The evolution of *mu* and the isotopic composition of lead in the early solar system and young Earth

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A loss of volatile elements during the condensation of the solar nebula is the main fractionating process of CM, CO, CV and ordinary chondrites. These building blocks (constituting 85% of meteorite falls), from which the terrestrial planets accrete over the next 10-40 Ma, retain CI refractory element relative abundances but display deficiencies in their volatile elements correlating with condensation temperatures. As a consequence, these earliest condensates from the cooling solar nebula display, on average, an order of magnitude increase in *mu* (m = $^{238}U/^{204}Pb$) from ~0.1 to ~1. Additional volatile element loss and further increase in *mu* continues to occur from impact melting on various scales throughout the accretion process. Differentiation of planetismal bodies, such as metal-silicate separation, also produces chemical heterogeneity that may affect *mu*. Our best value for the bulk Earth *mu* comes from analyses of terrestrial Pb, which has evolved uniformly in isotopic composition over geologic time and provides an integrated *mu* value of ~9 for the crust and upper mantle. However, the possibility of other reservoirs in the core and lower mantle has hampered efforts to precisely determine the total bulk Earth *mu* value.

New and published meteorite data are presented to examine the effects of volatile element loss on U-Pb isotope systematics in the early solar system. Recent studies using the extinct Hf-W chronometer have shortened older estimates of the time between the origin of the solar system and the separation of the Earth's core. Accordingly, some proposed solutions to the Pb paradox—the positioning of both the Earth's crust and mantle to the right of the Geochron on Pb-Pb diagrams—that were based on a >50 Ma time span for Earth's accretion and core formation, are invalid. Allowing only 10-20 Ma for production and loss of radiogenic Pb before being retained by the Earth causes but minor rotation of a Geochron anchored to Canon Diablo initial Pb. Scenarios for the evolution of *mu* in the early solar system and young Earth, and comparisons with Mars, the Moon and other meteorite parent bodies will be given. It is concluded that the Pb paradox as well as the *kappa* conundrum are due predominantly to long-term storage of radiogenic Pb in, and decoupled U, Th, and Pb transport among terrestrial reservoirs. In contrast, *mu* values are established at the time of planetary formation by the accretion of material that has suffered earlier and concurrent loss of volatile Pb, and can differ significantly among the terrestrial planets.

Relative and absolute timescales in metamorphism - Observations, calculations, estimations

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Presently there are several ways to record metamorphic processes through time. (i) In first order, metamorphic petrology is needed to set constraints on the relative record of metamorphic processes, and to provide information about the prograde and retrograde P-T evolution, and the metamorphic peak. Presently, detailed P-T paths can be reconstructed by comparison of information obtained from thin section observations (assemblage sequences, mineral zonations, mineral growth and resorption textures) and such gained by thermodynamic calculations, e.g. by using quantitative phase diagrams. (ii) Second, detailed petrographic observations are necessary to relate the evolution of rock forming minerals - used for P-T path reconstructions- to the evolution of accessory minerals commonly used for geochronology. In this context, trace element (TE) zonation patters of rock-forming and accessory minerals can be useful. However, their application as thermometers and as "correlators" must be considered with caution, because their incorporation in accessory and rock forming minerals, as well as their distribution among minerals on a thin section scale is far from well understood. These problems can strongly influence the interpretation of P-T-t paths as well as dating results (e.g. Lu-Hf dating of metamorphic garnet). (iii) Dating of accessory and rock-forming minerals will provide evidence about the absolute timing of metamorphic processes, and the duratiuon of orogenies. In addition it allows to discriminate between mono- and polymetamorphic evolutions, which cannot be distinguished unambiguously on the basis of structural and petrological data. Furthermore, the combined use of different dating techniques may allow to estimate cooling rates of metamorphic rocks, and our growing understanding between the evolution of accessory and rock-forming minerals to estimate the timing of prograde P-T paths. (iv) The use of T-t dependent processes, like mineral growth rates and diffusion rates, can set additional constraints on the timing of metamorphic processes. E.g. the knowledge of mineral growth rates may help to clarify the timing of prograde P-T histories, whereas diffusion rates can be used to model cooling rates of orogenic processes.

Finally, I should emphasize that only the combination of different techniques will lead us to a true understanding of the crustal evolution through time.