HYBRIDIZATION AND CRUSTAL GROWTH: EXAMPLES FROM THE USA

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Summary - We have investigated felsic igneous rocks of early to late Phanerozoic age from a variety of settings in the Appalachians and Cordillera of the USA (*extension-related volcanics and shallow to mid-crustal intrusions*: Quaternary high-silica rhyolites, Miocene rhyolites, dacites, and granitoids, California and Nevada; *orogenic intrusions:* Mesozoic granitoids, California and Nevada; Paleozoic granitoids, southern Appalachians)*(Fig. 1)*. These rocks range widely in geochemical characteristics, from metaluminous to strongly peraluminous, incompatible element depleted to enriched, and isotopically primitive to evolved (ε_{Nd} +5 to -17, Sr_i 0.7037-0.722). Nonetheless, all show clear evidence for mixed parentage, with contributions from both juvenile and mature crustal sources. Some intrusions contain outstanding examples of mafic-felsic melt interaction, and the high-silica rhyolites are clearly contaminated by their wall rocks, but there is no geochemical evidence for strong modification of felsic magma by these local processes. However, isotopic data for felsic rocks, regional crust, and coeval mafic rocks, together with zircon inheritance, suggest that *all* of the rocks are hybrids with substantial amounts (10's of %) of both crustal and juvenile mantle components; roughly 50-50 seems to be average. The important modifications apparently occurred in the deep crust via two mechanisms: mixing of juvenile mafic magmas with crustal melts and remelting of crust that was (geologically) recently injected by mafic magma. The former mechanism is supported by coexistence of mafic and felsic magma, and the latter by young inherited zircon (<~100 m.y. older than granitoids). Whatever the mechanism, it is clear that even very crustal-looking granites generally represent substantial juvenile additions to the continental crust.

Introduction- The question of origin of igneous rocks of the continents (juvenile or reworked continent?) remains contentious. Assessing contributions from crust in mantle vs. whether is central to evaluating questions of crustal growth and internal rearrangement. We have studied Phanerozoic, intermediate to felsic rocks from a variety of settings. Some of these suites include basalts, and some are prototypical "crustal" granites (highly felsic, peraluminous, very high Sr_i and ε_{Nd}, abundant zircon ± monazite inheritance). We discuss briefly several of these suites and the evidence for their origins below.

1. Convergence-related granitoids, Eastern Blue Ridge, southern Appalachians- Peraluminous granodiorite and trondhjemite (67-73 wt% SiO_2) of the Blue Ridge province of North Carolina and Georgia were emplaced during accretion of crust to southern Laurentia at 370-480 Ma (transition from subduction to collision?). These intrusions were not accompanied by any known mafic magmatism. Their elemental and isotopic compositions range continuously from highly immature (low K and LIL, high Sr and Na, depleted isotopic signature) to more "normal" *(Fig. 2a)*. The presence of abundant inherited zircon cores of Middle Proterozoic and rarely Archean age attests to a mature continental component even in the most primitive granitoids *(Fig. 3)*. However, elemental and isotopic compositions also require a very large proportion of juvenile material.

2. Convergence-related granitoids, Mojave Desert region- Abundant metaluminous and peraluminous granodiorites and granites and very sparse mafic magmas (most 60-74 wt% SiO_2, some to <50 % SiO_2) intruded the Paleoproterozoic crust of the eastern Mojave Terrane, California-Nevada, during oceanic-continental plate convergence between ~170 and 65 Ma. Ancient inherited zircons are abundant, none of the intrusives has a depleted mantle isotopic signature, and most of the peraluminous granites are decidedly "crustal" (ε_{Nd} -15 to -17, Sr_i 0.711-0.719), yet few or none of these granitoids matches the isotopic composition of exposed pre-existing crust or lower crustal xenoliths*(Fig. 2b)*. Sparse early Mesozoic inherited zircons and limited but striking evidence for deep-level mingling with mafic magmas suggest possible mechanisms for hybridization *(Fig. 4)*.

3. Extension-related granitoids, Colorado River rift- Between 15 and 17 Ma, at the onset of rapid crustal extension, copious metaluminous to weakly peraluminous granite and quartz monzonite (57-77 wt% SiO_2) and accompanying mafic magma invaded the Mojave Terrane crust of the Colorado River region, near the intersection of California, Nevada, and Arizona. The mafic magmas appear to have been derived primarily from ancient, enriched mantle lithosphere; the calc-alkaline granitoids are even more enriched isotopically (ε_{Nd} ~-10, Sr_i ~0.710) and contain some ancient zircon inheritance, but they do not come close to matching the composition of the old regional crust *(Fig. 2c)*. In spite of spectacular examples of mingling between mafic and felsic magmas, field and geochemical evidence indicate that mixing at the exposed level was not important. Extension-related Miocene volcanic rocks, exposed over a much wider area, also range from mafic to felsic and reflect juvenile/crustal hybridization.

Discussion and Implications- In all of the examples cited above, and we suspect in almost all granitoid rocks worldwide, there is evidence for a hybrid origin involving substantial contributions from both juvenile, mantle-derived and pre-existing crustal material. Estimates of proportions of each contributor remain imprecise, but regardless of choice of end members mixing calculations for our samples uniformly suggest at least 10's of percent each from both mantle and crust.

The mechanism of hybridization remains obscure and probably is variable. Wall rock contamination and magma mixing in the exposed shallow to middle crust appear to minor where they can be tested. Major *cryptic* hybridization must occur in the deep crust. Cryptic hybridization includes both *pre-hybridization* (melting of mixed crust relatively shortly [within ~100-200 m.y.] after injection by juvenile magma), and *syn-hybridization* (mixing [~MASH] between new juvenile magma and anatectic magma).

Near universal hybrid origin – even where magmas have very strong crustal signatures – implies that major crustal growth accompanies magmatism. Either the continental crust has grown steadily at an appreciable rate, or large amounts of crust must be returned to the mantle to balance the juvenile input.

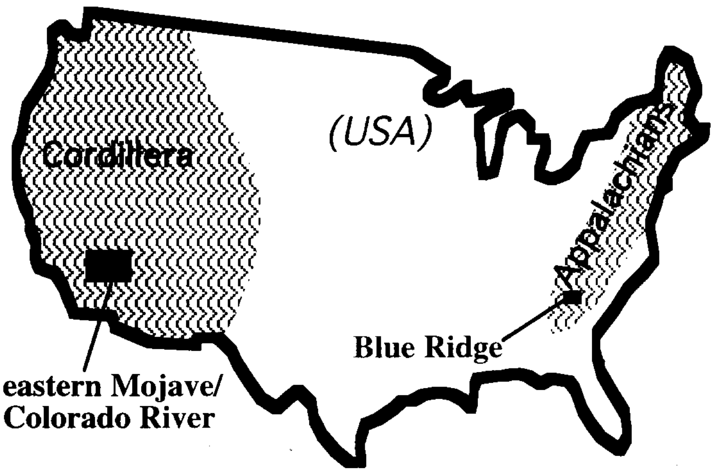
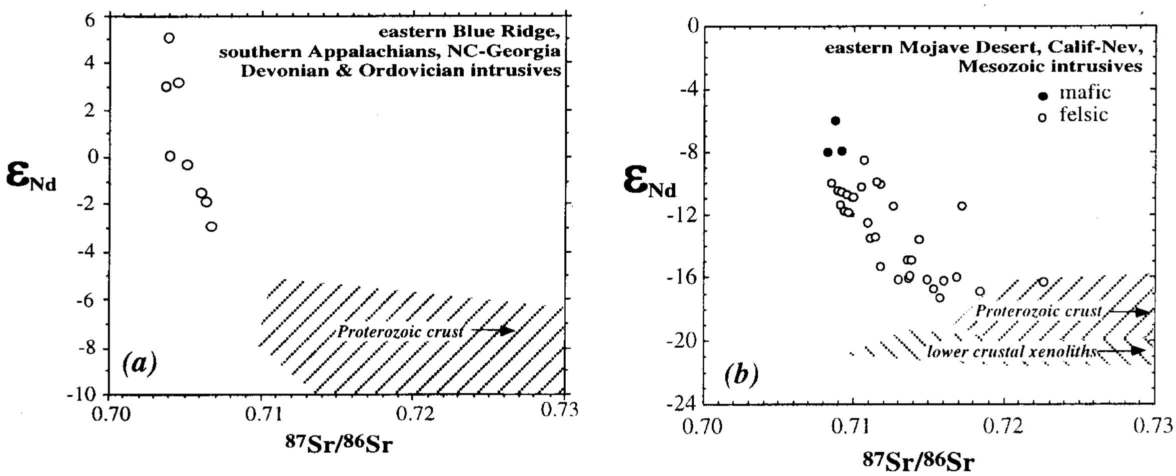


Figure 1. Locations of study areas.



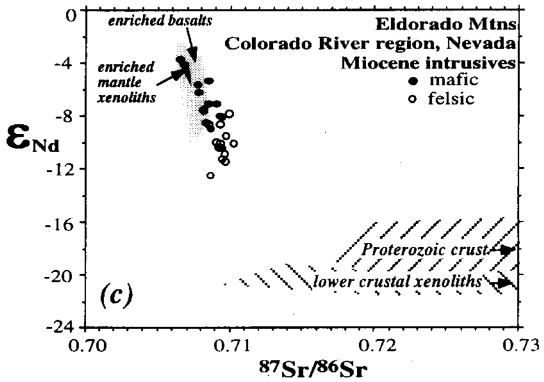


Figure 2. Nd-Sr isotopic compositions of intrusive rocks compared to probable contributing sources.

(a) Convergence/collision-related Paleozoic plutons, Blue Ridge, southern Appalachians.

(b) Convergence/subduction-related plutons, eastern Mojave terrane; xenoliths are high-P granulite facies, from a Tertiary dike.

(c) Extension-related plutons, Colorado River extensional corridor (easternmost Mojave terrane); fields of mantle xenoliths and basalts represent probable juvenile component .

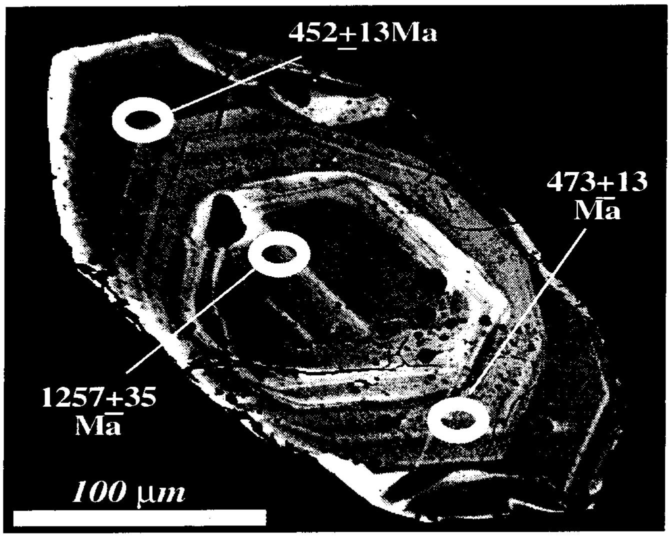


Figure 3. Zircon with Mesoproterozoic inherited core and magmatic rim. Whiteside pluton, North Carolina (trondhjemite with low Sr_i, high ε_{Nd}, LIL-poor). U-Pb ages by ion microprobe.

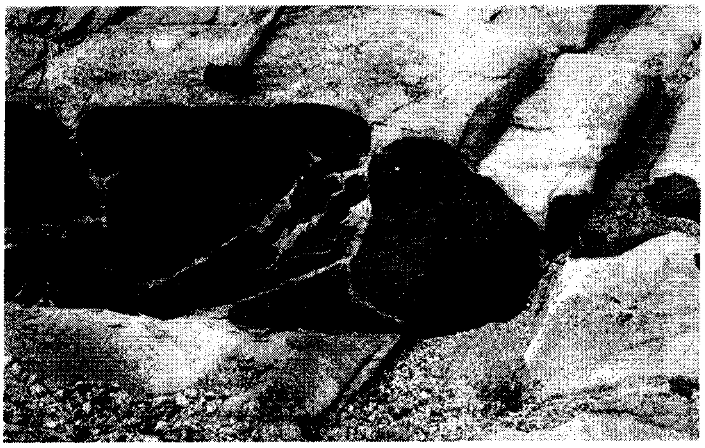


Figure 4. Mafic pillow injected by strongly peraluminous granite, 65 Ma Ireteba pluton, Nevada.