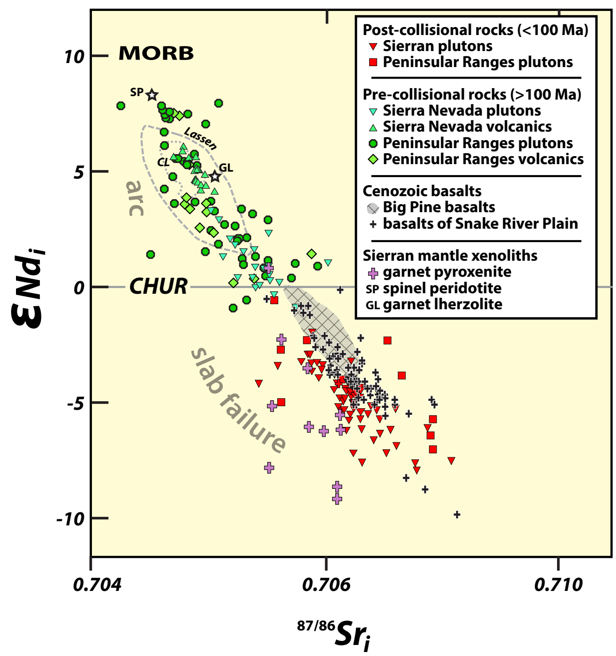

Fig. 7. εNd vs. $^{87/86}Sr_{initial}$ plot of various arc and slab failure plutonic and volcanic suites of the Peninsular Ranges and Sierra Nevada compared to some Cenozoic basalts of western North America (modified from Hildebrand and Whalen, 2017), illustrating the isotopic differences between arc suites and slab failure suites and the isotopic similarities of the Oregonian slab failure suites with basalts from the Snake River Plain (Jean et al., 2014; Hanan et al., 2008) and Big Pine volcanic field (Blondes et al., 2008). Fields for two Cascade volcanoes (CL–Crater Lake and Lassen) from Bacon et al. (1994); Sierran mantle xenoliths from Ducea and Saleeby (1998); CHUR—chondritic uniform reservoir.

higher than in pristine slab melts because melt was progressively consumed by reaction; however, elemental ratios such as Sr/Y and La/Yb remained constant. They also showed that 30% melts of hydrothermally altered MORB closely resemble the trace-element contents of adakites, except for Zr and Ti, which they attributed to residual accessory phases. One of their principal conclusions was that slab-derived melts can metasomatize the overlying mantle peridotite as they are consumed, which means that, although the mantle mineralogy will control the overall composition of younger melts, the incompatible trace elements from the slab will be available to be scavenged from the peridotite by younger melts.

Experimental data confirm that melting of garnet pyroxenite and eclogite can produce melts of the requisite composition, but as hornblende and biotite are ubiquitous in post-collisional slab failure magmas, the source melts were hydrous, likely with H_2O contents in the 3%–6% range (Sisson et al., 1996). The principle sources for fluids during slab failure – depending on the precise location of the tear within the subducted plate – are subducted and hydrothermally altered MORB, extended continental crust with its sedimentary veneer including evaporites, and the thick and extensive, tholeiitic basalt erupted on the continental lip during rifting (SDRs: for example: Jackson et al., 2000; Peate et al., 1992; Puffer, 1992).

4.5. *Tuolumne intrusive series*

Within the Sierra Nevada, several intrusive series, such as the John Muir, Tuolumne, and Sonora, are included within the Sierran Crest magmatic suite (Coleman and Glazner, 1998). We selected the 94–84 Ma Tuolumne intrusive series (Bateman and Chappell, 1979; Coleman et al., 2005; Memeti, 2009) for study to shed light on the progressive generation and modification of melts through time because we believe that they may provide tests of various competing models.

The Tuolumne intrusive series comprises four distinct intrusions that young inwards: the 94–92 Ma granodiorite of Kuna Crest, the 92–90 Ma Half Dome granodiorite, the 88–86 Ma Cathedral Peak granodiorite, and the 84 Ma Johnson granite porphyry (Bateman and Chappell, 1979; Bateman, 1992; Coleman et al., 2004). Originally, Bateman and Chappell (1979) argued that the compositional zoning within the series resulted from crystal fractionation of a single voluminous influx of magma. However, subsequent isotopic work (Kistler et al., 1986) ruled out the possibility of relating the compositions to any sort of fractionation scheme, and U-Pb zircon age determinations demonstrated that plutons of the series were emplaced over 10 Myr from 94 Ma to 84 Ma (Coleman et al., 2004). The length of time for emplacement ruled out the closed fractionation model and also the two-component mixing scheme favored by Kistler et al. (1986). Not only are the three granodioritic plutons unrelated by fractional crystallization or mixing, but fractionation within each of them was relatively limited (Paterson et al., 2014), so the overall geochemical variations in the series probably arose well below the level of emplacement (Coleman et al., 2012). Because the plutons were emplaced in the same location one after the other through time, their compositions might reflect temporal changes in source and/or depth of melting.

In order to evaluate this possibility, we plotted data compiled by Memeti (2009) from the three granodioritic plutons (Fig. 8). The most obvious feature of the series is that, except for K_2O and Na_2O, major elements define tight arrays on Harker-type plots, although the range of values for the middle Half Dome granodiorite approach the overall range of all three plutons combined. Compatible elements, such as V and Ni, also form linear arrays, whereas incompatible large ionic lithophile (LIL) and rare earth elements (REE) vary widely. Both K_2O and Na_2O increase with increasing SiO_2 but have large ranges in individual plutons. Ba, Rb and Sr have large ranges and clearly illustrate that the three plutons simply cannot be related to one another by any sort of fractionation or mixing scheme. However, the apparent disconnect between most major elements and the incompatible elements is readily explained by fractional melting (Wilson, 1989; Shaw, 2007) in each of the three magma bodies.

Although they have likely been overprinted by assimilation of REE and Na from the fractional melting of SCLM, the increases in Na/Ti and Sm/Yb ratios might shed light on deeper processes because higher ratios have been shown to be measures of increased melting depth (Putirka, 1999). Within the plutons, all values of Sm/Yb are above 2 with most above 2.5 (Fig. 8). Arc magmas typically have Sm/Yb < 2, which reflects their shallower source (Hildebrand and Whalen, 2017). Based on the increasing Na/Ti and Sm/Yb ratios, the plutons are reasonably interpreted to represent progressive deepening of the source with time.

Values for $^{87}Sr/^{86}Sr_i$ are quite heterogeneous for the two oldest bodies, especially the Half Dome granodiorite, but increase overall with time; coincident with the presence of less radiogenic Nd (Fig. 8). The Half Dome granodiorite has a range of εNd values ($>$ 4 epsilon units) as great as the other two plutons combined. As noted earlier, the plutons and younger basalts, such as the Steens and Big Pine lavas, all share similar εNd and $^{87}Sr/^{86}Sr_i$ isotope values. This makes it unlikely that the major element concentrations of the plutonic magmas were much modified by interaction with SCLM, as exemplified by the limited volume assimilated ($<$ 3% total lithosphere) by the much younger deep-seated plume basalts as they passed through the SCLM (Jean et al., 2014). Slab failure plutons elsewhere, such as the 100–85 Ma plutons of the Coast plutonic complex of British Columbia (Wetmore and Ducea, 2009; Girardi et al., 2012), have primitive εNd and $^{87}Sr/^{86}Sr_i$ values similar to primitive mantle-derived magmas of the plume generated Steens basalt (Camp and Hanan, 2008) – but have similar trace element profiles to slab failure plutons in the Sierra Nevada and Peninsular Ranges batholiths (Hildebrand and Whalen, 2017). Thus, we infer that the principal modifications to the rising magmas, as they passed

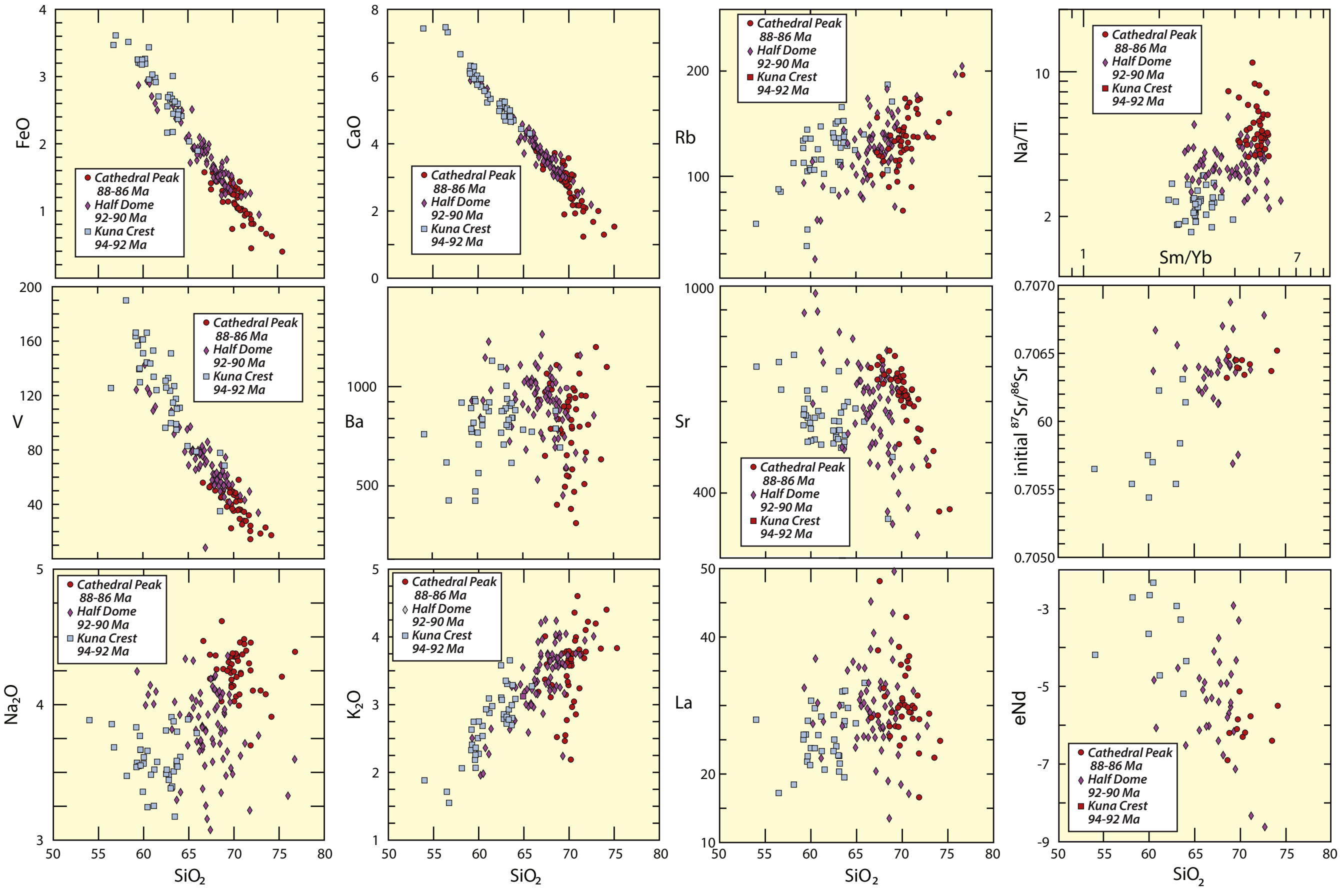

Fig. 8. Examples of major and trace elements plotted on Harker variation diagrams (majors in wt% oxide; traces in ppm) for Kuna Crest, Half Dome, and Cathedral Peak phases of the 94–84 Ma post- collisional Tuolumne intrusive suite of the Sierra Nevada batholith. Note that major and compatible trace elements form linear trends but that Na_2O and K_2O, as well as incompatible trace elements (LIL) and light rare earth elements (LREE), are widely scattered and decoupled from the bulk of major and compatible trace elements. Data are from Memeti (2009). See Supplementary Data for all elements plotted.

through the SCLM, were to radiogenic isotopes and elements with large ionic ratios (LIL) through the process of fractional melting.

The temporal increase in SiO_2 and LIL, coupled with higher Sm/Yb and Na/Ti ratios, within the Tuolumne intrusive series are mirrored in other "nested" plutons, such as the Whitney (Hirt, 2007) and the Sahwave (Van Buer and Miller, 2010) and could reflect progressive melting of greater amounts of rifted cratonic margin, with its voluminous volcanic veneer, as it sank into the mantle, or possibly lower fractions of slab melting with time. Increased sodium contents might come from evaporites of the rifted margin.

Our overall model for the generation of slab failure magmas involves initial melting of metabasalt and gabbro from subducted oceanic slab at depths > 2 Gpa to create siliceous magmas with the diagnostic trace element patterns, Nb/Y > 0.4, La/Yb > 10, Gd/Yb > 2.0, Sm/Yb > 2.5, and Sr/Y > 10. As the melts rise through the SCLM they are contaminated by fractional melting and, if the SCLM is old and enriched, they develop isotopic signatures commonly considered to be of crustal origin.

5. Adakites

Adakites were originally recognized within arcs as peculiar high-Sr–low Y and high-La/Yb magnesian andesites with low abundances of heavy rare earth elements (HREE) (Kay, 1978; Defant and Drummond, 1990). Adakites appear to form when the asthenospheric window of a spreading ridge is subducted and, driven by plate divergence and slab pull, widens as it descends into the mantle (Thorkelson, 1996). Most researchers interpret adakites to represent melting of the subducting slab (Defant et al., 1991, 1992; Yogodzinski et al., 1995; Martin, 1999; Martin et al., 2005; Gómez-Tuena et al., 2007).

Hildebrand and Whalen (2017) examined the trace element and isotopic characteristics of adakites related to ridge subduction from Kamchatka, Japan, the Antarctic Peninsula, southern South America, Panama, mainland Mexico, Baja California, and the western United States. They found that most slab window adakitic rocks had trace element concentrations and ratios similar to slab failure rocks with mantle-like Sr and Nd isotopic concentrations, except for those of western North America, which had less radiogenic isotopic compositions typical of the Snake River Plain, Sierran Crest magmatic suite, and the Big Pine volcanic field. These results support models that invoke melting of the oceanic slab at depths sufficient for partial melting of garnetiferous, plagioclase-free rocks to produce the observed trace element profiles in both adakites and slab failure rocks as well as the unradiogenic Sr and radiogenic Nd ratios in regions without old, enriched SCLM.

In an important study, Bindeman et al. (2005) measured oxygen isotope compositions in nearly three-dozen adakites from diverse locations and found them to have calculated $\delta^{18}O$ melt values from 6.36% to 8.17%, slightly higher than MORB. They also found that $\delta^{18}O$ correlated with Sr/Y and La/Yb, which suggested to them that the entire oceanic slab was melted, consistent with isotopic results from eclogite facies metabasalt and gabbro (Putlitz et al., 2000) and eclogite xenoliths (Eiler, 2001). Plutons such as those of the La Posta suite with their elevated $\delta^{18}O$ indicates that a larger proportion of the source material equilibrated with water near the surface, which suggests a higher basalt/gabbro ratio of melting in the subducted slab.

6. Archean TTG suites

Archean sodic leuco-granitoids, usually termed the tonalite-trondjhemite-granodiorite (TTG) suite, have been estimated to represent at least two thirds of surviving Archean continental crust (Condie, 1981; Martin, 1994). Recognition of the geochemical similarities between the Archean TTG series and potential modern equivalents such as adakites (Martin, 1986, 1987; Defant and Drummond, 1990; Drummond and Defant, 1990) and high Sr/Y plutonism (Tulloch and Kimbrough, 2003) spawned an enormous body of literature concerning TTG petrogenesis and implications for the crustal development of Earth (Drummond et al., 1996; Martin, 1994, 1999; Martin and Moyen, 2002; Martin et al., 2005, 2014, and references therein). Key geochemical features of Archean TTG suites and modern adakites are high La/Yb and Sr/Y values, which were collectively termed the *adakitic signature* by Moyen (2009). Today, most researchers accept that the distinguishing geochemical features of TTGs and adakites reflect partial melting of mafic protoliths under garnet-stable, plagioclase-unstable pressure-temperature conditions, but the tectonic setting where this occurred remains controversial (Condie, 2014). Using concepts developed to explain adakites in modern arcs, some workers have argued that TTGs formed from partial melting of garnetiferous oceanic lithosphere beneath arcs (Martin, 1986, 1994, 1999; Drummond and Defant, 1990). Other researchers suggested that they were generated in thick continental crust similar to that considered by many workers to exist beneath arcs and Cordilleran batholiths (Whalen et al., 2002; Nagel et al., 2012; Condie, 2014). Still others preferred to generate TTGs within, or at the base of, thick basaltic plateaux or crust (Bédard, 2006; Smithies et al., 2009; Willbold et al., 2009; Van Kranendonk et al., 2007; Johnson et al., 2017).

There are two fundamental problems with the basaltic plateau model: (1) siliceous rocks from Iceland, commonly considered the best modern example, do not have the characteristic depletion of HREE and Y of Archean TTG; and (2) Archean TTG have $\delta^{18}O_{zircon}$ values in the range of 5.5–6.5%, which indicate some interaction with the hydrosphere, and so rule out underplating by relatively dry melts of mantle plumes (Martin et al., 2010; Condie, 2014). Even if plume-generated-melting of thick basaltic plateaux could create similar composition rocks, they still wouldn't match the typical linear, 10–20 Myr belts of TTGs of Archean terranes (see, for example, Percival et al., 2012).

At its core, the "slab-melt" TTG petrogenetic model employs partial melting of a "conveyer-belt–like" supply of continuously subducted oceanic crust to generate the preserved voluminous Archean TTG suites. This model, based on modern plate tec- tonics, implies an ongoing process that occurred at destructive plate margins over extended time periods, providing continuous upwelling of TTG melt. However, in portions of Archean cratons where careful geological mapping is supported by high-precision U-Pb zircon analyses, such as the Wabigoon portion of the Western Superior craton, entire TTG suites were shown to have been emplaced over periods of time as short as 2–3 m.y. (Whalen et al., 2002, 2004). These pulses indicate that voluminous TTG magmatism formed during short-lived magmatic events or pulses rather than as products of a long-lived ongoing process, as implied in the continuous slab-melting model.

In our view, the compositional similarities of rocks that form TTG suites seem so similar to slab failure suites that a common origin is warranted. To evaluate this possibility we compiled analyses from the literature and filtered a huge number of analyses of TTG bodies obtained from various Archean cratons to give us over 400 modern analyses ranging from 3.8–2.5 Ga of high-alumina TTG with 60–70% SiO_2 to compare with Archean arc rocks, as well as a spectrum of Phanerozoic slab failure rocks. The results are shown in Fig. 9 and there it is obvious that slab failure and TTG rocks have similar trace element ratios and consistently plot, independent of age, in the requisite fields on our discrimination plots.

In addition to the many other experimental results presented earlier, Rapp et al. (2003) showed experimentally that "*partial melting of hydrous basalt in the eclogite facies produces granitoid liquids with major- and trace-element compositions equivalent to Archaean TTG, including the low Nb/Ta and high Zr/Sm ratios of 'average' Archaean TTG*". We plotted data from just over 300 samples from post-collisional 100–84 Ma plutons of the Peninsular Ranges and Sierran batholiths, as well as data from over 400 TTG samples ranging in age over the interval 3.8–2.5 Ga from our compiled database on a Nb/Ta versus Zr/Sm plot (Fig. 10). Although the Archean samples are widely distributed, which suggests compositionally diverse sources or possibly alteration, the bulk of samples from all three groups plot in a moderately tight cluster along with a variety of modern marginal basin basalts and much older boninites. For the most part, the samples do not fall within the field of modern MORB and rift-related tholeiites such as the Paraná. The Cretaceous geology of the Peninsular Ranges-Guerrero superterrane is readily interpreted to indicate that the 100–84 Ma slab failure magmas originated when a marginal basin – formed after the Neocomian Nevadan collision and open for about 30 Myr – closed at 100 Ma (Hildebrand and Whalen, 2014b, 2017). Based on kindred geology and temporal relations, a comparable setting is inferred for the Sierra Nevada as well (Hildebrand and Whalen, 2017).

7. Plate tectonics

The similar geochemistry of Phanerozoic slab failure and slab window magmas to Precambrian TTG suites suggests to us that the magmas were generated by a similar process, but, as pointed out by Korenaga (2008), even if plate tectonics were active during the early Archean, it might not resemble modern plate tectonics. In fact, whether or not plate tectonics, as we know it today, was even active during the Precambrian is contentious, with some workers arguing that it started as recently as the Neoproterozoic (Stern, 2005, 2007), and others as far back as the Hadean (Harrison, 2009). Most other models fall between these two extremes (Arndt, 2013, Table 5.1; Korenaga, 2013, Fig. 1). Here, we focus on the process of subduction of oceanic lithosphere, as during the Phanerozoic it has been a diagnostic feature of plate tectonics (Cawood et al., 2006) and generates both arc and slab failure magmatism.

There are two fundamental methods available to resolve the conundrum: theoretical modelling, and direct study of geological features. Theoretical modelling (Korenaga, 2013; Hynes, 2014) has demonstrated that even though the mantle was perhaps 200 K hotter than today, plate tectonics was feasible and probable during the Archean, although oceanic plates were perhaps about 3 times thicker then (Sleep and Windley, 1982); and plate movements were not faster as commonly surmised, but instead, more sluggish, so that when coupled with their greater thickness and buoyancy, subducting plates were older than today (Korenaga, 2006, 2008; van Hunen and Moyen, 2012). Geological features commonly used to support Archean plate tectonics include the presence of orogenic belts (Pease et al., 2008; Percival et al., 2012), supercontinents (Hoffman, 1997), continental margin prisms (Bradley, 2008), paired metamorphic belts (Brown and Johnson, 2018), volcanogenic massive sulfide deposits (Mosier et al., 2009), and constant tholeiitic index of basalts through time (Keller and Schoene, 2018). To these global features, we add the presence of arc, slab failure and slab window rocks as outlined here.

If oceanic crust was thicker in the past and subducting plates older, absent some form of crustal delamination (Hoffman and Ranalli, 1988), it is possible that following break off that there were greater quantities of oceanic crust to melt and so slab failure magmatism might have been more voluminous than during the Phanerozoic. Similarly, if the SCLM hadn't developed prior to 3.5 Ga and was only weakly developed prior to 2.9 Ga, as suggested by Herzberg and Rudnick (2012), then it is possible that during collisions, the thicker and older oceanic slabs were able to subduct significantly more continental crust than after the development of strong and thick continental lithosphere (Korenaga, 2013). As rifted margins, with their abundant evaporites and volcanic

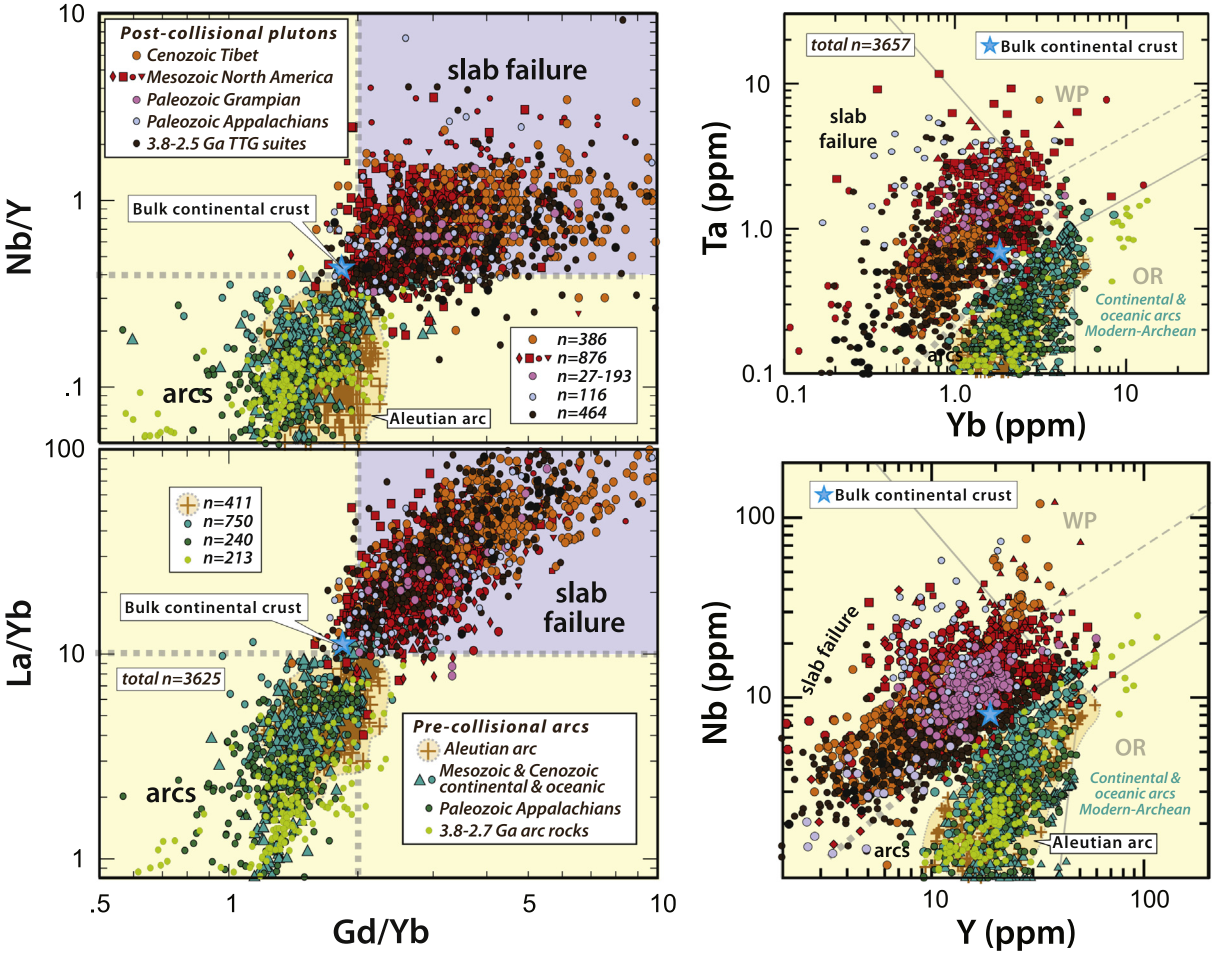

Fig. 9. Trace element discrimination plots of Hildebrand and Whalen (2017) showing over 3500 samples from both arc and slab failure suites using examples from the Cenozoic to 3.8 Ga. Note that the estimated composition of bulk continental crust (Rudnick and Gao, 2003) plots consistently between arc and slab failure suites, which suggests to us that continental crust was, and is, formed by mixtures of both arc and slab failure magmatism. WP—within-plate granite; OR—ocean-ridge granite. TTGs: Moyen (2011), Whalen et al. (2003, 2012), Wodicka and Whalen (unpublished), Berman and Whalen (unpublished), Ge et al., 2018, Huang et al. (2013), Satkoski et al. (2012), Liu et al. (2016), Champion (personal communication, 2017), Smithies (personal communication, 2017); Archean arcs: Polat et al. (2002, 2009, 2016, 2017), Wu et al. (2016), Polat and Hofmann (2003), Ordóñez-Calderón et al. (2009). Phanerozoic arc and slab failure: Hildebrand and Whalen (2017).

rocks, are scarce in Phanerozoic collisional orogens, presumably due to their subduction (Hildebrand and Bowring, 1999), it might be that prior to the stabilization of continents by a thick SCLM root, that entire passive margins, or even continents, were recycled into the mantle. Additionally, the warmer mantle and paucity of SCLM might have reduced thermal subsidence of rifted margins and accomodation space for passive-margin sedimentation (Hynes, 2008) so that passive margins might be weakly developed. Also due to increased mantle temperatures higher MgO contents of the Archean oceanic crust might rule out, on compositional grounds alone, the possibility of forming blueschists (Palin and White, 2015).

Given the theoretical modelling, direct study of Archean geological features, and the overall similarity between Archean and Phanerozoic slab failure and arc rocks, we find no compelling reason to invoke a mechanism other than plate tectonics to explain the origin of TTG. Their kindred geochemistry through time suggests to us that subduction and slab failure have been active processes on Earth since at least 3.8 Ga, the age of our oldest samples. Based on trace elements and radiogenic isotope data from Acasta gneisses in Canada (Bowring and Housh, 1995; Bowring and Williams, 1999) and Jack Hills detrital zircons from Australia (Wilde et al., 2001), all of which indicate the presence of continental crust, I-type magmatism, and probably oceans, in the Hadean, these processes might even have been active before 4.0 Ga (Harrison, 2009; Burnham and Berry, 2017).

8. Crustal growth and recycling

Our study of post-collisional, slab failure plutons indicates that they are derived from the mantle, initially from slab melting at depths greater than plagioclase stability, and later as the melts interact with SCLM, especially if it is old and enriched. Not only does our model for slab failure resolve the *crustal composition paradox*, but because the bulk of slab failure magmatism contains 60–70% SiO_2, it also negates the need for large volumes of residues/cumulates to magically vanish beneath arcs. Furthermore, based on similar geochemistry, our synthesis indicates that slab failure is, and has been, a major component of crustal growth, along with arc magmatism, possibly ranging back to at least 3.8 Ga. Alternative models require an entirely different and unrecognized tectonic process.

Whereas slab failure magmatism, along with arc magmatism, comes from the mantle and together created the bulk of continental crust, bulk crustal estimates for every element or oxide (Rudnick and Gao, 2003) should fall on a mixing line composed of arc and slab failure analyses for that element or oxide. For the most part, the Rudnick and Gao

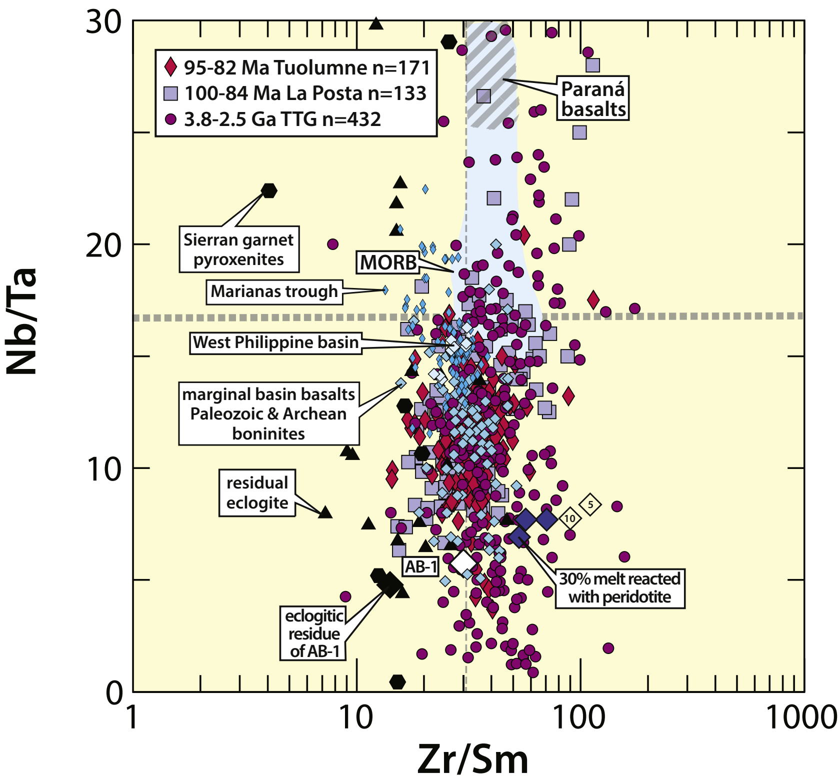

Fig. 10. Zr/Sm vs Nb/Ta ratios (after Rapp et al., 2003) of post-100 Ma slab failure rocks from the Peninsular Ranges and Sierran batholiths, Archean TTG, a variety of marginal basin, MORB, and rift basalts. Compositions for AB-1, its eclogitic residue, 5 and 10% partial melts and experimental TTG liquids formed by 30% melting of AB-1 and mantle-hybridized (with peridotite) equivalents of the TTG-liquid at 30% melting (from Rapp et al., 1999). Also plotted are a variety of pyroxenites and eclogites interpreted to represent Sierran and Archean TTG residues (Ducea and Saleeby, 1998; Rapp et al., 2003). Sources of data for TTGs as in Fig. 8.

estimates do fall on the mixing line (Fig. 11), but there are discrepancies for a few important elements such as MgO and Al_2O_3 (see Fig. 11 Supplemental). Where the estimated bulk crustal values do not fall on the line, then the value for the bulk crustal concentration of that element or oxide might be better approximated by adjusting it to fit the mixing line. As an initial test, we held the SiO_2 content steady at the value suggested by Rudnick and Gao (2003); examined many major and trace elements; and – although a more detailed and rigorous analysis is needed – believe that there might be merit to our approach (Fig. 11).

In a dynamic contribution in which he argued for early differentiation of Earth, Armstrong (1991) pointed out that the subject of crustal recycling is relatively new to geoscientists, as prior to the plate tectonic revolution of the late 1960's, the geologic consensus was that the continents, as well as the atmosphere and hydrosphere, developed progressively (for example, Rubey, 1951). Following the acceptance of subduction as a mechanism for recycling oceanic lithosphere, a few researchers modeled subduction of continental crust attached to oceanic slabs (Bird et al., 1975; Molnar and Gray, 1979), but the subject never caught on with geologists and languished. As geologists became more comfortable with plate tectonics they cautiously began to consider that small amounts of continental crust, mainly in the form of sediments distributed on the seafloor, could be recycled into the mantle (McLennan, 1988; White, 1989). Over the ensuing decades, arguments simmered over how much sediment could reasonably be eroded and subducted, with the bulk of researchers favoring limited recycling (Condie, 1989; Reymer and Schubert, 1984), and only a few (von Huene and Scholl, 1991) arguing for recycling of much larger volumes.

Hildebrand and Bowring (1999) noted that within Wopmay orogen, the western edge of the Archean Slave craton terminated abruptly, and was coincident with the palinspastically restored western edge of the Paleoproterozoic platform terrace and a suite of *syn*-collisional intrusions, which suggested to them that the majority of rift facies rocks, including attenuated continental crust, were subducted during collision and consequent slab break-off. They noted that several collisional orogens contained little in the way of rift facies volcanic and evaporitic rocks and so hypothesized that slab failure might be a general process for recycling significant volumes of continental crust. More recently, detailed studies of deeply metamorphosed xenoliths carried to the surface in younger volcanic eruptions have demonstrated that continental crust is subducted to great depths (Chopin, 2003; Chin et al., 2013; Shaffer et al., 2017). Based on mass balance calculations, a number of researchers have suggested that even more voluminous quantities of crust were subducted during the Indo-Eurasian collision (Replumaz et al., 2010; Ingalls et al., 2016), although it unclear what amount will rebound to the surface or relaminate to the base of the crust (Hacker et al., 2011) in the future.

Nevertheless, the discussion above indicates that huge amounts of continental crust are recycled during collisions because it is attached to dense oceanic lithosphere that is gravitationally returned into the mantle. This is perhaps the largest contributor to crustal recycling, but is commonly ignored in mass balance calculations. Although it is impossible to accurately measure the volume of all continental crust subducted or the volume of slab failure magmatism, a quick, “back-of-the-napkin” calculation suggests that the two are approximately equal.

Consider that the length of continental rifted margins subducted must approximate the length of slab failure during arc-continent collision, unless slabs are left dangling, which is not observed. If slab failure magmatism occurs over most of the crust in the 35 km thick southern Sierra Nevada, as suggested by Lackey et al. (2005), then the thickness of slab failure rocks would be larger than the thickness of extended crust. If large amounts of crustal stretching (Yakovlev and Clark, 2014) are invoked, say 100%, there would be twice the quantity of slab failure magmas emplaced; but as the width of intense slab failure magmatism, as estimated from the Sierras and Peninsular Ranges, is about 50 km, the average width of rifted margin recycled into the mantle would only have to be 100 km for the magmatism and subducted crust to roughly balance each other. Yet rifted margins are generally even wider, commonly 200–400 km (Klitgord et al., 1988; Bassi et al., 1993; Keen and Dehler, 1997; Jackson et al., 2000) so the amount of subducted crust could be much larger. While it is impossible to quantify the amount of

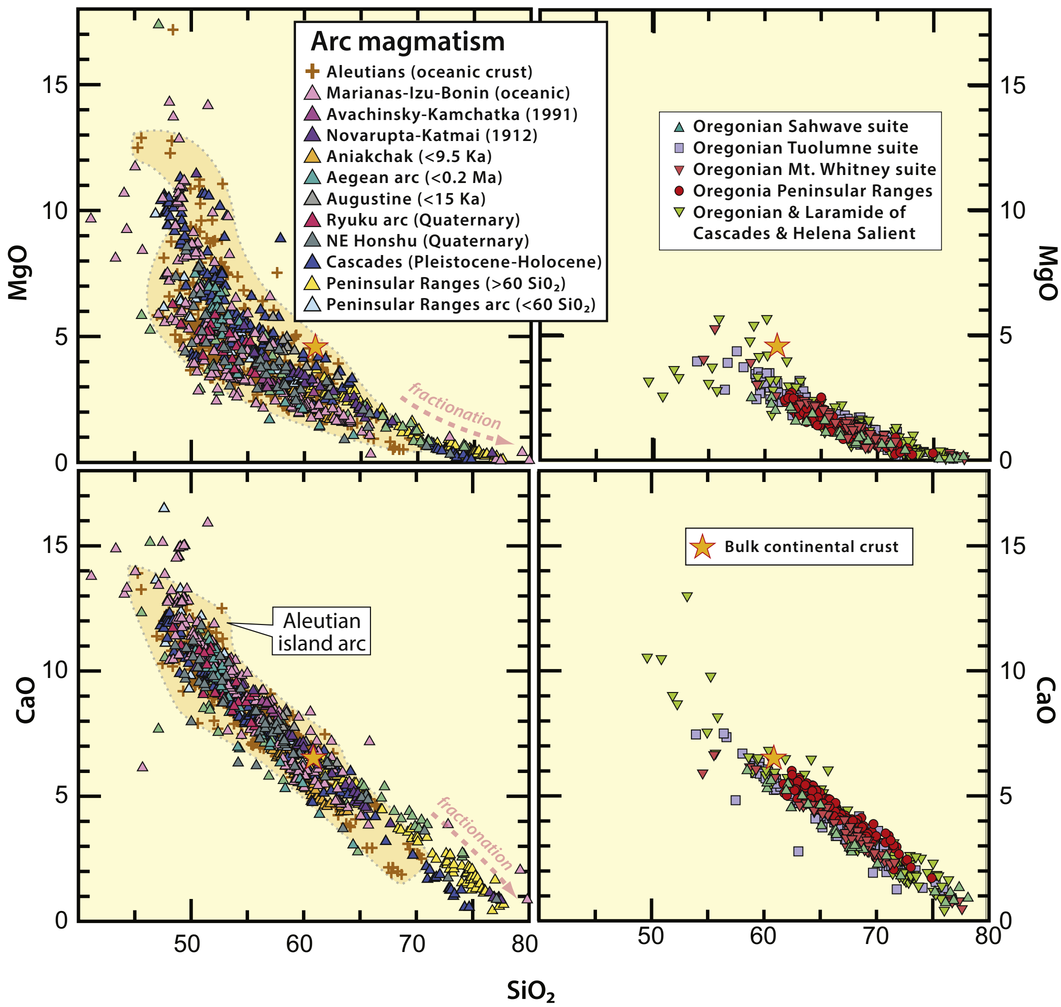

Fig. 11. We plotted major-oxide contents of samples from both our arc and slab failure reference suites on Harker-type variation diagrams. On these plots, most arc analyses fall above and to the left of estimated bulk continental crust of Rudnick and Gao (2003), whereas most slab failure rocks plot below and to the right, suggesting that continent crust is created by a mixture of arc and slab failure magmatism, as indicated on the previous plots utilizing trace elements and ratios. Note that the estimated MgO content for bulk continental crust is located slightly above and to the right of both arc and slab failure trends, so if our mixing model is correct, then perhaps a better value for bulk crustal MgO content would be about 3 wt%. See Supplementary Data for additional elements.

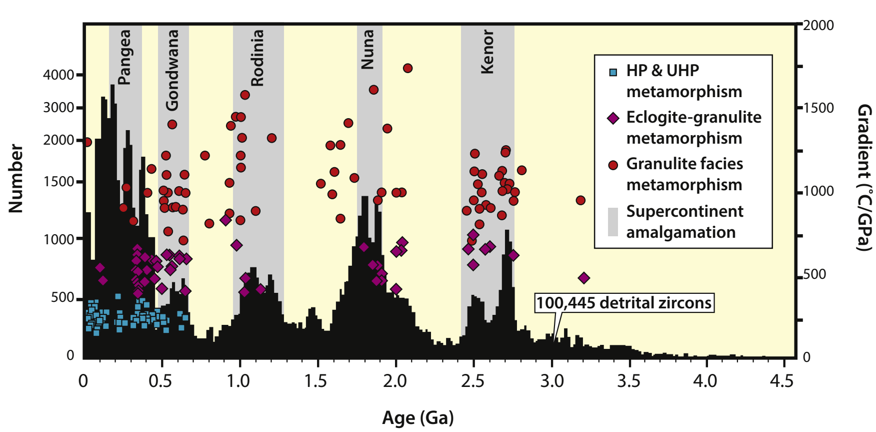

Fig. 12. The crystallization ages of > 100,000 detrital zircons coupled with ages of various types of metamorphism through geologic time (modified from Hawkesworth et al., 2016). The origins of the peaks and valleys on this plot are contentious, largely because they are difficult to interpret using crustal growth models where the bulk of crust is created by arc magmatism as that is a continuous process and would not lead to the observed peaks and valleys. Most workers (see text) interpret the peaks as some sort of "preservation" peaks, where crust is sequestered from subsequent recycling because it was isolated from younger collisions and recycling. However, they are precisely what one would expect if considerable quantities of continental crust are made from slab failure magmatism, as we argue here, for the peaks coincide broadly with periods of supercontinent assembly (labeled in gray fields), which require collisions and resultant slab failure magmatism. We conclude that the peaks were generated by slab failure and that continental crust is dominantly made from both arc and slab failure magmatism. HP- high pressure; UHP—ultrahigh pressure.

crust recycled into the mantle as much happens beneath the surface out of view, the quantity of sediment accumulated on the ocean floors (Scholl and von Huene, 2007, 2009), as well as potentially huge amounts of continental crust subducted during collisions, indicates that voluminous amounts of continental crust are recycled into the mantle. This suggests to us that Armstrong's (1981) model for continental growth, in which the bulk of crust was created early in Earth history and has been recycled through time, is most likely to be correct.

9. Detrital zircons and crustal growth

One of the more useful developments over the past few decades has been the ability to rapidly date single zircon grains in situ (Jackson et al., 1992; Fryer et al., 1993). This led to an overwhelming number of sedimentary provenance studies utilizing dated detrital zircons (for example: Dickinson and Gehrels, 2003). Several workers have used sands from large pan-continental rivers in attempts to constrain the crustal formation ages of continents (Rino et al., 2004; Iizuka et al., 2005; Belousova et al., 2010; Condie et al., 2011), whereas others have compiled extensive databases containing over 100,000 detrital and magmatic zircons (Condie et al., 2009; Hawkesworth et al., 2010, 2016). All of these workers noted concentrations, or peaks, of U-Pb zircon ages (Fig. 12) that coincided broadly with periods of known orogeny on a given continent and more broadly, supercontinental assembly (Nance et al., 1988; Nance and Murphy, 2013). The consensus among researchers, armed with certainty that the bulk of continental crust was formed by arc magmatism, was that the peaks were preservation peaks formed as collisions sequestered juvenile and reworked crust from recycling (Condie et al., 2011; Hawkesworth et al., 2009, 2016) because at that time the amount of new crust formed during collisions was thought to be very small (Stern and Scholl, 2010).

Our slab failure model not only provides a new way to look at how and when crust is formed; but also provides an actualistic process to reinterpret the peaks in plots of detrital zircons and metamorphism versus age, previously interpreted to represent preservation peaks (Cawood et al., 2013; Hawkesworth et al., 2009, 2016; Condie et al., 2011). In our model, the peaks, which, as is widely recognized, coincide broadly with periods of supercontinent assembly, form because they are periods of increased collision and hence, increased slab failure magmatism.

For the most part all of the rocks that we interpret to be products of slab failure derived from the mantle were previously considered to be the products of crustal assimilation and recycling, based in large part on radiogenic isotope compositions. Instead, the evolved Nd and Sr isotopes common to some slab failure suites, such as the Peninsular Ranges and Sierran batholiths involved assimilation by fractional melting of old, enriched SCLM as they ascended. Thus, it may be impossible to utilize radiogenic isotopes, such as Nd and Hf (Condie et al., 2011), which depend on a homogeneous mantle, to accurately infer whether a given pluton is juvenile or formed from crustal recycling – at least in regions underlain by old and enriched SCLM. Radiogenic isotopes are commonly used to determine model ages for continental growth, but, as pointed out by Korenaga (2013), a hotter mantle implies less vigorous convection than today such that mantle mixing must also have been much diminished. Thick oceanic lithosphere and slow convection could create a heterogeneous mantle that would produce unreliable model ages.

10. Conclusions

1. Our geochemical compilation and evaluation of Cretaceous batholiths in the North American Cordillera indicate to us that most are not the products of arc magmatism, but instead are post-collisional products of slab failure.
2. On the basis of trace elements, isotopic studies, and comparison with much younger basalts of western North America, we conclude that the bulk of the batholithic magmas were derived by melting of subducted oceanic crust at greater depths than magmas of arc terranes, and then modified by fractional melting as they rose through old, enriched subcontinental mantle lithosphere.
3. Because we found that most of the batholiths were not generated by arc magmatism as commonly believed; but instead originated from the mantle during the waning stages of collision and consequent slab failure, and because they typically have silica > 60%, we assert that they are the missing link in the formation of continental crust.
4. Cordilleran slab failure magmas are compositionally similar to tonalite-trondhjemite-granodiorite (TTG) suites as old as 3.8 Ga, which, when combined with evidence for long-active arc magmatism, lead us to opine that slab failure and plate tectonics have been active for most of Earth history.
5. Compiled arrays of detrital zircons show episodic peaks that coincide with periods of supercontinent amalgamation. Because geologists hypothesized that arc magmatism produced the bulk of crust and was incapable of producing large bursts of crustal growth, the peaks were generally interpreted as crustal sequestration and preservation peaks. In our model of slab failure, the peaks are readily interpreted to represent new continental crust generated by slab failure during the collisions that formed the supercontinents.
6. The dearth of rift facies basalts and evaporites in many collisional orogens implies that during collisional slab failure, most of the extended continental crust and overlying rift facies rocks are subducted. Because the total volumes of recycled continental crust are so large, we favor Hadean whole-earth-differentiation models over progressive growth models for the development of continental crust.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2018.04.001.

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