Controls on the concentration of zirconium in magmatic-hydrothermal systems

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As zirconium is a high field strength element, it is incompatible and consequently reaches its highest concentration in the continental crust (over 150 ppm versus ~ 10 ppm in the mantle), where it occurs most commonly as the accessory mineral, zircon. Although zirconium (as zircon) is typically undersaturated in basic magmas, it saturates at high temperature in acidic magmas, despite its low concentration, because of the high activity of silica. In peralkaline magmas, even those of granitic composition, the formation of alkaline zirconosilicate complexes increases the solubility of zirconium by orders of magnitude, leading to the development of magmas with percentage level concentrations of zirconium. Instead of saturating with zircon, these magmas crystallise alkali zirconosilicates, such as vlasovite ($Na_2ZrSi_4O_{11}$), at relatively low temperature. Indeed, the crystallisation of zirconosilicates, instead of zircon, has led to the classification of the resulting rocks as agpaitic, rather than miaskitic, the term applied to rocks in which the zirconium is hosted by zircon. Until relatively recently, zirconium was also considered to be an immobile element, i.e., to not be mobile in hydrothermal fluids. As a result, it has been used extensively in igneous petrology, even for hydrothermally altered rocks, as an element with which to trace magmatic evolution. Numerous studies, however, notably those of Zr-rich systems, have shown that zirconium can be mobilised hydrothermally, supplying evidence of the occurrence of zircon in equilibrium with other minerals in hydrothermal veins and of more complex zirconosilicates having replaced primary zirconium minerals at subsolidus conditions. Here, we explore the behaviour of zirconium and the controls on this behaviour at conditions ranging from those of magmas, including peralkaline magmas, to those of high and low temperature hydrothermal fluids. In so doing, we provide new insights into the processes that concentrate this increasingly important green element to potentially economic levels.