GRANITES, LEUCOGRANITES, HIMALAYAN LEUCOGRANITES…

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PREFACE

I am not an expert on Himalayan leucogranites, although I have followed their coverage in the literature for more than 40 years and have studied granites and rhyolites more generally for over 50 years (cf. Fig. 1). Coming from this perspective, I aim—in this *Elements Perspective*—to provide a felsic magma context for pondering leucogranites in general and Himalayan leucogranites in particular.

FELSIC MAGMAS, FELSIC ROCKS: GRANITES AND RHYOLITES—AND LEUCOGRANITES

Himalayan leucogranites, the subject of this special issue of *Elements*, are a prominent (arguably *the* prominent) example of the rocks known as leucogranite. Leucogranites themselves are a volumetrically minor component of the broader group, felsic[1] igneous rocks (granites and rhyolites[2]). So what are the characteristics of leucogranites generally and of Himalayan leucogranites specifically? How do they compare with other felsic rocks? Why are they important in understanding Earth processes and history? And why do they remain a major focus of the geoscience community?

Felsic magmas[3] have formed throughout almost all of Earth history and been emplaced in or on the crust in all tectonic environments. Their solid product rocks constitute a large fraction of Earth's crust, and they are the most common material expelled by explosive super-scale eruptions.

What, specifically, is *leuco*granite? This term refers to a white (leuco), or very pale, granite—a granite with a very low mafic (dark[4], Fe- and Mg-rich) mineral content. There is no specific, uniformly applied definition, though the International Union of Geological Sciences suggests that "leuco-granite is granite with <5% mafic minerals" (LeBas and Streckeisen 1991). In the field, the name is generally applied to rocks with ≤3% dark minerals, in contrast to typical, salt-and-pepper-looking granite with ~5%–10% dark minerals. It is the most silicic of granites, with relatively abundant quartz and SiO_2 chemically constituting ≥74 wt.%. The chemical equivalent of leucogranite among volcanic rocks is commonly referred to as high-silica rhyolite.

Diversity of Felsic Rocks

Granites, when defined in more or less *sensu stricto* fashion, seem at first glance to be boringly uniform (mineral content ~ 80%–99% quartz + feldspar with K-feldspar abundance similar to or greater than that of plagioclase; chemically ~70–80 wt.% SiO_2)—and, consequently, perhaps frustratingly uninformative. The same could also be said about their erupted equivalent, rhyolites. However, when observed in more detail (beyond the generalization that they are simply combinations of a lot of quartz and feldspar), they reveal noteworthy diversity. This diversity supports a wide range of interpretations, and spirited debates, concerning their origins and broader significance, and not just among specialists.

The most obvious differences among granites, and rhyolites, lie in the abundances and identity of their minor minerals: minerals other than quartz and feldspar that are evident in hand samples. These variations reflect subtle but important contrasts in melt chemistry and conditions of crystallization and constrain magma histories. Important distinguishing minerals include:

- Hydrous (biotite mica, amphibole) versus anhydrous (pyroxene, rare Fe-rich olivine) mafic minerals. The hydrous minerals imply a relatively water-rich ("wet") and cooler magma, compared with the "hot and dry" anhydrous minerals.
- Aluminum-rich versus Al-poor minor minerals. The second most abundant cationic element in granite and the crust as a whole, Al is largely contained within feldspars. Rocks, or magmas or minerals, with extra Al beyond that necessary to combine with all the available Ca + Na + K to form feldspar (Al > [2*Ca + Na + K])[5] are *peraluminous* and, if the excess is significant, they contain minerals that demonstrate this compositional characteristic (garnet, muscovite, cordierite, tourmaline, andalusite, sillimanite). With a near balance or modest Al deficiency ([2*Ca + Na + K] ≥ Al > [Na + K]), compositions are *metaluminous*, marked by Al-poor Ca minerals (amphibole [e.g., hornblende], Ca pyroxenes [e.g., augite]). Much less commonly, granites may be *peralkaline* ([Na + K] > Al), marked by Na-rich pyroxene or amphibole (e.g., aegirine, riebeckite). Peraluminous versus metaluminous versus peralkaline compositions are commonly considered to be key to interpreting magma genesis (see following discussion, especially regarding Himalayan leucogranites).

Also important to the interpretation of felsic rocks, but typically not visible in hand samples:

- Accessory minerals—minerals whose presence is dictated by a minor chemical constituent that is incompatible with the common silicate minerals (e.g., P, Zr, rare earth elements, Fe^{3+}) and are widespread but low in abundance. Minerals such as zircon, apatite, magnetite, ilmenite, monazite, and titanite (sphene) are sensitive indicators of melt composition, oxidation state, and temperature, as well as being the premier materials for radiometric dating.

Phase Equilibria Unifies Felsic Magmas and Felsic Rocks (Sort Of…)

How are felsic rocks, and the magmas from which they formed, related to one another? Do granites, leucogranites, and rhyolites have essentially a single common origin, or do they form in multiple distinct ways? Prior to the mid-20th century, geoscientists were strongly divided regarding whether or not some, or even all, granites formed from magma—that is, were granites igneous rocks (Gilluly 1948)? Moreover, the relationship between granite and rhyolite was strongly disputed or simply ignored. General views changed dramatically in the 1950s and 1960s, largely in response to experimental work.

Studies of *phase equilibria* reveal identities and compositions of stable minerals, liquids (melts), and gases (volatile fluids) as a function of system composition, pressure, and temperature. In 1958, Tuttle and Bowen published results of their experiments for magmas of granite composition, demonstrating that the compositions of silicate melts saturated with quartz and feldspar coincide closely with the compositions of both granites and rhyolites (Fig. 2). The lowest temperature portion of this *quartz + feldspar cotectic*, referred to as "the granite minimum," was especially close to the compositions of what we now call leucogranites and high-silica rhyolites. This match between the composition of the lowest-*T* melts that can coexist with the most common minerals of Earth's crust and the most silicic plutonic and volcanic rocks convinced almost all geoscientists that granites and rhyolites both had origins as magmas. The origin of granite was thus not as a solid material transformed by subsolidus processes. But the transformative work of Tuttle and Bowen left open two possible pathways to the favored

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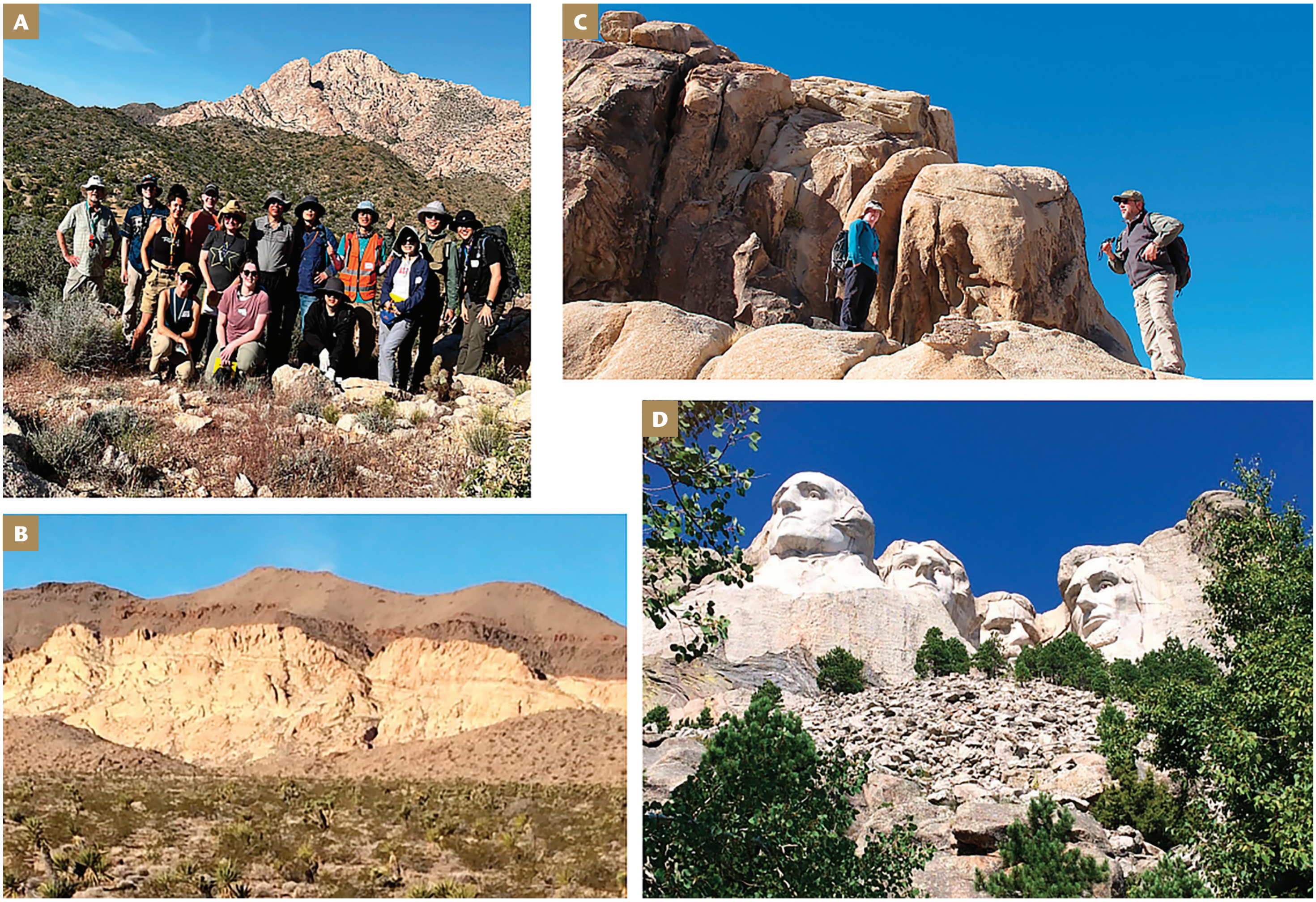

FIGURE 1 Examples of leucogranite and high-silica rhyolite. (**A**) Spirit Mountain/Avi Kwa Ame, locus of the creation story of Colorado River tribes and centerpiece of the newly established National Monument, Nevada, USA. The mountain is part of a thick, weakly peraluminous leucogranite sheet at the roof of the Miocene Spirt Mountain batholith (Walker et al. 2007). Pictured: China-USA-UK field trip group, May 2024; Guest Editor of the present *Elements* issue Prof. Fu-Yuan Wu is in the center of the back row. PHOTO: LEI YANG. (**B**) Highland Range, Nevada, USA. White unit is weakly peraluminous high-silica rhyolite tuff and lava sequence, interpreted to have erupted from leucogranite zone of nearby Searchlight pluton (Wallrich et al. 2023). (**C**) Painted Rock, Old Woman Mountains, California, USA. Cretaceous peraluminous muscovite-biotite-garnet granite in Cordilleran belt (Miller and Barton 1990; Chapman et al. 2021). Pictured: Stacy Phillips and Prof. John Hanchar, Memorial University of Newfoundland. (**D**) Mount Rushmore, South Dakota, USA: Harney Peak pluton (Paleoproterozoic peraluminous, collisional leucogranite; Nabelek 2020).

felsic magma compositions: by rising temperatures within the solid crust, eventually leading to partial melting (*anatexis*), or by fractional crystallization during cooling of less felsic magmas, which would lead to essentially the same low-T quartz + feldspar-saturated melt composition. As it turned out, Bowen had long favored the latter origin (fractional crystallization), and it was consistent with these results; Tuttle, along with many in the granite community at the time, leaned toward the former (crustal anatexis). Their results were quite definitive, except that they could not directly distinguish between these two ostensibly very different origins. Furthermore, although their results strongly indicated that both granites and rhyolites owed their similar compositions to magmatic processes—low-T crystal–melt equilibria—they did not reveal whether or not the volcanic and plutonic rocks were directly related.

Characterizing the Diversity, Constraining the Origins: Felsic Magmatism in Space and Time

Constraints of phase equilibria indicate a clear link among felsic magmas, both erupted and emplaced beneath the surface, across all tectonic environments and through almost all of the history of Earth. But that linkage does not require a single origin. In fact, the relatively subtle but clear variations among felsic rocks and their variable abundances and styles of emplacement and eruption in different tectonic environments imply that they have multiple modes of origin and magmatic evolution. Furthermore, late 20th century advances in analytical geochemistry have greatly augmented petrogenetic constraints that had been provided by “classical” techniques in wide use by the mid-century (field and petrographic observations, major element chemical analysis). In particular, analysis of trace elements and isotopes has sharpened the understanding of origins of and relations among felsic igneous rocks. The low abundances of trace, or dispersed, elements do not influence the stability of minerals, but concentrations and ratios of these elements are nonetheless very sensitive to magma sources and melting

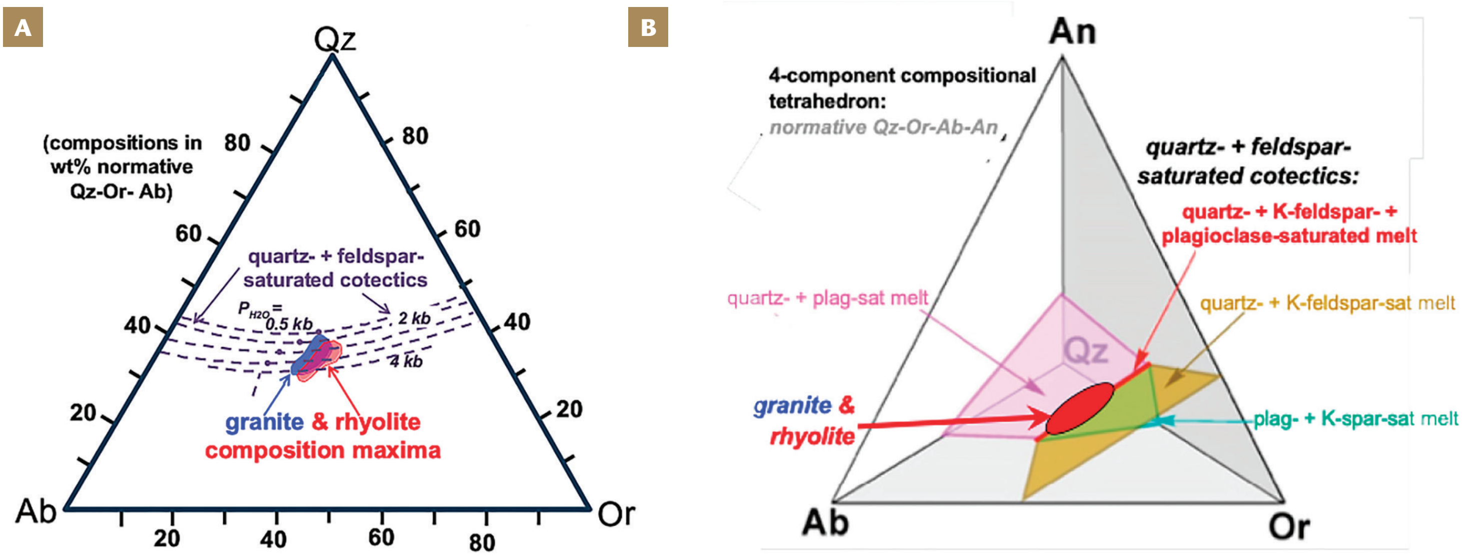

FIGURE 2 (**A**) Ternary phase diagram for simplified "pure" granite-rhyolite system (Ab-Or-Qz + H_2O) (Tuttle and Bowen 1958). Key features are the cotectics—loci of quartz + alkali feldspar-saturated melt compositions in Ab-Or-Qz-temperature space, which vary as a function of H_2O pressure (shown in kb), and the minimum temperature points on the cotectics. Compositional ranges of rocks with normative Qz + Ab + Or > 80% (granite and rhyolite), shown for comparison, cluster at the minima. (**B**) Phase relations shown schematically within Qz-Or-Ab-An compositional tetrahedron; including An reflects the fact that An (calcic plagioclase end-member: $CaAl_2Si_2O8$), although low in concentration, is significant in felsic magma phase equilibria.

and crystallization histories. Widespread and increasingly sensitive radiometric dating has greatly improved knowledge of Earth history in general and magmatic histories in particular (especially using the U-Pb chronometer in zircon). Radiogenic isotope ratios (e.g., $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{176}Hf/^{177}Hf$, $^{206}Pb/^{204}Pb$) of igneous rocks and minerals further constrain the age and nature of magma sources; stable isotope ratios (e.g., $^{18}O/^{16}O$) document contributions from materials that have interacted with cool near-surface materials, especially water. Isotopic data can also provide information about open-system magma processes; for example, mixing of magmas or contamination by host rocks.

Some generalizations about felsic magmas and rocks in space and time:

1. *Through time.* Granites and rhyolites span the last four billion years of Earth's history for which there is a rock record. Their existence during much of the Hadean—the first 540 million years of Earth history, for which no rocks remain—is suggested by the compositions of surviving pre-4-Ga zircon grains in younger sandstones (e.g., Harrison 2020). Granites have exhibited compositional changes through time, but relatively subtly (e.g., Bucholz and Spencer 2019). Trends in rhyolites are more difficult to assess, at least in part because the volcanic record of the early Earth is more poorly preserved than that of plutonic rocks.

2. *Spatial distribution (tectonic settings).* Felsic magmatism, as manifested by granites and rhyolites, although extremely sparse, is present in oceanic basins. Granite *sensu stricto* is very abundant in continental collision zones and in strongly convergent continental interiors, where it commonly is the dominant igneous rock type; it is also fairly common, but less dominant, in zones of continental extension and in typical continental margin arcs, and much less abundant in island arcs. Ratios of rhyolite to granite are near zero in collision zones and fairly high in other settings.

3. *Correlations between compositions and tectonic settings.* Strongly peraluminous granites are mostly found in convergent continental settings, especially collision zones; elsewhere, in subduction-related arcs and extensional settings, most granites are metaluminous to weakly peraluminous. The rare granites in oceanic crustal settings are mostly metaluminous to very weakly peraluminous. Uncommon peralkaline granites and rhyolites are largely restricted to extensional zones on continents and to oceanic islands.

4. *Isotopic and trace element characteristics and constraints (cf. FIG. 3).* Radiogenic isotope ratios unequivocally identify ancient crustal contributions to many granites, especially to strongly peraluminous granites and most clearly to granites in collisional settings. In subduction arc settings, crustal signatures, when present, are less pronounced, in part because subjacent crust is generally younger; in some cases, evidence for crustal contributions are absent, either because the felsic magmas are purely mantle-derived or because the contributing crust is newly formed. Very high $^{18}O/^{16}O$ ratios in some, but not all, strongly peraluminous granites indicate major source contributions from weathered metasedimentary rocks ("S-type"[6]); slightly elevated $^{18}O/^{16}O$ ratios of many granites hint at lesser sedimentary input. Evidence for ancient crustal and/or sedimentary contributions to felsic magmas in primitive oceanic arcs and ocean basins is essentially absent. Isotopic indications of crustal contributions to rhyolites are generally more muted than for granites. Trace element compositions of most granites and rhyolites are permissive of an influence of fractional crystallization, in some cases strongly so. Trace element ratios constrain possible anatectic processes, e.g., high Sr/Y suggests equilibration with high-pressure (deep or subducted) crust with limited plagioclase and abundant garnet (plagioclase sequesters Sr, garnet retains Y). Modern data and interpretations clearly reflect a two-end-member spectrum: mantle derivation, refined by fractional crystallization, versus crustal anatexis (Moyen et al. 2021).

FELSIC CONVERGENCE TO "PURITY": LEUCOGRANITES AND HIGH-SILICA RHYOLITES

Leucogranites and high-silica rhyolites are similar to each other, and distinguished from other felsic rocks by, their "purity." They are almost entirely composed of quartz and feldspars, with minimal mafic minerals

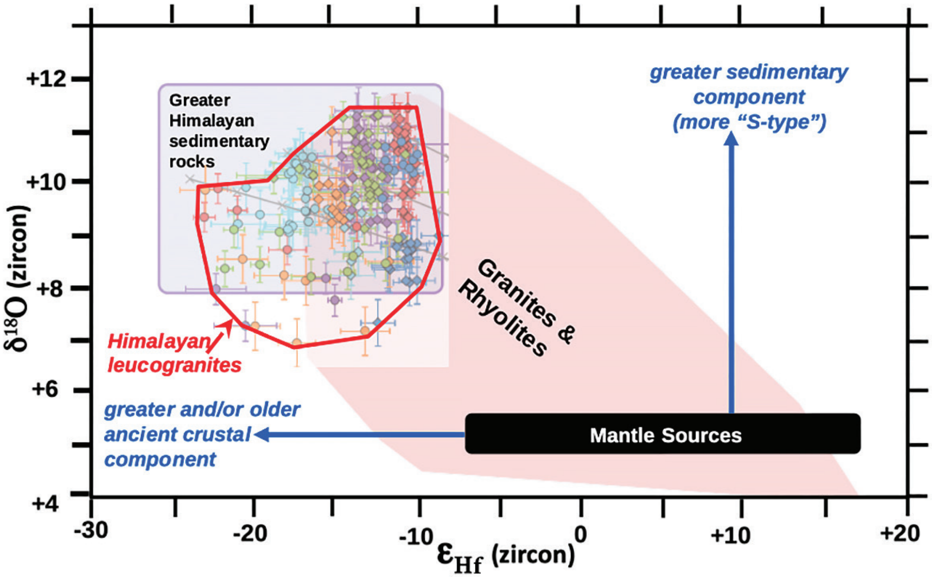

Figure 3 Schematic distribution of zircon O and Hf isotopic compositions of felsic magmas (granites and rhyolites). $\delta^{18}O$ is a value that compares $^{18}O/^{16}O$ in a given material to that of modern seawater; the δ sign stands for parts per mil variations; in zircon, values of ~+5 to +7 suggest magma origin in the mantle or in crust that has not interacted with surface-derived water; values > +7 suggest some involvement of weathered sediment; values ≥+8 to +10 suggest a dominantly sedimentary source. ε_{Hf} compares $^{176}Hf/^{177}Hf$ in a given material to that of chondritic meteorites (~bulk Earth average); the ε sign stands for parts per 10,000 variations; values of <–5 to –10 suggest a substantial ancient crustal source contribution (more negative values are associated with larger and/or older crustal contributions). Data for Himalayan leucogranite zircons and sedimentary rocks of Himalayan crust are from Hopkinson et al. (2017)

and very low Fe and Mg contents. Importantly, they cluster even more tightly around the "granite minimum" (Fig. 2) than other granites and rhyolites, and therefore variation among the ostensibly "pure" highly silicic magmas and rocks is even subtler than among granites and rhyolites in general. They reflect convergent evolution toward the lowest-temperature melt compositions, saturated in quartz and feldspar. But, as emphasized above, the minimum can be reached by either down-temperature or up-temperature pathways, and furthermore, multiple parent materials and processes can be involved in the generation of "granite minimum" magmas (cf. Fig. 4). The subtle variations among leucogranites and high-silica rhyolites, and the correlations of different variants with different crustal and tectonic settings, suggest important diversity in their origins that roughly parallels that of felsic magmas more broadly. Below are some general, rough groupings based on their characteristics, distributions, and inferred origins.

1. *Strongly peraluminous leucogranites*. Most famously, this group includes the Himalayan leucogranites (see following section and the six thematic articles in this issue of *Elements* for more detail). Strongly peraluminous leucogranites are characterized by distinctive aluminous minerals (muscovite, garnet, tourmaline, cordierite); lack high-T anhydrous mafic minerals (pyroxenes); and often form entire intrusions that lack less aluminous, more mafic rocks. They are commonly associated with continental collision ("collisional leucogranite," CLG; Nabelek 2020), and in some cases with strongly convergent interior zones of continent margin arcs (e.g., Chapman et al. 2021). These granites commonly, but not invariably, have radiogenic isotopic compositions (low initial $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, high $^{87}Sr/^{86}Sr$) that suggest major ancient crustal contributions and high $^{18}O/^{16}O$, indicating sedimentary contributions (akin to S-type).

2. *Metaluminous to weakly peraluminous leucogranites*. These leucogranites are widespread as relatively minor facies (dikes, sills, roof zones) in more mafic, metaluminous granitic intrusions in subduction-related continental arc settings (much less common in oceanic arcs) and continental extension zones (e.g., Fig. 1A). They lack highly aluminous minerals but commonly contain minor amphibole and in some cases pyroxene. Oxygen isotopic compositions generally preclude a large sedimentary component; radiogenic isotopic compositions range relatively widely and can permit primitive mantle, juvenile or ancient crustal, or hybrid sources. Fractional crystallization from a less silicic parent magma is commonly suggested by trace element compositions.

3. *High-silica rhyolites*. Most high-silica rhyolites are metaluminous to weakly peraluminous, similar in all respects to the equivalent leucogranites and by implication have similar likely origins (fractional crystallization from diverse less silicic magmas; e.g., Fig. 1B).

Peralkaline high-silica rhyolites occur but are much less abundant than their metaluminous counterparts. Strongly peraluminous rhyolites are of great interest but exceedingly rare (e.g., the Macusani volcanics, Peru; Pichavant and Montel 1988). Interstitial melts, preserved as glass and finely crystallized matrix in crystal-rich volcanic rocks of less silicic compositions (e.g., dacite), are commonly of high-silica rhyolite composition; they thus demonstrate the fractional crystallization pathway to high-silica rhyolite and leucogranite composition.

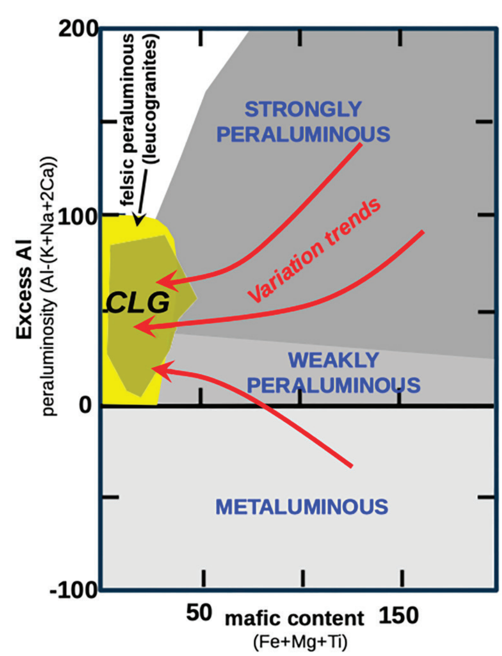

Figure 4 Peraluminosity (Al – [K + Na + 2Ca]) plotted against mafic content (Fe + Mg + Ti) of highly felsic peraluminous granites (leucogranites; yellow field) and potentially related rocks and magmas (variably metaluminous to strongly peraluminous sources, parent magmas, and cumulates). CLG = collisional leucogranite compositions; red arrows converging into felsic peraluminous field represent regional trends of associated rocks. Modified from Villaseca et al. (1998) and Nabelek (2020).

HIMALAYAN LEUCOGRANITES: THEIR PLACE WITHIN THE SPECTRUM OF FELSIC MAGMATISM

Himalayan leucogranites do not typify Earth's high-silica igneous rocks in general, or leucogranites specifically. Yet they are almost certainly the best-known examples of such rocks—as evident from the fact that they are the subject of this entire issue of *Elements*. Why is there such emphasis on them? Where do they fit in among leucogranites—are they unique, or do they have closely similar counterparts?

Most obviously, although Himalayan leucogranites and the widespread metaluminous to weakly peraluminous leucogranites share major element compositions that approximate the granite minimum, they differ in ways that preclude a close relationship. In addition to the difference in aluminosity, they differ critically in petrogenetically diagnostic isotopic characteristics (e.g., Fig. 3). Similarly, peralkaline leucogranites and high-silica rhyolites are clearly distinct from Himalayan leucogranites with respect to both habitat and details of petrochemistry and mineralogy.

The Himalayan leucogranites have affinities with several important, partially overlapping granite groupings, all of which at least partly comprise strongly peraluminous leucogranites:

1. The closest match is to the collisional leucogranites (CLG)—in fact, Himalayan leucogranite is the most prominent representative of this group, which includes examples in ancient continental collision zones that are up to at least three billion years old (e.g., Frost and Da Prat 2021; Nabelek 2020).
2. The belt of ~40–80 million-year-old granites exposed from northwestern Mexico to British Columbia (the North American Cordilleran anatectic belt of Chapman et al. 2021 [Fig. 1C]) includes common peraluminous granites and is very similar in scale to the Himalayan leucogranite belt.
3. Rocks referred to as S-type include fairly common leucogranites, are in most cases strongly peraluminous, and are well represented in collision zones. In fact, CLGs are referred to as S-type. However, so-called S-types have been described in many other settings as well, and the criteria applied for this designation vary widely; many examples appear not to be entirely derived from sedimentary sources, and some might even be devoid of a sedimentary component altogether (e.g., Miller 1985; Hopkinson at al. 2017).

An interesting speculative possibility is that Himalayan-like, sediment-derived granitic magmas existed more than four billion years ago (Harrison and Wielicki 2016; Jiang et al 2024). This is based on the only tangible relics from the Hadean, >4-Ga detrital zircons whose compositions and mineral inclusions suggest crystallization from low-temperature, "wet," peraluminous magmas.

Further comparison with putative Hadean granites is not possible. The similarities between the North American Cordilleran anatectic belt and the Himalayan leucogranite belt are compelling, but there are also stark differences in addition to their contrasting tectonic settings. Coeval intrusions in the Himalayan belt are all peraluminous granite and mostly strongly peraluminous leucogranites with high $^{18}O/^{16}O$, whereas a large proportion of plutons in the Cordilleran belt are metaluminous to weakly peraluminous and less silicic, and even the strongly peraluminous leucogranites rarely appear to be entirely derived from mature sedimentary sources (Miller and Barton 1990).

Himalayan leucogranites are treated informally as the "type" collisional granite, and justifiably so: they are well exposed in an enormous, well-studied, active zone of collision, and they have distinctive petrologic characteristics. Other examples (e.g., the Hercynian of Europe; the Black Hills, South Dakota, USA [Fig. 1D]; Stone Mountain, Georgia, USA) share strongly peraluminous elemental compositions and mineralogy (tourmaline seems particularly characteristic) and isotopic ratios that suggest an anatectic origin. Exposures of other CLGs are less extensive and informative than those of the Himalayan leucogranites, in large part because they are much older and have been modified by complex post-collision processes.

The definitions used for S-type granite are highly variable and often loose, resulting in unsatisfying petrogenetic comparisons and generalizations. Hopkinson et al. (2017) make a convincing case that Himalayan leucogranites, in contrast to most other proposed "S-types," are "pure(ly) sediment-derived" and provide a "suitable type locality for 'S-type granites.'" They point out that for most rigorously studied examples (e.g., those of the Australian Lachlan fold belt), there is good evidence for non-sedimentary (often mantle) contributions. In addition to strongly peraluminous composition, they advocate convincingly for using combined zircon Hf and O isotopic ratios as the critical criterion for assessing crustal sedimentary origin: elevated $^{18}O/^{16}O$ (weathered sediment), relatively low $^{176}Hf/^{177}Hf$ (with values appropriate for the age of the regional crust), and no trend toward Hf-O compositions of potential mantle contributions (Fig. 3).

From my perspective, Himalayan leucogranites, although not typical representatives of leucogranites or of extremely felsic rocks generally, uniquely serve as a well-characterized, essentially end-member, type example of

1. ancient sedimentary crust-derived magmas: S-type, anatectic granites; and
2. collisional leucogranites (CLGs).

As well-exposed, young, "type" examples of collision-related granites, they provide unique opportunities for assessing processes of anatectic magma generation (sources, melting reactions, conditions, role of fractional crystallization versus preservation and emplacement of primary magmas) and tectonic controls, feedbacks, and implications (e.g., relations to crustal thickening and thinning, facilitating of and guidance by deformation processes). This issue of *Elements* provides cutting-edge insights into these questions.

ABOUT THE AUTHOR

Calvin Miller grew up on the Peninsular Ranges batholith in southern California, USA, fascinated by the granite boulder landscapes there and in the nearby Mojave Desert. Fortunate experiences in volcanic terrains on wide-ranging family trips cemented his deep appreciation of magmatically formed scenery and stimulated his curiosity about the processes behind it. Granites (*sensu lato*) remained central throughout his formal education (Pomona College BA; George Washington University MS; UCLA PhD, all in the USA). During his 41-year teaching career at Vanderbilt University, USA, he maintained his focus on felsic magmatism. But—like many felsic magmas—he migrated upward through the crust, beginning with peraluminous granites in ancient deep-seated crust of the Mojave and Appalachian Mountains (somewhat similar to Himalayan leucogranites); then to younger, upper crustal plutons in Nevada; and finally to young and active volcanism and associated shallow granites in Iceland, the southwestern USA, and the Cascades (cf. Fig. 1).

ENDNOTES

1 Felsic: composition dominated by quartz + feldspar or, in the case of melts, their chemical constituents; silica (SiO_2)-rich; “silicic” is approximately equivalent to felsic.

2 Granite in the strict sense of the term refers to phaneritic (constituent grains visible to the naked eye) rock dominated by quartz and feldspar (potassium-rich ± plagioclase). “Granitic rock” (or granite in the broad sense of the term) is a more comprehensive expression that also includes rocks with less quartz and little or no potassium feldspar. Rhyolite has an aphanitic matrix (glass, or constituent grains not visible to the naked eye—interpreted to reflect rapid cooling) and has an elemental composition essentially equivalent to granite *sensu stricto*.

3 Granites, and rhyolites, form from magma (melt ± crystals ± bubbles). This is obvious for rhyolites, which are mostly erupted, but until the mid-20th century, the magmatic origin of granite was a subject of intense debate. The fact that textures, and to some extent compositions, of deep-seated granites may be modified after solidification is an ongoing matter of discussion: should such modified granites be regarded as strictly magmatic? Regardless, the initial magmatic origin of even such modified granites is now rarely disputed.

4 Dark mineral % is commonly referred to as “color index,” which, although a misnomer (because color is not involved), is a handy term for an important visible characteristic: leucogranites are low-color index granites.

5 The atomic ratio Al/(2*Ca + Na + K) is commonly expressed as A/CNK (metaluminous < 1.00 < peraluminous). The divide between “weakly peraluminous” and “strongly peraluminous” is considered to be important, but it is not uniquely defined. A value of 1.10 is fairly widely used (thus, A/CNK ≥ 1.10 is strongly peraluminous).

6 Chappell and White proposed the designation “S-type” in 1974 to apply to granites whose characteristics suggested origin from a chemically mature (weathered) sedimentary source. They proposed multiple criteria to indicate sedimentary parentage, the most important of which was strongly peraluminous composition. The S-type designation has been widely applied ever since, but unfortunately, there has been little consistency in the criteria used. A combination of strongly peraluminous composition and high $^{18}O/^{16}O$ (“heavy” oxygen) provides the strongest evidence for true S-type origin.

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