Crustal history and metallogenic fertility:
Terrane-scale assessment with detrital zircons

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ABSTRACT

The integrated in situ analysis of zircons for U-Pb age, Hf-isotope composition and trace-element composition using LAM-ICPMS, LAM-Multi-Collector (MC) ICPMS and electron microprobe (EMP) provides a powerful methodology (TerraneChron®) for studying crustal evolution and evaluating the metallogenic potential of terranes. The method can be applied to zircons separated from single rocks or to zircons picked from drainage samples judiciously collected within a defined catchment (on scales of 10 - 1000 km depending on the objective). The use of drainage samples has many advantages: nature has separated and concentrated a statistically more meaningful sample than is achievable by conventional single rock sampling and methods, and this can provide a more comprehensive coverage of rock types from the drainage region. The variations of Hf-isotope composition vs time in zircon populations is presented as curves (Event Signatures) reflecting the relative contributions of juvenile vs reworked material to each magmatic episode through time. These curves can be used to recognise patterns of crustal evolution favourable to mineralisation, to compare the evolution of different terranes, and to evaluate major crust-forming processes. The methodology provides a rapid, cost-effective tool for characterising the crustal history of areas ranging from single drainage basins to large terranes.

THE *TerraneChron*® METHODOLOGY

Most mineral exploration models require an understanding of the geological evolution of the crust in the area of interest; critical information includes the timing of magmatic events, and the types and sources of the magmas. Acquiring this type of information from scratch, or even checking the reliability of existing data, can be very costly in terms of both time and money. However, modern analytical technology has provided a rapid and cost-effective solution to this problem. GEMOC has developed the *TerraneChron*® methodology for studying crustal evolution and evaluating the metallogenic potential of terranes. It is based on the integrated *in situ* analysis of zircons for *U-Pb age, Hf-isotopic composition and trace-element composition* using laser-ablation microprobe (LAM) and electron microprobe (EMP) techniques.

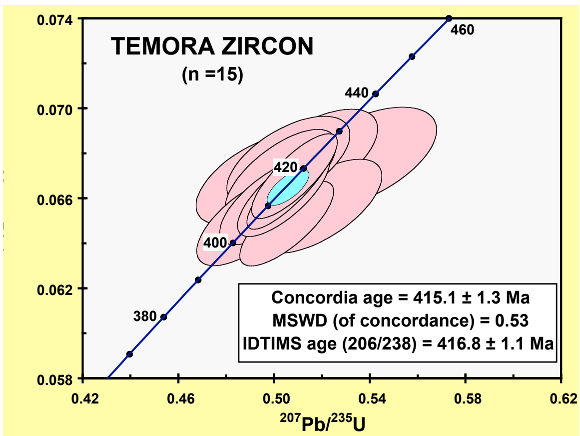

Figure 1. LAM-ICPMS dating of zircons from the Temora granodiorite, illustrating typical precision and accuracy (after Jackson et al., 2004)

The methodology can be applied to zircons separated from single rocks or to zircons from drainage samples judiciously collected within a defined catchment (on scales of 10 - 1000 km depending on the objective). The use of drainage samples has many advantages: nature has separated and concentrated a statistically more meaningful sample than is achievable by conventional single rock sampling and methods, and this can provide a more comprehensive coverage of rock types from the drainage area. Several studies (eg Griffin et al., 2006) have shown that *TerraneChron*® sampling, with Nature separating and concentrating the zircons, can provide ages for rocks (e.g. amphibolites, gabbros, dolerites) that conventional geochronology may have put in the "too-hard basket". For a meaningful analysis, a sample should comprise 60 - 80 randomly selected grains, as well as non-random grains judged to be representative of minor and/or potentially important detrital populations (Andersen, 2005).

The *U-Pb analyses* are done by LAM-ICPMS techniques, which provide rapid and cost-effective age determinations with precision equivalent to the ion microprobe, at a fraction of the cost (eg Jackson et al., 2004; Fig. 1, 2).

The *Hf-isotope data* are collected by LAM-multicollector (MC)-ICPMS (eg Griffin et al., 2000). Hf isotopes provide information on the source of the magmatic rock from which each zircon crystallised; they tell whether the magmatism involved young mantle-derived input ("juvenile" source), if only pre-existing crust was involved (ie crustal reworking), or a combination of these processes. The basis of using the Hf isotopic ratios is the decay of ^{176}Lu to ^{176}Hf; ^{177}Hf is a stable isotope. During mantle melting, Hf is partitioned more strongly into the melts than Lu. Over time ^{176}Hf/^{177}Hf therefore evolves to higher values in the mantle than in crustal rocks. Thus in magmatic rocks, high values of ^{176}Hf/^{177}Hf (ie $\varepsilon_{Hf} >> 0$; Fig. 3) indicate "juvenile" mantle input (either directly via mantle-derived mafic melts, or by remelting of young mantle-derived lower crust). Low values of ^{176}Hf/^{177}Hf ($\varepsilon_{Hf} < 0$) provide evidence for the reworking of older crustal material. Mixing of mantle-derived and crustally-derived magmas may produce heterogeneity (including zoning within single crystals) in the Hf-isotope composition and trace-element abundances within zircon populations.

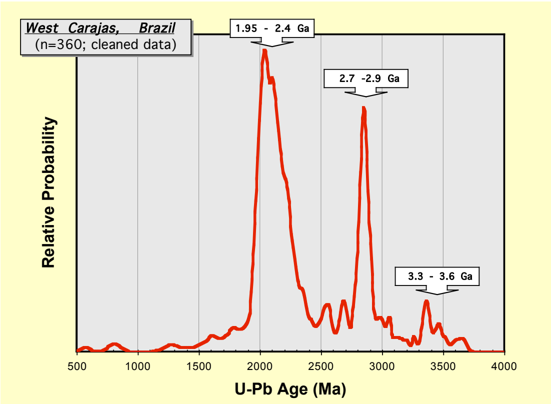

Figure 2. Age spectrum derived from detrital zircons, Carajas area, Amazon craton, Brazil.

The analysis of *trace elements* (Y and Hf from the EMP; U and Th from the U-Pb analysis; Yb and Lu from the Hf-isotope analysis) provides information about the composition of the magmatic rock that precipitated the zircon (eg Belousova et al., 2002). Thus the TerraneChron® approach provides more layers of information than the conventional approach based on U-Pb age spectra.

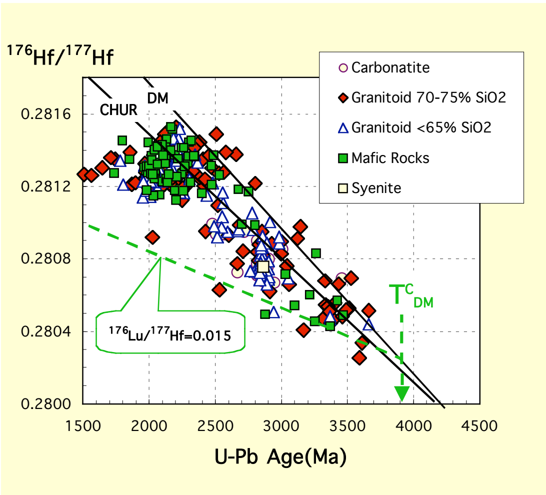

Figure 3. Plot of Hf-isotope composition vs age for detrital zircons from the Carajas area, Brazil. Grains are classified by modelled rock type. Dashed line shows evolution of $^{176}Hf/^{177}Hf$ in 3.9 Ga "average continental crust". The two mantle evolution lines for $^{176}Hf/^{177}Hf$ are CHUR (CHondritic Uniform Reservoir), representing the primordial undifferentiated mantle values and DM (Depleted Mantle) representing mantle evolution through melt removal (and hence depletion).

Event Signatures

The combination of age data with information on the composition and sources of the magmas yields an "Event Signature", which is a fingerprint of crustal evolution events (Griffin et al., 2005). This "Event Signature" is represented in a diagram (Figure 4) in which the vertical axis shows the mean residence age of the magma source, given by the difference between the mean crystallisation age and the mean Hf model age (T_{DM}) for the zircons in each time slice. This is plotted against the magmatic crystallisation ages of the grains from selected time intervals.

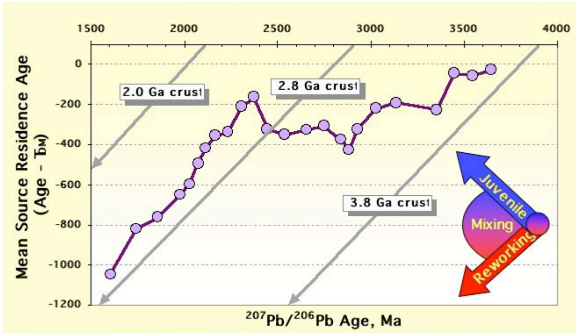

Figure 4. Event Signature for the Carajas area, Brazil.

In this diagram, trends toward the *lower left* (see key on Figure 4) indicate events dominated by *reworking of pre-existing crustal material*. *Juvenile* (young mantle) *input* is shown by trends towards the *upper left*. Trends of intermediate slope imply contributions from both juvenile and pre-existing crustal sources. The "Event Signature" pattern thus combines the information from U-Pb age (Fig. 1) and Hf-isotopic data (Fig. 2) in a form that gives a broad picture of crustal evolution in the sampled area.

Interpreting Event Signatures

Figure 4 shows the Event Signature for the Carajas area in the Amazon Craton, Brazil; the age spectrum and Hf-isotope data are given in Figures 2 and 3 respectively. Juvenile crust formed 3.6-3.4 Ga (with contributions from still older crust; Fig. 3) was reworked, with minor additions, up to ca 2.7 Ga. A peak of juvenile addition occurred around 2.3-2.4 Ga, but subsequent (mainly granitic) magmatism simply involved reworking of this Paleoproterozoic crust.

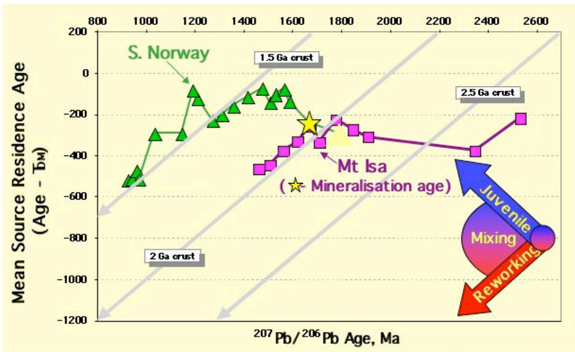

Figure 5. Event Signatures for the Mt Isa Eastern Succession (Queensland, Australia) and S. Norway.

Figure 5 compares the Event Signatures for the Mt Isa Eastern Succession (Australia) and southern Norway. *Mt Isa's tectonic history*, as shown by these zircons (Griffin et al., 2005), starts with a short episode of Late Archean crustal reworking, followed by several episodes of juvenile addition and mixing with magmas derived from reworked crust up to about 1.8 Ga. A short period dominated by crustal reworking is followed by a significant juvenile input at ca 1650 Ma, associated with the main Mt Isa mineralisation. This was succeeded by crustal reworking over a period of about 200 Ma, producing rocks such as the Williams Batholith and Marramungee granites and minor later intrusives. This pattern reflects *repeated extensional tectonism and magmatism superimposed on an ancient crustal substrate.*

In contrast, the Event Signature for *southern Norway* (a poorly mineralised area) shows no Archean prehistory (Fig. 1), but is dominated by juvenile input from 1.6-1.4 Ga, and by crustal reworking from 1.4-1.3 Ga. This pattern reflects the *continual buildup of new crust at a convergent margin.* The Sveconorwegian (Grenville) episode started with pulse of juvenile input at ca 1.2 Ga (associated with ilmenite deposits in anorthosites), but the later magmatism (1.1- 0.9 Ga) was dominated by crustal reworking.

Thus the Hf isotopic composition of zircons has potential for identifying mineralised terrains. Deposit types whose formation requires concentration by crustal processes will be dominated by the signature of a reworked crustal source. Those requiring mantle input will be characterised by more radiogenic Hf-isotope values, as seen for the Mt Isa and Broken Hill mineralisation (Figs 3, 4).

Correlating Terranes

Event Signatures reveal the timing and geochemical patterns of mantle magmatic events and crustal orogenesis that have affected each terrane sampled. If the patterns for two crustal blocks are coincident for part of their tectonic history, this suggests either that they were joined during that time (analogous to interpretations of Polar Wander Paths in paleomagnetic studies) or that they coincidentally underwent geochemically similar magma-generation processes at the same times.

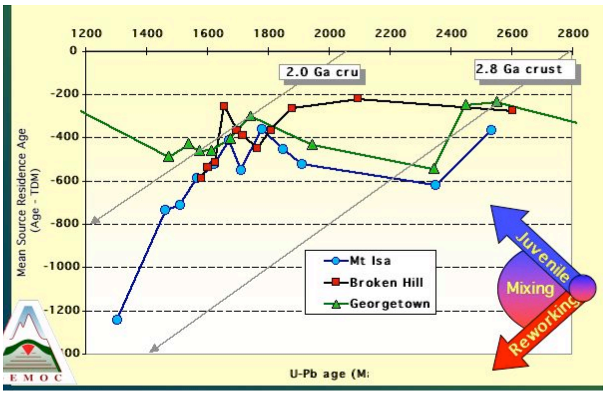

Figure 6. Event Signature diagrams for Mt Isa (Qld), Georgetown (Qld), and Broken Hill terranes (NSW).

The Event Signatures in Figure 6 show that the Broken Hill and Mt Isa terranes have separate evolutionary histories until about 1.85 Ga (the time of the Barramundi Orogeny) but similar patterns after that time, including a major juvenile input around 1.65 Ma, coinciding with major mineralisation. These two previously separate terranes may have docked around 1.85 Ga. The Georgetown Inlier and Mt Isa Event Signatures are very similar from about 2.6 Ga to about 1.75 Ga, suggesting these terranes were joined. After 1.75 Ga the curves (and perhaps the terranes) separate; Georgetown did not experience major juvenile input after ca 1.75 Ga, but went through ca 200 Ma dominated by crustal reworking.

MAGMA SOURCES AND GOLD MINERALISATION: MT LEYSHON, N. QUEENSLAND

The $^{176}Hf/^{177}Hf$ ratio of zircons provides a tool to assess the relative importance of mantle and crustal contributions to single magmas and hence can be used to track the mechanisms that generate magmas and concentrate elements such as gold.

In the Mt Leyshon Igneous Complex in North Queensland, early granitic melts contain zircons with identical ages, but very large ranges in $^{176}Hf/^{177}Hf$ (from high juvenile values to low crustal values) and trace-element patterns (Murgulov et al., 2007). This is evidence for the production and mixing of several different magma batches; modelling of the Hf isotope data gives a mean age for the crustal source component of 1.04 Ga. The gold mineralisation at Mt. Leyshon is associated with late-stage dykes, and the zircons in these have very homogeneous $^{176}Hf/^{177}Hf$ values, which lie in the middle of the wide range seen in the early magmas. This suggests the late magmas reflect the homogenisation and differentiation of the early ones; there is no detectable new juvenile input during the mineralisation stage, and Au apparently was simply concentrated by magmatic differentiation/fluid separation processes.

A *TerraneChron®* CASE HISTORY: THE YILGARN CRATON

Figure 7 summarises data for 550 detrital zircons from modern drainages across the northern part of the Yilgarn Craton and the adjacent Capricorn Orogen, providing a broad view of their crustal evolution in the Archean and Proterozoic (Griffin et al., 2004). The oldest crustal components (3.7 Ga) are identified in the Yeelirrie geophysical domain that runs N-S down the middle of the craton, separating the 2.8-2.6 Ga Southern Cross and Eastern Goldfields terranes. Older ages also are found in the Murchison and Narryer provinces to the west.

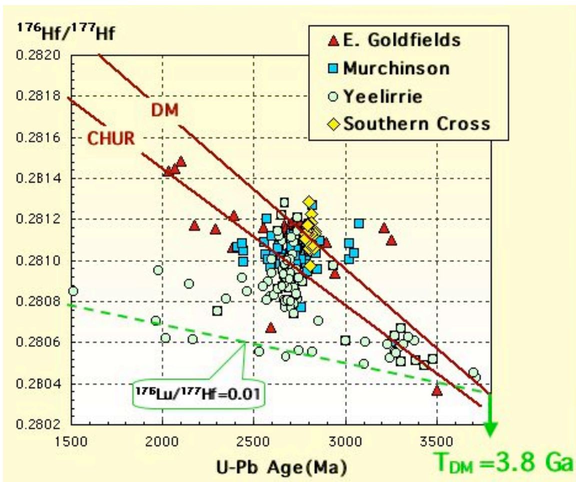

Figure 7. Age-Hf data for detrital zircons from the northern part of the Yilgarn craton, W. Australia

The late (2.7-2.6 Ga) granites that intruded across the area have been used as probes of the deeper crust; the Hf isotope compositions of zircons from these rocks, sampled in modern sediments, allow us to map out the evolution of the different terranes (Fig. 8). The ancient crust of the Yeeliree domain is clearly evidenced in the low ε_{Hf} values of the zircons from the late granites, which were derived from a crustal source with a model age of 3.7 Ga.

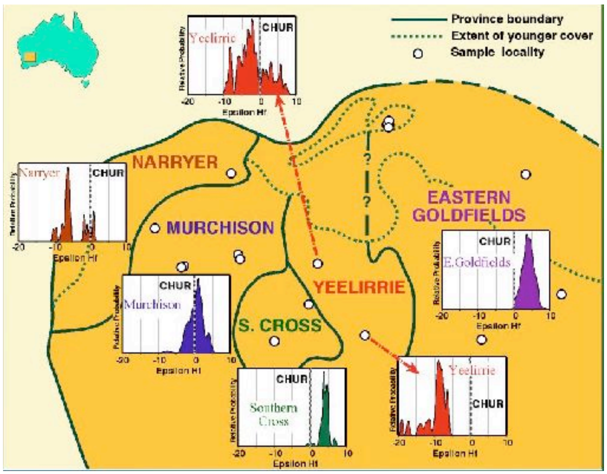

Figure 8. Relative probability histograms of εHf data for zircons with ages of 2.6-2.8 Ga provinces in the Yilgarn Craton, (W. Australia). Note the juvenile character (εHf >0) of the magmatism in the Eastern Goldfields and Southern Cross provinces, and the major contribution of ancient crust (εHf < 0) in Yeelirrie and Narryer. (Griffin et al.,2004).

Ancient (>3.4 Ga) crust also contributed to the generation of younger magmas in the Narryer Province, and the proportion of ancient recycled crustal material increases from east to west across the Murchison Province. In contrast, the Hf isotope data for zircons from the Southern Cross and Eastern Goldfields domains provide no evidence for crust older than 2.9-3.0 Ga. The Yeelirrie domain and the composite Narryer-Murchison block are thus interpreted as representing discrete ancient microcontinents, sandwiched with the juvenile terranes of the Southern Cross and Eastern Goldfields domains, which contain the major deposits of Au and Ni.

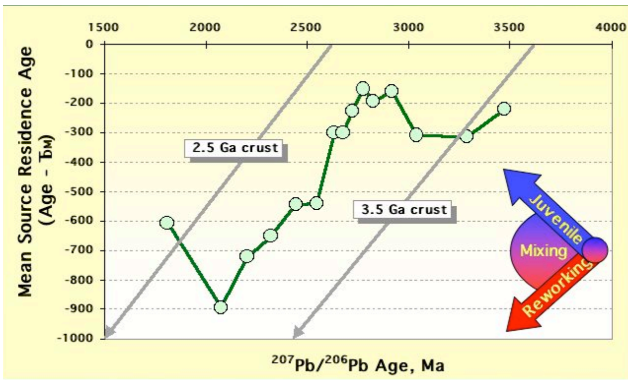

Figure 9. Event Signature for the northern part of the Yilgarn craton, showing juvenile input at 2.8-2.9 Ga, followed by several episodes of crustal reworking.

The Yilgarn study demonstrates that the integrated application of U-Pb dating, Hf-isotope analysis and trace-element analysis to detrital zircon populations offers a rapid means of assessing the geochronology and crustal evolution history of different terranes within a composite craton, and hence has relevance to exploration targeting.

UNDERSTANDING CRUSTAL EVOLUTION PROCESSES

In many TerraneChron™ studies carried out so far, there is clear evidence for the existence of ancient crust, not exposed and not known from previous studies, even in intensively studied areas. This is recognised by the observation of low $^{176}Hf/^{177}Hf$ in young zircons, which implies remelting of older crust. The age of this crustal component can be modelled by projection of the measured $^{176}Hf/^{177}Hf$ value back in time until it intersects the mantle value, indicating its time of original isolation from the mantle (Figs. 3, 7). In Fig. 7, line through the lowest (least radiogenic) $^{176}Hf/^{177}Hf$ values corresponds to a Lu/Hf ratio typical of felsic rocks, with a mean mantle-extraction age of ca 3.8 Ga; it indicates that a lower-crustal source of this age is present beneath the area and has contributed to magmatism well into the Proterozoic.

Another important feature shown clearly in Event Signature plots is that tectonic events that involve significant mantle input are invariably followed by periods of crustal reworking that persist for 200 Ma or longer (eg Figs 4, 6, 9). This appears to reflect the time needed for thermal equilibrium to be attained in that lithospheric domain and probably involves both conductive cooling and redistribution of the heat-producing elements within the crust as described by Sandiford and McClaren (2002). This period of prolonged crustal thermal activity could prove to be a critical concentrating mechanism for some elements important in metallogenic fertility. The regularity of this pattern of mantle magmatic input and subsequent crustal reworking strongly suggests a repetitive and important process in crustal evolution which may lead to prediction of metallogenic prospectivity.

SUMMARY

The *TerraneChron*® methodology thus:

- Yields a synthesis of the tectonic history represented in the region sampled and identifies relative crust and mantle contributions to specific magmatic episodes
- Can be used as a cost-effective reconnaissance tool in remote, inaccessible or complex terranes for evaluation of regional exploration potential
- Can potentially fingerprint the magmatic signatures associated with different styles of mineralisation
- Defines timescales for crustal reworking and thermal relaxation after major crustal-generation events
- Shows that intracrustal magmatism in different terranes of different ages persists for 200-300 Ma after major tectonic events involving mantle-derived magmatism
- Can be used to assess whether specific tectonic terranes were once part of the same orogenic domain (and if so, when) or if they have always been discrete entities
- Reveals the nature of crustal evolution by tracking the nature and timing for reworking episodes and new mantle inputs

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