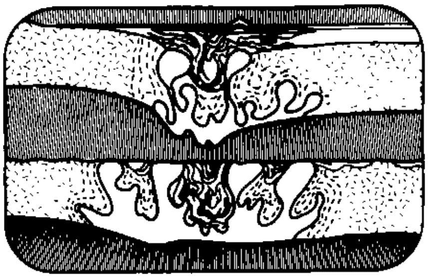

Relationships Between Archean Granites and Greenstones

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This conference was held in Mont Ste Marie, Quebec, from October 11 to 14, 1977. It was organized by A. J. Baer, W. R. A. Baragar and J. Veizer, with at least two purposes in mind. The first was to assess the state of the art in Canada (and elsewhere). Timing coincided with a vist by A. Y. Glikson (Australian Bureau of Mineral Resources) to the University of Ottawa, so that comparisons could be made with Gondwana geology. The second purpose was to mark the formal start of the IGCP project on Early Precambrian Sedimentary Processes. About 60 people attended, including the majority of Canadian geologists concerned with Archean problems, and a few visitors from the U.S. and South Africa. The relative isolation of Mont Ste Marie (60 miles from Ottawa) and the excellent facilities of its conference centre were deemed particularly favourable to a meeting of this type. Because we had to be financially self-supporting, we had trouble attracting as many graduate students as we would have liked. In fact, in at least one case, graduates could not get support from their department because the meeting would not result in published proceedings. We hope that this case is not indicative of things to come, but it could be construed as a logical step in the "publish or perish" fight for survival. We also found out that most speakers could have said in 10 minutes what they thought required 20. In two-and-a-half days we obtained, however, an overall view of who is doing what, where, and an indication of recent trends in the trade. We also established or renewed numerous personal contacts with workers in a great variety of fields. From positive reactions received from all quarters, similar meetings are worthwhile even though (and in part because) no proceedings are published.

The first session was opened by R. Lambert, who discussed heat flux in the Archean. If the geothermal gradient were higher than now, and modelling suggests that it was, consequences should be examined. For instance, if heat flow were comparable to that of Iceland, all Archean continental crust could be produced in about 35 Ma, and greenstone belts would sink under their own weight. In fact, the only reason for their preservation would be the continental crust stuck to either side that would keep them afloat. The high Archean geothermal gradient was implicitly or explicity accepted by most participants, but Glikson remarked that the present gradient is not uniform and it need not have been so in the past. High averages tell us very little about the range of gradients and we do not know if they were higher under greenstone belts than under granitic rocks, for instance. This is a critical problem that will be difficult to solve.

Various evolutionary models were presented, with a wide range of assumptions. Many emphasized the all important role of gravity (West, Gorman, Glikson, Schwerdtner, Baer). Overall tendency towards isostatic equilibrium must control crustal evolution. In detail, emplacement of granitic plutons is dominantly controlled by vertical tectonics, with localized lateral compression. It is possible that the presence of a continent in any one area would act as a thermal blanket over the mantle (West) thus raising the temperature and decreasing the specific weight of the material. Removal of this blanket by erosion would of course have the opposite effect. Models for the origin and formation of greenstone belts tended to represent variants of the rift-model, symmetrical (Glikson) or asymmetrical (Baer). In fact, a significant characteristic of the conference was the apparent demise of subduction as an answer to Archean tectonics. It is clearly not invoked as often as it used to be, and appears not to be fashionable any more.

Petrology and geochemistry of Archean rocks were abundantly discussed. Low-temperature geochemistry is discussed later in this paper, in connection with sedimentology. Although the conference was dealing with granites and greenstones, the emphasis of petrological work clearly remains on the latter. Interesting relationships were revealed in the few papers on "granitic" rocks. For instance, studies of rare earth elements (REE) show that quartz monzonite plutons from the western USA and Rhodesia cannot derive from mafic materials or from tonalites. A possible source, however, would be siliceous granulites (Condie). Scourian granulites from Scotland could also represent the residuum left behind by formation of granitic plutons (Pride). Problems arise with $^{87}Sr/^{86}Sr$ initial ratios, however, because numerous Archean "granites" have mantle-like I. R. and compositions that are more commonly tonalitic than truly granitic-eutectic. We clearly cannot generalize data on so-called "granites" but must distinguish their composition, their age and their structural environment if we are to understand how the various types formed. Volcanic rocks of the Abitibi were discussed by the dynamic Montreal duo of Gélinas and Lajoie. A clear and systematic description of ultramafic flows in the Rouyn-Noranda area (Gélinas) was followed by a description and discussion of so-called "rhyolites" in the same area (Lajoie) and a demonstration that most are probably pyroclastic rocks with well preserved sedimentary primary features. Abitibi lavas do not display island arc characteristics (Jolly) but neither do they correspond to modern oceanic material, because they contain too much intermediate and felsic material and grade upwards from Mg-rich to Al-rich rocks. REE studies on volcanics of the Prince Albert Group (Fryer) provoked considerable discussion on what REE modelling means, what the constraints are and what non-specialists should do with results of such studies. Some care is obviously required here, because unless limitations and constraints are clearly spelled out, a potentially most useful technique may fall in disrepute. Field studies of volcanic rocks were discussed by numerous speakers, but none was more impressive than the caldera complex described from the eastern Slave Province (Lambert). The complex is exceptionally well preserved, hardly deformed or metamorphosed and stands out as an excellent example of an Archean felsic volcano.

Some problems of petrology of Archean rocks were critically assessed in a thought-provoking and relaxed presentation (Pearce). The fact that quenched pyroxenes and quenched plagioclase are so commonly preserved in the Abitibi must mean something about their formation. What do the differences between textures of Archean andesites and Phanerozoic andesites tell us? In fact, are Archean andesites truly andesites, after all? The reaction to this last question showed that the majority of the audience feels that all andesites are andesite . . . but majorities have been known to be wrong!

Little was said of ore minerals, with the exception of a clear and systematic description of those that are present in Archean rocks (Boyle). One may argue that a conference of this type is too far removed from economic geology to interest those specialists, but this may only be an easy excuse.

By contrast with petrological studies that gave more importance to volcanic rocks than to the surrounding granitic areas, the structural studies presented at the meeting emphasized information to be gained from non-greenstone regions. Extremely complex relationships in the English River gneiss belt near Kenora (Gower) can be unravelled by careful field work. In fact, only this type of work by experienced researchers is going to give us some of the answers. It would be unfair to propel new Ph.D. candidates into these difficult areas, but a person who already has a good background in gneissic terrains can come up with first class results. More and more details of vertical tectonics (gravity tectonics) in granitic plutons are coming to light. Within "pink areas" of the geological maps, some crescents of volcanic rocks are now showing (Schwerdtner) that presumably formed like this, and not from late deformation of previously straight segments. Strain patterns of plutons, based on textural evidence, are helping us to understand how they were emplaced. For instance, the Jackfish Lake pluton of the Rainy Lake dome, appears to have risen, sheet-like, along a pre-existing, synformal, granite-greenstone contact (Sutcliffe). If granitic domes are rising everywhere, greenstone belts caught in between must be squeezed in thin bands or in triangular synforms at the junction of three domes. Such a synform in Savant Lake area is still amenable to methods of kinematic structural analysis, in spite of multiple folding and intense deformation (Shegalski). The importance of incorporating detailed studies of small areas to overall structural reconnaissance was well demonstrated in the case of the Slave Province (Fyson). Different rock types do not necessarily display the same phases of deformation, and only an overall integration will give answers. Vertical tectonics are well displayed in the Slave Province, but late vertical cleavages indicate the presence of horizontal compression. One way to achieve this would be a deformation of the Slave block with left-handed rotation along two major shear zones along Great Slave Lake and Bathurst Inlet. In the Superior Province, major east-west faults appear to be long-lived lineaments. The fact that the Sydney Lake fault is "late", and right-lateral, does not exclude the possibility that it moved differently at an earlier time. It is becoming increasingly evident that "old" structures, possibly dating back to the time of volcanism and sedimentation can be reactivated more than once.

Regional studies and careful field mapping are still the basis of geology, and they are a powerful method of integrating data from various disciplines, as shown for instance in this conference by Ermanovics, Frith, Glikson, Gower and Ridler. Reports and slides on such studies also give one a "feel" for the geology that no amount of reading can hope to equal. To many workers in the Canadian Shield, the remarkable quality and amount of data visible from coloured air photographs presented by Glikson for Western Australia shows clearly that "Canada is not the place to study the Archean" as one discouraged participant put it. However, if glaciers have left behind a thick cover of sand and gravel (compared by some famous geologist to the dust on beautiful furniture!) they have also scraped outcrops clean of weathering products, allowing for highly sophisticated studies of detailed geology.

Geochronological studies are critical to our better understanding of the Archean. It was most instructive, in this regard, to see what appeared at first to be a confrontation between Rb-Sr and U-Pb methods and their protagonists. However, in an impromptu evening session, agreement was reached on what can be expected of which technique. Zircons (U-Pb) are beautiful crystals to work with, giving extreme accuracies on minute amounts of material (Krogh). Differences of 20 to 50 Ma between dates can now be considered as geologically significant when obtained by this technique. Rb-Sr whole rock isochrons on the other hand are known to have slopes that occasionally "flatten out" towards the top, and to give dates that are commonly younger than those of the U-Pb system. Careful selection of samples can remedy many such problems however. In particular, the elimination of samples with relatively high H_2O or CO_2 contents appears to give isochrons ages comparable to zircon ages (Brooks). Blanket statements about validity of techniques are valueless, and each case must be stressed on its own merits. A fascinating aspect of geochronological studies is the possibility to obtain in some cases "mantle isochrons" (Brooks) giving ages well in excess of that of the rock, but possibly corresponding to major changes in the mantle. The reappearance in more than one case of 1600-1700 Ma "ages" for these "isochrons" suggests that formation of the asthenosphere may date from that period.

Paleomagnetism of Proterozoic dykes has been extensively studied, but few data exist on Archean material. Two presentations suggested that early Proterozoic dykes are more significant than hitherto realized. It appears that they are everywhere perpendicular to the greenstone belts they cut (Halls) and when they formed, all of them had a north-south trend (Morris). This very specific distribution remains unexplained, but the fact that these dykes formed more abundantly in equatorial regions suggests that their formation may be controlled by the shape of the geoid. The changing curvature of the drifting continents is a possible cause for such "membrane tectonics".

In the section dealing with sedimentation and low-T geochemistry, computer modelling of sedimentary recycling during geologic history was presented (Veizer). It was argued that sediments contain about 30% excess mafic components, which can be accounted for by cannibalistic recycling of a mafic early sedimentary mass. This should result in mafic-felsic secular variations in chemical composition of sediments and suggests an early mafic crust with associated ores of mafic affinities (Ni, Cu, Au).

Secular variations in $\delta^{18}O$ of sediments, contrary to previous consensus, were not interpreted as due to continuous equilibration with meteoric waters. Knauth suggested that the trend is due to progressively increasing temperature of ancient oceans (70°C in the Archean). In contrast, Perry maintained that the $\delta^{18}O$ of the Archean ocean was controlled by weathering and/or low temperature hydrothermal alteration of volcanic rocks, while reactions on mid-oceanic ridges (at T > 250°C) became progressively more important during later stages of terrestrial history. Garrels presented quantitative steady state models of exogenic cycles for C and S. He demonstrated that it is very difficult to introduce perturbations, which could result in a runaway development, into the system. Instead, the system will adjust rather rapidly to a somewhat modified new steady state. Dimroth discussed chemical composition of Archean sediments and concluded that the data are as yet incomplete, but indicated that they do not suggest that the composition of the Archean hydrosphere-atmosphere differed from the present one. In the subsequent discussion it was pointed out that the criteria utilized were open to interpretation and not diagnostic. Sedimentology of the 3.3 b.y. old Moodies Group was treated extensively by Eriksson, who interpreted the facies as interacting alluvial, estuarine-deltaic, beach-offshore and tidal depositional system, similar to Holocene counterparts, but on a narrower shelf. Such stable shelf assemblages, indicating stable crust with granitic component, are not the rule in the Canadian Shield. Donaldson, however, compared sedimentary sequences from S. Africa, Australia and Canada, and suggested that the quartz-rich clastic rocks were derived from well-sorted older sediments and ultimately prexisting basement. In a combined sedimentological and stable isotope study Lowe and Knauth showed that Onverwacht Group sediments contain abundant evidence of sulphates and salts, which were later replaced by chert and carbonate. This, however, is not to be confused with massive sulphate and salt deposits, but rather compared to Holocene evaporitic carbonate assemblages with local concentrations of gypsum and salt. Finally, the session was concluded by a presentation (Glikson) showing a uni-directional mafic-felsic development of the source of detrital sediments (crust) during the Archean-Early Proterozoic interval.

The Organizational meeting of the IGCP project "Early Precambrian Exogenic Processes" was attended by 16 participants from four countries. The meeting was informed (Veizer) that the organization was essentially completed and nine countries (Canada, USA, Australia, South Africa, German Federal Republic, Great Britain, Denmark, India, Switzerland) and about 30 scientists agreed to participate. After extensive discussion it was recommended that the study of sedimentation (associated ores) and low-T geochemistry should not be limited to the Archean and the term "Early" be deleted from the title. If this new mandate is approved at the forthcoming meeting of European and Indian participants, the project must be enlarged and consolidated by inclusion of the Proterozoic studies. The initial field conferences for participants in this project have been scheduled for Quebec City (May, 1979) and Perth, Australia (1980).

If participants to a meeting of this type tell you that it was a success, their opinions may be influenced by numerous psychological factors, but for non-participants, what was significant? new data? ideas? mood? Let us try and suggest some possible conclusions. First of all, it is clear that the Archean community in Canada is alive and well; it is enthusiastic and actively working. Even though we have a long way to go to understand the early evolution of the earth, our understanding is growing fast.

If this conference is a true reflection of trends, in terms of general models, rifting is gaining in favour and island arcs are losing. This may be considered to be in good part a geochemical and petrological problem. How do Archean andesites differ from younger ones? or do they?

Archean continents (as one supercontinent or as individual units) had similar evolutions. So far few fundamental differences appear between Gondwana and Laurasia, which may not ultimately be reconciled. Differences have more to do with schools of thought than with rocks.

Relative roles of gravity and tangential tectonics need to be defined much more carefully, as a function of time and at all scales. Gravity tectonics is important in the Archean, but how is this importance affected by structural level, by age and by physical behaviour of the materials concerned?

Average Archean geothermal gradient was probably higher than now. It remains to see where it was high and where it was low. Blanket statements about high gradient and thin crust do not help our understanding of the Archean one bit. We need figures (how hot is hot?, how thin is thin?) and locations (where was it thin and hot?). Sedimentology and low-temperature geochemistry can also supply us with some information, particularly about paleo-temperatures, source area composition, composition of the hydrosphere - atmosphere, and stability and nature of the tectonic environment.

In general, progress is being made towards greater and better communication between scientists. It remains that some "problems" are not with the geology but with the geologists! The opposition between "sialic crust" and "simatic crust" is a case in point. We need to define rigorously what "sialic" means in a given context, and to clarify in each and every case the composition of rocks and minerals, their locations (depth in particular), the structural level and the time that we are discussing. We tend to forget that the Archean lasted four times as long as the Phanerozoic and that the levels of erosion vary considerably from one place to another.

Even in a conference on granites and greenstones, the "granites" tended to be short-changed. The interface between the two groups of rocks, possibly the most critical component of the system, is even more neglected and should be studied much more extensively. The limits of too many project areas appear to follow the edges of greenstone belts!

Almost to a man, the fact that the Archean is a major souce of metals was completely ignored. It may be that the study of ore metals as interesting elements is simply not catching on, or that the group was not representative of the community at large. The long awaited merger of economic geology with earth sciences in general has yet to come. Is a Europium anomaly really more significant than a Copper anomaly?!

We feel strongly that it is absolutely critical to ask the earth the right questions. In the earth science community, we have a large capacity for obtaining data, from black boxes to field surveys. We can misuse this capacity or we can get key answers through it. All depends on the questions we try to answer. The choice is ours, individually, and we should be well aware of it. The role of a conference like that at Mont Ste Marie is to improve coordination of efforts and to help all interested parties to focus better on those problems that must be solved first. In a limited sense, this is a "grass-roots science policy".

Looking at the broad picture of Archean research and more generally at Precambrian research, one is struck by the accelerating pace of progress over the last ten years or so. Is it possible that we could soon jump by some quantum into a new era of understanding of the Precambrian Earth, when a generalized theory will be developed, doing for the Precambrian what plate tectonics has done for Phanerozoic?

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