Evolution of the Slave Province and Abitibi Subprovince Based on U-Pb Dating and Hf Isotopic Composition of Zircon

John W.F. Ketchum[1], Wouter Bleeker[2], William L. Griffin[1], Suzanne Y. O'Reilly[1], Norman J. Pearson[1] and John A. Ayer[3]

[1]GEMOC ARC National Key Centre, Department of Earth & Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia
[2]Geological Survey of Canada, 601 Booth St., Ottawa, ON, K1A 0E8, Canada
[3]Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, On, P3E 6B5, Canada
Email: *jketchum@els.mq.edu.au*

Introduction: Zircon ($ZrSiO_4$) is a physically- and chemically-robust mineral that occurs in a wide variety of rock types. During mineral growth, zircon crystals typically incorporates trace amounts of uranium but largely excludes lead from its crystal structure. As U radioactively decays to Pb at a known rate, this allows zircon to be exploited as a natural chronometer –particularly in determining the absolute age of plutonic and volcanic rocks. Zircon also incorporates significant amounts of the element hafnium during its crystallization. Hf is useful in that its isotopic composition (a type of geological 'fingerprint') provides insights on the relative contributions of crustal and mantle sources involved in the generation of continental crust.

We have determined the U-Pb age and Hf isotopic composition of zircons separated from rock samples from the western Slave Province and southern Abitibi subprovince of the Canadian Shield. These regions were targeted in separate LITHOPROBE transects that both addressed the origin and evolution of Archean continental crust (i.e., crust formed during the period 4.0-2.5 billion years ago). The western Slave Province has a protracted history of crustal growth between 4.0 Ga and 2.6 Ga whereas the southern Abitibi subprovince formed over a relatively short interval at ca. 2.7 Ga.

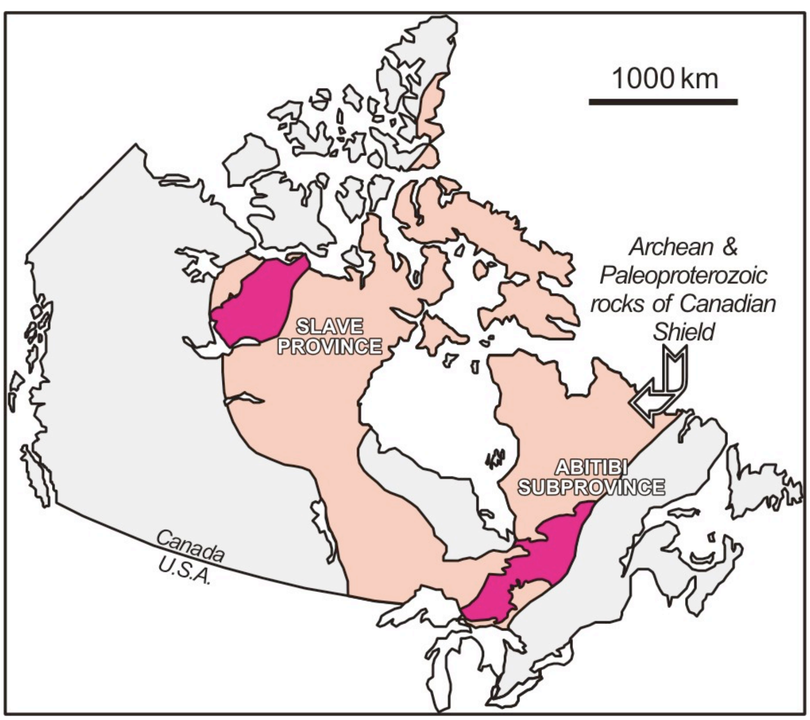

Figure 1. Location of the Slave Province and the Abitibi Subprovince (Superior Province) in the Canadian Shield. The studied samples are from the western, 'old' segment of the Slave Province and the southwestern portion of the Abitibi subprovince in Ontario.

Data collection and interpretation: The U-Pb age of zircon was measured by one or more of three techniques: (i) isotope dilution – thermal ionization mass spectrometry (ID-TIMS); (ii) laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS); and (iii) sensitive high resolution ion microprobe (SHRIMP). Hf isotopes in zircon were measured by a single technique: laser ablation – multiple collector – inductively coupled plasma mass spectrometry (LA-MC-ICPMS). Both laser ablation and SHRIMP analysis of zircon allows small areas within single zircon grains to be studied, which is important as some grains contain multiple growth zones or zircon cores inherited from older rocks.

The combined U-Pb and Hf isotopic data are depicted in two ways. The first diagram type compares zircon age with the $^{176}Hf/^{177}Hf$ isotopic ratio, back-calculated to the time of zircon formation. This calculation is required because zircon contains trace amounts of lutetium, and ^{176}Lu radioactively decays to ^{176}Hf over geological time. However this correction is very minor because of the low Lu/Hf of zircon. The second type compares zircon age with epsilon Hf, also calculated at the time of zircon formation. Epsilon Hf represents the deviation (multiplied by 10,000) of the $^{176}Hf/^{177}Hf$ ratio from this ratio for the bulk Earth, which is modelled on the composition of chondritic meteorites. This model has the acronym CHUR (chondritic uniform reservoir). Epsilon Hf may be either positive or negative depending on the nature of the material(s) that melted to form the magma from which the zircon crystallized. Values that are significantly positive suggest that the source rock(s) mainly reside in the Earth's mantle and experienced earlier periods of melt removal to form the oceanic and continental crust. Hf is concentrated in the melt relative to Lu during this process, yielding a residual mantle with relatively high Lu/Hf, known as the depleted mantle (DM). On the other hand, significantly negative epsilon Hf values indicate that pre-existing continental crust was involved in magma genesis. However this crust must be more than ~100-200 million years old at the time of melting in order to produce isotopically distinct magmas. Hence the Lu-Hf isotopic system, in conjunction with precise age control, provides a window on the mechanisms of continental crust formation over time.

Slave Province data: Eighteen granitoid rock samples from the western Slave Province with ages between 4.0-2.58 Ga have initial $^{176}Hf/^{177}Hf$ isotopic compositions that plot mainly between the DM and CHUR evolution lines. However, important exceptions exist – most apparent in the epsilon Hf vs age diagram. The oldest zircons, from samples of Acasta gneiss, suggest both the existence of a depleted mantle at 4.0-3.8 Ga and the involvement of older crust in magma genesis, particularly at ca. 3.8 Ga and again at 3.53 Ga. The most positive epsilon Hf values (above DM) must be treated with caution at this stage until we can fully assess whether zircon alteration or partial recrystallization has modified Hf initial ratios. Additional work on these samples is underway. At younger ages, both depleted mantle and crustal signatures are apparent at various times. For example, zircons with ages of 3.32-3.25 Ga show mainly high epsilon Hf values with little evidence for a distinct crustal signature. This situation is reversed at 3.0-2.8 Ga with most analyses lying well below DM and extending to negative epsilon Hf values. Both depleted mantle and crustal signatures are evident at 2.73-2.67 Ga.

Abitibi subprovince data: Our data for seven granitoid samples from the Kenogamissi and Round Lake plutonic complexes indicate generation predominantly from a juvenile source such as the depleted mantle or very young crust formed from depleted mantle. This is consistent with

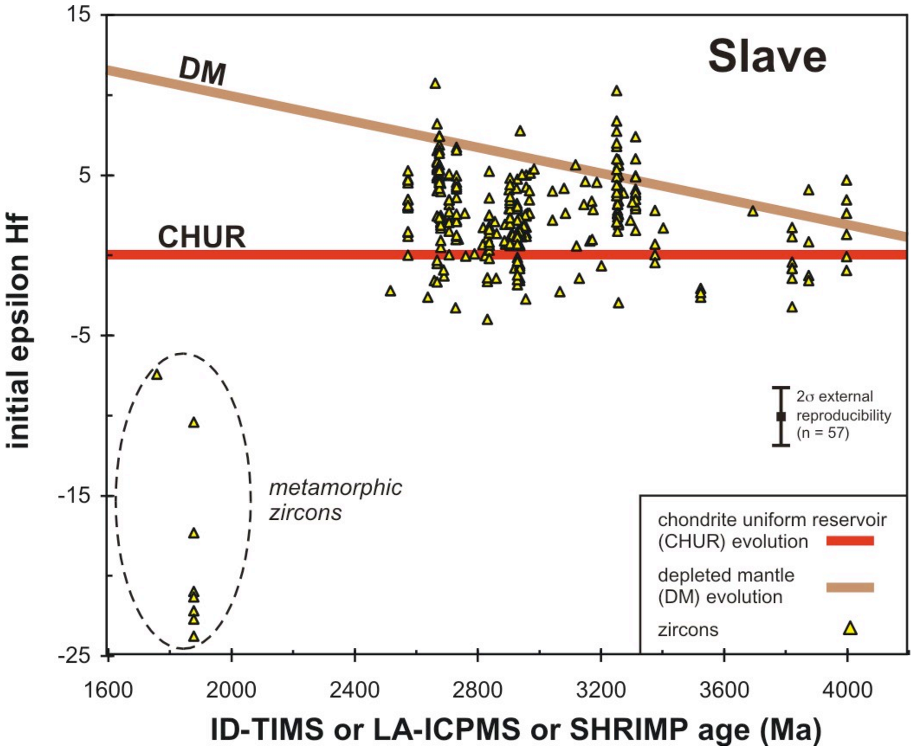

Figure 2. U-Pb age versus initial epsilon Hf for zircons from (mainly tonalitic) rocks of the western Slave Province. Most zircons are plotted at an 'assigned age' based on extensive U-Pb dating. This minimizes errors in epsilon Hf associated with U-Pb discordance. Detrital zircons from one sample are plotted at their $^{207}Pb/^{206}Pb$ ages (mostly concordant and near-concordant analyses). Ca. 1.88 Ga zircons labelled as metamorphic (not discussed in text) are from an exposure of Slave basement gneiss in the Proterozoic Wopmay orogen.

the results of earlier workers. Epsilon Hf values are negative only for a sample of 2684 Ma quartz diorite from the Kenogamissi complex. This sample is geochemically similar to post-2.7 Ga sanukitoid suites that occur throughout the Superior Province and may have been isotopically influenced by a subducted slab component, in this case probably subducted older sediments. The quartz diorite also has evidence of crustal contamination in the form of two zircons with ages of ca. 2725 Ma. We interpret these grains to have been inherited from ca. 2725 Ma Abitibi crust during formation and/or transport of the quartz diorite magma.

Our U-Pb results suggest the presence of even older crust in this region of the Abitibi subprovince. In an early TIMS analytical session, four single zircon crystals from two Kenogamissi samples provided $^{207}Pb/^{206}Pb$ ages of 2.84 Ga. Attempts to find more zircons of this age during later TIMS and LA-ICPMS sessions were unsuccessful, and we are therefore uncertain whether the 2.84 Ga zircons are 'real' or represent a rare and unusual case of laboratory contamination. However, the presence of inherited zircons of the same age in two units of the batholith complex is not unexpected, and variations in $^{176}Hf/^{177}Hf$ for nearly all Kenogamissi samples are much greater than for Round Lake samples, suggesting that variable crustal contamination of may have played an important role in Kenogamissi plutonism.

$^{176}Hf/^{177}Hf$ isotopic variations: As alluded to above, our Hf isotope data from both study areas indicate significant $^{176}Hf/^{177}Hf$ variations within individual samples. We are confident that the sampled units have igneous protoliths (with the exception of one metasedimentary unit from the Slave Province) and therefore that the zircons are derived predominantly from igneous populations (as demonstrated by U-Pb age; inherited and metamorphic components providing the

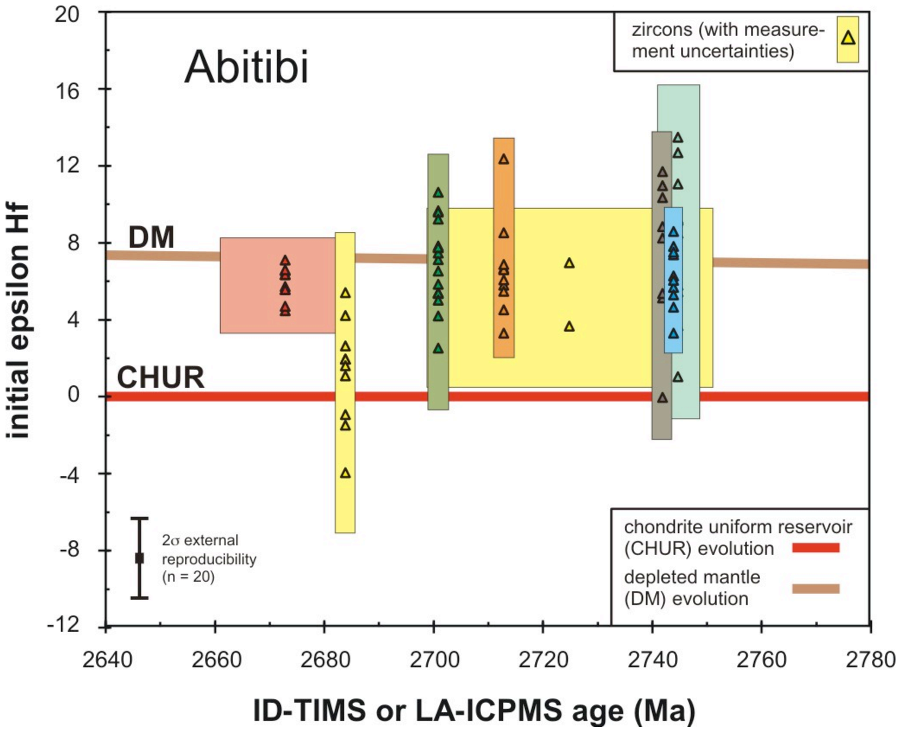

Figure 3. U-Pb age versus initial epsilon Hf for zircons from the Kenogamissi and Round Lake batholiths, Abitibi subprovince. Zircons ages are based mainly on precise ID-TIMS dating confirmed by LA-ICPMS dating, with most analyses concordant or near-concordant. DM and CHUR evolution lines shown here and in Fig. 2 are based on parameters discussed in Griffin et al. (Geochim. Cosmochim. Acta., 64: 133-147, 2000).

exceptions). Variations of ^{176}Hf/^{177}Hf in these populations therefore must reflect analytical uncertainty and/or isotopic heterogeneity. Assessment of the former indicates that the observed Hf isotope variation typically exceeds analytical error, so a geological explanation is required. It has been previously demonstrated that the Lu-Hf system can be disturbed during episodes of zircon alteration or recrystallization. In some cases, open-system behaviour results in the addition of radiogenic Hf, often in conjunction with partial resetting of the U-Pb system so that significant Pb loss correlates with higher ^{176}Hf/^{177}Hf. Addition of Lu represents another possible disturbance, although this would influence ^{176}Hf/^{177}Hf significantly only if the zircons are old (e.g., Archean) and Lu addition occurred not long after zircon crystallization. Although we have tried to select grains or portions of polished grains of good to excellent quality for analysis, some samples simply do not contain high-quality zircon, with the result that U-Pb discordance ± Hf isotopic disturbances may be unavoidable. Although this is of concern for some of our Slave Province samples, on the other hand some of the greatest Hf isotope variability is seen in very high quality Abitibi zircons with concordant U-Pb ages.

Another geological explanation that is probably applicable to this study involves isotopic variations that can occur in a magma chamber. Large epsilon Hf variations in igneous zircon have been reported in recent laser ablation studies and are interpreted to reflect the mixing of isotopically distinct source magmas, such as those that would likely occur if both mantle and crustal sources or even just a variety of crustal sources were involved. In addition to zircons that crystallize in the primary magma chamber before, during, and after this mixing, each source magma may potentially contribute its own zircons of unique (and in some cases end-member) Hf isotope composition. The U-Pb age of all these zircons will be essentially the same, therefore Hf isotope variations within and between grains will provide the evidence of this mixing process. Less pronounced isotopic variations have been observed in studies where single- or multi-grain zircon fractions are dissolved and analysed in solution, but this procedure will naturally disguise to some degree the isotope variability within (and in some cases between) individual zircons. Except in instances where core and rim components of different age were analysed, we have not investigated intragrain Hf isotope variations in detail. However, these variations are evident in some zircon populations due to the time-resolved nature of the laser sampling technique.

Speculations on crustal growth: Variations in the Hf isotopic signature of Slave Province magmatism likely indicates both local and regional changes in the competing processes of crustal growth and crustal recycling. At various times, magmas derived from the depleted mantle were fundamentally involved in crustal growth whereas at other times, new magmas contained a much higher proportion of melted older crust. What is interesting is that our data suggest that during periods of crustal melting, the melted rocks were probably no more than a few hundred million years old, or contributed only minor volumes of magma, thus accounting for epsilon Hf values that extend to no lower than -4. This is somewhat surprising as very old crust was available for melting during late Archean magmatic events. One possible reason for this is that pre-3.5 Ga crust was mainly restricted to the core of the Slave proto-continent and was therefore isolated from melting during later crustal growth around the continental margins. Another reason may be that once a melt is extracted from a crustal volume, it becomes difficult to extract subsequent melts from the same volume. In a tectonically and magmatically active regime, crustal melting is more likely to have occurred relatively soon after crust formation. Yet another consideration is the bias of our sample set toward tonalitic protoliths, which are thought to represent predominantly juvenile additions of crustal material.

In the southern Abitibi region, both this study and earlier work indicate that crustal growth was dominated by mantle-derived magmatism. However, epsilon Hf for some of our zircons extend well above DM, suggesting one or more of: (i) some degree of mantle heterogeneity, including the presence of ultra-depleted mantle, at 2.7 Ga; (ii) granitoid magma generation from different sources (e.g., plume, shallow mantle, juvenile crust), and; (iii) the possible need for another depleted mantle model for this region at 2.7 Ga. Limited involvement of older crust is suggested by our data, and there is already some existing U-Pb evidence for the presence of pre-2.8 Ga crust in the subsurface. The Hf isotope data permit, but are not able to clearly identify the involvement of ~100 m.y. old crust during construction of the two plutonic complexes. It should be remembered that not all Abitibi lithologies such as the well-studied mafic and ultramafic volcanic assemblages need have interacted with remnants of older continental crust, and therefore their juvenile chemistry and isotopic signatures do not rule out the existence of this crust. We observe from our U-Pb and Hf data that the Kenogamissi plutonic complex has reasonable evidence for crustal contamination whereas the Round Lake complex does not. Given the closer proximity of the Kenogamissi complex to the Wawa subprovince, which is underlain by rocks as old as 2.93 Ga, this observation is perhaps not surprising. The presence of remnants of 2.9-2.7 Ga sialic crust in the Abitibi subprovince, perhaps originating from the adjacent Wawa and Opatica subprovinces, has already been postulated by one of us (WB). If additional evidence for the presence of this crust at depth is obtained, this will help to further clarify the plate tectonic setting of the Abitibi subprovince.