The magmatic model for the origin of Archean Au-quartz vein ore systems: An assessment of the evidence

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ABSTRACT: The magmatic model for the origin of Archean Au-quartz vein ore systems suggests that Au was derived by partition between silicate (± sulphide) melts of certain compositions and H_2O-CO_2-NaCl magmatic fluids (~~cf. porphyry systems; skarn systems~~). Supporting evidence includes spatial/structural geological relationships ~~(e.g. TTG terrain hosted, igneous stock-hosted~~ and ~~dyke swarm associated systems),~~ timing relationships (~~e.g. syn-mafic "albitite" dyke swarm Au-quartz vein mineralization, Kerr Addison-Chesterville.~~ ~~N. Ontario; Smith and Spooner, 1990~~), H and C isotope geochemistry, probable primary Au enrichment in the Lamaque stocks, and fluid inclusion volatile geochemistry (Spooner and Bray, 1990). Geochemical data indicate shoshonitic/calc-alkaline and TTG genetic associations. Evidence is currently negative with respect to various within- and sub-greenstone belt metamorphic/deep crustal fluid models for primary Au mineralization; however, a U-Pb age for vein stage #3 sphene from the Camflo deposit, Québec which is ~55-60 Ma younger than the host stock at 2685-2680 Ma (Zweng and Mortensen, 1989; Jemielita et al., 1989) indicates dissolution/reprecipitation of Au by late, (?) upper crustal saline fluids. Evidence is accumulating that epithermal-mesothermal Au-Ag mineralization in island arc and cordilleran settings may also have been magmatically derived ± high level fluid mixing from calc-alkaline, shoshonitic and other igneous compositions (e.g. geological relationships; stable isotope geochemistry; fluid volatile geochemistry). Hence, by comparison with the Archean, a possibility exists for a unification of genetic interpretations reflecting common, or similar, genetic processes.

1. INTRODUCTION

In simplest terms, the magmatic model for the origin of Archean Au-quartz vein ore systems suggests that Au was derived by partition between silicate (±sulphide) melts of certain compositions and H_2O-CO_2-NaCl magmatic fluids, transported in solution with or without fluid mixing, and deposited. The magmatic model is plausible in general terms because of the occurrence of proximal Au skarns (e.g. Meinert, 1989), porphyry Cu-Au deposits (e.g. Solomon, 1990) and Au mineralization in intrusion-centred systems (e.g. Sillitoe and Bonham, 1990); in these deposit types there is significant geological and geochemical evidence for magmatic Au derivation.

2. EVIDENCE

2.1 Spatial/structural geological relationships

(a) TTG terrain/batholith hosted systems: A number of Archean Au-quartz vein ore systems occur outside the confines of greenstone belts in TTG terrains and batholiths. Examples include Renabie, N. Ontario (~41 tonnes Au; Callan and Spooner, 1989), which can be placed in a Superior Province Archean crustal context through its occurrence in the greenstone belt/TTG layer/granulite-anorthosite sequence exposed in the Kapuskasing section; Zimbabwe; Novo Astro/Salamangone Hill, N.E. Brazil; and the Arcadia Bay property, Slave Province, N.W.T., in which a large Au-quartz vein system (1-4x6 km) occurs within the ~12x25 km granodiorite/tonalite Anialik batholith with some veins located as much as ~5 km into the batholith from the contact (e.g. Abraham and Spooner, 1989).

(b) Igneous stock hosted systems: Examples include the Lamaque system, Val d'Or, N.W. Québec in which 94% of the total production of 138 tonnes Au (5.4 g/tonne) was derived from bulk mineable stockworks and quartz-tourmaline vein systems contained within three late, undeformed, vertically elongate plugs. 82% of the total production was derived from stopes within a relatively small (~100 x 250 m), zoned granodiorite plug over ~1,100 vertical metres (e.g. Burrows and Spooner, 1990).

(c) Dyke associated systems: Examples include the large Kerr Addison/Chesterville system, N. Ontario

(~340 tonnes Au) in which green carbonate mineralization/alteration is spatially and structurally related in detail to a mafic "albitite" dyke (~5000)/plug system (Smith and Spooner, 1990; Smith et al. 1990), the Arcadia Bay property, N.W.T., 1990 (e.g. Sidewalk~ 6m wide x~2 km vein/dyke swarm association), and several deposits in the Yilgarn block, W. Australia (e.g. Mt. Percy, Sauter et al., 1988; Hampton-Boulder, Cullen and Norris, 1988;Norseman, Johnson, 1988; pers. obs.,1988).

2.2 Relative/absolute timing relationships

Examples include (a) Kerr Addison/Chesterville in which there is completely clear, observational cross-cutting evidence for both intra-mafic "albitite" dyke main stage Au-quartz vein mineralization and the converse, intra-main stage Au dyke intrusion, and the dykes show no discontinuities in primary geochemistry (Smith and Spooner, pers. obs., 1987-1990; Smith and Spooner, 1990; Smith et al., 1990) and (b) the Fairview deposit, Barberton greenstone belt, South Africa for which de Ronde et al. (Precambrian Research, in press) have shown that Au-quartz vein mineralization was time bracketed between a single zircon U-Pb age of 3126±21 Ma (2σ) for a cross-cut porphyry dyke 1,400m below surface and a green rutile minimum age of 3084±18 Ma; these constraints almost overlap within 2σ uncertainties, but are younger than the adjacent Kaap Valley tonalite at 3229±5 Ma.

2.3 Geochemical evidence

(a)δD values: The hydrogen isotope composition of hydrothermal ore fluids is a reasonable source tracer because it is relatively little affected by water/rock interaction compared with, for example, oxygen isotope compositions. Fluid inclusion δD values for the Lamaque system of -50.8±13.9 per mil (n=10; Burrows, 1991) are quite compatible with a magmatic derivation since they significantly overlap the general range of -50 to -85 per mil estimated for magmatic fluids (Taylor, 1979) and also overlap (1σ level) the δD values of independently identified Archean magmatic fluids in the Mink Lake granodiorite stock, N.W. Ontario (-73±14 per mil; n=10; Burrows and Spooner, 1987).
(b) $\delta^{13}C$ values: Carbonate $\delta^{13}C$ values for Archean Au-quartz vein ore systems reflecting the $\delta^{13}C$ values of the high fluid CO_2 contents are relatively restricted giving means typically in the ~-6 to -2 per mil range. These values are quite compatible with a magmatic derivation (e.g. volcanic CO_2 from the White Island andesite/dacite volcano, New Zealand; -6.0 to -2.5 per mil; Giggenbach, 1982): magmatic CO_2 in the Long Valley, Steamboat Springs and Coso Range thermal areas; -8.2 to -4.0 per mil; Taylor and Gerlach, 1984: magmatic liquid CO_2 from a maar volcano, S. Australia; -4.3 to -3.7 per mil; Chivas et al., 1987), but different from metamorphic, granulite CO_2 values which are compatible with variable oxidized organic carbon/carbonate mixtures (e.g. cordierite channel CO_2 from 9 metamorphic terranes; -34.9 to -6.9 per mil, n=20; Vry et al., 1988: fluid inclusion CO_2, Bamble area, S. Norway; -21.9 to -4.5 per mil, n=10; Hoefs and Touret, 1975.
(c) Intrusion Au geochemistry: The Lamaque plugs (3), which host the Lamaque stockwork Au-quartz vein mineralization, appear to show a primary Au enrichment (G=7+24/-7 ppb; n=32) compared with other analyzed intrusions in the Val d'Or and Timmins areas (G=1±2/-1 ppb; n=47) with, in many cases, equal proximities to Au mineralization (Burrows and Spooner, 1989).

3. FLUID INCLUSION VOLATILE GEOCHEMISTRY

A widely accepted result regarding Archean Au-quartz vein systems is that the ore fluid was H_2O-CO_2-NaCl, low/moderate salinity in composition (e.g. Superior Province: Yilgarn block; Barberton greenstone belt). We (Spooner and Bray, 1990) have recently shown using heated (~105°C) crushing/gas chromatography on 1-2 g samples (11 analyzed species) that Barberton Archean Au-quartz vein ore fluids (e.g. de Ronde et al., 1991) and Mink Lake stock Au/W enriched MoS_2 Archean magmatic fluids (i) show definite compositional similarities to each other in terms of H_2O-CO_2-N_2-CH_4, C_2-C_4 hydrocarbons and COS contents, (ii) are distinctly different in composition from an externally derived H_2O-CH_4-CO_2-C_2H_6-N_2, higher salinity (~10-20 equiv. wt. % NaCl(?) metamorphic fluid from the Border Unit of the Tanco pegmatite, S.E. Manitoba (Thomas and Spooner, 1990) and (iii), in terms of $H_2O/CO_2/N_2$ and C/O/H/ atomic proportions, are very similar to volcanic gas/magmatic fluid compositions from the White Island volcano (New Zealand), Mt. St. Helens (U.S.) and the Tanco zoned granitic pegmatite (S.E. Manitoba). Hence, the H_2O-CO_2-N_2-CH_4 and COS compositions of Barberton Archean Au fluids have been found to be similar to analyzed volcanic gas compositions. The volatile species used for this work are relatively unaffected by water/rock interaction (cf.δD).

4. GEOLOGICAL EVIDENCE AGAINST METAMORPHIC MODELS FOR ARCHEAN Au FLUID GENERATION IN THE WAWA AND ABITIBI SUB-PROVINCES, SUPERIOR PROVINCE, CANADA

In the central Superior Province a discussion of possible Archean Au fluid sources can take advantage of the unusual, oblique cross-section through Archean greenstone belt crust exposed in the Kapuskasing section. This section, see also below, specifically defines a restricted set of lithologies relevant to the origin of Archean Au fluids in this particular area, and at the appropriate scale (e.g. the Renabie main ore zone is 40x140m on the 3,265 ft. level and is known to a depth of ~1,300m). It shows the Michipicoten greenstone belt underlain, with igneous intrusive contacts, by the ~10-15km thick igneous Wawa Domal Gneiss (TTG) Terrain, in turn underlain by a high grade granulite/anorthosite complex at the top of the lower crust (e.g. Percival et al., 1989); "subcreted" sediments (e.g. Kerrich, 1989) are not conspicuously apparent. A key point is that recent deep seismic reflection data indicate that a similar crustal section occurs beneath the Abitibi greenstone belt in the Larder Lake area near the Kerr Addison/Chesterville Au-quartz vein ore system (Green et al., 1990). Hence, observations on the Kapuskasing section are applicable to the sub-structure of the Abitibi belt.

4.1 Contra within-greenstone belt metamorphic Au fluid generation.

(a) Archean Au-quartz vein systems with representative geochemistries can occur outside the confines of greenstone belts suggesting that greenstone belt lithologies may not actually be very relevant to Archean Au ore fluid generation (see above: e.g. Renabie; Novo Astro; Arcadia Bay). (b) Amphibolite facies material which could have been produced, but not necessarily (? coeval with greenschist facies metamorphism) by metamorphism of pre-existing greenschist/sub-greenschist facies assemblages with fluid release (e.g. Carmichael, 1990) is limited in volume, and occurs quite specifically only around large intrusions in the Abitibi belt (e.g. Fig. 4 of Jolly, 1978); however, Archean Au-quartz vein ore deposits neither show analogous arcuate distributions nor obvious spatial relationships to these greenschist/amphibolite facies transitions. The basal contact of the Michipicoten greenstone belt with the underlying TTG layer, which was well exposed in the Renabie mine on the 3105 ft. level, shows no significant differences in character. (c) Within greenstone belt amphibolite/granulite or granulite metamorphic processes would not appear to be relevant since granulite facies rocks do not occur at the bases of greenstone belts in the Wawa/Abitibi area, and the sub-structure of the Abitibi belt appears to be similar to the sequence exposed in the Kapuskasing section (Green et al., 1990).

4.2 Contra sub-greenstone belt metamorphic Au fluid generation

(a) Greenstone belts with contained or marginal Au-quartz vein ore deposits in the Wawa/Abitibi area occur above a TTG igneous intrusive substrate which separates them from the high grade granulite/anorthosite layer by ~10-15 km in the case of the Kapuskasing section, and ~3-9 km in the Larder Lake area. (b) The Renabie area Au-quartz vein structures, which are quite small, appear to "root" in TTG layer tonalite (e.g. Nudulama; C zone; Braminco #21 zone). (c) There are no observed channelways in the Kapuskasing section through the ~10-15 km thick TTG layer from the granulite/anorthosite layer. (d) Au enrichments have not been observed in the granulite-anorthosite layer.

4.3 Au/intrusion relationships

The close spatial, structural and timing relationships between Au-quartz vein mineralization and igneous intrusions discussed above (e.g. small, elongate stock-hosted ore bodies, Lamaque; coincident space/structure/time mafic "albitite" dyke/main stage Au mineralization relationships, Kerr Addison/Chesterville) do not disprove a possible metamorphic origin for Archean Au fluids, but are definitely more indicative of magmatic genetic links which are supported by, for example, $\delta^{13}C$ and fluid inclusion volatile data (see above). Both of the latter data sets are currently negative with respect to metamorphic fluid origins; however, it is important to define the volatile, cation/anion and isotope geochemical characteristics of relevant Archean metamorphic fluids for further discriminatory testing.

5. ASPECTS NOT ACCOUNTED FOR BY THE MAGMATIC MODEL, AND DISCUSSION OF CONTRADICTORY EVIDENCE

5.1 Clustered Au-quartz vein deposits

Major and minor Archean Au-quartz vein ore systems occur highly clustered in specific areas (e.g. Timmins, N. Ontario; Kalgoorlie) and, as is well known, related to major structures (e.g.~300 km long Larder Lake-Cadillac Break, Ontario-Québec; Boulder-Lefroy shear W. Australia). Clearly Archean terrains have dense distributions of major structures; however, only some contain mineralization whereas many have the potential to act as structural controls on fluids and/or igneous intrusions. Hence, a possibility is that only a certain range of intrusion compositions may produce

Archean Au fluids, and/or that certain intrusive compositions may be particularly significant sources of Au fluids relative to other compositions. For example, the association of Archean Au-quartz vein mineralization with enriched calc-alkaline/shoshonitic, subduction-related compositions in the Val d'Or (Lamaque; Pascalis Nord), Timmins (Hollinger-McIntyre "albitites") and Virginiatown (Kerr Addison/Chesterville "albitites") areas, rather than with TTG (e.g. Renabie) or other igneous compositions, may be the basis for providing an explanation for the unusual amount of Archean Au in the Timmins-Val d'Or area, specifically (~3,700 tonnes Au; Burrows and Spooner, 1989; Spooner, 1990). The common, but not exclusive (e.g. Kerr Addison/Chesterville), association with second and third order structures may reflect specific timing relationships.

5.2 Au vein sphene U-Pb date~55-60 Ma younger than the host intrusive stock, Camflo deposit, N.W. Québec

U-Pb dates on coarse sphene from coarse Au bearing vein stage #3 in the Camflo deposit, N.W. Québec of ~2625 Ma have been found to be ~55-60 Ma younger than zircon U-Pb dates for the host stock at~2685-2680 Ma(Zweng and Mortensen, 1989; Jemielita et al., 1989). This age difference has been interpreted as reflecting dissolution/reprecipitation (c.f. Butte, Montana: secondary Au mineralization, Chibougamau, Québec; Guha and Kanwar, 1987) by later, upper crustal, saline, low CO_2 (sphene not rutile) fluids which interacted with a primary Au concentration, since the entire stock is geochemically anomalous at ~250 ppb Au down to 1-10m apophyses (Chainey, 1983; Spooner, 1990). N.B. Excellent observational evidence from mafic "albitite" dyke/main stage Au cross-cutting relationships indicates synchronous Au-quartz vein mineralization and igneous intrusive activity in the Kerr Addison/Chesterville Au system (Smith and Spooner, 1990; Smith et al., 1990). However, no igneous intrusive age younger than 2673+6/-5 Ma, for a Hollinger-McIntyre "albitite" dyke, is yet known in the southern Abitibi greenstone belt indicating that a ~2625 Ma age (Camflo sphene) for primary Au mineralization is highly unlikely.

5.3 Au related rutile U-Pb dates (~2630-2580 Ma) ~40-90 Ma younger than the youngest dated igneous intrusive event in the Abitibi Sub-province (2673 + 6/-5 Ma).

U-Pb dates for fine grained rutile associated with Au-quartz vein systems in or near the Abitibi Sub-province are consistently younger than the youngest dated igneous intrusive event for the Hollinger-McIntyre Au system "albitite" dyke at 2673 +6/-5 Ma: Renabie rutile, ca. 2580 Ma; Kerr Addison rutile, ca. 2580 Ma; Camflo rutile, ca. 2625-2620 Ma.; Lamaque rutile, ca. 2630 Ma; Sigma rutile, ca. 2600 Ma (Jemielita et al. , 1990). However, the rutile U-Pb ages are considered to be minimum, not actual, dates for primary Au-quartz vein mineralization (Spooner, 1990) for the following reasons: (a) Primary Au-quartz vein mineralization in the Kerr Addison-Chesterville system is definitely syn-"albitite" dyke intrusion in relative age (Smith and Spooner, 1990; Smith et al., 1990) and therefore, according to currently available data, highly unlikely to be younger than ~2673 Ma in absolute age. However, the Kerr Addison rutile date at ca. 2580 Ma is ~90 Ma younger, and therefore, with a high degree of probability, a minimum, not actual, estimate for the age of primary Au-quartz vein mineralization. (b) Mezger at al. (1989) have shown that the U-Pb diffusive thermal retention characteristics of fine grained, prograde rutile are similar to $^{40}Ar/^{39}Ar$ retention characteristics intermediate between biotite and hornblende (≃muscovite), thus explaining the similarity between rutile U-Pb and muscovite $^{40}Ar/^{39}Ar$ plateau ages at the Sigma Mine (2592±2 Ma [U-Pb] for rutile cf. 2579±3 Ma [$^{40}Ar/^{39}Ar$] for muscovite; Wong et al., 1989). Hence, U-Pb dates for fine grained rutile have to be interpreted as minima in the same way as muscovite $^{40}Ar/^{39}Ar$ plateau ages. (c) The latter deduction is confirmed by Heaman and Tarney (1989) who conclude that "It is evident that rutile was either formed, or the U-Pb systematics reset, after emplacement of even the youngest known Scourie dyke at 1,921 Myr. In either case, the ~1700 Ma rutile age is clearly the result of a later Laxfordian metamorphic overprint".

In summary, the rutile U-Pb dates have not been shown to be other than minima.

5.4 Contradictory evidence

General evidence which has been suggested to be contradictory to a magmatic model for the origin of Archean Au-quartz vein mineralization will be discussed and evaluated.

6. COMPARISON WITH MESOZOIC/TERTIARY Au-Ag MINERALIZATION IN ISLAND ARC AND CORDILLERAN SETTINGS

Evidence is accumulating that epithermal-mesothermal Au-Ag mineralization in island arc and cordilleran settings may also have been magmatically derived ±high level fluid mixing (e.g. Sillitoe,1983; Ahmad et al., 1987; Henley and Hoffman, 1987; Sillitoe and Bonham, 1990; Spooner, 1990). The associated igneous rocks are principally calc-alkaline and shoshonitic in composition (e.g. Emperor Au-Ag-Te deposit related to shoshonitic magmatism, Fiji). By comparison with the Archean, therefore, a possibility exists for a unification of genetic interpretations reflecting common, or similar, genetic processes.

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REFERENCES

Abraham, A.P.G. and Spooner, E.T.C. 1989. Co-structural, syn-shear felsic dykes and Archean Au-quartz veins in shear zones within the Anialik TTG tonalite batholith, Arcadia Bay area, Slave Province, N.W.T. Geol. Assoc. Canada-Mineral Assoc. Canada, Program with Abstracts, 14: A46

Ahmad, M., Solomon, M. and Walsh, J.L. 1987. Mineralogical and geochemical studies of the Emperor gold telluride deposit, Fiji. Econ. Geol 82: 345-370.

Burrows, D.R. 1991. Relationships between Archean lode gold quartz vein deposits and igneous intrusions in the Timmins and Val d'Or areas, Abitibi sub-province, Canada. Unpub. Ph.D. thesis, Univ. Toronto: 217 p.

Burrows, D.R. and Spooner, E.T.C. 1987. Generation of a magmatic H_2O-CO_2 fluid enriched in Mo, Au, and W within an Archean sodic granodiorite stock, Mink Lake, northwestern Ontario. Econ. Geol. 82: 1931-1957.

Burrows, D.R. and Spooner, E.T.C. 1989. Relationships between Archean gold quartz vein-shear zone mineralization and igneous intrusions in the Val d'Or and Timmins areas, Abitibi Subprovince, Canada. Economic Geology Monograph #6: 424-444.

Burrows, D.R. and Spooner, E.T.C. 1990. Archean intrusion-hosted, stockwork Au-quartz vein mineralization, Lamaque mine, Val d'Or, Québec: Part I. Geologic and fluid characteristics. NUNA Research Conference on Greenstone Gold and Crustal Evolution, Val d'Or, Québec; Abstract Volume: 20-21.

Callan, N.J. and Spooner, E.T.C. 1989. Archean Au-quartz vein mineralization hosted in a tonalite-trondhjemite terrane, Renabie mine area, Wawa North Ontario, Canada. Economic Geology Monograph #6: 9-18.

Carmichael, D.M. 1990. Gold and the greenschist facies. NUNA Research Conference on Greenstone Gold and Crustal Evolution, Val d'Or, Québec; Abstract Volume: 22

Chainey, D. 1983. Paramètres pétrographiques et géochimiques du gisement d'or de la mine Camflo, Québec, Canada. Thése de maîtrise, Ecôle Polytechnique: 215 p.

Chivas, A.R., Barnes, I., Evans, W.C., Lupton, J.E. and Stone, J.O. 1987. Liquid carbon dioxide of magmatic origin and its role in volcanic eruptions. Nature 326: 587-589.

Cullen, I. and Norris, N. 1988. Gold deposits of the New Celebration gold mine. Bicentennial Gold 88, Excursion No. 6 Guide, Part III: 87-90.

de Ronde, C.E.J., Kamo, S., Davis, D.W., de Wit, M.J. and Spooner, E.T.C. In press. Field, geochemical and U/Pb isotopic constraints from hypabyssal felsic intrusions within the Barberton greenstone belt, South Africa: implications for tectonics and the timing of gold mineralization. Precambrian Research.

de Ronde, C.E.J., Spooner, E.T.C., Bray, C.J. and de Wit, M.J. 1991. Mafic-ultramafic hosted, shear zone related, Au-quartz vein deposits in the Barberton greenstone belt, South Africa: structural style, fluid properties and light stable isotope geochemistry. This volume.

Giggenbach. W.F. 1982. The chemical and isotopic compositions of gas discharges from New Zealand andesitic volcanoes. Bull. Volcanol. 45-3: 253-255.

Green, A.J., Milkereit, B., Mayrand, L.J., Ludden, J.N., Hubert, C., Jackson, S.L., Sutcliffe, R.H., West, G.F., Verpaelst, P. and Simard, A. 1990. Deep structure of an Archean greenstone terrane. Nature, 344: 327-330.

Guha, J. and Kanwar, R. 1987. Vug brines-fluid inclusions: a key to the understanding of secondary gold enrichment processes and the evolution of deep brines in the Canadian Shield. Geol. Assoc. Canada Special Paper 33: 95-101.

Heaman, L.M. and Tarney, J. 1989. U-Pb baddeleyite ages for the Scourie dyke swarm, Scotland. Nature 340: 705-708.

Henley, R.W. and Hoffman, C.F. 1987. Gold: sources to resources. Pacific Rim Congress 87: 1-10.

Hoefs, J. and Touret, J. 1975. Fluid inclusion and carbon isotope study of Bamble granulites (south Norway). Contrib. Mineral. Petrol. 52: 165-174.

Jemielita, R.A., Davis, D.W., Krogh, T.E. and Spooner, E.T.C. 1989. Chronological constraints on the origin of Archean lode gold deposits in the southern Superior Province from U-Pb isotopic analyses of hydrothermal rutile and titanite. Geol. Soc. America Ann. Mtg., Abstracts with Programs, 21: A351.

Jemielita, R.A., Wong, L., Davis, D.W. and Krogh, T.E. 1990. The greenstone-gold relationship in the southern Superior Province: constraints from U-Pb dating of hydrothermal minerals. NUNA Research Conference on Greenstone Gold and Crustal Evolution, Val d'Or, Québec; Abstract Volume: 60.

Johnson, K. 1988. The Norseman gold deposits. Bicentennial Gold 88, Excursion No. 6 Guide, Part III: 114-121.

Jolly, W.T. 1978. Metamorphic history of the Archean Abitibi belt. Geol. Surv. Can., Paper 78-10: 63-78.

Kerrich, R. 1989. Geodynamic setting and hydraulic regimes: shear zone hosted mesothermal gold deposits. Geol. Assoc. Canada, Short Course Notes, 6: 89-128.

Meinert, L.D. 1989. Gold skarn deposits - geology and exploration criteria. Economic Geology Monograph #6: 537-552.

Mezger, K., Hanson, G.N. and Bohlen, S.R. 1989. High precision U-Pb ages of metamorphic rutiles: application to the cooling history of high-grade terranes. Earth Planet. Sci. Lett. 96: 106-118.

Percival, J.A., Green, A.J., Milkereit, B., Cook, F.A., Geis, W. and West, G.F. 1989. Seismic reflection profiles across deep continental crust exposed in the Kapuskasing uplift structure. Nature 342: 416-420.

Sauter, P.C.C., Hyland, S.J. and Bradley, T. 1988. The Mount Percy gold mine. Bicentennial Gold 88, Excursion No.6 Guide, Part III: 84-86.

Sillitoe, R.H. 1983. Styles of low-grade gold mineralization in volcano-plutonic arcs. Nevada Bureau of Mines and Geology Report 36: 52-68.

Sillitoe, R.H. and Bonham, H.F., Jr. 1990. Sediment-hosted gold deposits: distal products of magmatic-hydrothermal systems. Geology 18: 157-161.

Smith, J.P. and Spooner, E.T.C. 1990. Evidence for a mafic "albitite" intrusion/ Archean Au structure - time association, Kerr Addison - Chesterville mines, northern Ontario. NUNA Research Conference on Greenstone Gold and Crustal Evolution, Val d'Or, Quebec, Abstract Volume: 85-87.

Smith, J.P., Spooner, E.T.C., Broughton, D.W. and Ploeger, F.R. 1990. The Kerr Addison - Chesterville Archean gold - quartz vein system, Virginiatown: time sequence and associated mafic "albitite" dike swarm. Ont. Geol. Surv. Misc. Paper 150: 175-199.

Solomon, M. 1990. Subduction, arc reversal, and the origin of porphyry copper - gold deposits in island arcs. Geology 18: 630-633.

Spooner, E.T.C. 1990. Archean intrusion - hosted, stockwork Au - quartz vein mineralization, Lamaque mine, Val d'Or, Quebec: Part II. Light stable isotope (H,O,C and S) characteristics and enriched calc - alkaline/ shoshonitic igneous geochemistry. NUNA Research Conference on Greenstone Gold and Crustal Evolution, Val d'Or, Quebec, Abstract Volume: 88-90.

Spooner, E.T.C. and Bray, C.J. 1990. The fluid inclusion volatile geochemistry of Archean Au/W enriched MoS_2 mineralization, Mink Lake stock, N.W. Ontario and Archean Au - quartz vein mineralization, Barberton greenstone belt, southern Africa. Third Biennial Pan - American Conference on Research on Fluid Inclusions, Toronto, Ontario; Program and Abstracts: 83-84.

Taylor, B.E. and Gerlach, T.M. 1984. Mantle CO_2 degassing at Long Valley, Steamboat Springs, and the Coso Range. EOS 65: 1150.

Taylor, H.P., Jr. 1979. Oxygen and hydrogen isotope relationships in hydrothermal mineral deposits. In H.L. Barnes (ed.), Geochemistry of hydrothermal ore deposits, p.236-277. New York, Wiley - Interscience.

Thomas, A.V. and Spooner, E.T.C. 1990. Distinguishing between Archean fluids of different origins: an example using volatile analyses of fluid inclusions from the Tanco granitic pegmatite, S.E. Manitoba. NUNA Research Conference on Greenstone Gold and Crustal Evolution, Val d'Or, Quebec, Abstract Volume: 93-95.

Vry, J., Brown, P.E., Valley, J.W. and Morrison, J. 1988. Constraints on granulite genesis from carbon isotope compositions of cordierite and graphite. Nature 332: 66-68.

Wong, L., Davis, D.W., Hanes, J.A., Archibald, D.A., Hodgson, C.J. and Robert, F. 1989. An integrated U-Pb and Ar-Ar geochronological study of the Archean Sigma gold deposit, Val d'Or, Quebec. Geol. Assoc. Canada - Mineral. Assoc. Canada, Program with Abstracts, 14: 45.

Zweng, P.L. and Mortensen, J.K. 1989. U-Pb age constraints on Archean magmatism and gold mineralization at the Camflo mine, Malartic, Quebec. Geol. Soc. America Ann. Mtg., Abstracts with Programs, 21: A351.