TerraneChron™: delivering a competitive edge in exploration

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TerraneChron™ is GEMOC's unique 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 GEMOC's laser-ablation-microprobe (LAM) ICPMS, LAM-Multi-Collector (MC) ICPMS and electron microprobe (EMP).

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. For a meaningful analysis, a sample should comprise 50 - 70 randomly selected grains as well as non-random grains judged to be representative of minor and/or potentially important detrital populations (T. Andersen, in prep.).

The *U-Pb analyses* provide rapid and cost-effective age determinations with precision comparable to the ion microprobe. The *Hf-isotopic data* provide information on the source of the magmatic parent rock to each zircon; they tell whether the relevant tectonic event was accompanied by young mantle-derived magmatic input ("juvenile" source), if only pre-existing crust was involved (ie crustal reworking), or a combination of these processes. The *trace elements* provide information about the composition of the magmatic rock that precipitated the zircon. Thus the TerraneChron™ approach provides more layers of information than the conventional U-Pb age-spectrum approach.

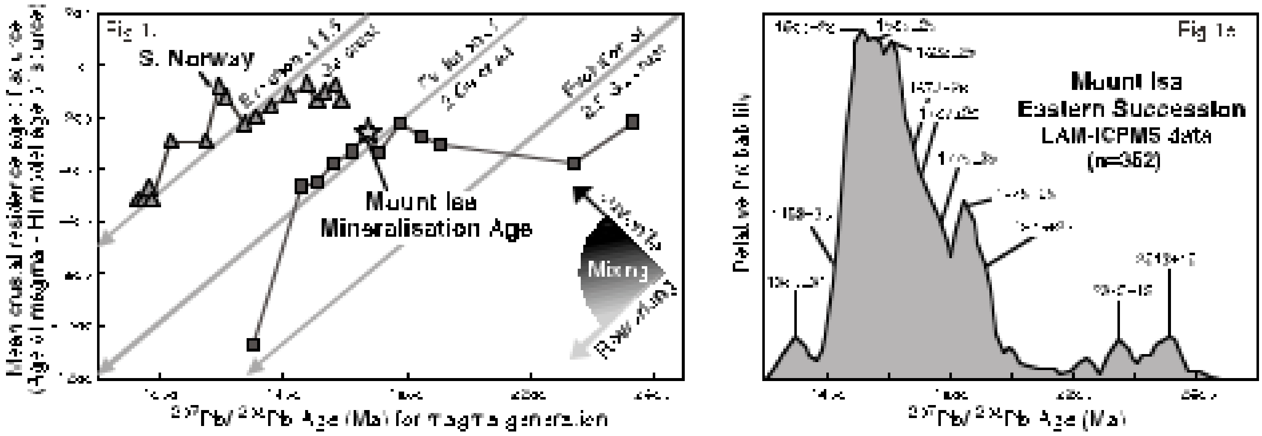


Figure 1a. Event Signature diagram for detrital zircons from the Mt Isa (Australia) and north Norway terranes. Figure 1b. U-Pb age spectrum (relative probability plot) for the Mt Isa terrane.

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., 2004). This "Event Signature" is represented in a diagram (Figure 1a) in which the vertical axis shows the mean age of the magma source (calculated from the Hf isotopic data) plotted against the magmatic crystallisation ages of the grains from selected time intervals.

In this diagram, trends toward the *lower left* (see key on Figure 1a) indicate tectonic 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. 1b) and Hf-isotopic data in a form that is easy to interpret in terms of tectonic history.

Examples of Event Signature diagrams

Figure 1a shows the Event Signatures for the Mt Isa Eastern Succession (Australia) and southern Norway. *Mt Isa's tectonic history,* as shown by these zircons (Belousova et al., 2001; in prep.), starts with a short episode of Late Archean crustal reworking, followed by several episodes of juvenile addition and mixing with magmas from reworked crust up to about 1.8 Ga, then a short period dominated by crustal reworking, 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, but the later magmatism (1.1- 0.9 Ga) was dominated by crustal reworking.

Thus the use of Hf isotopic composition of zircons has significance for identifying potentially mineralised terranes. Deposits that require 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 isotopic values, as seen for the Mt Isa and Broken Hill mineralisation (Figs 1, 3).

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. The basis of using the Hf isotopic ratios is the decay of ^{176}Lu to ^{176}Hf, while ^{177}Hf is a stable isotope. During mantle melting, Hf is partitioned more strongly into the melts than Lu. Over time the $^{176}Hf/^{177}Hf$ therefore evolves to higher values in the mantle than in crustal rocks.

During the production of granitoid magmas, high values of $^{176}Hf/^{177}Hf$ (ie $\varepsilon_{Hf} >> 0$; Fig. 2) indicate "juvenile" mantle input (either directly via mantle-derived mafic melts, or by remelting of young mantle-derived mafic lower crust). Low values of $^{176}Hf/^{177}Hf$ ($\varepsilon_{Hf} < 0$) provide evidence for crustal reworking. Mixing of mantle-derived magmas during granite production can also be detected by inhomogeneity (including zoning) in the Hf-isotope composition and trace-element abundances in zircon populations.

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, 2002). 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 and $^{176}Hf/^{177}Hf$, in the middle of the range for 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 of the Yilgarn Craton

Figure 2 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. These components are represented by ancient U-Pb ages for zircons but, very significantly, are also clearly evidenced in the low ε_{Hf} values of zircons from younger magmas, which show that these granites were derived from a reworked crustal source with a model age of 3.7 Ga. 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 from zircons from the Southern Cross or Eastern Goldfields (including the Marymia Inlier) 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.

The Yilgarn results demonstrate 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.

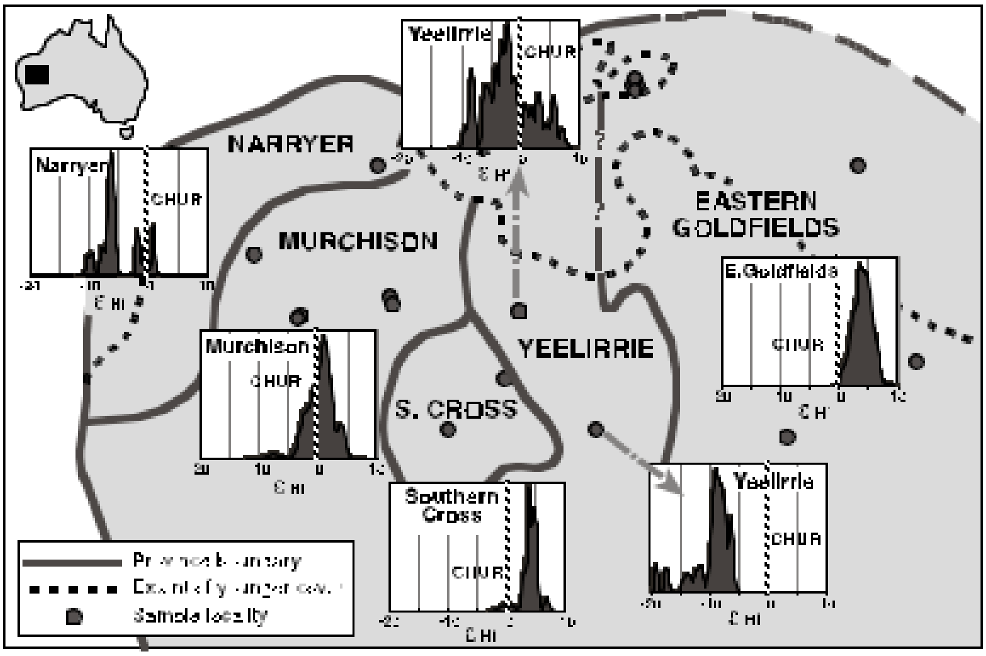


Figure 2. Relative probability histograms of εHf data for zircons with ages of 2.6-2.8 Ga provinces in the Yilgarn Craton, (W. Australia). Note the juvenile character (εHf >0) of the magmatism in the Eastern Goldfields and Southern Cross provinces, and the major contribution of ancient crust (εHf < 0) in Yeelirrie and Narryer.

Correlating moving terranes?

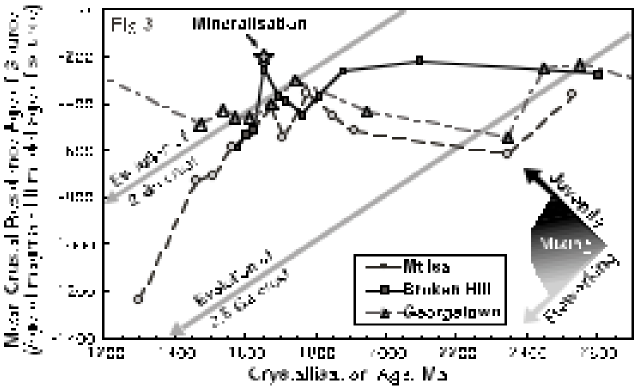
Event signatures reveal the timing and geochemical patterns of mantle magmatic events and crustal orogenesis that have affected each terrane sampled. If the patterns for two crustal blocks are coincident for part of the tectonic history, this suggests that either they were joined for that time (analogous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

The Event Signatures in Figure 3 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.

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 such intensively studied areas as Mt Isa. This is recognised by the presence 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. This is shown in Figure. 4 for Mt Isa. The line through the lowest (least radiogenic) $^{176}Hf/^{177}Hf$ values corresponds to a Lu/Hf ratio typical of intermediate to mafic rocks, with a mean mantle-extraction age of ca 2.8 Ga; it indicates that a mafic lower-crustal source of late Archean age is present beneath the Mt Isa area and has contributed to magmatism throughout much of 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 about 200-300 Ma (eg Figs 1, 3) . This appears to reflect the time needed for thermal equilibrium to be attained in that lithospheric domain and probably involves conductive cooling and redistribution of the heat-producing elements within the crust as described by Sandiford & 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.



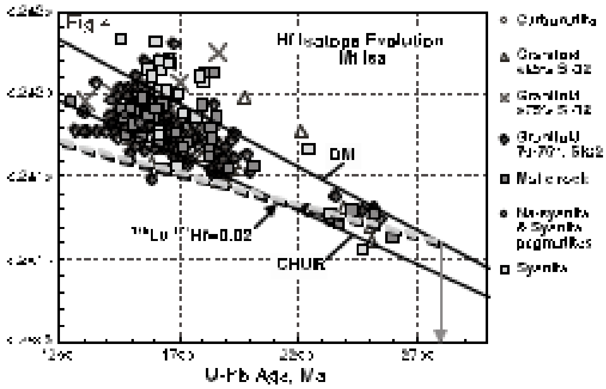


Figure 3. Event Signature diagrams for Mt Isa (Qld), Georgetown (Qld), and Broken Hill terranes (NSW).

Figure 4. $^{176}Hf/^{177}Hf$ vs U-Pb age for zircons from the Mt Isa region, with each point coded according to rock type. Dashed line represents evolution (growth curve) fitted to the least radiogenic Hf isotopic values and represent old rocks with $^{176}Lu/^{177}Hf = 0.02$. The two mantle evolution lines for $^{176}Hf/^{177}Hf$ are: (i) CHUR (CHondritic Uniform Reservoir), representing the primordial undifferentiated mantle values and (ii) DM (Depleted Mantle) representing mantle evolution through melting (and hence depletion).

Summary

The TerraneChron™ method 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 tectonic signatures associated with different styles of mineralisation
- Defines timescales for crustal reworking and thermal relaxation after major crustal-generation events
- Shows that crustal magmatism in different terranes of different ages persists for 200-300 Ma after major tectonic events involving mantle 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
- Reveals the nature of crustal evolution by tracking the nature and timing for reworking episodes and new mantle input

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References

Belousova E.A., Griffin W.L., Walters S.G. & O'Reilly S.Y. 2001. Crustal evolution and crust-mantle interaction in the Mount Isa Eastern Succession: TerraneChron analysis of detrital zircons. Abstract, 2001: A Hydrothermal Odyssey, Townsville, Queensland, 17 - 19 May 2001

Griffin W.L., Belousova E.A., O'Reilly S.Y. & Walters S.G., 2004. TerraneChron™: new light on crustal evolution. Abstract, 17th Aust. Geol. Convention, Hobart, Tasmania, 8-13 February 2004.

Griffin, W.L., Belousova, E.A., S.R. Shee, S.R., Pearson, N.J. & O'Reilly, S.Y., 2004. Archean crustal evolution in the northern Yilgarn Craton: U-Pb and Hf-isotope evidence from detrital zircons. *Prec. Res. 127, 19-41.*

Sandiford, M. & McLaren, S., 2002. Tectonic feedback and the ordering of heat producing elements within the continental lithosphere. Earth and Planetary Science Letters, 204: 133-150.

Murgulov, V., 2002. Magma sources and gold mineralisation, North Queensland: a zircon-based study. Unpublished Honours thesis, Department of Earth and Planetary Sciences, Macquarie University.