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Conference Reports

GAC NUNA Research Conference: Greenstone Gold and Crustal Evolution [1]

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Lode gold deposits in greenstone belts throughout the world have been the focus of intense research and exploration efforts over the last decade, as well as the object of many international meetings. After so many years of intense research, it was felt that the time had come to assess our understanding of these greenstone gold deposits, to discuss remaining problems and controversies, and to explore future ideas. Such were the objectives of the first NUNA Research Conference of the Geological Association of Canada [NUNA is an Inuktituk word, meaning "the Earth"]. This conference, entitled Greenstone Gold and Crustal Evolution, was convened by S.E. Kesler, G.N. Phillips and F. Robert and held at Val d'Or, Québec, on 24-27 May 1990.

The conference was attended by 60 participants from North America, Western Europe and Australia, representing industry, government agencies and universities. A significant number of invited participants were not gold experts, but rather were specialists in related fields of geology. The conference proceeded in an informal atmosphere with ample time for discussions, which continued late in the evenings and during the field trip.

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The four-day meeting consisted of two days of oral presentations and working group discussions, a full-day field trip to examine gold deposits and aspects of greenstone belt geology, and a final day of plenary discussions. Presentations and discussions were organized around six sessions addressing the following themes: (1) genetic models for greenstone gold deposits, (2) structural aspects of greenstone gold deposits, (3) nature and composition of auriferous fluids, (4) late evolution of greenstone belts and gold deposits, (5) fluid generation, fluid circulation and deformation, and (6) wall-rock alteration and P-T environments of gold deposition. Overview presentations by invited participants in the morning set the stage for afternoon discussions, in which participants were split into working groups to address a list of questions and problems related to each theme. These afternoon discussion sessions also included short presentations, so that all participants had the opportunity to present their work in the course of the conference. The chairmen of the working groups summarized the discussions and recommendations in the plenary sessions.

Some of the most important points that emerged from the presentations and working group discussions for each of the six themes and from the plenary sessions are summarized below.

GENETIC MODELS FOR GREENSTONE GOLD DEPOSITS

This session started with presentations of the various genetic models for greenstone gold deposits together with supporting data as seen by proponents of each model (J.A. Fyon: granulitization of the lower crust; E.T.C. Spooner: the magmatic model; G.N. Phillips: the metamorphic model; and B.E. Nesbitt: the meteoric water model). R. Kerrich followed with a critique of all of these models. He pointed out that none of the models, which are essentially fluid-source models, could adequately explain all available geological, geochemical and geochronological data. He also emphasized the need for integrated models of global applicability (*i.e.*, to Archean and younger analogues).

The working group, chaired by J.M. Franklin, concluded that the currently available geochemical data did not permit unambiguous determination of the source(s) of fluids in these deposits. It was suggested that studies of magmatic and metamorphic fluids closer to their points of origin would lead to a better characterization of such fluids and would provide a better basis for comparison with fluids in gold deposits. It was clear that the question of the timing of gold mineralization relative to other geological events is a fundamental one in assessing the various proposed models. However, the group considered the interpretation of the currently available age determinations to be ambiguous and that additional data are required. The group also considered that Phanerozoic mesothermal gold deposits represent reasonable analogues to Archean and Proterozoic deposits and that they probably formed by similar processes. However, it was emphasized that the meteoric water model proposed by B.E. Nesbitt for Cordilleran deposits could not be rigorously tested for the older deposits because of the lack of data on meteoric water composition at that time.

A series of questions was also raised by the group. Is a specific heat source required for the formation of these deposits? Are large gold deposits the product of single or multiple geological events? Were single or multiple fluids involved in the formation of these deposits? Did the auriferous fluids leak to the surface, and what was their character at higher crustal levels? These questions were not answered and could be the focus of future work.

STRUCTURAL ASPECTS OF GREENSTONE GOLD DEPOSITS

To set the ground for discussions, J.R. Vearncombe reviewed the structural setting of gold deposits in Archean greenstone terranes of Australia and Africa, emphasizing the association of gold deposits with both high-angle reverse and strike-slip structures. He also illustrated the common association of these deposits with structures that are subsidiary to transcrustal ones along which gold districts are distributed. C. Hubert presented a tectonic framework for the southern

Abitibi greenstone belt, in which juxtaposed lozenge-shaped domains of differing internal structural histories are separated by narrow high strain zones, pointing to the complex structural evolution of these belts.

Chairman D.I. Groves reported that the working group divided structural aspects of gold deposits into deposit- and regional-scale problems, and emphasized the question of fluid focussing. The group recognized that structural and geological characteristics of gold deposits, as well as the focussing mechanisms, varied according to crustal depth, as represented by the metamorphic grade of their host rocks. It was obvious that additional detailed structural studies of deposits hosted in amphibolite and lower granulite grade rocks are needed. At the deposit scale, the discussions emphasized the greenschist deposits and focussed on the mechanics and implications of the "fault-valve" model (Sibson *et al.*, 1988), which integrates many structural characteristics of these deposits. Evidence for transient fluid pressure fluctuations during vein formation as predicted by the model were also discussed. It was also pointed out that, if high-angle reverse to reverse-oblique faults are common host structures for gold deposits and are most favourable for promoting large fluid pressure variations, some deposits also occur in strike-slip and normal faults. The role of anisotropies in controlling the location and geometry of deposits was also emphasized. On the regional scale, the group recognized the complexity of the structural history of transcrustal shear zones and emphasized the need for documentation of the geometric and kinematic relationships between mineralized structures, subsidiary faults and transcrustal faults, as well as the potential fluid connectivity among these structures.

Finally, the need for better documentation of deposits hosted in subgreenschist and amphibolite to lower granulite grade rocks was emphasized. Additional detailed structural documentation of individual deposits and of the regional regime in which they form is also needed.

NATURE AND COMPOSITION OF AURIFEROUS FLUIDS

At the beginning of this session, S.B. Romberger reviewed existing data on the solubility of gold and precipitation mechanisms. He stressed differences between precipitation mechanisms as a function of the nature and stability of the gold complexes (chloride *versus* bisulphide). For example, he pointed out that progressive cooling of an unbuffered solution from 400°C will lead to precipitation of gold from chloride complexes; further cooling will then lead to dissolution (remobilization?) of gold as bisulphide complexes and its reprecipitation upon continued cooling. J.K. Bohlke presented Cl, Br, I and noble gas data from fluid inclusions in gold-quartz veins of the Sierra Nevada, California, suggesting that a large portion of the water in the auriferous fluids is of meteoric origin.

S.E. Kesler, chairman of the working group, reported that discussions focussed on the information obtained from ore and alteration minerals and from fluid inclusions. The emphasis was placed on the limitations of such data. The group concluded that detailed analyses of better characterized and smaller samples will be necessary to determine the nature and direction of compositional changes in the fluids during mineralization. It also recommended careful examination of possible post-depositional isotopic re-equilibration of hydrothermal minerals.

In discussing the available fluid inclusion data, the group noted the significant range of homogenization temperatures (in the range of 250°-400°C) documented in several deposits. It was considered unlikely that ore deposition took place over such a temperature range and it was suggested that these observations could reflect pressure fluctuations. The group also indicated that, although there was some permissive evidence in a few deposits, unequivocal documentation of phase separation was needed. Pressure determination from appropriate sets of inclusions should carefully take into account the complex composition of the fluids because the position of the two-phase field in the P-T space and estimates of the trapping pressure are sensitive to the presence of additional components such as CH_4, N_2 and $CaCl_2$. The significance of high salinity fluids in several Archean deposits must also be assessed (product of phase separation, or later, unrelated basement brines?). The group indicated that studies will have to be carried out on fluid inclusions more directly related to gold, in all associated minerals (*e.g.*, scheelite, tourmaline, sphalerite), from increasingly small and well-characterized samples. The group emphasized the need for "far field" isotopic and fluid inclusion studies, to provide information on fluid compositions beyond the ore deposits.

LATE EVOLUTION OF GREENSTONE BELTS AND GOLD DEPOSITS

This session started with a review of geochronologic constraints on the tectonic evolution of the Archean Superior Province by D.W. Davis. He proposed that the development of most greenstone belts consists of an oceanic phase, in an arc or back-arc environment, followed by an orogenic phase resulting from accretion of oceanic and island arc material. The orogenic phase, marked by K-magmatism, deformation, uplift and sedimentation, occurred at 2740-2700 Ma and 2710-2675 Ma in the northern and southern Superior Province, respectively. The few ages obtained on gold deposits are younger than the orogenic phase and similar to the age of a post-orogenic phase documented in exposed deep crustal rocks.

This working group, chaired by R. Kerrich, noted that the geotectonic setting of greenstone belts like Abitibi and Wiluna was comparable to that of Phanerozoic, northern Cordillera-type convergent margins, involving accretion of volcanic arcs and oceanic terranes. The chemical signatures of shoshonites and lamprophyres commonly associated with Archean gold districts also suggest such geotectonic settings. The empirical association of gold deposits with greenstone belts was regarded as indicating either that the greenstone belts themselves are the source of gold (not necessarily that of the fluids), or that they reflect special geodynamic controls, such as subcretion of special types of mantle.

The significance of "young" ages obtained for gold mineralization in Archean greenstone belts, postdating peak metamorphism and syn-tectonic plutonism by several tens of million years, was also discussed. It was pointed out that where several dating techniques have been applied in the same district, the results are either concordant (*e.g.*, Val d'Or) or highly discordant (*e.g.*, Timmins). The discordant ages could result from resetting of isotopic systems by later fluids or could represent protracted mineralization. It was also suggested that time gaps of tens of Ma between peak metamorphism and gold mineralization could reflect P-T-time evolution of tectonically overthickened crust, involving slow thermal rebound and thinning of the crust. Such timing would be compatible with gold deposits forming during uplift in orogenic belts. Calculated uplift rates of 0.1-0.2 $mm \cdot yr^{-1}$ for Kambalda, Western Australia (based on data presented by M.E. Clark) were considered slow compared with other active mountain ranges. Overall, the group agreed that gold mineralization is part of a global process characteristic of the termination of orogenic activity in convergent geodynamic settings.

FLUID GENERATION, FLUID CIRCULATION AND DEFORMATION

S.F. Cox and R.H. Sibson started this session by reviewing the controls of fluid migration, fluid pressure regimes in the crust, and processes of faulting and accompanying variations in fluid pressure, with analogies to currently active faulting. Both emphasized evidence for high fluid pressures in these deposits and the existence and importance of pressure variations during faulting.

As reported by chairman S.F. Cox, the group considered that the fluid-generating processes required for formation of greenstone gold deposits were probably linked with subduction-related metamorphism at accreting terrane boundaries. However, in reference with turbidite-hosted gold deposits in Central Victoria (Australia), the question was asked if accretionary plate margins were the only tectonic setting in which gold deposits could have formed.

There was general agreement on the importance of transcrustal fault zones, with which gold deposits are associated, in controlling crustal-scale fluid migration in these systems. R.H. Sibson suggested that the distribution of gold districts along major fault zones could be related to irregularities in fault geometry. These irregularities would be the locus of repeated slip events and represent zones of enhanced transient permeability which would focus fluid migration. It was also noted that fluid migration will take place only along the active fault segments at the time of fluid production. Thus, the timing of active slip relative to fluid generation could explain why some major fault zones are mineralized and others are not. The irregularities and structures controlling the focussing of fluids upward to the actual mineralized sites could be located a few kilometres below the actual deposit. At the deposit scale, it was felt that better understanding of fault mechanics, kinematics and related processes (*e.g.*, fault-valve behaviour) could be used effectively in locating new orebodies. Finally, the group stressed the need for better three-dimensional documentation of fault architecture and kinematics in greenstone belts and for better documentation of fluids flushing through greenstone belts outside deposits at the time of mineralization. Comparative studies of ancient and active faults were also considered important.

WALL-ROCK ALTERATION AND P-T ENVIRONMENTS OF GOLD DEPOSITION

This session addressed the important question of the range of crustal (P-T) conditions over which greenstone gold deposits could develop. Based on a study of gold districts at different metamorphic grades, G. Albino suggested that the composition of auriferous fluids in a deposit reflected very little of the geochemical and isotopic signature of the source, due to continuous interaction with rocks along the pathways. D.I. Groves presented an example (Griffin's Find, Western Australia) of a lode gold deposit formed at lower granulite facies. D.M. Carmichael illustrated the importance of mapping metamorphic bathozones (see Carmichael, 1978) in greenstone belts by showing that mineral assemblages in subgreenschist parts of the Abitibi greenstone belt indicate pressures or depths of post-metamorphic erosion similar to those in greenschist and even lower amphibolite parts of the belt. On related topics, J.L.R. Touret reviewed the current status of fluids and fluid inclusions in granulites, and J.W. Peterson presented new experimental data showing that the presence of CO_2 lowers the P-T conditions of melting of biotite granite. Upon cooling, the resulting residual melts will have lamprophyric compositions and will be charged with volatiles. This could provide a link between felsic porphyries, lamprophyres and CO_2-bearing fluids in transcrustal shear zones and gold districts.

As reported by chairman G.N. Phillips, the group focussed its attention on deposits hosted in rocks at higher metamorphic grades. Examples of deposits in amphibolite and lower granulite grade rocks, interpreted to have formed both at peak and post-peak metamorphic conditions, were examined. The group noted that it was relatively easy to recognize gold deposits formed after peak of metamorphism (retrograde), but difficult to distinguish metamorphosed deposits from those formed at peak metamorphic conditions. Deposits formed at higher metamorphic grades show some geochemical differences, such as higher Cu, Bi, Mn, Ag and base metals, as well as Ca metasomatism, and a lack of (recognized?) associated porphyries and lamprophyres. The morphology of these deposits also appears to be different from that of deposits at lower metamorphic grades, whose morphology (*e.g.*, veins) should be recognizable through subsequent metamorphism. The predominance of gold deposits in greenschist facies rocks was considered to reflect crustal conditions favourable for rapid change of gold solubility with temperature, for unmixing of H_2O-CO_2-NaCl fluids, and for brittle-ductile behaviour. These are factors which may contribute to the more efficient development of gold deposits in greenschist facies terranes. Finally, the group emphasized that there is good potential for gold deposits in higher grade rocks. These deposits would not be as easily recognized due to the general lack of veins and different associated alteration assemblages. However, the group felt that there was a lack of basic geological and geochemical data on these deposits.

PLENARY DISCUSSIONS

Several additional aspects of greenstone gold deposits were discussed in plenary sessions: the salient points are reported below.

In order to derive practical applications from what was discussed at the conference, the participants were asked to define criteria for selecting a greenstone belt for gold exploration, for selecting ground within that belt, and for selecting targets within a given area. It is interesting to note that most of the criteria suggested for selection of a belt and of areas within the belt were based on geology, structure and geophysics, and that many of them were based on long-recognized empirical relationships. New suggestions for target selection include the use of well-established zonal patterns of hydrothermal alteration, especially in mafic and ultramafic lithologies, as an indication of proximity to ore (for example along strike in shear zones). Resistant alteration products, such as rutile in heavy mineral concentrates or in laterites, can also be used to define targets. At the deposit scale, reverse to reverse-oblique shear zones appear to be favourable host structures, perhaps due to the larger pressure variations accompanying their development. Finally, analogies with modern active faults may help to focus attention on certain types of irregularities along shear zones that may localize slip, transient higher permeabilities and fluid flow. It was apparent from these discussions that many of the geochemical, isotopic or even fluid inclusion studies have not reached a state of refinement or understanding where the results can be applied in exploration.

The nature of the major transcrustal shear zones was then discussed. Evidence was presented by C. Hubert that the Larder Lake-Cadillac structure in the Abitibi greenstone belt had a long and complex history of activity which involved early juxtaposition of two "blocks", prior to uplift and deposition of sedimentary rocks and subsequent penetrative deformation. G.M. Stott reviewed the types and nature of major fault zones in northwestern Ontario and proposed that some of the large transcrustal faults are, in fact, terrane boundaries.

Finally, the question was also raised as to why there are more Archean greenstone gold deposits than younger equivalents. After some discussion, it was agreed that the over-abundance of greenstone gold deposits in the Archean relative to younger terranes is essentially a matter of preservation of greenstone terranes rather than a matter of differences in geological processes.

GENERAL RECOMMENDATIONS FOR FUTURE RESEARCH

At the conclusion of the conference, the following general recommendations for future research on greenstone gold deposits could be formulated:

1. Study gold deposits in amphibolite- to granulite-grade terranes in order to provide a better documentation of the characteristics of gold deposits at all crustal levels. Attention should also be given to the timing of mineralization relative to peak metamorphism, in order to assess whether or not such deposits are deeper equivalents of those in greenschist-grade terranes.
2. Document, in greater detail, the structural regime and the overall three-dimensional fault architecture (geometry and kinematics) in greenstone belts, and verify the commonly inferred three-dimensional fluid connectivity between crustal-scale faults and the subsidiary shear zones hosting the gold deposits.
3. Undertake "far field" studies in order to document: (a) the composition of the fluids circulating in shear zones away from the known mineralization, (b) the evolution of fluid compositions at various stages of metamorphic and deformation during the evolution of greenstone belts, and (c) the compositions of the various types of fluids that have been proposed for the generation of greenstone gold deposits (*e.g.*, metamorphic, magmatic, *etc.*) closer to their points of origin.

4. Study the solubility and precipitation mechanisms of gold at amphibolite to granulite grade conditions.
5. Document the post-depositional history of these deposits and explore the possible isotopic (stable and radiogenic) re-equilibration of hydrothermal minerals.

One of the most important overall agreements reached at this meeting is that greenstone gold deposits are the product of large, crustal-scale fluid systems and represent one of several concurrent processes characterizing the last stages of collisional orogenies. It is clear that future research will also have to place greenstone gold deposits more accurately within the geologic and tectonic evolution of their host environment. This will require multi-disciplinary efforts and the active involvement of experts in several fields of geology.

More information on the content of the conference can be found in the NUNA Conference Volume on *Greenstone Gold and Crustal Evolution*, edited by F. Robert, P.A. Sheahan and S.B. Green and published by the Geological Association of Canada/Mineral Deposits Division. This volume contains six invited papers, written reports by the chairmen of the working groups, transcripts of the plenary discussions, and abstracts submitted by the participants. It can be obtained through the headquarters of the Geological Association of Canada.

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GAC NUNA Research Conference: Late Proterozoic Glaciation, Rifting and Eustasy: Windermere Supergroup

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During the week 8-16 September 1990, 35 stratigraphers, structural geologists, sedimentologists, climatologists, paleontologists and all-round general geologists gathered for a NUNA Research Conference, the second sponsored by the Geological Association of Canada, on the theme "Late Proterozoic Glaciation, Rifting and Eustasy, as illustrated by the Windermere Supergroup". NUNA is the Inuktituk word for Earth, and the meeting was a field research conference to explore the problems of Late Proterozoic geology and their possible solutions. The meeting combined formal technical presentations with presentations and discussions in local field trips during the conference and formal pre-and post-conference field trips. To facilitate the field components, the conference began near Invermere, and then moved northward more than 300 km to Valemount. Both sites are in eastern British Columbia in the outcrop belt of the Late Proterozoic Windermere Supergroup.

Talks and poster sessions were held at approximately one to one and a half day intervals, punctuated by local field trips. Oral presentations were given as longer overviews or as shorter talks on specific topics. Posters were grouped according to topic. Technical presentations ran the gamut from causes of glaciation (climatic and plate tectonic controls), to sedimentology, and to the major stratigraphic and correlation problems in the Western Cordillera of North America and in Australia. The local field trips were led by individuals and teams of geologists who, along with Jim Aitken (conference co-ordinator), successfully choreographed what had the potential to become a logistical nightmare. Pre- and post-meeting field excursions, including helicopter transport to more inaccessible sections, also provided a wealth of opportunity for participants to see the superb Late Proterozoic outcrops in the Canadian Rockies and in the ranges west of the Rocky Mountain Trench. Ample time was set aside for dialogue (and argument) among the participants, who were largely from universities and government surveys, with a sprinkling from industry. Registrants were largely from Canada and the United States, but included significant and very active contributors from Australia and Germany.

The first half of the meeting was held at Panorama Ski Resort near Invermere, during beautiful Indian summer days. Panorama is nestled in the valley of Toby Creek, along the sides of which occur massive cliff sections of the Toby diamicton — a Late Proterozoic unit of possible glacial and debris flow origin. Huge blocks occur as dropstones within the Toby diamicton, and a spectacular variety of lithologies occurs in both the diamicton and the older Mount Nelson Formation, providing interest for those with a more petrographic bent.

The meeting started Monday on glaciogenic sedimentation with the lead-off paper presented by John Crowell on the factors responsible for Late Proterozoic glaciation. In the afternoon, we examined Toby conglomerate (diamictite) on Toby Creek and at least some participants agreed that some parts of the Toby are glaciogenic while others are not. The next day, we continued with rift tectonics and Geri Eisbacher led us through the different kinds of rifts we might contemplate for the Windermere. That afternoon, we remained inside and learned about Proterozoic basins in Spitzbergen, the Adelaide Geosyncline of South Australia, and Proterozoic rocks in Idaho and the Yukon. Andy Knoll also encouraged us with his successes in combining microfossils with carbon and strontium isotope systematics in carbonates as a powerful correlation tool for Late Proterozoic strata in Spitzbergen.

On Wednesday, we packed ourselves into the vans and spent the day travelling northward through Lake Louise and Jasper to Valemount. *En route*, everyone had an opportunity to see key localities in the Late Proterozoic Miette Group of the Rocky Mountains.

Thursday morning was devoted to eustasy. Jim Gehling introduced the topic with a discussion of the depositional sequences in the Late Proterozoic to Early Cambrian of the Adelaide Geosyncline. This was followed by papers dealing with a widespread marker in the Windermere succession of the southern Cordillera that probably represents an important eustatic event. Its occurrence in the middle of a 3 km thick sequence of stacked turbidites over an area of more than 200,000 km^2 has many implications and led to lively discussions. In the afternoon, we had an opportunity to visit key localities of Winder-