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Constraints on the Locations of Volcanic Arcs (August Love Medal Lecture)

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Partial melting of the mantle in subduction zones is a leading mechanism of chemical differentiation of the Earth. Whereas the broad outlines of Earth's other major system of partial melting – the oceanic ridges – seem clear, the greater dynamic and thermodynamic complexities of subduction zones obscure fundamental aspects of the system, in particular the conditions under which melting initiates and the pathways by which the melt travels towards the Earth's surface. The vast majority of studies of these problems rest on interrogation of petrological and/or geochemical data on rocks erupted at the volcanic arcs, but this approach has resulted in the co-existence of mutually incompatible explanations for the locations of the volcanic arcs. An alternative to the complexity of petrological and geochemical argument is to focus on the geometrical simplicity of volcanic arcs. The observations (i) that the fronts to volcanic arcs fit small circles to within about 10 km and (ii) that the depth to the slab beneath the arc fronts correlates negatively with the descent speed of the slab provide a strong clue to the melting processes occurring at depth. Localized release of fluids by reactions taking place near the top of the slab are incapable of explaining this correlation. However, scaling analysis based on the physics of heat transfer in the wedge shows that such a correlation is predicted if the location of the arcs is controlled by a temperature-critical process taking place in the mantle wedge above the slab. Numerical experiments using realistic physical properties for the mantle in subduction zones support the scaling analysis and, when combined with the observed positions of the arcs, strongly imply that the arcs are localized above the places where the mantle wedge reaches a critical temperature of $\sim$1250o-1300oC. Therefore, despite the importance of hydrous fluids for the overall magmatic budget in subduction zones, it is melting in the region above the anhydrous solidus that determines the location of the arcs. Heat carried by magma rising from this region is sufficient to modify the thermal structure of the wedge and determine the pathway through which both wet and dry melts reach the surface.