GEOL5690 Class Notes: Detrital Zircons

Back when it took 100 pounds of rock to get enough zircon to get an U-Pb date, there wasn't much point in using zircons in sedimentary and metamorphic rocks for age dating or provenance work. At most, zircon populations were separated into different fractions depending on their geometry and zonation with the hope that relict zircons could be identified and put aside so a true igneous emplacement/eruption age could be determined. But as techniques began to allow measurements of individual zircons, two different approaches to using them emerged. One was to date sedimentary deposits otherwise undatable; the other was to explore the origins of sedimentary or metamorphic rocks through the distribution of zircon ages. This last technique, initially expected to resolve many knotty problems (like the Baja-BC controversy we will explore later on; Cowen et al., *Am J Sci.*, 1997), has proven to be less successful than originally anticipated. More recently some groups are using a double-dating approach, for instance combining a U-Pb date with a Lu-Hf isotopic measurement or with a U-Th/He low-temperature geochronometer. (Odds are triple dating has already been tried somewhere).

A useful history written by one of the main advocates of this technique is Gehrels, *Ann. Rev*., 2014.

Overall the progression that led to the current infatuation with detrital zircons was an improvement in techniques, both in terms of speed and sample size. Initially work was done with ID-TIMS, which is a time-consuming chemically-based approach. This is still a preferred technique when high precision is needed. The SIMS technique started allowing for individual zircon measurements in the early 1980s; this is much faster (10-15 minutes/sample) than ID-TIMS. But the use of detrital zircons zoomed with the development of LA-ICP-MS (laser-ablation inductively coupled plasma mass spectrometry) in the mid 1990s. This technique shared the same resolution as SIMS (~1-2% accuracy) but takes only ~1 minute/sample.

Sedimentary dating

The Law of Components says that a rock was formed after the youngest of the pieces it contains. So, for instance, a conglomerate with a chunk of lava was deposited after that lava erupted. It isn't a very big leap, once you can date individual zircons, to apply this law to clastic sedimentary rocks. At the simplest level, the age of the youngest zircon present is the maximum depositional age (MDA) of the rock. That is, the rock cannot have been formed before any of the components were created. In general, the need for a substantial number of zircon measurements tends to limit this approach to dating to SIMS or LA-ICP-MS measurements.

There is one obvious bias: the maximum age can be long before the rock was created if there were no zircon sources in the right age range. This comes up, for instance, in parts of the Basin and Range where isolated basins might not have had any magmatic sources for a long time prior to deposition of a sandstone.

A clue that MDA ages might be close to depositional ages is if the MDAs young upward in a sedimentary sequence. While it is possible this reflects a growing drainage area permitting inclusion of younger zircons, in most cases it is revealing that older deposits predated the younger zircons found in higher deposits.

Perhaps surprisingly, there are situations where the MDA is not, in fact, a maximum, and this has led to a rather large number of approaches to identifying the best estimate of a MDA. In some cases, the youngest age comes from a single zircon. Might this be an analytical error? A zircon that snuck in from another sample? A response was to suggest that there need to be three zircons with a similar age to define the MDA. Another aspect is that the SIMS or LA-ICP-MS measurements are relatively low precision: when we talk about 95% confidence intervals, it does suggest that 1 of 20 measurements will be outside that interval. When measuring 100 zircons, five should be outside that range, so having one be outside on the young side is potentially fairly likely.

Somewhat surprisingly, there is no agreement yet on the best approach. Many approaches have been considered by Dickinson and Gehrels (2009), Coutts et al (2019) and Vermeesch (2021). Schwartz et al. (2023) illustrates the issues in a more recent paper on sediments near Death Valley. Here are some options in the literature:

- Youngest Single Grain (YSG). Pretty obvious what that is, and what the risks are. Related are averages of the youngest three (Y3Z) or four (Y4Z) grains.
- Youngest Graphical Peak (YPP). On a histogram or probability plots of ages, the peak value of the youngest distinct peak.
- Weighted mean age of 2 or more grains within 1 standard deviation of each other, also called youngest grain cluster (YC1σ(2+)). Also a 2 σ variant exists (YC2σ(2+))
- Weighted mean age of 3 or more grains within 1 standard deviation of each other (YC1σ(3+)). As above, a 2 σ variant exists (YC2σ(3+))
- Youngest Detrital Zircon from program Isoplot (YDZ). This is based on thousands of resamplings of the ages using their uncertainties; basically a Monte Carlo approach. (There are some other semi-specialized codes as well, like TuffZirc6+)
- Maximum Likelihood Age (MLA) is a more statistically based approach (Vermeesch, 2021). This is often displayed on a radial plot of age/σ (radial coordinate) vs. log(age) (circumferential coordinate)

Some of these vary whether a mean, median, or mode of a peak is picked. Some approaches might be a poor match to some datasets. For instance, the average of the youngest three grains might be biased if most of a large collection of zircons are near the youngest age. Conversely, some of the more properly probabilistic approaches might drop the few young grains from smaller samples more heavily biased to older zircons. At present, many workers will have tried several of these approaches, though they might decide to only share one in a publication. Schwartz et al. (2023) found the MLA technique to be most reliable, though in a few instances preferred their own measure of the central age of the youngest peak in a zircon distribution.

Provenance use

For the western U.S., a pair of 1995 papers really launched the use of detrital zircons as a means of tracing the history of sediments (Gehrels et al., *Am J. Sci.*, 1995; Gehrels and Dickinson, *Geology*, 1995). In these initial efforts, the authors attempted to identify all the possible contributing sources by examining the zircons to get samples from each type of color and morphology present. Individual zircon measurements were made with the TIMS approach, which made each zircon measurement important. Thus, in these earlier studies, it was the presence or absence of a specific age that was used for comparison between different sedimentary units. These early papers usually displayed the results as a straight histogram of zircon ages versus age.

This initial work generally ignored the analytical uncertainties (beyond excluding measurements too far from the concordia), but very quickly the histograms were being replaced with probability distribution plots. In their most basic form, each zircon produces a bell curve shape with a width determined by its analytical uncertainty, a height making the area under the curve identical to all other samples, and a position at the age determined for the sample. These curves are then summed to make a probability curve.

Very quickly many researchers decided that the relative abundance of zircons of different ages was significant. With collections of zircons now exceeding 1000 from some units or sampling localities, relative abundances are fairly robust. With this in mind, modern zircon collections do not attempt to pick and choose which zircons to date.

As with getting maximum depositional ages, comparing age-probability information has led to a number of different approaches. Studies of detrital zircons within modern river systems reveal much complexity in which zircons make it where in a major river system and how abundances can vary over fairly short distances. Thus it is wise to be cautious in assigning much to the difference in magnitude of age peaks between different sites. More robust is the presence or absence of specific peaks. For instance, sedimentary rock younger than 1 Ga but lacking the common Grenville 1.0-1.3 Ga zircons would be a robust observation given the ample supply of these zircons. The differing quantitative measures employed to compare different sampling sites vary in exactly how they reward matches in amplitude vs. merely common presence of certain ages.

Limitations. There is one major blind spot in this approach and at least one more subtle complication rarely worth considering. The blind spot is that you are only seeing the traces of rocks that contain zircon. Zircons are far rarer in more mafic rocks, and some rocks are incredibly rich in zircon. For instance, the intrusions associated with the Grenville Orogeny produced huge windfalls of zircons that flooded across the continent. Erosion of mudstones or carbonates will not yield usable zircons, so sediment primarily made up of materials from these sources might yield a few zircons from a minor source, misleading estimates of the paleogeography of a fluvial system. More classical approaches, such as heavy mineral concentrations and clast identification, can help reveal difficulties.

Less misleading, most zircons are thought to have travelled fluvially or with eolian sands. Rounded shapes and some textural observations generally supports such transport. However it is possible for airfall ashes to contain zircons; the few rare Eocene zircons in some fluvial sediments in the northern Sierra Nevada seem better explained as airfall than indicating a fluvial connection to source volcanoes. Similarly, it is quite likely that some fluvial deposits contain materials that were transported by wind, which could lead to a mistaken idea of where a fluvial divide existed.

Other systems

While the zircon-based systems have taken up most of the oxygen, there are other, similar approaches out there (and probably more to come) with monazite, rutile, and apatite all being exploited. More unusual seems to be use of lead isotopes in potassium feldspar as a provenance tool (e.g., Shulaker et al., EPSL, 2019). In this case, U and Th don't go into these feldspars but the lead isotopes reflect the variations in time and U and Th content in different areas over time before the feldspars crystallized.

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