icelandite melts; they cannot be derived from fractional crystallization of a parental icelandite. The chemistry for 1480 Ma anorogenic terranes of granite and rhyolite from the St. Francois Mts., Missouri, suggested to *B.K. Nelson* a likely origin, subduction-related tectonics at a craton margin.

The last session was Symposium XII, **Arc Magmatism.** The origin of Kamchatka flows was found by *M.P. Semet*, A. Zaimi, J.L. Joron, G.E. Bogoyavlenskaya and V.M. Okrugin to have resulted from high ($\sim$10 $cm \cdot yr^{-1}$) subduction rates. Mixing MORB-type magma with elements from the sinking slab can explain trace element patterns. Using trace element concentrations across five volcanoes in the Sunda-Banda Arc, Indonesia, *P.Z. Vroon*, M.J. Van Bergen, J.C. Varekamp and R.P.E. Poorter postulated sources varying from N-type MORB magma mixed with 3-5% subducting sedimentary material to E-type MORB magma mixed with 1-3% sediment. From a study of the major and trace element concentrations in fresh high-Ca boninites from the North Tonga ridge, *T.J. Falloon* and A.J. Crawford suggested an origin by crystal fractionation in a mixture of depleted OIB mantle rich in incompatible elements, carbonatite melts, and hydrous fluids from subducting lithosphere. The Tonga boninites seem to be comparable to the upper pillow lavas in the Troodos ophiolite. *G. Wörner*, S. Moorbath and R.S. Harmon studied the trace element composition of Central Andean Neogene-Recent volcanics, where the continental crust is extremely thick (60-70 km), to determine an origin for sub-arc mantle wedge mafic melts that have risen through and interacted with the recently thickened continental crust. In cummingtonite phenocrysts from 3 ka silicic Mt. St. Helens magmas, *C.H. Geschwind* and M.J. Rutherford found a stability temperature of slightly less than 810°C. Since cummingtonite is absent from all magmas erupted in the last 3 ka and the flows have changed to basalts and andesites, chamber temperatures have probably increased by 100°C, while water pressure has probably decreased. After extensive stratigraphic and geochronologic studies at Vulcano, southern Italy, *P.Y. Gillot*, S. Chiesa and G. Alvarado developed a detailed evolution for magmatic activity during its 120 ka history.

Nine field trips were held in conjunction with the conference. Pre-congress excursions were run in Germany to the East and West Eifel Volcanic Fields to examine Quaternary volcanism, to the Rhinegraben for Cenozoic alkaline intraplate volcanism, and to see Devonian/Early Carboniferous submarine intraplate volcanism in the Lahn-Dill area and Sauerland Rhenish Massif. An excellent mid-conference excursion visited the Laacher See for the day. Post-congress excursions included the Eifel Volcanic Fields again, alkaline and carbonatite volcanism in the Kaiserstuhl, Steinheim and Nördlinger Ries impact craters, and the oceanic volcanic island, Gran Canaria.

The excellent two-day trip to the Ries craters, run by Dr. Günther Graup, concentrated on impact breccia suevite, its variable composition and formation at differing locations in and around the crater. With only 16 people and 8 stops, there was time for many stimulating discussions with contributions from everyone.

An excellent video, called "Volcanic Hazards", by M. Krafft, C. Newhall and S. Brantley, that discussed many types of dangers inherent in volcanic activities, was shown several times each day throughout the conference.

All who attended the conference would acknowledge the friendly conference personnel who went to all lengths to take care of everyone. Many young scientists (including the writer) benefited from financial aid generously offered by the organization to assist with expenses incurred in attending the conference. Overall, this was an excellent conference, and many people are looking forward to the next International Volcanological Congress.

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A Decade of Evolution in Archean Thought: The Third International Archean Symposium

Andrew Kerr
Geological Survey Branch
Department of Mines and Energy
St. John's, Newfoundland A1B 4J6

The Third International Archean Symposium (3IAS) was held in Perth, Western Australia, on 17-21 September 1990. It was closely followed by the Seventh International Conference on Geochronology and Isotope Geology (ICOG7), held in Canberra on 23-29 September. Geochronology and Precambrian geology are inextricably linked, and some relevant aspects of the Canberra conference are also addressed in this report.

The Archean symposia are held at ten-year intervals to review the developments of the past decade and provide a forum for presentation of current research. The vast 3IAS program included about 50 oral and over 100 poster presentations squeezed into five days of technical sessions. The oral program emphasized "keynote" review presentations of recent work and outstanding problems in specific fields or geographic areas. Poster sessions focussed on more localized and/or problem-oriented studies, and contained much "current" (*i.e.*, late 1980s) research. Although there were the usual complaints from some delegates about a "lack of new information", I found the oral program a useful framework that placed the numerous posters in a wider context. In terms of numbers of delegates, Canada was second only to the host country, and our contributions were mostly lucid and well presented.

The symposium was broken into sequential thematic sessions, which I have used as a framework for discussion. It was augmented by seven field trips, including a 10-day marathon to the classic Pilbara Craton and Hamersley Basin sequences, visits to gold and nickel deposits of the Yilgarn Craton, and a trip to the Mount Narryer gneiss terrane, where the oldest crustal materials have been identified in the form of *ca.* 4.3 Ga detrital zircons in metaquartzites.

I made a very minor contribution to the second symposium in 1980, but have not been *directly* involved with Archean geology since that time. However, like most who are exposed to the subject, I have continued to follow it with interest. Conference reports (in my opinion) should be aimed at readers who are *not specialists in the conference theme*, and I have thus attempted to provide an "outsider's view" of 3IAS. I must apologize in advance to those whose fields of interest are inadequately discussed below, as I have, in many cases, chosen readability at the expense of detail.

THE EARTH-MOON SYSTEM AND EARLY EARTH HISTORY

The primordial Earth is a no man's land where terrestrial geology meets comparative planetology. It is a highly speculative area, as direct lines of evidence are virtually nonexistent; I suspect that this is why it is so interesting to many of us!

Ted Ringwood (Australian National University (ANU), Canberra) approached the topic from experimental and theoretical perspectives, and suggested on this basis that a completely molten proto-mantle would have developed a distinctive geochemical signature via perovskite fractionation. The absence of this signature implies that at least the upper mantle accreted *after* core formation, as the gravitational energy released by this would have melted the mantle totally. It was suggested that siderophile element (*e.g.*, Fe, Ga, Ni, Co, W) patterns may provide unique fingerprints of specific planetary bodies. The similarity between terrestrial and lunar siderophile signatures implies that the Moon was derived from material ejected by major impacts soon after core formation. Such ideas are, however, not universally accepted, as Robert Malcuit (Granville, Ohio) advocated lunar capture at *ca.* 3.9 Ga, and suggested that tidal heating initiated Mare volcanism.

Bill Compston (also of ANU) approached the problem from a terrestrial perspective, and pointed out that the oldest rocks on Earth are broadly similar to modern calc-alkaline granitoid rocks, and radically different from the lunar crust. Nd isotope studies of early Archean gneisses hint at the existence of yet older precursors, now glimpsed directly as *ca.* 4.3 Ga detrital zircons in Australia. These zircons are geochemically akin to those from younger granitoid rocks, suggesting similar parent magmas. Hence, despite ten years of searching and a veritable explosion in geochronological studies, no sign of a pre-4.0 Ga anorthositic crust analogous to the lunar highlands has been detected. A widespread crust of this composition is implied by most thermal models, which suggest the formation of fractionating magma lakes or oceans in the uppermost mantle soon after accretion. It was argued that impacts may have destroyed (or deeply buried) most of this material, and perhaps also the earliest sialic crusts, now found only in detrital form. Ideas about massive impacts are not new in Archean geology, but the popular "impact extinction" concept (with help from the late, lamented dinosaurs!) has led to a wider acceptance of their importance in early crustal evolution, and throughout all of Earth history.

ARCHEAN CRUSTAL PROVINCES ON A WORLDWIDE SCALE

This lengthy session reviewed ten years of intensive research conducted since the second symposium, and also discussed models for Archean crustal evolution. Most of the Canadian contributions focussed on the Superior Province, which Phil Thurston (Ontario Geological Survey (OGS), Toronto) described as "a model for shield development". More than anything else, this session attested to the profound impact that U-Pb zircon geochronology has had upon our knowledge of and models for Archean geology.

The Superior Craton of Canada and the Yilgarn Craton of Australia have become the type areas for Archean crustal evolution, as they are the *only* areas where geochronological control allows models to be tested. Earlier views of craton-wide correlations amongst greenstone belts have now mostly been abandoned; the "terrane accretion" concept derived from Cordilleran geology during the 1980s has strongly influenced researchers weaned on plate tectonics. Phil Thurston and John Myers (Geological Survey of Western Australia) presented the Superior and Yilgarn Cratons, respectively, as *composite* provinces in which terranes with different histories have been tectonically juxtaposed. Fernando Corfu (Royal Ontario Museum) reviewed regional age zonation patterns that indicate southward growth of the Superior through the late Archean. A similar eastward younging is present in the Yilgarn, although the database is smaller.

Detailed mapping of individual greenstone belts has shown that they vary greatly in composition and structure. Phil Thurston and John Percival (Geological Survey of Canada (GSC), Ottawa) described them as Archean analogues of epicontinental platform, oceanic ridge (or "mafic plain") and island-arc environments — assemblages that resemble the "exotic" terranes of younger orogenic belts. A fourth association, important in gold metallogeny, probably represents unconformable "pull-apart" basins developed *after* terrane accretion. Essentially, the same associations have been recognized in the Yilgarn Craton, but their parallels with modern environments are not as widely accepted or emphatically presented. Structural studies of greenstone belts indicate that earlier ideas of "vertical development" are probably simplistic; evidence for early thrusting and nappe formation was presented from several areas.

These lines of evidence converge in a view of Archean cratonic evolution via amalgamation of island arcs and back-arc basins (± microcontinental blocks) as the intervening oceanic crust was consumed. High-grade metasedimentary terranes, particularly evident in the Superior Province, were interpreted by John Percival (GSC) as derivatives of forearc sedimentary prisms caught up in this accretionary chaos. The origin of the more extensive granulite-facies orthogneiss provinces, which host some of the oldest terrestrial rocks, remains more controversial. Clark Friend (Oxford, UK) reviewed evidence for the existence of discrete terranes, similar to those now recognized in low-grade greenstone belts, in the classic high-grade Early Archean gneiss terrane of west Greenland.

Although there is convergent thought in Canada and Australia, we should not be too eager to define a "model craton". Bill Padgham (Department of Indian and Northern Affairs, Yellowknife) emphasized the lithological, compositional and metallogenic contrasts between the Slave and Superior Cratons in Canada. There are also differences between the Yilgarn and its smaller counterpart, the Pilbara Craton, which received little attention at 3IAS. Finally, available U-Pb geochronological data suggest greater involvement of pre-existing, older, sialic crust in the Australian Archean than in the Canadian Shield. This may partly be a function of differences in investigative techniques, as discussed later, but it could also indicate a fundamental contrast in their evolution.

ARCHEAN SEDIMENTATION AND THE ORIGINS OF LIFE

I am poorly qualified to comment on all of the contributions in this segment of the program. Comparisons of Archean and post-Archean sedimentary associations are complicated by the question of preservational bias, but there seems to be concensus that stable-shelf associations are less abundant in the oldest crustal provinces. Wulf Mueller (Université du Québec à Chicoutimi) drew analogies between Superior Province sedimentary sequences and those of Pacific marginal basins. As a general comment, "emphatic" comparisons of this type were more prevalent amongst North American workers than those from the southern hemisphere. An interesting poster by J.P. Vanyo (Santa Barbara, California) suggested that stromatolite heliotropism (*i.e.*, inclination of growth bands in response to sun angle) might provide Archean paleolatitudes and polar wander paths. Thomas Reimer (Wiesbaden, Germany) and Kent Condie (New Mexico) both addressed the problems of estimating bulk Archean and post-Archean crustal compositions via the trace element patterns of pelitic sediments. Condie suggested that many of the geochemical changes at the

Archean-Proterozoic boundary are indirectly attributable to declining geothermal gradients; for example, changes in the Cr/Th ratio reflect the waning of ultramafic volcanism.

ARCHEAN MAGMATISM AND METAMORPHISM

The problems of Archean magmatism are linked to uncertainties about early thermal conditions. Archean igneous rocks are broadly similar to those of the Phanerozoic, but have higher Ni and Cr, greater HREE depletion, and include ultramafic lavas. Such features, and the supposed rarity of alkalic magmas, imply more extensive partial melting of a hotter Archean mantle.

Mike Bickle (Cambridge, UK) modelled the thickness and composition of Archean oceanic crust for various thermal regimes. Calculations suggest an approximately 20 km thick oceanic crust, and a total basalt flux of 250 $km^3 \cdot yr^{-1}$, roughly ten times the present value. However, even the most extreme thermal regime does not produce model komatiites, whose petrogenesis remains elusive. Komatiites were described by Nick Arndt (Mainz, Germany) as "unreliable witnesses of the Archean mantle", as most are probably contaminated as a consequence of their great capacity to digest other rocks. An oceanic island analogue was preferred over a mid-ocean ridge setting, with the inference that komatiites might be related to Archean mantle plumes. John Ludden (Université de Montréal) questioned the prevailing "island arc" theory for mafic and intermediate volcanic rocks in the southern Superior Province, and suggested that some resemble modern regions of thick oceanic crust, such as Iceland.

A hotter Archean mantle also implies high degrees of partial melting above subduction zones, where volatiles flux hot mantle, but simple models are impossible, because we do not fully understand the present-day analogue. The related question of how (or if) a 20 km-thick oceanic crust would behave during subduction (or obduction) was not generally addressed. A controversial view of Late Archean granitoid magmatism and cratonization as a result of the evolution of largely molten lower continental crust was presented by John Ridley (University of Western Australia (W.Aus.)), and keenly discussed on the basis of geotherm calculations. However, if we accept the effects of a hotter mantle, we cannot avoid the related problem of a hotter, and more mobile, early sialic crust. Archean granitoid rocks received relatively little attention at 3IAS, although they underly more than 85% of most cratons.

Archean high-grade regions also received minimal attention at 3IAS, but John Percival (GSC) discussed cross-sections of the Archean crust in the Kapuskasing and Pikwitonei areas of the Superior Province. The granulites of these areas are interpreted to have formed at depth below magmatic arc systems, in contrast to metasedimentary granulites, which are interpreted as relics of forearc basins. It was my impression that most delegates feel that granulite orthogneiss terranes may now be viewed as deep-level equivalents of granite-greenstone provinces. Martin Van Kranendonk (Queen's University, Ontario) reviewed parallels between the structural evolution of Archean gneisses from Labrador and the patterns of deformation now recognized in many greenstone belts.

ARCHEAN METALLOGENY

Exploration for gold has directly and indirectly improved our understanding of greenstone belts since 1980. Metallogeny is also important in defining the various tectonic settings of Archean rocks. The Yilgarn craton of Australia received the most attention, with good participation from the Australian private sector. In view of the importance of gold to Canada, and the influential work of the OGS on lode-style deposits, our contributions to this session were disappointing. An *integrated* review of metallogeny in the Superior Province was sorely missed, as most Canadian presentations highlighted deposit-scale studies, where wider ideas were lost in local detail.

Mark Barley (University of W.Aus.) emphasized that both Au and Ni mineralization reach their maximum frequency in the Archean, but that Au is also strongly localized in modern arc systems. The regional association between volcanogenic massive sulphide (VMS) deposits and Au in some Archean provinces is considered to be largely coincidental. Gold mineralization in western Australia was linked to the process of accretion of oceanic and arc terranes, with or without included syngenetic deposits of VMS or komatiite Ni type. Deposits appear to be controlled by minor structures associated with major (crustal-scale?) terrane boundary faults or shears. Gold mineralization is thus viewed as an integral part of Late Archean craton assembly in western Australia.

David Groves and others (University of W.Aus.) presented an integrated model for gold mineralization in environments ranging from sub-greenschist to granulite facies, and explained most inter-deposit variations as a function of depth. From a mineral exploration viewpoint, they emphasized wallrock interaction, particularly with Fe-rich rock types, in controlling ore deposition. They also argued that the "depth continuum" amongst deposits implies a mantle or deep-crustal fluid source, and crustal-scale fluid migrations. Isotopic data presented by Bob Kerrich (U Saskatoon) and N. McNaughton (University of W.Aus.) are generally consistent with this view.

The inexorable link between mineral deposits research and metal prices probably explains the scarcity of papers dealing with VMS and komatiite Ni deposits at 3IAS. These are, however, of great interest with respect to Archean magmatism and early thermal conditions, and also in the characterization of island arc and "ophiolitic" associations within the tectonic collages that Archean cratons are now thought to represent.

Several presentations emphasized similarities between Archean deposits and those of the circum-Pacific region. The recent discoveries of huge gold-rich porphyry-type deposits in British Columbia, Papua New Guinea and Pacific island arcs, as discussed at the 1990 Vancouver GAC-MAC meeting, raise the question of Archean analogues of such deposits. This idea was not discussed formally at 3IAS, but seems a natural extension of the tectonic and metallogenic models presented at the symposium.

ARCHEAN CRUSTAL PROCESSES AND CRUSTAL EVOLUTION

This final session was an artificial division, as every session at 3IAS included discussions of crustal processes, and some of the closing contributions are covered under previous headings. Some papers re-emphasized comparisons between Archean terranes and younger accretionary orogens. Some North American contributions were highly emphatic: for example, Timothy Kusky (Houston, Texas) interpreted much of the Slave Province in terms of arc-continent collision tectonics. Given the significant influence of the hotter Earth on Archean magmatism, it is perhaps naïve to assume *direct* equivalence of modern and Archean tectonic processes and environments, but there was a far wider acceptance of a grossly "uniformitarian" view of the Archean Earth than at previous symposia. There are some significant non-uniformitarian events to consider (notably impacts, and unquantified secular variations related to declining heat flow), but most delegates seemed to feel that plate-tectonics was operating prior to 2.5 Ga. As the primary mechanism for heat loss in a wet, convecting, ultramafic planet (to paraphrase W.S. Fyfe), it is hard to see it as anything but a fundamental, long-term feature of the Earth. However, such views are not unanimous, particularly in Australia, where the importance of such processes in the Proterozoic and Phanerozoic is actively debated by some.

The latest alternative model is "plume tectonics", presented by Ian Campbell and Robert Hill (ANU), and also discussed at the ICOG7 conference. This view holds that thermal plumes emanating from sources deep in the mantle are responsible for the development of granite-greenstone provinces upon an older sialic basement. "Plume tectonics" and conventional plate tectonics are viewed as *independent* processes, and the former is considered to have had greater influence in the Archean. The main evidence for separation of the two is that plumes supposedly come from the core-mantle boundary whereas plate tectonics is driven by processes higher in the mantle. As this seems rooted in largely theoretical ground, it is viewed with caution by some, including the author. A more conventional view is that thermal plumes are an integral part of an overall plate-tectonic cycle.

Although controversial, the "plume tectonics" model raises important points. Given the probable high mantle temperatures during the Archean, the volumes of magmas produced by plumes would have been immense. Other presentations (see above) alluded to Archean volcanic sequences as possible analogues of modern oceanic hot-spots, and Mike Bickle noted that komatiites would be difficult to generate at an Archean mid-ocean ridge setting, and may have had deep-seated sources. There is a great deal more to plate tectonics than the *horizontal* motions of the Earth's crust, which are what we tend to focus upon most in regional geology. Perhaps the question for the fourth international Archean symposium should not be "are plate tectonic models applicable to the Archean?", but rather *"what can the Archean tell us about the evolution of plate tectonics in a cooling planet?"*

GEOCHRONOLOGY IN THE 1990s

If a single topic were to be nominated for its impact upon Archean geology, it would have to be U-Pb zircon geochronology. In 1980, models and syntheses were based upon Rb-Sr studies, where even the basic tenets of isochron behaviour were in doubt, and errors were commonly 100 Ma or greater. In discussions at 3IAS, errors were routinely quoted at less than ±5 Ma, and events were precisely correlated. Geochronology has become the key that can unlock the Archean cipher, and it is the tool with which models are tested.

The work of Tom Krogh and associates at the Royal Ontario Museum revolutionized our understanding of the Canadian Shield, and their high-precision methods have now become standard techniques. In Australia, the 1980s culminated in the development of an innovative new instrument termed the sensitive high-resolution ion microprobe (SHRIMP), that allows dating of single zircon grains. This method is capable of recognizing and quantifying inheritance on an almost routine basis, and can even separate multiple growth events in a single grain. Many of the SHRIMP studies conducted in the late 1980s are very impressive, and the descendants of this instrument will inevitably have a major impact in the coming decade.

The SHRIMP method has received criticism from some workers using traditional U-Pb multigrain and single-grain techniques, who state, correctly, that the *precision* of their Pb isotopic determinations is far greater than that afforded by the SHRIMP. They claim that the small uncertainties (±5 Ma or less) quoted on many SHRIMP dates are underestimated, and question the statistical arguments used in their calculation. The ion-microprobe school contends, in response, that many multigrain dates are simply precise measurements of *mixed* zircon populations, and that the very small errors (±2 Ma or less) are illusory. Needless to say, there were heated discussions at both 3IAS and ICOG7, and both sides presented very persuasive, but at times obtuse, arguments. As a non-specialist, I have now come to the conclusion that errors quoted by both methods should perhaps be treated with a measure of caution in some cases.

Many delegates at these conferences were, however, very impressed by the SHRIMP and the results it has produced. In the context of dating, it has shown that physically homogeneous zircon populations may be of composite age. In the context of the Archean, it has shown that *complex* inheritance patterns are widespread in Australia, in direct contrast to inferences based on multigrain results from the Superior Craton. Is this is real difference, or does it partly reflect the contrasts in the techniques?

The greatest problem with the prototype SHRIMP is that it is less precise than a conventional mass spectrometer, because it deals with very small quantities of material. The SHRIMP II prototype, currently being tested, will hopefully resolve many of the conflicts noted above with considerably greater precision and accuracy. I think that SHRIMP-type instruments will have a very important role in geochronology during the coming decade. The principal end-users of geochronological information are geologists seeking to develop and test ideas, and the ion-microprobe method is highly adaptable to many of the problems and questions that we face. It also opens the door to more *direct* involvement of geologists in their own geochronological research.

In conclusion, I wish to emphasize that I *do not* feel that the methods currently employed in North America are in any way obsolete or inappropriate. On the contrary, they have made, and will continue to make, very important contributions to Canadian and global geology. On the other hand, I believe that many delegates returned from Australia with the realization that Canadian geoscience should *also* become involved with ion-microprobe geochronology. The impact that the prototype SHRIMP instrument has had upon Australian geoscience was very evident at both of these conferences, and this type of information would be a powerful tool in the Canadian Shield, and, indeed, in all areas of Canadian geology.

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