100 years of geochronology: a look back and two ahead

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Exactly a century ago, E. Rutherford had the idea that alpha particles emitted by radioactive uranium could be accumulated in minerals, thus making it possible to determine a mineral's age by physical means (Phil. Mag. 12 (Oct. 1906) 348-371). An exciting century started for the geological sciences. Some papers, besides Rutherford's alley-opener, left a deeper mark than others, when viewed in hindsight.

In the post-WWII years, A.O. Nier revolutionized mass spectrometry by developing new sources for rare gases and for thermal ionization of solid elements (Rev. Scientif. Instr. 18 (1947) 398-411). In a series of papers over the following decade, he determined the isotopic ratios of several dozen elements. This laid the foundation both for precise analyses and for the first routine isotopic age determinations.
In these same years, W.F. Libby (Science 109 (1949) 227-228) developed the radiocarbon dating technique: for the first time, historical legends and late prehistorical remains were accessible to quantitative validation. Later massive improvements (foremost the development of accelerator mass spectrometry, AMS) have extended the radiocarbon dating range to 50 ka and more, making it one of the most widespread chronometers in Quaternary geology.
The discovery of a ^{129}Xe isotopic anomaly in some meteorites due to decay of protosolar, extinct ^{129}I (J.H. Reynolds, J. Geophys. Res. 65 (1960) 3843-3846) spawned two alleys of fruitful research. On one hand, the analytical approach of analyzing rare gases in irradiated samples led to the development of the ^{39}Ar-^{40}Ar technique (C.M. Merrihue & G. Turner, J. Geophys. Res. 71 (1966) 2852-2857), one of the most widely used dating tools today. On the other hand, further search for other extinct radionuclides led cosmochronologists to establish the link between isotopic anomalies at the sub-permil level in many elements, and supernovae and other modes of galactic nucleosynthesis (G.J. Wasserburg, Earth Planet Sci Lett 86 (1987) 129-173).
The exploration of the moon, initially a matter of political prestige, provided unprecedented funding to enable suitably precise and accurate measurements on these unique rocks. New dating methods (such as Sm-Nd: G.W. Lugmair, Meteoritics 9 (1974) 369) were invented in the wake of enthusiasm over unlimited opportunity. Multi-isotopic investigations proved their vast superiority. Cosmo- and geochemistry of radiogenic systems came of age (see Nägler, this meeting). Size limitations of lunar samples forced analysts to improvements that later benefitted the terrestrial samples as well. Rare gas analyses obtained with a focussed laser beam were the first successful attempt at obtaining spatially resolved isotope data within individual mineral grains (M.N. Munk, in: Meteorite Res. (P.M. Millman, ed.), Reidel 1968). Intra-grain mapping of ^{39}Ar-^{40}Ar age data soon followed (G.H. Megrue, J. Geophys. Res. 78 (1973) 3216-3221). It took almost two decades until the presence of heterochemical microstructures that never had reached diffusive equilibrium was

demonstrated for terrestrial samples as well (T.C. Onstott et al., Chem. Geol. 90 (1990) 145-168).

U-Pb dating, the most reliable geochronological tool, underwent three bursts of progress. Fifty years ago, the concordia diagram was invented (G.W. Wetherill, Trans. Am. Geophys. Union 37 (1956) 320-326); this allowed diagnosing and unravelling the ages of samples that gave concordant or discordant apparent ages. The second breakthrough was the development of a low-contamination chemical dissolution protocol (T.E. Krogh, Carnegie Inst. Yearbook 69 (1971) 341-344) that made it possible to date individual zircon grains with high precision. Finally, the most recent improvement allowed understanding the causes of discordance and required the combination of two separated analytical approaches: the ability to obtain spatially resolved isotope data, and the ability to establish the microtextural-petrological context of the analysed spot by cathodoluminescence (D. Gebauer et al., Schweiz. Mineral. Petrol. Mitt. 68 (1988) 485-490).

Fundamental work on the legitimation of commonplace geochronology has demonstrated that one of the basic assumptions made in older literature was unlikely to be verified: isochron calculations require initial equilibrium amongst all samples that are regressed together. Even if exceptions may exist, as a rule this is not verified in metamorphic terrains: neither in whole-rock dating (A. Cattell et al., Earth Planet. Sci. Lett. 70 (1984) 280-290) nor amongst minerals of one and the same rock (M. Thöni & E. Jagoutz, Geochim. Cosmochim. Acta 56 (1992) 347-368). When new metamorphic minerals and old relics do not attain equilibrium for lack of diffusion, apparent ages are meaningless. Countless papers in the last decade (see references in Lithos 87 (2006) 155-173) have amplified these ideas by correlating petrology and isotope analyses; they report and quantify chemical and isotopic disequilibria at the µm scale, which led to understanding that isotopes behave just like any other trace element, especially in their lack of diffusive reequilibration. Therefore, it is vital to relate the geochronological data to the complete microtextural, microchemical, and petrological record (D. Vance et al., Geol. Soc. London Spec. Pub. 220 (2003) 1-24; M. Williams et al., Chem. Geol. 225 (2006) 1-15), without which isotope data are worthless.

The landmark papers of the past are the giants on whose shoulders we now stand. It is up to us to progress in new directions. The development of better mass spectrometers is very often a source of progress, provided the delicate balance between „project-oriented machines“ and „machine-oriented projects“ is struck. In all sciences, it is only good questions that can lead to good results; the special complexity of geological systems requires interdisciplinarity, lateral thinking, and the ability to recognize a context between seemingly unrelated bits of information. Amongst the themes considered exciting today are:

- unravelling the relative importance of metastability versus equilibrium in processes such as dissolution/reprecipitation and recrystallization at the nanoscale, coupling these processes to the isotopic record;
- trying to push the analytical resolution to the sub-µm scale, so as to gain a more accurate understanding of time in geology and of the controls of isotopic record and signature in the respective archive;
- devising precise chronometers and proxies for the Late Quaternary, so as to tighten constraints on climatic change;

- increase the number of isotopic systems that can be employed simultaneously, so as to expand multi-chronometric and multi-proxy approaches, gaining reliability by redundance.

Decisive help is (gradually, and not exclusively) coming from the use of multicollector plasma-source mass spectrometers, which allow ionization of all elements, while at the same time cutting analytical time requirements by an order of magnitude.

Better analyses are only half the work that needs to be done. The other half is psychological: geologists need less attention to Confucian dogma, to assuming that nothing changed ever since someone else had it all written down decades ago. Unlike physics or chemistry, where experiments stimulate a rapid and complete modification of theories, belief revision is extremely sluggish in geology; the very idea of progress has often been fought against in this same century whose end we now celebrate. The most prominent example was the 40-year-long rejection of A. Wegener's idea of continental drift.

I hasten to add that it is difficult to foresee what the new insights of the next decade will be; as an example, who would have bet, in 1996, on U-Th dating of speleothems as the driving force of a revolution in paleoclimatology? The moral, which politicians should heed, is that fundamental research yields the best results serendipitously, and that any attempt to straightjacket it is only going to produce mediocre me-tooism.