North America was subducted to the west under Rubia.

Does the composition of the arc evolve appropriately for subduction of a continental margin?

Kyren Bogolub

1 Introduction

A unique feature of the Hildebrand's hypothesis for the Mesozoic assembly of North America, is the theory that North America was subducted to the west under the ribbon continent of exotic terrains he has termed Rubia [7]. Hildebrand suggests that several plutonic bodies in the Cordillera formed as a result of this westward subduction, specifically the Coast Plutonic Complex, and the Omineca, Sierra Nevada, Peninsular, and Sonoran batholiths, all of which are shown in Figure 1. If his theory is correct, I might be able to identify evidence in the literature suggesting that the composition of the magmatic rocks in these locations can be attributed to the subduction of continental margin of North America.

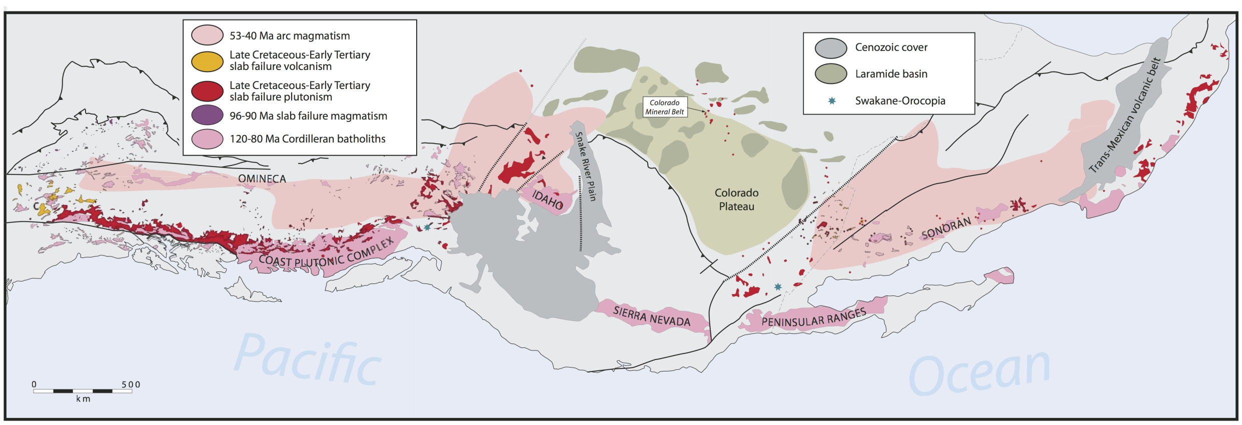

Figure 1: Locations of ∼124-80 Ma North American Cordilleran batholiths. Figure used in Hildebrand 2009 [7].

The composition of an arc magma is dependent on a large number of factors such as mantle composition, subduction mechanism, slab composition, overriding plate composition, and distance from trench [8]. Due to these complexities, it can be difficult to determine exactly which factors are dominating a particular arc magma's composition. Typically, it is necessary to correlate one or more major element, trace element, or isotopic signatures between an arc magma and a potential source before a direct relationship can be inferred. However, there a few characteristics that can help identify that a magma is (at least partially) derived from continental crustal: high silica (>65 wt%) content [6] and high δ^{18}O (>6‰) values [1], high initial εSr (>+50 or ^{87}Sr/^{86}Sr>0.7053) and low initial εNd (<-8 or ^{143}Nd/^{144}Nd<0.51265) values [6] [8]. In the case of a subducting continental margin, the magma composition tends to become more "continental" (higher initial εSr and lower initial εNd values) in magmas further away from the trench [5].

In this paper, I will review a small selection of geochemical studies on the magma compositions of several North American Cordilleran batholiths. In doing so I will attempt to compile and evaluate the evidence they present about the tectonic setting of western North America during the Late Cretaceous. In addition to presenting the interpretations made by the researchers who conducted these studies, I will be considering if their results are consistent with any of the aforementioned conditions for continental crust-derived magma.

2 Coast Plutons

The Coast Plutonic Complex in southwestern British Columbia was the subject of an Nd-Sr-Pb isotope study published by Cui and Russel (1995) [2]. In this study, they examined 18 samples of plutonic rocks ~151-101 Ma (mostly U-Pb ages) from a 180km long transect across the southern Coast Belt. The results of their Nd and Sr analysis are summarized in Figure 2. These results show consistently low $^{87}Sr/^{86}Sr$ (+0.70324 to +0.70433) and high εNd (+4.2 to +8). They also found no significant spatial or temporal patters in isotope compositions.

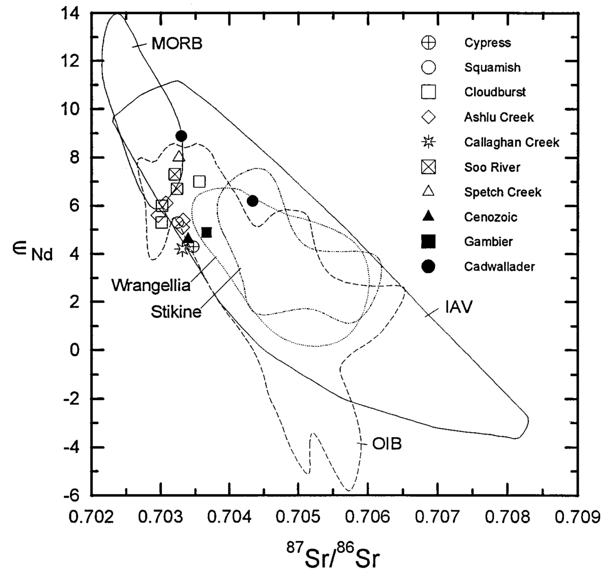

Figure 2: Initial εNd and initial $^{87}Sr/^{86}Sr$ for Coast pluton samples from Cui and Russel (1995) [2].

Although this study did not present silica content or $\delta^{18}O$ data, the results of this study do not suggest that magma was derived from continental material (section 1, this paper). Cui and Russel (1995) conclude that the Coast plutons are largely derived from juvenile mantle material with little to no crustal contributions. They do however point out that the isotopic signatures of most of the country rock can be similar to the compositions of the pluton, as indicated by the Wrangellia and Stikine fields marked on Figure 2. While this interpretation is consistent with a subduction zone setting, it does not shed much light on the direction of subduction nor the nature of the subducting crust.

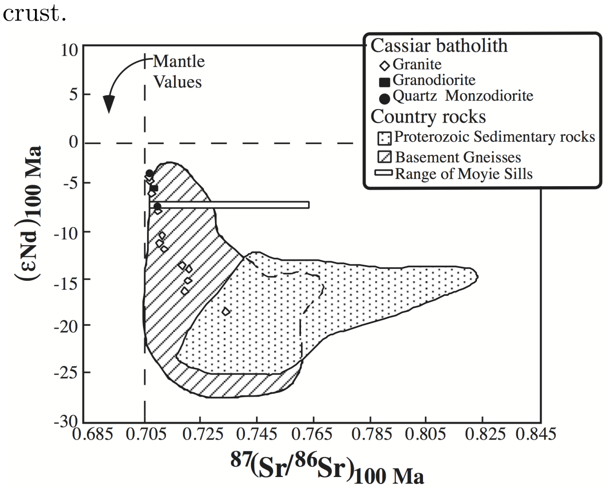

Figure 3: Initial εNd plotted against initial $^{87}Sr/^{86}Sr$ for the Cassiar batholith as well as fields for country rock composition from Driver et al. (2000) [4].

3 Omineca Plutons

Driver et al. (2000) presented a geochemical analysis of 15 samples from the 100 Ma Cassiar pluton, the largest pluton in the Omineca batholith. These samples have generally high silica content (>65 wt%), varied but high $\delta^{18}O$ (9.0 to 11.2‰) and initial $^{87}Sr/^{86}Sr$ (+0.706 to +0.734), and varied but low initial εNd (-17.1 to -2.7). The initial εNd and initial $^{87}Sr/^{86}Sr$ results are plotted in Figure 3. In addition to the batholith, Driver et al. (2000) also analyzed 8 potential source materials from the country rock in the area. Isotope data from the country rocks in this study as well as other published data was used to draw the country rock fields in Figure 3.

Based on the conditions described in section 1, these results suggest that the Cassiar pluton magma was derived from a crustal source. Driver et al. (2000) interpreted the data in Figure 3 along with other correlations in trace element signatures and magma evolution modeling to imply that the magma was derived strictly from crustal sources with no mantle contribution. This has lead them to conclude that the batholith was not formed in a subduction zone of any kind, but rather was formed from crustal thickening. Although they attribute this crustal thickening to be a consequence of a distant convergent plate margin, there is no clear evidence for this in the geochemical data [4].

4 Sierra Nevada and Peninsular

DePaolo (1981) presented results of a geochemical study in the Sierra Nevada and Peninsular ranges of southern California and Baja California. In the Sierra Nevada, they had samples (both new data and previously published work) with a range of Mesozoic ages but 3 of the samples that had previously published ages between ∼126-120 Ma. Those Early Cretaceous aged plutons had moderately high $\delta^{18}O$ (>8.2‰), low εSr (-16 to -10), and high εNd (+5.1 to +6.5). These values along with the rest of their data set are plotted in Figure 4. In examining pluton data, DePaolo (1981) also noticed a geospatial pattern with higher εNd in the northwest, as well as a correlation with paleogeographic boundaries. Despite most age groups having a wide range of isotope signatures, the lowest εSr values were from samples with Late Jurassic to Early Cretaceous ages.

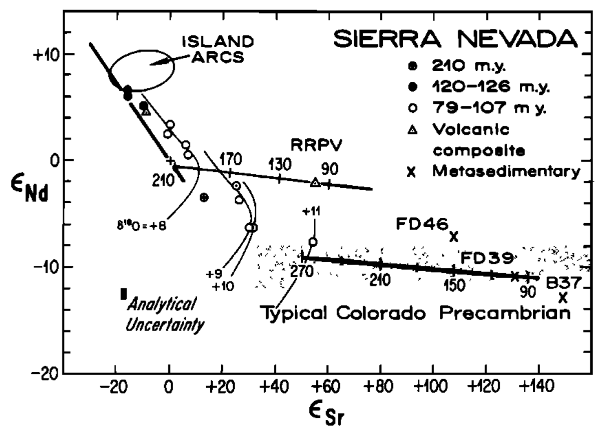

Figure 4: Initial εNd plotted against initial εSr in the Sierra Nevada batholith from DePaolo (1981). Contours are for $\delta^{18}O$. Shaded region is composition of typical Colorado Precambrian basement [3].

DePaolo (1981) also presented results from the geochemical analysis of the Peninsular batholith in Baja California. Again, the samples have a range of Mesozoic ages but in this data set the ages were all estimated. 10 samples of the samples were estimated to be between ∼120-110 Ma. Of these samples, the compositions had moderately high $\delta^{18}O$ (mostly >8.0‰ a few 5.5 to 7.8‰), low εSr (-16 to +2), and high εNd (+1.3 to +8.2). These values along with the rest of the Peninsular data set are plotted in Figure 5. Again, DePaolo (1981) observed a geospatial trend with higher εNd in the west. These results from the Peninsular plutons are very similar in composition to the Sierra Nevada, however εSr had a slightly lower average value, and $\delta^{18}O$ was generally higher. Aside from these differences, the broad patterns in isotope trends were interpreted in the same way as those of the Sierra Nevada.

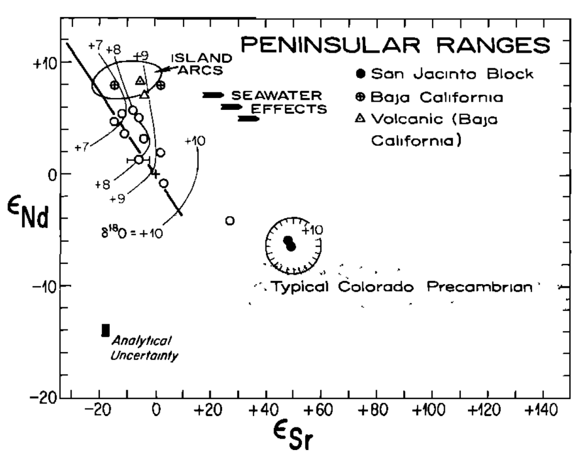

Figure 5: Initial εNd plotted against initial εSr in the Peninsular batholith from DePaolo (1981). Contours are for $\delta^{18}O$. Shaded region is composition of typical Colorado Precambrian basement [3].

The isotopic compositions suggest that there is a continental crust contribution to the Sierra Nevada and Peninsular pluton magma compositions, but it is unlikely to be the only magma source (section 1, this paper). The trend of increasing "continental-ness" to the east also suggests that the subduction is east dipping [5], but this trend may result from many other factors such as changes in country rock composition [8]. DePaolo (1981) suggests that the results of this study, integrated with other published data, indicate a mantle derived magma that has incorporated Precambrian crystalline basement, or metasedimentary rocks derived from the crystalline basement. This interpretation is consistent with eastward dipping subduction under the North American crust.

5 Sonora Batholith

Valencia-Moreno et al. (2003) conducted a geochemical analysis of the Sonora batholith in northwestern Mexico. They presented results from 5 new samples in the Coastal Sonora along with results from pervious studies which included the eastern Sonora. The estimated ages range from ∼142-60 Ma but are poorly constrained. 84 Ma was used in initial isotope analysis. These samples had high silica content, (62.5 to 71.2 wt%), moderately high initial $^{87}Sr/^{86}Sr$ (+0.70586 to +0.70679), and moderately low initial εNd (-4.7 to -2.3). The initial εNd and initial $^{87}Sr/^{86}Sr$ results are plotted in Figure 6 with the western and eastern samples distinguished by different markers (western samples with white squares and eastern samples with black diamonds). Valencia-Moreno et al. (2003) point out that there is a regular trend of increasing initial $^{87}Sr/^{86}Sr$ and decreasing εNd from west to east, which can be seen in Figure 6.

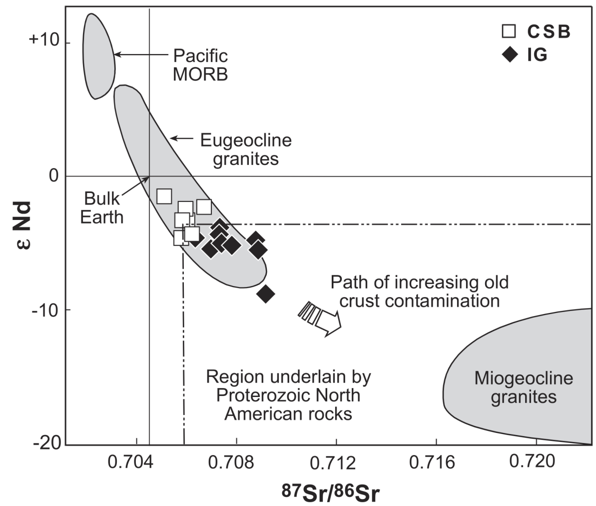

Figure 6: Initial εNd plotted against initial $^{87}Sr/^{86}Sr$ for the Sonora batholith from Valencia-Moreno et al. (2003). White squares represent samples from the western section of the batholith. Black diamonds represent samples from eastern Sonora [9].

Reminiscent of the Sierra Nevada and Peninsular batholiths, the isotopic compositions of the Sonora suggest that there is a continental crust contribution to magma composition, and that the spatial variation in magma composition may indicate eastward dipping subduction, or a change in country rock material (section 1, this paper). Valencia-Moreno et al. (2003) does not present a comparison to country rock isotope compositions, so a direct relationship between country rock and magma is difficult to infer. However, Valencia-Moreno et al. (2003) has drawn on the similarities of isotopic signatures between the eastern Sonora and the Peninsular batholiths to infer that eastern Sonoran plutons are composed from mantle derived magma combined with old, continental crust material. They contrast the isotopic signatures of the western and eastern Sonora to infer that the differences in magma composition result from differences in the crustal material of the overlying plate. Specifically, old, cratonic crust in the east and young, mafic to intermediate crust in the west.

6 Summary

With such a brief venture into such a complicated topic, I am hesitant to make any definitive conclusions however, there are no obvious indications in any of the four batholiths I examined that imply they formed in a western facing subduction zone. The composition of the Omineca pluton suggests that it wasn't formed in a subduction zone at all, and yet it may be the pluton that is most consistent with Hildebrand's collisional model. Harris et al. (1986) describes the characteristics of magma produced at four stages of a collisional boundary. The Omineca pluton is similar to Harris et al.'s (1986) description of a post-collision alkaline intrusion which are composed of magma generated in overly thickened crust. On the other hand, the Sierra Nevada, Peninsular and Sonora batholiths are consistent with a subduction zone setting. These batholiths all have signals of a Precambrian continental crust contribution to the magma. DePaolo (1981), who assumed an east dipping subduction zone, ruled out the possibility of these Precambrian signals being derived from a subducting slab on the basis that the isotopic signatures were actually "too continental" to the west, near the trench. Hypothetically, if the crustal signals were from a subducting slab, the isotope trends are entirely reversed of what is expected in a westward dipping subduction zone [5].

References

[1] J G Arth, C C Zmuda, N K Foley, and R E Criss. Isotopic and Trace-Element Variations in the Ruby Batholith, Alaska, and the Nature of the Deep Crust Beneath the Ruby and Angayucham Terranes. *Journal of Geophysical Research: Solid Earth*, 94(B11):15941–15955, 1989.

[2] Y Cui and J K Russel. Nd-Sr-Pb Isotopic Studies of the Southern Coast Plutonic Complex, Southwestern British-Columbia. *Geological Society of America Bulletin*, 107(2):127–138, February 1995.

[3] Donald J DePaolo. A Neodymium and Strontium Isotopic Study of the Mesozoic Calc-Alkaline Granitic Batholiths of the Sierra-Nevada and Peninsular Ranges, California. *Journal of Geophysical Research: Solid Earth*, 86(B11):10470–10488, 1981.

[4] L A Driver, R A Creaser, T Chacko, and P Erdmer. Petrogenesis of the Cretaceous Cassiar batholith, Yukon–British Columbia, Canada: Implications for magmatism in the North American Cordilleran Interior. *Geological Society of America Bulletin*, 112(7):1119–1133, 2000.

[5] M A Elburg, M Van Bergen, J Hoogewerff, J Foden, P Vroon, I Zulkarnain, and A Nasution. Geochemical trends across an arc-continent collision zone: magma sources and slab-wedge transfer processes below the Pantar Strait volcanoes, Indonesia. *Geochimica Et Cosmochimica Acta*, 66(15):2771–2789, August 2002.

[6] N B W Harris, J A Pearce, and A G Tindle. Geochemical characteristics of collision-zone magmatism. *Geological Society, London, Special Publications*, 19(1):67–81, 1986.

[7] R S Hildebrand. Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera? *Geological Society of America Special Papers*, 457:1–71, 2009.

[8] J A Pearce and D W Peate. Tectonic Implications of the Composition of Volcanic ARC Magmas. *Annual Review of Earth and Planetary Sciences*, 23(1):251–285, May 1995.

[9] M Valencia-Moreno, J Ruiz, L Ochoa-Landín, R Martínez-Serrano, and P Vargas-Navarro. Geochemistry of the Coastal Sonora batholith, Northwestern Mexico. *Canadian Journal of Earth Sciences*, 40(6):819–831, June 2003.