meetabst/komaport.lwp Extended abstract of a 30min talk given at conference on "Komatiites, norites, boninites and basalts"(Dr R.Peter Hall, organiser) University of Portsmouth, UK. 16-17 December 1999. (Owing to an error by the organiser, only the 1-page website-intended abstract was included in the meeting abstract book, but copies of the version below were circulated at the meeting.)

The early history of the Earth and Phanerozoic plate tectonics; some new keys to the mantle state and tectonic environment of komatiite genesis and Archaean greenstone belt evolution

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The direct study of Archaean komatiites is hampered by a screen of petrological alteration and by wide uncertainty about the defining tectonic environment and mantle state (apart from a presumed higher temperature). In this contribution I seek to narrow the latter uncertainties by approaching the matter from 'the outside', i.e. from both ends of the Earth's history. In brief I think the Archaean mantle was markedly wet but that komatiite melts managed to lose that component (rich in mineralisation and with a komatiitic geochemical signature) before eruption. Paradoxically this wetness opens the door to the Archaean applicability of major aspects of Phanerozoic plate tectonic environments.

The logic runs like this. The state of the Archaean mantle was inherited from Earth formation, notably core formation. Neither of the two existing models for doing that is viable. The two-stage accretion model of H.Wänke (Wänke et al 1984) requires fine tuning that is too far-fetched to achieve for all the terrestrial planets because the condensation temperature for silicates and Fe differ by only ~18K. The popular percolation-through-the-mantle model won't work either because the mantle Ni:Co is chondritic (~20), and (as evidenced in magmas) hasn't changed since 3.8Ga (Delano & Stone 1985); but Ni partitions 10 times more readily than Co into liquid Fe metal, so core percolation would have given the mantle a ratio of ~2. Moreover the high rate of convective overturn would give little opportunity for percolative separation. A suggestion that the partition coefficients may even up at high pressure is of little avail because the highest degree of melting (and therefore the most percolative separation) would inevitably have been at shallow depth and low pressure.

The percolation model has faced a similar problem with the eight highly siderophile elements (HSEs) Au, Re and the PGEs, in that they still have near-chondritic relative abundances (despite very different metal/silicate partition coefficients) and a depletion far less than their highly siderophile character would cause in the model. This has led to the 'late veneer' hypothesis (see O'Neill & Palme 1998) which argues that the present mantle abundances of these elements derive from a post-core-formation addition of a late accretionary veneer, rich in HSEs and water. The nebular derivation and provision of such a composition has never been elucidated, however, and is out of the question if, as the percolation model requires (see below), core formation was not complete until long after the solar wind had driven the nebular remnant out of the system.

These problems are easily overcome. I argue that the core was formed by 'subduction' of surface Fe, derived by chemical reduction, at the time of eruption, of magmatic (convective overturn during accretion) FeO by the nebular 'atmosphere' surrounding the protoplanet. For this reaction to proceed, the gas density around the protoplanet may need to have been rather higher than has usually been envisaged but this is consistent with the only limited loss of volatiles from chondrules (small melt droplets) in chondrites (Hewins 1997). Star-forming clouds have very high dust-caused opacity; this dust both radiates away the nebular heat (astronomers detect them by their infra-red emission) and would provide an environment around each protoplanet that primarily arose from accretionary (not solar) heating. So core formation could proceed in each of the terrestrial planets with little regard to orbital distance. Metallic (including FeS) loading of the convective down-going limb would ensure that the loop went down as far as the growing core.

In the case of the Earth the reaction produced many (potentially >400) ocean volumes of H_2O, from which the Earth acquired a wet mantle by the 'subduction' of hydrated primitive crust. (There is good evidence that present-day subducted crust is only partly dried out by sourcing arc magmatism.) Core formation necessarily ceased when the nebula departed at ~4561Ma, the age of the youngest chondrules known. Hitherto, based on the percolation-through-the-mantle model for core formation, the 60-100Ma duration of Pb extraction from the mantle, derived from the complex of Pb-ended decay systems, has been regarded as defining the duration of core formation (see McCulloch & Bennett 1998). I propose that in the new circumstances Pb transfer to the core took place across the core-mantle boundary (CMB) during the ensuing 60-100Ma until it was sealed by formation of the seismological D" zone at the base of the mantle by the accumulation of subducted primitive/'oceanic' crust. (This sealing function of D" is necessary anyway because depletion of mantle Pb has to be halted early on. So plumes cannot start at the CMB, as many people like to believe.) This early 'burial' of mantle differentiates has the potential to explain an early drop in Rb/Sr and the (still debated) rise in epsilon Nd by 3.8Ga (Moorbath et al 1997; McCulloch & Bennett 1998) without much manufacture of continental crust.

Mantle wetness lowered its viscosity ~100-fold (relative to present mantle)(Karato & Wu 1993) and ensured that whole-mantle overturn was amply able to remove early-Earth heating without resort to plumes. The wetness had a further effect on the mantle thermal environment in that it would have increased the measure of interstitial melt fluid present below the lithosphere. Based upon recent measurements of thermal conductivity of silicate melt (Snyder et al 1994 and sequels), each 1% of interstitial melt would reduce the thermal conductivity of the bulk rock by ~10%. Another property of interstitial melt is that any water partitions strongly into it, thus removing the water-weakening of the mineral fabric and potentially raising its strength by two orders of magnitude (Karato 1986; Hirth & Kohlstedt 1996). Thus the standard perception that the interstitially-melted zone would, by definition, be mobile and therefore have an adiabatic temperature gradient through it is now unsound. Such a zone would, on the contrary, have a much steepened (superadiabatic) thermal gradient through it. Thus, on the one hand, the acquisition of the eruption superheat widely inferred to have been possessed by komatiites becomes much easier to explain and, on the other, the not-so-steep metamorphic temperature gradients inferred from crustal sequences becomes attributable to the insulating effect of the underlying low-thermal-conductivity zone.

These insights into Archaean physical circumstances enable us to entertain the possibility that Phanerozoic-style plate tectonics may be relevant. My work on the subduction process, in particular, during the past 20 years has highlighted the widespread Phanerozoic occurrence of two major processes, basal subduction tectonic erosion (STE) and post-subduction magmatism (PSM) (e.g. Osmaston 1985, 1992a,b, 1994, 1995, 1997, 1999b) and their possible relevance in the Archaean (1992b, 1999a).

STE stems from recognizing that the plate downbend mechanism is not one of elastic flexure but is one of escalator-like step faulting, consistent with widespread through-plate seismic rupturing, but is still capable of explaining the presence of outer rises. Step-throw evolution beneath the hanging wall continually entraps and removes slivers of the hanging wall. This STE mechanism demonstrably (on Phanerozoic examples) has the ability, when the subducting plate is younger than 70Ma, to shallowly and rapidly undercut margins to distances approaching 1000km (Laramide USA), at rates of the order of 300km in 10Ma (Andes). To be able to do this the young subducting plate must have buoyancy, achievable if a substantial thickness of interstitially melted low-velocity zone is regarded as an integral part of the young plate. That is rendered possible by the previously-discussed physical properties of such material. In turn, this means that the subducted plate has a high heat content. When such young-plate subduction is halted the heat can soak upward, reheating the plate's thin lithosphere and causing widespread, wholesale melting of the subducted crust, yielding a widespread silicic/granitoid event in the crust of the upper plate.

This is PSM, hitherto much discussed as 'post-*collision* magmatism', but not actually dependent upon the occurrence of collision.

In the Archaean there was certainly no shortage of young, hot, rapidly subducting plates, so widespread and rapid STE would have been likely. Any interruption would then have produced widespread PSM, seen in the form of TTG intrusion. But why the interruptions if the mantle was very hot? The answer seems to be that towards the end of the Archaean the much-enhanced heat extraction capability of the wet, low-viscosity mantle had markedly lowered the mantle temperatures, rendering subduction liable to interruption by, for example, the arrival of a cratonic nucleus. The important point is that the resulting PSM had the effect of advecting heat to the surface that would otherwise have been returned to the mantle heat budget, had subduction continued. This, in turn, rendered interruptions easier to cause. This is interpreted as the reason for the dramatic increase in frequency of TTG events and continental crustal additions as the Archaean drew to a close.

Ultimately, just after the end of the Archaean, this precipitated a mantle heat budget crisis and the convective mode changed to one in which the lower mantle became the recipient of subducted upper mantle differentiates (e.g. upper mantle epsilon Nd began to rise much more rapidly) and water (thus drying out the upper mantle), but with relatively little exchange in the other direction.

That transition is well-defined in that it resulted directly in major other changes, such as:- onset of massive unroofing of cratons, great reduction of atmospheric CO_2, first glaciations, unparalleled BIF deposition, rise of oxygen. Details and linkages of all these have been submitted for publication elsewhere. A principal feature of the transition is that increasingly, over more than a decade, it has become clear that there are no good quality zircon dates either for greenstones or for orogenic granitoids in the interval 2.45-2.22Ga (Windley 1995; Condie 1997), here interpreted as a complete hiatus in upper mantle convection and plate tectonics, marking the mantle heat budget crisis.

Komatiites and related basalts show many compositional features characteristic of wet melting, so a subduction-related environment has often been proposed (Burke et al 1976; Allègre 1982). A wet mantle undoes that particular tie and I argue that greenstone belts were indeed generated at the Archaean equivalent of MORs, but sometimes as the passive margin of a craton (e.g. Zimbabwe greenstone/craton unconformity). The original thickness of that 'oceanic' crust is indeterminate, but probably exceeded 25km until the very late Archaean, with a lower part consisting mainly of komatiite. Subsequent subduction beneath that margin put the greenstone belt into a forearc situation where rapid STE beneath it removed in most cases the lower part of the section including the sheeted dykes, ready for TTG intrusion from PSM, as outlined above.

Notable wet-melting chemical features of komatiites are the constant association of felsics, wide occurrence of silicified komatiite tuff, presence of negative Nb anomalies (Arndt 1994), and the high FeNiCo content and associated sulphide mineralisation. The latter may be explained as a consequence of the flushing of sulphur from the mantle, which appears to be facilitated by wet melting of the mantle (Weichert 1999). On this basis the subsequent drying-out of the upper mantle is recorded by the major drop in the Ni and Cr content of basalts since ~2Ga (Cattell & Taylor 1990). Interestingly, the -Nb anomaly in komatiites may have faded in the late Archaean because of a complementary +Nb anomaly that had built up in the mantle source (Puchtel et al 1999); this is still seen as a relict +Nb anomaly in the present OIB-source mantle (but is currently interpreted as wisps of subduction-modified oceanic crust in the source region). Similarly the U:Th* in MORB suggests a mantle whose ratio has been modified by wet extraction (which the present MORB process certainly isn't).

*<u>Erratum</u> (added Feb 2000) This ratio should read "Nb:U", which is the same in both IOB and MORB, at 1.5 times chondritic.

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