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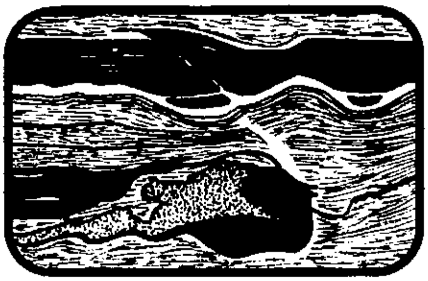
Article abstract

The Sensitive High Resolution Ion Micro-probe (SHRIMP) at the Geological Survey of Canada, Ottawa, has been used to show that the oldest-known continental crust is even older than previously thought. Zircon grains from a deformed igneous rock from the Acasta Gneiss Complex, Northwest Territories, Canada, are interpreted, based on their U-Pb isotope systematics, to have crystallized at-4.03 Ga. Subsequent high-grade metamorphism at -3.36 Ga and later resulted in extensive Pb-loss and growth of metamorphic zircon. This is one of the few rocks known to have survived the first 500 million years of Earth's history.



Age of the World's Oldest Rocks Refined Using Canada's SHRIMP: The Acasta Gneiss Complex, Northwest Territories, Canada

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SUMMARY
The Sensitive High Resolution Ion Microprobe (SHRIMP) at the Geological Survey of Canada, Ottawa, has been used to show that the oldest-known continental crust is even older than previously thought. Zircon grains from a deformed igneous rock from the Acasta Gneiss Complex, Northwest Territories, Canada, are interpreted, based on their U-Pb isotope systematics, to have crystallized at ~4.03 Ga. Subsequent high-grade metamorphism at ~3.36 Ga and later resulted in extensive Pb-loss and growth of metamorphic zircon. This is one of the few rocks known to have survived the first 500 million years of Earth's history.

RÉSUMÉ
Des analyses réalisées à la Commission géologique du Canada utilisant la microsonde ionique à haute résolution ultrasensible SHRIMP ont permis de réaliser que la plus vieille croûte continentale terrestre connue est encore plus ancienne qu'on ne l'avait cru. L'étude des rapports U-Pb des analyses radiométriques sur des grains de zircon provenant d'un échantillon de roche ignée déformée du complexe de gneiss de Acasta, Territoires du Nord-Ouest au Canada, montre que ces grains de zircon se sont cristallisés il y ~ 4,03 Ga. Une poussée métamorphique subséquente de forte intensité, il y a ~ 3,36 Ga, a provoqué une grande déperdition de la fraction Pb et entraîné la recristallisation subséquente d'une phase métamorphique de zircons. Il s'agit là d'un des rares échantillons de roche ayant subsisté aux événements des premiers 500 millions d'années de l'histoire de la Terre.

Geological Survey of Canada Contribution No. 1997258

AGE OF THE EARTH AND GROWTH OF THE CONTINENTS
For millennia, humans have attempted by various methods to determine the age of the Earth, but it was the discovery of radioactivity in the late 19th century and the development of the modern mass spectrometer in the early- to mid-20th century that provided the tools for today's accurate radiometric age determinations. Beginning with the classic papers by Rutherford (1929) and Patterson (1956), the formation of the Earth (*i.e.*, accretion from the Solar Nebula) is now considered to have been completed 4.5-4.6 x 10^9 years ago (Ga). These and subsequent age estimates depend mainly upon Pb-isotopic ratios measured in meteorites and various Pb ores from the Earth (see Dalrymple, 1991 for a review). The age of the Earth, therefore, is inferred from indirect isotopic evidence, as actual terrestrial rocks of this early age and the subsequent 0.5 Ga of Earth's history (the geological period termed the Hadean era) have not yet been identified.

It is probable that any crustal rocks formed on the Hadean Earth were recycled rapidly into a partially molten magma "ocean" that was being bombarded by meteorites up to the size of small planets (*e.g.*, Abe, 1993; Carlson, 1996). However, the amount of buoyant, continental crust generated in the Hadean remains a controversial topic. One extreme view is that, within a few hundred million years of the formation of the planet, a mass of continental crust similar to that preserved today had already been generated. Another perhaps more widely held view is that the continental mass grew episodically and at an increasing rate through to the end of the Archean (~2.5 Ga; see Taylor and McLennan, 1985 for a review of these models). One of the principal arguments used in support of episodic addition of continental crust is that the areal extent of rocks of a specific age decreases as the age increases. Although this pattern might have more to do with erosion and preservation than rates of addition, it is quite clear that the oldest rocks are indeed the hardest to find, and that resolving the controversy over the growth rates of the continental crust depends in large part upon locating and studying these old rocks (*e.g.*, Bowring and Housh, 1995; Vervoort *et al.*, 1996).

THE ION MICROPROBE AND THE QUEST FOR OLD ROCKS
Since the early 1980s, the use of the Sensitive High Resolution Ion Microprobe (SHRIMP; Compston *et al.*, 1984) has led to a gradual closing of the gap between the Pb-isotope model ages of the Earth's formation and the actual crystallization ages of terrestrial rock samples. The oldest known crustal *materials* are detrital and recently discovered inherited zircon ($ZrSiO_4$) grains from the Narryer Gneiss Complex, Yilgarn Block, Australia, which have SHRIMP U-Pb ages of 4.1-4.3 Ga (Froude *et al.*, 1983; Compston and Pidgeon, 1986; Nelson, 1997). Although none of these ages are of *rocks*, they nevertheless provide unequivocal evidence that sialic crustal rocks were in existence as early as 4.3 Ga. That such ancient inherited zircons occur within Archean granites (Nelson, 1997) suggests that old crust could potentially reside at depth in the present day crust of Western Australia.

Rocks with radiometric ages in excess of 3.6 Ga (*i.e.*, Eoarchean) are found in several Archean cratons (*e.g.*, Nutman *et al.*, 1996), but those with ages older than 3.9 Ga are known only within the North Atlantic Craton of Greenland (Itsaq Gneiss Complex; Nutman *et al.*, 1996), Antarctica (Napier Complex; Black *et al.*, 1986), and the Slave Province of Canada (Acasta Gneiss Complex; Bowring *et al.*, 1989b). Accurate and precise isotopic ages of the oldest rocks in these areas were determined by U-Pb dating of zircon largely using the SHRIMP at the Australian National University (ANU). There is good reason why other analytical techniques, whether based on analysis of single or multiple minerals or whole-rocks, have been unable to measure as precisely and accurately the ages of these ancient and battered rocks. Fundamentally, it comes down to the fact that the answers to the age questions remain preserved only at the intra-grain scale of minerals that resist younger isotopic disturbance. Zircon is practically the only mineral in common igneous rocks capable of recording in its U-Pb isotopic system its original time of growth, despite subsequent metamorphic history. The zircons in very ancient rocks

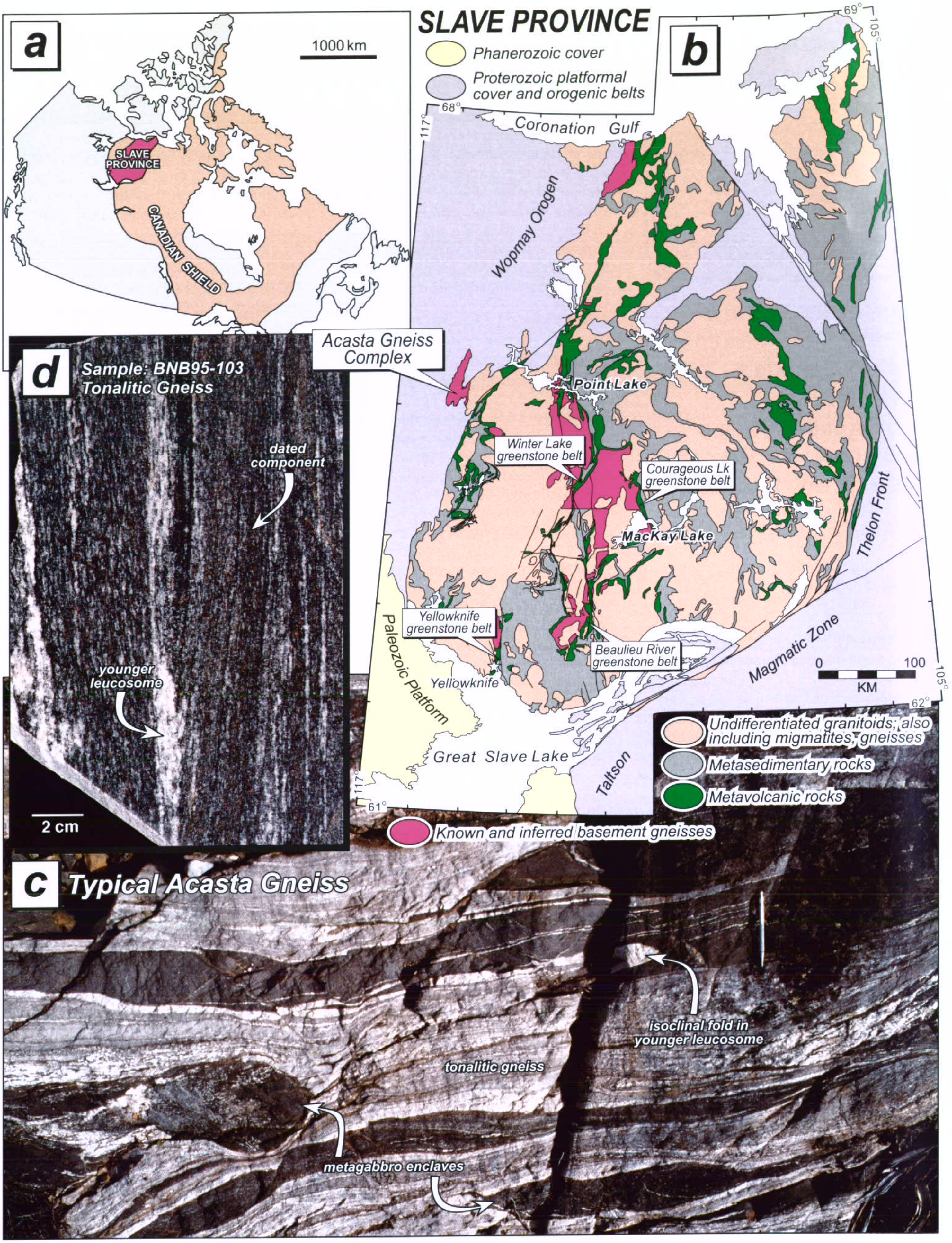

Figure 1 The Acasta Gneiss Complex (AGC): (**a**) location of the Archean Slave Province within the Canadian Shield; (**b**) simplified geology of the Slave Province, showing location of the AGC; (**c**) typical multicomponent gneiss of the AGC, showing complexly layered and folded tonalite-amphibolite with younger pink to white granitic leucosome veins (pen for scale toward right); (**d**) close-up of dated tonalite gneiss sample BNB95-103.

are usually very complexly structured and commonly severely isotopically disturbed owing to their long residence time in the crust, and it is only possible to obtain radiometric ages from the few isotopically undisturbed regions within such grains using an *in situ* analytical method. The SHRIMP allows U-Pb isotopic ages to be determined *in situ* from spots on zircon as small as 5 μm in diameter, without destroying the grains (Stern, 1997). This technological capability has greatly advanced our understanding of ancient rocks in practically all Precambrian terranes (*e.g.*, Nutman *et al.*, 1996).

THE ACASTA GNEISS COMPLEX

The Acasta Gneiss Complex, (AGC; King, 1985), first recognized during a regional mapping program carried out by the Geological Survey of Canada (King, 1986; St-Onge *et al.*, 1988), lies at the western margin of the Archean Slave Province, Canada, about 300 km north of Yellowknife (Fig. 1). This area of Archean rocks, several hundred square kilometres in extent, is exposed in a set of structural culminations within the foreland fold and thrust belt of the Paleoproterozoic Wopmay Orogen (King, 1986; St-Onge *et al.*, 1988). The AGC comprises polydeformed, strongly metamorphosed and migmatized amphibolitic-tonalitic-granitic orthogneisses that are cut by several generations of granitic veins and dykes (Fig. 1). Bowring *et al.* (1989a) demonstrated using conventional zircon U-Pb dating (*i.e.*, isotope dilution thermal ionization) that a component of a zircon crystal recovered from a tonalitic gneiss was older than 3.842 Ga, and feldspar Pb-isotopes and whole-rock Sm-Nd isotope model ages also supported the extreme antiquity of the sample. With the use of the ANU SHRIMP, Bowring *et al.* (1989b) were able to determine more accurately the age of this sample and one other rock. The combined age, 3.962 ± 0.003 Ga, made these the oldest known terrestrial rocks.

In 1995, the Geological Survey of Canada initiated an in-depth geological and geochronological study of the complex (Bleeker and Stern, 1997) as a component of a broader program to understand the evolution of the Slave Province. Employing a newly acquired SHRIMP II ion microprobe (Stern, 1996), we began our geochronological study by examining the grey tonalitic gneiss (BNB95-103) shown in Figure 1. This sample is representative of a rock unit considered to be one of the oldest based on cross-cutting relationships, and to our knowledge it has been collected from the same outcrop area as one of the very old samples studied by Bowring *et al.* (1989a,b).

SHRIMP U-PB ZIRCON DATING OF BNB95-103

The abundant zircons recovered from the tonalitic component of the layered orthogneiss BNB95-103 are divided equally into irregularly shaped, turbid grains with rounded and embayed grain edges (Type 1) and prismatic grains with turbid, rounded cores (Type II; see Fig. 2, inset). The least-magnetic zircons were mounted in epoxy, polished and their internal growth structures imaged using plane light and scanning electron microscopy. The imaging techniques allow the detailed internal structure of the zircons to be ascertained so that the SHRIMP sample spot is always placed, within the limits of our understanding of zircon growth, on only one generation of zircon.

The SHRIMP results (see Stern, 1997 for analytical techniques) obtained from several grains are shown in Figure 2, plotted on a standard concordia diagram, each 95% confidence error ellipse representing the results from a single 10-15 μm diameter spot analysis. The analyses of prismatic overgrowths of Type II grains are quite uniform and indicate an age of 3.356 ± 0.014 Ga. This zircon has characteristically low Th/U values (0.05-0.14), a feature typically associated with metamorphic rather than igneous zircon. This observation, coupled with the fact that the overgrowths are thin or absent in many grains, suggests to us that 3.356 Ga is not the age of the tonalitic protolith, but rather the age of a period of high-grade metamorphism coincident with injection of leucosome (Fig. 1). Metamorphic zircon of this age has previously been documented (Williams *et al.*, 1992; Williams and Bowring, 1997) and our work indicates that this was perhaps the dominant period of high-grade metamorphism within the AGC (Stern *et al.*, 1997). Our hypothesis can be tested by the analysis of zircon isolated from the leucosome of this particular sample.

The remaining data for Type I grains and cores of Type II grains form an array that overlaps concordia and extends slightly below it, with apparent ages ranging from >4.0 Ga to ~3.4 Ga. It could be argued that the spread in the data reflects a real age range for detrital or inherited grains. As is common in studying gneissic rocks, the nature of the protolith can sometimes be in doubt, but on bulk compositional and textural grounds a sedimentary origin for this sample seems unlikely. For example, the tonalite occurs with bands of amphibolite that give the appearance of having been mafic inclusions in an original tonalitic magma (Fig. 1). The spread of ages appears not to be related to analytical mixing of inherited and younger igneous zircon during the SHRIMP analyses, as the

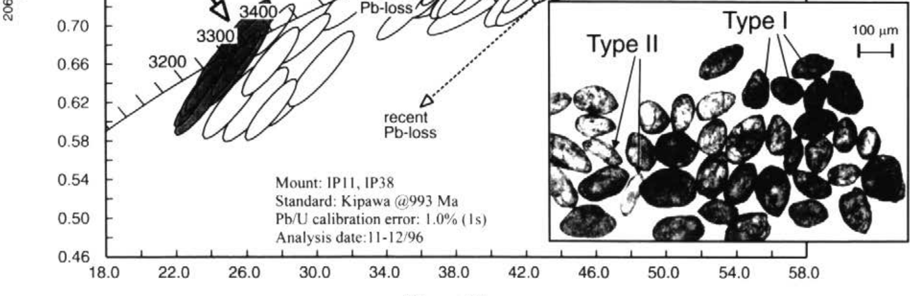

Figure 2 U-Pb concordia diagram for zircons from tonalite BNB95-103 from the Acasta Gneiss Complex. Data were collected using the GSC SHRIMP II ion microprobe, and each error ellipse (95% confidence limits) represents a single age determination from a spot measuring 10-15 μm in diameter. Inset shows plane light image of typical zircon morphologies.

spots were located only on zircon considered to be a single generation of growth based on the imaging analysis.

Instead, we suggest that the range in ages for Type I zircons and cores of Type II grains is due to partial radiogenic Pb-loss from magmatic zircon, probably caused by the metamorphism at 3.356 Ga and at later periods, including recently (Fig. 2). This interpretation is supported by detailed studies of the Pb-loss patterns of individual grains, which indicate that U abundance and $^{207}Pb/^{206}Pb$ ages are inversely correlated. It appears that Pb-loss has preferentially affected the parts of the zircon that have suffered the greatest amount of accumulated radiation damage.

The complex results for Type I zircons and cores of Type II grains do not permit a precise age to be easily deduced. However, if one accepts the assumption that these data are from one generation of zircon having undergone both ancient and recent Pb-loss events, then the $^{207}Pb/^{206}Pb$ ages can be sorted and analyzed statistically to determine the likely age of the zircon within a specified level of confidence. Averaging of the eight oldest $^{207}Pb/^{206}Pb$ ages, which are identical within analytical uncertainty, obtained from four separate grains indicates that the assumed protolith zircon is at least 4.025 ± 0.015 Ga at the 95% confidence level. If any of these eight ages has been reduced by Pb loss, then the true age of the rock would be closer to oldest ages measured, namely 4.037 ± 0.024 Ga and 4.034 ± 0.026 Ga. It is our interpretation that almost all the old zircon has undergone some extent of Pb loss, with the exception of rare 10-20 mm diameter domains of zircon with lowest U contents that appear to have remained relatively undisturbed since their formation. Unfortunately, the analytical uncertainties inherent in the SHRIMP analysis of zircon (Stern, 1997) limit our ability to measure the small amounts of isotopic discordance that would allow us to demonstrate this for every spot age determination.

To summarize, Type I zircons and the cores of Type II zircons are thought to be original igneous grains formed in the tonalitic component of BNB95-103 at 4.025 ± 0.015 Ga, whereas the prismatic rims of Type II grains are believed to be related to metamorphism at 3.356 Ga. From this brief report it can be seen that the geochronology of this one sample is quite complicated, and, as with all complex zircon U-Pb systematics, alternative interpretations may be possible. We are currently preparing a full report expanding on the results of this sample and another with equally complicated isotope systematics, but which also yields an identical age.

CONCLUSIONS

The SHRIMP data suggest that the crystallization age of tonalitic gneiss BNB95-103 from the Acasta Gneiss Complex is ~4.03 Ga. If accurate, this result extends by about 0.07 Ga the age of similar rock types reported by Bowring *et al.* (1989b). Our result is indistinguishable from the age of 4.031± 0.004 Ga reported by Williams and Bowring (1997) for another AGC tonalite, and the agreement of these independent findings lends strong support to the accuracy of the age interpretations. Although the AGC clearly contains what are the oldest known terrestrial rocks, such ancient rock types appear to form only a small proportion of the outcrop area of the AGC. It is astonishing and rather humbling to realize that the true age of these rocks, and therefore evidence of Earth's earliest history, has been almost totally wiped out by younger geological events, the only evidence remaining being rare, undisturbed micron-scale domains preserved in tiny zircon grains.

Despite these findings, there remains a gap of ~0.5 Ga of Earth's earliest geological history for which we have little direct evidence, and no known rock samples. Locating such rocks will be crucial for understanding the chemical, thermal and tectonic evolution of the Hadean Earth, both the crust and the mantle. For example, the trace element chemistry of the rocks may shed light on the prevailing magmatic conditions, and the Nd- and Hf-isotopes can be used to track the isotopic composition of the mantle through time (Vervoort *et al.*, 1996), in turn providing constraints on whether large masses of continental crust were generated during the Hadean era.

A great deal of hard work, both in the field and in the laboratory, and no small amount of good luck will be required if we are to extend the known rock record beyond the 4.03 Ga presently documented. High-resolution ion microprobes such as the SHRIMP have played and will continue to play a major role in this endeavor, allowing geochronologists to obtain isotopic information at the micron-scale at which it is preserved in accessory minerals. We are continuing to apply this technology to understanding the first few hundred million years of geological history of our planet.

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