

**U-Pb CHRONOMETRY OF METEORITES: NEW OPPORTUNITIES, NEW LEVEL OF COMPLEXITY.**

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**U-Pb, what's new?** U-Pb was among the first (along with K-Ar) isotopic dating methods applied to meteorites. What makes the impact of today's U-Pb dating different?

First, the number of interesting meteorites that deserve a detailed study greatly increased, mainly due to meteorite recovery from Antarctica and deserts. In some cases, in place of a unique meteorite (e.g. AdoR during the consortium study of 1975-76), we have groups of meteorites with diverse compositions, structures and ages (e.g., 13 angrites are known today). Studying compositional and age patterns in such a group can tell us more about early solar system history. The number of meteorites studied with a variety of isotopic methods is also rapidly increasing.

Second, modern techniques of Pb isotopic analysis (plasma ionization mass spectrometry, and double-spike TIMS) give much improved precision and reproducibility, and can yield <sup>207</sup>Pb/<sup>206</sup>Pb dates with precision as high as 0.1-0.2 Ma under favorable conditions. Better methods of common Pb removal help to improve precision and accuracy.

Third, improvements in the blanks and ionization efficiency using special reagents (e.g. high efficiency silicic acid emitter) in the last few years, allow analyses of much smaller samples to obtain high precision.

Many complexities in U-Pb systematics, which appeared insignificant compared to analytical errors in the past, are revealed at the new level of precision, and must be considered in order to turn <sup>207</sup>Pb/<sup>206</sup>Pb dates into meaningful ages. Here are some of the questions we have to address:

**Inter-laboratory standardization and other analytical issues.** Ages of the same minerals from the same meteorite, determined using the same isotopic system but different techniques (e.g. TIMS vs. MC-ICPMS, dry plasma vs. wet plasma) or at different laboratories, vary in many instances well outside of the claimed error limits. Understanding and eliminating

these variations by inter-laboratory standardization and calibration is essential for the progress of cosmochronology. A three-fold approach is required to achieve inter-laboratory reproducibility. First, we need to prepare standards that are both homogeneous and as close in composition to the samples as possible, and to make sure that the influence of all sources of errors on standard and sample analyses is the same. Second, we need to explore whether radiogenic <sup>207</sup>Pb/<sup>206</sup>Pb ratios can be influenced by extensive leaching (such a possibility was suggested for zircons). Third, we have to revise our methods of data reduction to make certain that the total errors include all individual sources of errors, and account for their correlations.

**Evolution of the protoplanetary disk - what are we dating?** If Pb was completely lost from the system (e.g., a mineral) during, or after, formation, and the U-Pb system subsequently remained undisturbed, then we would date that episode of Pb loss. In a system cooling from hot gas, we would date the time at which Pb retention began. In a system being heated from cold dust to its melting point, we would date the time of volatile loss. If the Pb isotopic composition was completely homogenized between all minerals, then we would date the event that caused homogenization.

But what if there were multiple episodes of U-Pb fractionation, or separation and/or homogenization of Pb were incomplete? This is a likely situation for chondrules, which could have exchanged matter with nebular gas, and could include igneous material along with melted nebular condensates [e.g., 1, 2]. If the total duration of multi-episodic evolution was short compared to the dating error, then we can consider the integral chemical effect to all be of one episode, and use a conventional single-stage approach to age calculation. As precision of the dates increases, the single-stage approach becomes invalid. As the typical error of the dates becomes much shorter than the lifespan of the protoplanetary disk, consideration of a multi-stage

evolution becomes a standard requirement in U-Pb dating.

A related problem can affect dating of angrites and eucrites, which come from volatile-depleted asteroids. Even a short time period between volatile loss (during, or shortly after, accretion) and crystallization of angrite/eucrite parent bodies could have been sufficient to produce measurable amounts of radiogenic Pb with very high  $^{207}\text{Pb}/^{206}\text{Pb}$  ratio. During subsequent magmatism and impacts, this anomalous Pb can be redistributed and embedded into other minerals, or deposited in grain boundaries. The excess, or deficit, of such Pb (tentatively called “aborted high- $\mu$  Pb”, also referred to as “parentless Pb” in Lunar soils and breccias) can produce anomalously old, or anomalously young,  $^{207}\text{Pb}/^{206}\text{Pb}$  single-stage dates. Possible uneven distribution of such Pb between minerals further complicates the situation.

Closed system behavior can be verified by comparing  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{238}\text{U}/^{206}\text{Pb}$  dates, but we need to develop methods of removing damaged parts of crystals as efficient as air abrasion and chemical abrasion used for zircons.

**Dating geological history of asteroids.** In order to date asteroidal processes, such as cooling, metamorphism, aqueous alteration, and disruption by impacts, we need to separate the effects of volume diffusion, alteration, and shock on the U-Pb system in primary and secondary minerals. Interpretation of the data critically depends on the availability and quality of experimental data. The database of experimentally determined rates of Pb diffusion in minerals that contain U and radiogenic Pb in meteorites has been recently expanded [e.g. 3], but experimental data on alteration and shock effects on the U-Pb system are still scarce or non-existent.

Knowing the distribution of U between meteoritic minerals is equally important for understanding effects of diffusion, alteration, and shock. The current database of U distribution in meteorites is quite insufficient, both in quantity and quality. Detailed studies, using preferably high-sensitivity ion microprobes, are required.

Re-distribution of U and diffusion of Pb should be considered together. This is demonstrated by the meaning of U-Pb data from chondritic phosphates. Phosphates in many type 6 chondrites contain all the U of the sample, and the process we date is diffusion of Pb out of the phosphate crystals during high-temperature metamorphism. In contrast, phosphates in type 4 chondrites contain only a small part of the U of the sample, the rest is in silicate minerals. We are dating migration of U, or possibly growth of phosphate minerals. When we compare Pb-isotopic dates with the

readings of other isotopic chronometers, in particular in meteorites that came from metamorphosed parent bodies, we need to be sure that we date the same event with both isotopic systems.

**Possible heterogeneous  $^{235}\text{U}/^{238}\text{U}$**  in the early solar system may render  $^{207}\text{Pb}/^{206}\text{Pb}$  dates inaccurate. Such heterogeneity may be caused by the presence of  $^{247}\text{Cm}$ , or by addition of U with isotopic composition different from that in the nebula from a late supernova ejection (analogous to, and possibly brought in together with  $^{60}\text{Fe}$  [4]). Precision of U isotopic analyses performed in the 1970's and early 1980's, which confirmed homogeneity of  $^{235}\text{U}/^{238}\text{U}$  in the Solar System [e.g. 5], is not sufficient at the current level of precision of U-Pb dating (the  $^{235}\text{U}/^{238}\text{U}$  ratio has to be determined with a precision of 0.01-0.02%). There are recent high-quality U isotopic determinations at this level of precision [6, 7], but many key meteorites and their components (e.g., CAIs) have not yet been studied.

**Providing reliable age benchmarks** for extinct nuclide chronometry of the early solar system is one of the main goals of U-Pb dating of meteorites. Having multiple “absolute” age reference points for each extinct nuclide chronometer allows direct testing of heterogeneous vs. homogeneous distribution of the parent nuclide, as well as detecting element migration and disturbance of extinct nuclide chronometers. The requirements of meteorites that can serve as age reference points are, however, very high. They are similar to the requirements of minerals for decay constant determination by age comparison [8]. Discovery of many new meteorites, together with development of analytical methods that combine high precision with improved throughput, improves our chances of establishing new, and better age benchmarks for the early solar system timescale.

**At the MetChron 2007 meeting**, we need to exchange information about methodology and the application of U-Pb geochronology to meteorites, to outline tangible goals for the coming several years, and find appropriate and acceptable tests to inter-calibrate extinct and extant nuclide chronometers. We also need to get our techniques ready for dating Lunar, Martian or asteroid samples, and materials such as those delivered by the Stardust mission, from future space programs.

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