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FINAL TECHNICAL REPORT

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Differentiating Crustal Fluids in the Eastern Tintina Gold Province of Alaska and Yukon: Implications for the Genesis and Distribution of Gold Ores

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PREAMBLE

Late metamorphic hydrothermal activity in the Tintina gold province (TGP) of east-central Alaska and adjacent Yukon Territory was investigated, in particular the major component and multi-element natures of both the hydrothermal fluids associated with gold mineralisation and of fluids of hydrothermal activity away from known gold mineralisation. The research of this project links with the 2002-2007 USGS Regional Mapping Project *'Tintina metallogenic province: Integrated studies of geologic framework, mineral resources and environmental signature'*.

SUMMARY OF PROJECT PURPOSE

Within the complex and long cordilleran style of metamorphism and deformation, epigenetic gold ores in the Tintina gold province formed during a relatively narrow time period of the mid-Cretaceous, 104 – 87 Ma (McCoy et al., 1997; Selby et al., 2002). The time period of gold mineralisation thus post-dated peak regional metamorphism and associated multi-phase deformation, including a proposed phase of crustal extension (125 – 105 Ma, Pavlis et al., 1993), and overlapped one of the ages of widespread granitic magmatism in the province (e.g. Hart et al., 2004). A range of hydrothermal deposit types which formed at 2 – 10 km depth in the crust and for which gold is the economically most important commodity formed within this narrow time range. Of these, the most significant are:

- <u>Intrusion hosted deposits</u> with similarities in setting and style to porphyry deposits. These are large-tonnage, low-bulk-grade deposits with Au in association with Bi-Mo-Te, in and within the haloes of spaced sheeted to stockwork narrow quartz rich veins, hosted dominantly in and around cupolas and stocks of felsic intrusions (e.g. Fort Knox, Dublin Gulch).

- Shear zone and fracture hosted <u>quartz-vein deposits</u> in metamorphic rocks. These deposits have a range of vein styles, the variation indicative in part of formation at a range of pressure-temperature conditions, from fracture fillings (e.g. Cleary Hill) to syn-deformational quartz veins in ductile shear zones (e.g. Pogo). Within the province these veins have strongly anomalous to ore grades of As and Sb, variably high Pb, Zn, Cu and Ag, and in the case of Pogo, relatively high concentrations of the same suite of elements that are co-enriched with gold in the intrusion hosted deposits (Bi, Te, Mo).

In addition, there are deposits and ores that have been argued to be genetically related to one or more of these gold deposit types and which contain anomalous concentrations of gold, including W skarns and veins mined predominantly for Ag-Pb-Zn.

There are currently two end-member models for the range of styles of gold mineralisation in the Province. For the intrusion-related gold deposits (IRGD) model, it is argued that the gold deposit types in the Province are different expressions of zoned gold-bearing hydrothermal systems (e.g. McCoy et al, 1997) centred on felsic (ore-generating) igneous intrusions. Alternatively, it is argued that only those deposits that are most intimatedly associated with intrusions are IRGD's, and that deposits in shear and fracture zones in metamorphic rocks are "orogenic" (mesothermal) deposits, as would be expected to be present in a deeply eroded cordilleran orogenic belt (e.g. Goldfarb et al., 2005).

Earlier fluid inclusion studies have demonstrated that the ore fluids of Alaskan IRGD's are low- to moderate-salinity aquo-carbonic fluids indistinguishable from those of orogenic gold deposits (e.g. Baker and Lang, 2001; Mair et al., 2005). In view of the similarity of ore fluids and other overlapping characteristics of IRGD's and orogenic gold deposits, fluid inclusion petrography and microthermometry was here combined with newly available single fluid inclusion multi-element analytical techniques (LA-ICP-MS) in this project to investigate the question:

What different hydrothermal ore fluids, as defined by volatile and trace-element signatures, were present in the Province during the mid-Cretaceous time period of gold mineralization?

The research gave data pertinent to two further questions:

- What constraints do the volatile and trace element signatures of fluids give for the processes controlling mineralisation and for the sources of gold-related fluids in the TGP? Can we resolve the uncertainty in existing gold deposit type models for the northern Cordillera?
- What is the Au prospectivity of rock units and segments of the TGP?

PROJECT METHODS

Field Work

Six man-weeks of field work was undertaken in the Tintina Gold Province of Alaska and adjacent Yukon Territories, visiting vehicle accessible outcrops, active and historical mines, and examining core. Outcrop is poor through most of the Province, and most field work was concentrated at isolated large (> 30 m minimum dimension) roadside outcrops and at mines.

The mineralogy of veins, visible mineralisation and alteration, and structures indicative of the timing of hydrothermal activity were recorded. In general, observations and sampling was concentrated on hydrothermal features that could be inferred to be (a) broadly of the same age relative to deformation and regional metamorphism as known gold mineralisation, i.e. post-dating the main phases of ductile deformation, but while metamorphic temperatures were still elevated, and (b) potential pathways of regional metal transport. To allow comparison of fluid compositions, earlier and later vein generations were sampled at some localities.

Sites for field observations and sampling were chosen within a matrix with two variables: (a) gold mineralised versus un-mineralised, and (b) metamorphic versus granitoid hostrocks. Figure 1 summarises the geographical areas of study.

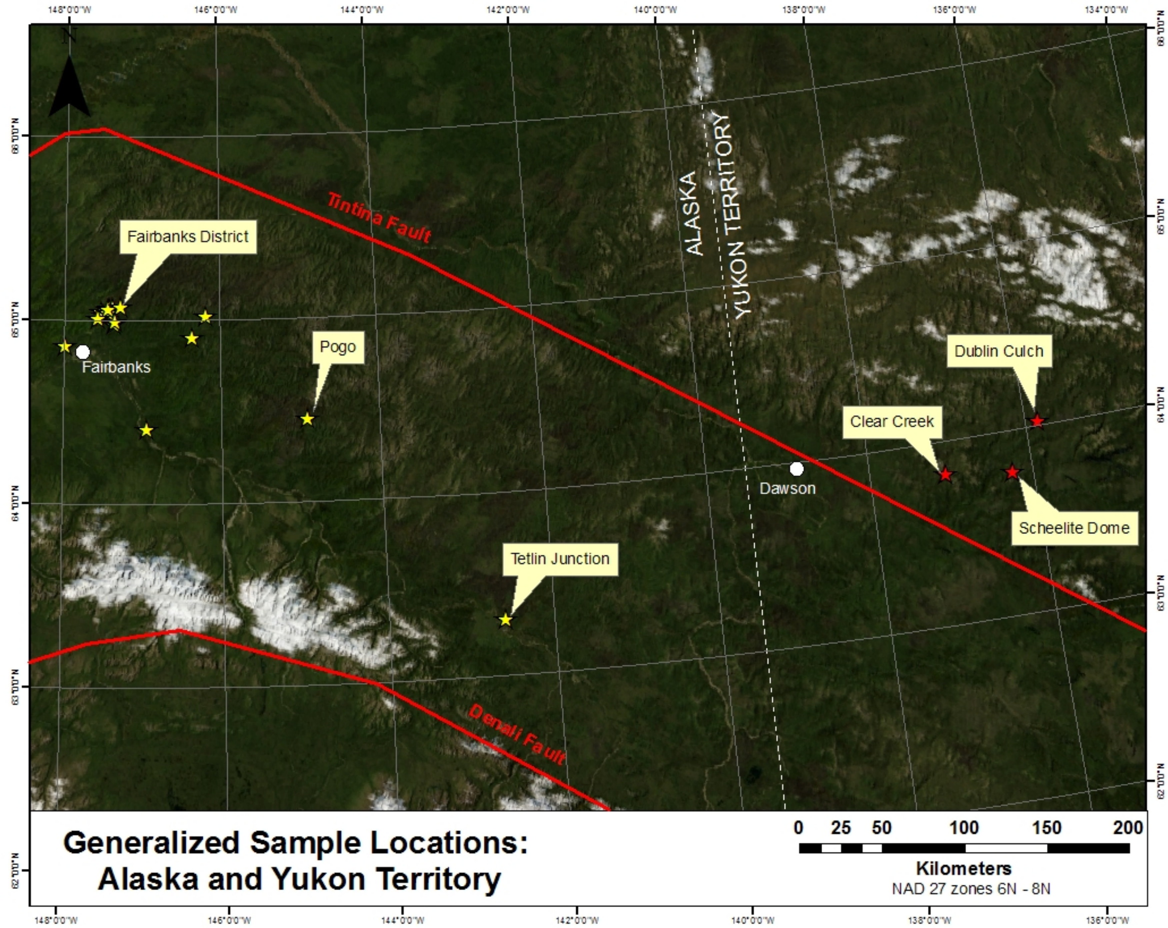

Figure 1. Generalised map of the Tintina gold province of east-central Alaska and adjacent Yukon Territories showing the areas of specific study in this project.

Outcrops were observed in detail in:

(i) The Yukon-Tanana Upland tectonites (nomenclature after Hansen and Dusel-Bacon, 1998) distant (> 1 – 2 km) from known gold mineralisation and of metamorphic grade of greenschist or amphibolite facies (Chena and Fairbanks subterranes, lower-grade margins of the Salcha River gneiss dome). Most outcrops that were targeted in the metamorphic terrains are composed of pelitic schists, mixed pelitic and quartzitic schists, calcareous schists and calc-silicate rocks, or of mafic rocks interbedded in schists.

(ii) Gold and associated deposits and prospects in metamorphic hostrocks, including fracture and shear zone hosted quartz vein gold deposits and W-skarn deposits. The vein style of the sampled gold deposits includes stockworks of narrow veinlets, narrow discrete fracture infills (e.g. Golden Summit, Cleary Summit), large quartz veins in brittle shear zones (e.g. Tolovana) and ductile shear-zone vein infill (e.g. Pogo).

Core traversing ore zones in the tectonites was examined and sampled at Golden Summit, Dublin Gulch and Pogo.

(iii) Granitoids distant from known gold mineralisation. The granitoids sampled are stock to pluton sized calc-alkaline granodiorites, granites and quartz-monzonites that intruded into the Yukon-Tanana Upland tectonites after regional penetrative deformation and peak metamorphism. At a number of sampled localities, narrow discrete shear zones and fracture zone sets give evidence of continued deformation after intrusion.

Many of the sampled intrusions are known to be mid- to late-Cretaceous, of the range 103 – 88 Ma (e.g. Newberry, 2000). Some are undated, and it is possible that these are either early Cretaceous or are early Tertiary intrusions (Dilworth et al., 2007; Day et al., 2007). In the Fairbanks area, the intrusions are low-magnetite, but sampled intrusions in the southern central TGP in the area of Tetlin Junction are magnetically positive (Saltus and Day, 2006).

(iv) Gold deposits and prospects in mid- to late-Cretaceous intrusive rocks. Many deposits in intrusive rocks are comprised of stockwork to sheeted quartz veins, which is the 'type' style of the proposed Intrusion Related Gold Deposit group (Dublin Gulch, Fort Knox). Sulfidic veins hosted in discrete shear zones e.g. (Silver Fox) also occur.

Petrography and fluid inclusion microthermometry

Approximately 50 thin sections and 80 double polished (fluid inclusion) sections were examined from representative samples of veins and wallrocks from all categories of environment (mineralised, unmineralised, metamorphic, granitic). Sixteen samples from 9 localities have been selected for fluid inclusion study. These samples are mainly from ores, but cover all categories of the sampling matrix (Table 1).

Fluid inclusion petrography and microthermometry was undertaken with a Linkam THMS 600 stage at Colorado State University. Standard observations and experiments were made to determine:

- The relative timing of fluid migration events.
- The composition of fluid types in with respect to salinity, whether the inclusions are aqueous, aquo-carbonic or carbonic, and whether the carbonic phase is dominated by CO_2 or contains significant concentrations of CH_4 or other gases.
- Phase transitions pertinent to estimation of fluid inclusion densities, and hence constraints on temperatures and pressures of entrapment.

Cathodoluminescence (CL) imagery (Department of Geology and Geophysics, University of Wyoming) was trialled to provide textural information pertinent to constraining the timing of fluid migration, but as a result of equipment malfunction, no results are available to date.

Sample	Location	Lat. (N)	Long. (W)	Host Rock	Mineral -isation	Sample Description
CH06-1	Cleary Hill	65.062	147.429	M	Au (-As-Sb)	5 cm Qtz fissure vein @ 30' mark in Wachowitz Trench
CS06-3	Cleary Summit	65.048	147.441	M	Au-Sb-As-Pb	10 cm Stibiconite w/ Qtz fissure vein
CS07-3	Cleary Summit	65.048	147.441	M	Au-Sb-As-Pb	10 cm Stibiconite, scorodite, Qtz fissure vein
ED06-5C	Ester Dome	64.861	147.991	G	-	1 cm quartz stockwork vein in sericite-pyrite altered granodiorite
FK06-1	Ft Knox	64.994	147.356	G	high-grade Au-Bi-Mo	1-2cm qtz (-K-spar- carbonate) vein in shear zone with sulfides (Mo, Asp, Py, Bismuthinite)
FK06-2	Ft Knox	64.994	147.356	G	Au (-Bi-Mo)	2 cm pegmatitic (qtz - K-spar) vein in shear zone
FK06-4	Ft Knox	64.994	147.356	G	Au?	1-2 cm qtz vein in coarse to medium grained granite
GD06-9	Gilmore Dome	64.971	147.411	G	-	Pegmatitc aplite with euhedral qtz phenocrysts
GD06-12	Gilmore Dome	64.981	147.315	G	W	2 cm quartz vein in granodiorite
GD07-6	Gilmore Dome	64.990	147.900	G	Au?	1 cm quartz stockwork vein with K-spar growth on rims
GS06-49	Golden Summit, Cleary Hill	65.062	147.429	M	Au	4mm vuggy Qtz fissure vein w/ minor sulfides (Core #2, 305.5')
PG07-4	Pogo	64.291	145.125	M	Au-Bi-As	L1 zone, level 1350' (569' face) - 2-phases of massive shear-zone Qtz vein (web - with Py-Asp-Po + massive)
PG07-19	Pogo	64.291	145.125	M	Au	5 cm X-cut massive quartz shear-zone vein (Core 07-399 @ 683')
PG07-22	Pogo	64.291	145.125	M	Au	1-2 cm Qtz shear-zone vein in altered pelitic schist (Core 07-396)
RL06-10	Ryan Lode	64.860	147.995	M	Au (-As-Sb)	20 cm carbonate-rich shear vein (Dol - Qtz - Py)
TV06-6C	Tolovana	65.060	147.453	M	Au (-Sb)	1m vein in brittle-ductile shear, vuggy Qtz w/ sulfides (±Au)
TV06-7	Tolovana	65.060	147.453	M	Au (-Sb)	1m brittle-ductile shear vein, Qtz w/ laminations of Asp

Table 1. List of samples analysed by fluid inclusion microthermometry and LA-ICP-MS. Abbreviations: M = metamorphic rock, G = granitoid.

Laser Ablation Inductively Couple Plasma Mass Spectrometry (LA-ICP-MS)

Multi-element analyses of quartz hosted fluid inclusions were made at Virginia Tech (laboratory of Prof. R Bodnar), on all 16 samples selected for fluid inclusion analysis. In addition to fluid inclusions, some analyses were made of host quartz and of solid inclusions petrogenetically related to fluids inclusions. Typically between 5 and 12 inclusions were analysed from each assemblage in order to assess homogeneity and to obtain improved confidence in the detection and quantification of trace elements.

The normal operating procedures of the facility were followed (see http://www.geochem.geos.vt.edu/fluids/laicpms/images/PosterWeb.pdf), including calibrations with NIST610 glass. The strategy for quantification of fluid inclusion composition is detailed in Appendix A.

Systematic analysis was of 25 or 26 elements (atomic weights of analysed isotope) - Li (7) B* (11) Na (23) Si (28/29) K (39) Ca (40) Mn (55) Fe (56) Cu (65) Zn (66) As (75) Rb (85) Sr (88) Y* (89) Mo (98) Ag (107) Sn (120) Sb (121) Cs (133) Ba (138) La (139) Ce (140) W (182) Tl (205) Pb (208) Bi (209). Elements indicated with * were not analysed in all inclusions.

Metal rich solid inclusions associated with fluid inclusions in veins at Fort Knox were analysed with a restricted range of elements (Na, K, As, Sb, Au, Bi) in order to provide quantification of trace elements in this metal-rich phase, in particular, of gold.

SEM microanalysis

EDS elemental analysis and element mapping of solid metal rich inclusions associated with fluid inclusions was undertaken using a JSM-6500F housed at the Central Instrumentation Facility, Department of Chemistry, CSU. This allowed determination of the full major element composition of these inclusions (including S), which is not possible with LA-ICP-MS.

TIMING, DISTRIBUTION AND NATURE OF HYDROTHERMAL FLUID FLOW IN THE TINTINA GOLD PROVINCE

Quartz-rich veins and rarer carbonate-dominated veins are widespread but not pervasive in the metamorphic and intrusive rocks of the TGP, both at and distant from ore bodies. Multiple generations of vein are distinguishable at many localities. We here summarise field and petrographic data pertinent to large scale fluid and metal transport through hydrothermal activity in the Tintina Gold Province.

Hydrothermal activity in metamorphic rocks distant from known ore or prospects.

Veins are most commonly abundant (up to a density of greater than one per metre) in pelitic and calcareous schists in the greenschist to amphibolite metamorphic zones. Two styles of veins are recognised which are interpreted to record large scale transport over the time period of interest.

(i) Steeply dipping, discrete post-peak metamorphic quartz veins that sharply crosscut schistose fabrics and that are laterally or vertically continuous over distances of at least a few metres. A small number of isolated veins of this style have been documented, most abundantly along the southern edge of the Salcha River gneiss dome, within and around the Richardson Goldfield. These veins are up to about 15 cm wide, typically weakly curviplanar, are independent of any shear zones or fault zones, and have visible but weak and narrow sericite ± pyrite alteration haloes. Maximum vein densities of two per kilometre are estimated from the limited outcrop. The alteration around these veins suggests correlation with gold ore veins in the metamorphic rocks. Correlation with auriferous veins described and sampled by Gough et al. (2005) in metamorphic hostrocks distant from known mineralisation in the Delta B1 Quad is also suggested.

(ii) Fracture and shear zone hosted veins. These vertically or laterally continuous veins are narrower, mm- to cm-thick, and are hosted in discrete fractures and brittle-ductile shear zones that formed at a late stage in the deformational history of the rocks. These veins are widespread in some localities, but are rare or absent at most. One locality of abundant veins is the north side of Pedro Dome, where there are multiple generations of structurally hosted quartz, quartz-calcite and calcite veins of both steep and gentle dip. The hosting structures and all vein types cut the irregular contact between the schists and the late-Cretaceous Pedro Dome granodiorite at this locality.

Hydrothermal activity in granitic rocks distant from known ore or prospects

The density and abundance of veins in granitoids is very variable. Veins are absent within some extensive outcrops. Veins in granite of the ages sampled may be either veins which either record intrusion devolatilisation, or record fluid flux in the terrain during or after the mid- to late-Cretaceous magmatic event.

Two types of structure were recognised that are interpreted to record fluid exsolution from crystallising granites:

(i) Laterally continuous quartz veins a few centimetres wide, for instance at Angel Rocks (W146.189º N65.026º). The lack of visible alteration of primary igneous minerals in the vein haloes, the presence of euhedral growth of K-feldspar across vein margins, and the curviplanar geometry of these veins, together imply that these are pathways of fluid flow during the late magmatic history or immediately postdating crystallisation.

(ii) Dyke-like aplitic – pegmatitic segregations (Gilmore Dome, Scheelite Dome, Tetlin Junction). In some cases contacts between these segregations and the host granitoid are gradational. Aplitic segregations with distinct large euhedral quartz phenocrysts (up to 2 -5 cm across) or aplitic segregations around which similar phenocrysts are present in hostrock granite occur at a number of localities in the Gilmore Dome intrusion.

A variety of post-intrusion vein types and styles with lateral or vertical continuity were recognised in granitoids. They include planar, thin (mm-scale) quartz veins without distinct alteration haloes, and calcite, calcite – quartz, and pyrite – quartz – calcite veins in discrete shear zones. At some localities these late veins are parallel to and spatially associated with aplite dykes.

A swarm of veins with mineralogy and mineral textures similar to veins of epithermal ore deposits (bladed calcite – quartz – chalcedony) and associated with widespread sericite alteration and weak iron-hydroxide (after pyrite) staining was mapped over a hundred metre wide outcrop of granite at the Tor Trailhead on Chena Springs Road (W146.362º N64.905º). No evidence of concentrations of any ore metals was observed at this locality.

Ore veins in metamorphic hostrocks

Gold ore veins in metamorphic hostrocks are generally quartz dominated with minor carbonate and sulfides. They can generally be readily distinguished from other generations of syn- and post-metamorphic quartz-carbonate-, calcite- and quartz-veins by their sulfide content and the presence of potassic (sericitic or biotitic) alteration haloes. Some of the veins have a more complex and abundant sulfide mineral assemblage than is typical of orogenic gold-quartz veins, including minor sphalerite, galena and sulfo-salts (cf. Hill, 1933). Visible alteration haloes are generally much narrower relative to vein width than has been reported to be typical of orogenic gold deposits (e.g. Ridley and Diamond, 2000).

There is a range of style of metamorphic hosted gold ore veins, from drusy veins to shear zone hosted veins with massive quartz infill. This variability has been previously recognised and described by other workers and has been interpreted as reflecting epizonal to deeper levels and hotter conditions during vein formation (e.g. Hart et al., 2002). Our observations are of a range of vein infill styles that overlap those described from orogenic gold deposits in other mineralised terrains in the world (e.g. Groves et al., 1995). A distinct and unique vein style in the TGP contains massive stibnite (± arsenopyrite) pods, or veins dominated by Sb- and As-bearing secondary oxide minerals, with embedded euhedral quartz grains.

Ore veins in granitoids

The nature of ore veins at the major Fort Knox and Dublin Gulch deposits has been previously described (Bakke, 1995). Ore veins form low-density, vertically and laterally continuous sheeted swarms. The veins are generally planar to weakly curviplanar, of width between 1 mm and a few cm's. Mineralogically the veins are quartz-dominated with minor K-feldspar or ankerite + sericite, and contain up to a few percent sulfide minerals (pyrite, molybdenite, bismuthinite etc). Wallrock alteration is either cryptic or marked by narrow (cm-width) sericite-pyrite-carbonate zones. We confirm the observations of Jensen (unpublished data) that not all veins of this style at Fort Knox are equally strongly sulfide mineralised.

The styles of quartz veins that are present at Fort Knox were identified to be locally developed at a number of localities in the small granitic stocks of the Fairbanks mining district. In addition, some intrusions in the district host stockworks of foliation cross-cutting, steeply-dipping, planar quartz veinlets, in most cases less than 1 mm wide, that extend over areas of few tens of metres in extent and are associated with more prominent sericite and pyrite-bearing alteration. Similar veinlet swarms are recognised above likely buried extensions of intrusions. These veinlet swarms are provisionally interpreted to be lower temperature equivalents of vein swarms such as at Fort Knox. The locality at Fox Creek Summit (W147.628º N65.001º) was sampled in detail by Hawkins and Forbes (1971), who demonstrated anomalous gold concentrations in veinlets and associated altered wallrock.

FLUID INCLUSION PETROGRAPHY AND MICROTHERMOMETRY

Inclusion timing

The relative timing of inclusion entrapment was defined within the discipline established three categories using normal textural criteria:
Primary – lining growth faces of vein quartz. These are preserved only in a few quartz 'fissure' veins in metamorphic rocks (Cleary Hill, Cleary Summit, Golden Summit).
Pseudosecondary – inclusions interpreted as being likely entrapped during the period of vein development. Textures used to indicate this timing are most commonly one of: discontinuous curved planes restricted to within single quartz grains; isolated inclusions that are large compared to host quartz, or; isolated 3-dimensional clusters of inclusions.
Secondary – transgranular planes.

Preservation of fluid inclusions

Well preserved primary or pseudosecondary fluid inclusions large enough for microthermometric study occur in vein quartz in most samples from the gold deposits. Early (pre- or syn-ductile deformation) veins in metamorphic rocks in the Province, samples from the Main (Liese) Zone vein at Pogo, and from some veins at Fort Knox lacked such inclusions. The quartz in veins that lack preserved fluid inclusions larger than 1 – 2 µm in size is granoblastic, and it is thus interpreted that syn-vein growth fluid inclusions were destroyed during one or more phases of intracrystalline (plastic) deformation of quartz after entrapment. The quartz of some samples (e.g. Fort Knox) shows a minor degree of intracrystalline (plastic) deformation marked by sub-grains and incipient mortar texture. The presence of fluid inclusion textures such as spreading out of inclusion planes (Roedder, 1984) and annular and hooked inclusion shapes (Vityk and Bodnar, 1995) in this quartz are interpreted to indicate inclusion modification after entrapment.

Inclusion compositional types and their trapping conditions.

Table 2 summarizes microthermometric and context data of the samples analysed. Two compositional types of fluid inclusion are distinguished:

(i) Aqueous - H_2O solutions of low to moderate salinity (2 – 10 wt % eq. NaCl). This compositional class includes both pseudosecondary and secondary inclusions. Assemblages that are clearly secondary have temperatures of homogenisation (T_h) of 130 – 200 ºC; those that are pseudosecondary have T_h of 260 – 300 ºC.

(ii) Aquo-carbonic - H_2O – CO_2 ± CH_4 mixtures with a water phase at ambient temperature of low to moderate salinity (3 – 10 wt % eq. NaCl). Estimates of the degree of filling (f_V = L:V ratio) are generally between 0.3 and 0.9, and hence X_{carb} between 0.05 and 0.5. The composition of the carbonic phase as determined from microthermometry to vary from nearly pure CO_2 (< 2 mol % CH_4 or other gases) to mixtures with up to 50 – 70 mol % CH_4 (or other low-boiling point gases).

Homogenisation of the carbonic phase ($T_{h,carb}$) is to liquid at values that indicate a relatively narrow range of carbonic phase molar volume ($m_{v,carb}$ = 60 – 80 cm^3). As is consistent with the bulk inclusion compositions, $T_{h,total}$ ranges from 250 – 370 ºC. As there is no evidence for heterogeneous trapping, these are minimum values for the temperature of entrapment. Typical inclusion isochores are at 1.0 – 2.5 kbar at the minimum temperatures of entrapment (250 – 370 ºC), and at 2.5 – 4 kbar at granite minimum melt temperatures (650 – 700 ºC).

A correlation was noted between a minor degree of recrystallisation of host quartz and aquo-carbonic fluid inclusion assemblages with large variations of inclusion degree of filling at room temperature. From this observation, it is suggested that previous studies have overlooked effects of post-entrapment fluid inclusion re-equilibration and have mis-interpreted heterogeneous fluid trapping (e.g. at Fort Knox) from these assemblages (cf. McCoy et al., 1997).

No highly saline inclusions were found in this study, although it is noted that they were reported from some small lode-gold deposits in the TGP in earlier studies (e.g. McCoy et al., 1997).

Location	Sample nos	Incl. timing	Fluid system	$T_{m,CO2}$	$T_{m,ice}$	$T_{m,clath}$	$T_{h,CO2}$ (→ L)	$T_{h,total}$ (→ L)	Salinity	$X_{CH4,carb}$	$m_{v,carb}$
									eq wt% NaCl		cm^3
Cleary Hill	CH06-1	p									
Cleary Summit	CS06-3	ps	aq.		-1.1			265	1.9		
		ps	aq.		-6.1				9.3		
		ps	aq.-carb.	-60.1		6.4	28.6	283	5.9	0.1	-
		p	aq.-carb.	-62.2		5.9	27.9	279	6.6	0.35	-
		ps?	aq.-carb. (±solids)	-63.7		2.8	15.1	353	10.7	0.4	-
	CS07-3	ps	aq.-carb								
Ester Dome	ED06-5C	ps	aq.-carb.	-66.4		8.7	27.9	331	2.2	0.6	65
		ps	aq.-carb.	-58.3		11.0	21.1	313		0.06	65
Fort Knox	FK06-1	ps	aq.-carb.								
	FK06-2	ps	aq.		-4.0						
	FK06-4	ps	aq.-carb.			7.7					
Gilmore Dome	GD06-9	ps	aq.-carb.	-56.8		5.9	26.5	308	6.6	0.01	75
		ps	aq.-carb.	-59.7		7.6	18.6	308	4.0	0.1	68
		ps	aq.-carb.	-59.6		8.1	21.5	307	3.2	0.1	75
		ps	aq.-carb.	-58.9		7.8	20.5	308	3.7	0.07	80
		p	aq.-carb.	-57.2		8.3	25.6		2.9	0.02	72
		p	aq.-carb.	-59.8		7.8	19.7		3.7	0.12	-
		s	aq.		-1.3			159	2.1		
	GD06-12	s	aq.		-0.6			202	1.1		
		ps	aq.-carb.	-57.6		7.5	23.4	375	4.2	0.03	68
	GD07-6		aq.-carb.								
Golden Summit	GS06-49	p	aq.-carb.								
Pogo	PG07-4	ps	aq.		-5.7						
		ps	aq.-carb.	-56.6		8.0	18.6			0	56
	PG07-19	ps	aq.-carb.	-58.3		9.1	17.1			0.05	60
		ps	aq.-carb.	-58.9		8.1	18.0			0.07	70
		ps	aq.-carb.	-58.4		9.0	19.8-23			0.06	78
		ps	aq.-carb.	-56.9		9.0	21-23			0.01	60
	PG07-22	ps	aq.-carb.	-65.0		15-16.9	-30.0			0.5	58
		ps	aq.-carb.	-68.0		20.0	-4.8			0.75	-
		ps	aq.-carb.	-66.3		-5.0	-14.0			0.6	-
Ryan Lode	RL06-10	s	aq.		-1.3			130	2.2		
		ps	aq.		-5.7			301	8.8		
Tolovana	TV06-6C	ps	aq.		-2.3			288			
		ps	aq.-carb.	-58.7		7.8	29.9	300	3.7	0.08	-

Table 2. Summary of fluid inclusion petrographic and microthermometric data. Data from distinct inclusion assemblages is separated where appropriate. Abbreviations: p, primary; ps, pseudosecondary; s, secondary; aq., low- to moderate salinity aqueous; aq.-carb., aquo-carbonic.

MULTI ELEMENT COMPOSITIONS OF FLUID INCLUSIONS

Laser-ablation (LA-ICP-MS) analysis was concentrated on inclusions interpreted as primary and pseudosecondary. In most samples these are aquo-carbonic inclusions that are volumetrically dominated by the aqueous phase and have salinity between 3 and 10 wt. % eq. NaCl. Summary tables of the analyses are presented in Appendix B. Because of the narrow range of salinities, and for ease of comparison between samples, elemental concentrations are reported assuming a salinity of 7.9 wt % eq NaCl.

The majority of elements analysed were below Limits of Detection (reported at 3σ) in the majority of inclusions. A larger number of elements were reliably detected in a few large inclusions, and concentrations determined for these inclusions are assumed to be indicative of the sample.

With respect to many parameters, the results show a remarkable uniformity of inclusion compositions in the whole suite, regardless of whether inclusions are in igneous quartz, in veins in igneous rocks, or in veins in metamorphic hostrocks, and regardless of whether the samples are within or distant to gold deposits. Within the overall uniformity, analytically significant compositional differences were determined for fluid inclusion assemblages of apparently similar paragenetic relations, both in individual samples and amongst sets of samples from a single vein or vein system.

Major elements

Na – all analysed inclusions are Na dominated (> 60 % of summed cations by weight).

K – is generally as the second most abundant cation with concentrations from 1000 – 10000 ppm. The highest K contents are in a granite-hosted pegmatitic aplite (Gilmore Dome) and in some inclusion assemblages in relative thick quartz veins of two metamorphic hosted gold deposits (Ryan Lode and Tolovana).

Ca – this element is poorly quantified in low-salinity inclusions because of high limits of detection. Concentrations range from 150 to > 3000 ppm, hence one to two orders of magnitude lower than Na.

Fe, Mn – quantified analyses range from about 25 to 2000 ppm for Fe and 25 to 1000 ppm for Mn. The concentrations in many samples are below detection, and in most cases can be constrained to < 100 ppm for both elements. The lower end of concentrations is indicated for most assemblages, with higher concentrations being a feature of a distinct but minor fluid that was present at some localities, including Au-bearing fissure veins in metamorphic rocks (Cleary Summit), in shear-zone hosted Au-quartz veins (Pogo), and in pegmatitic aplite at Gilmore Dome.

Cu – concentrations can be constrained to < 100 ppm in almost all samples, with quantified concentrations of 20 – 30 ppm in large inclusions. The only exceptions are a small number of inclusions at Pogo with concentrations of up to about 3000 ppm in association with relatively high Fe contents.

Zn, Pb – these elements have generally similar order of magnitude concentrations, and both range widely, from about 20 ppm to > 1000 ppm. It is noted that the full range of concentrations that are recorded regionally is present within single samples from both a fissure vein (Cleary Summit) and from a Au-quartz vein in higher metamorphic grade hostrocks (Pogo).

Trace elements

B – is a significant component in inclusions in all samples in which it was analysed, and ranges from 200 – 3000 ppm.

Li – is reported as a significant component in the fluid inclusion analyses, but inspection of time traces demonstrates that the reported fluid concentrations are artefacts of ppm level concentrations in host quartz. Fluid concentrations are estimated to be < 100 ppm.

As – is likewise reported as a significant component in inclusions in most samples, but care was needed to differentiate a component in quartz from a component in the fluids. Fluid concentrations are determined to be mostly in the range 50 – 500 ppm, with no clear correlation between concentration and setting.

Mo – where detected, concentrations are in the range of 2 – 8 ppm, irrespective of sample setting.

Ag – was detected in some samples in the range 2 – 10 ppm. Significantly higher concentration of up to 100 ppm, correlated with higher Fe, Pb etc, are implied in some inclusion assemblages at Cleary Summit.

Sn – was detected only in a few inclusions at Cleary Summit (≈ 5 ppm) and in pegmatitic aplite from Gilmore Dome (< 20 ppm).

Sb – is detected and quantifiable at all localities except for inclusions in fissure veins at Cleary Hill, in which extremely high concentrations are present in the host quartz. Fluid concentrations range from 5 – 300 ppm, possibly as high as 2000 ppm, with the majority in the range of 30 – 90 ppm.

W – is detected in the range of a few ppm in a small number of samples, the highest concentrations of about 7 ppm being in a pegmatitic aplite from Gilmore Dome.

Tl – concentrations of 1 – 2 ppm are indicated in large inclusions from a variety of quartz veins in the gold deposits.

Bi – concentrations of up to a few ppm are detected in a number of samples, with the highest concentrations (< 20 ppm) in fluids in the granitoid-hosted Fort Knox deposit.

Lithophile element ratios

The ratio of Na/K is of interest because of its potential as a geothermometer. If the fluid equilibrated with two feldspars, this ratio should be a function of temperature, with lower ratios at higher T (Orville, 1963; Rusk et al., 2004). Molar Na/K ratios range from 2-3 to about 50, with the lowest ratios in inclusions in pegmatitic aplite from the Gilmore Dome stock, and also in some assemblages in thicker quartz veins in metamorphic host rocks (Ryan Lode and Tolovana). The higher ratios are recorded both in Au-quartz veins in metamorphic host rocks (e.g. Cleary Summit) and in quartz vein swarms in sericite altered granitoid (Ester Dome).

Ratios of the lithophile elements (K – Rb – Cs – Ba – Sr), are of interest as they are conservative in hydrothermal systems as a result of the very limited relative fractionation in common mineral-fluid reactions (e.g. Kerrich and Fryer, 1988). The ratios can be indicators of fluid source rock, in particular of fractionated granitic sources (e.g. Audetat et al., 2008). The minor lithophile elements were detected in inclusions in a minority of samples, and ratios can thus be determined for these fluids. K:Cs and K:Ba are significantly lower than average crustal values at some localities (e.g. K:Cs of 20 – 30 in the fissure vein at Cleary Summit and in metamorphic-rock hosted veins at Pogo). K:Rb varies from values close to average crust (300, e.g Gilmore Dome pegmatitic aplite) to significantly lower values (70 – 100, e.g. Cleary Summit).

TRACE ELEMENT COMPOSITIONS OF VEIN QUARTZ

Partial vein quartz compositions determined from LA-ICP-MS analyses are summarised in Appendix C. Time traces of laser ablation analyses were checked to confirm the absence of spikes which would be indicative of sub-microscopic fluid or solid inclusions, but a component from scattered small dilute fluid inclusions can not be ruled out. Of interest are contents of:

Li - which is uniformly present in all quartz analysed at concentrations of 4 – 50 ppm.
Na - at a few ppm, variably from < 1 – 15 ppm.
Fe, Zn - detected at ppm levels in a few samples.
As - detected in the majority of quartz samples, most typically at approximately 1 ppm, but at up to 10 ppm in fissure fill quartz at Cleary Summit.
Sb - similarly to As, detected in the majority of quartz samples at approximately 1 ppm concentration, but with significantly higher concentrations (< 30 ppm) in some fissure fill quartz.
Pb - detected at concentrations of order 0.1 ppm in many samples, but concentrations to 3 ppm in fissure fill quartz that hosts high concentrations of As and Sb.

Lanthanum "spikes", one or two magnet scans in time length, were detected during inclusion ablation, or more rarely during ablation of quartz distant from fluid inclusions. These spikes were commonly recorded in many samples, in both vein and igneous quartz. They are interpreted to be the result of submicron sized solid inclusions of La-rich minerals, and although co-incident Y and Ce spikes are rarely recorded, La-allanite is provisionally interpreted as the source of the spikes.

SULFIDE AND METALLIC INCLUSIONS

The presence locally of solid metallic inclusions in quartz veins in the Fort Knox intrusion related gold deposit was described by Ridley and Gibson (2008). These inclusions have textures and sizes similar to the aquo-carbonic fluid inclusions in the host quartz, and in some cases share inclusion planes with the aquo-carbonic inclusions. Combined LA-ICP-MS and SEM analysis shows the solid inclusions to be composed of dominantly Bi (> 99% by weight) with measurable concentrations of Sb (220 ppm), As (400 ppm) and Au (40 ppm). In addition they include detectable Pb, Fe, Mo and Sn. SEM imaging shows them to be fine-grained intergrowths of crystalline bismuth.

DISCUSSION AND PRELIMINARY INTERPRETATION OF RESULTS

Comparison of fluid inclusion compositions with those of inclusions from well characterised settings world wide

A comparison of major components and multi-element compositions of the Tintina Gold Belt samples is made against reported compositions of the following types of low- to moderate salinity fluids:

(a) Magmatohydrothermal fluids – the compilation of analyses of fluids in ore-related quartz veins (Cu, Mo, Sn-W, REE-U) and in quartz in miarolitic cavities in both barren and ore-associated granitoids of Audetat et al. (2008), and additional analyses reported in Rusk et al (2004), Yardley (2005) and Klemm et al. (2008).

(b) Aquo-carbonic fluids from a typical orogenic gold deposit of the European Alps (Yardley et al., 1993).

(c) Fluids in sedimentary basins and in low-temperature metamorphic terrains reported in Yardley (2005).

<u>Comparisons with magmatohydrothermal fluids</u>

Magmatohydrothermal fluids for which analyses are available are mainly from shallow-level (e.g. porphyry) intrusive centres. The fluids in these settings are aqueous without a separate carbonic phase, although a minor carbonic component is indicated by clathrate formation during inclusion freezing experiments at some localities (e.g. Klemm et al., 2008).

Boron and As have similar ranges of concentrations in fluids in the TGP as recorded in low- to moderate salinity magmatohydrothermal fluids. The lower end of the range of fluid Na/K ratios are similar to those at porphyry deposits, as is expected for fluids that equilibrated with wallrock at magmatic or near magmatic temperatures. Higher ratios were however recorded in this study in Au-ore granite hosted veins which are interpreted as having formed at relatively high temperature. It is suggested (following Yardley et al., 2007), that anions other than chloride (e.g. bicarbonate) may have a significant affect on Na/K equilibrium ratios of some geological fluids.

The concentrations of Pb, Zn, Mo, W, and Bi in the TGP are similar to the lower ends of the large ranges reported for magmatohydrothermal fluids. Although all of these commodities are present in at least some of the ores in the TGP, it is clear from this comparison that no fluids have been analysed in the TGP that are unusually strongly enriched in any of these elements.

The works of Audetat et al. (2008) and Klemm et al. (2008) have demonstrated that there can be orders of magnitude variation in fluid Cs and Rb concentrations at different stages of the magmatohydrothermal evolution of a single magmatic centre, as a result of magmatic fractionation. By analogy with these works, the Cs and Rb contents in the TGP fluids allow inference of at most moderate degrees of fractionation in the Alaskan magmatic systems.

The most significant differences of all TGP fluids compared to reported magmatohydrothermal fluids are the lower concentrations (by at least one order of magnitude) of Mn, Fe and Cu. Iron and Cu have both been reported as the dominant cation in some fluids at porphyry copper deposits. It is noted, however, that high-temperature aquo-carbonic fluids in pegmatitic quartz reported by Yardley (2005) show similarly low concentrations of these elements.

Comparisons with fluids of an orogenic gold deposit

There are close similarities with respect to most parameters (bulk components and elemental compositions) of the TGP fluids with the aquo-carbonic fluids analysed from the Brusson deposit (Italy) by Yardley et al. (1993). Of particular note are the similarities of relatively elevated B and As, and of relatively low concentrations of Mn, Fe and Cu. The Na/K ratios at Brusson are similar to those of fluids in most Au-quartz veins in the TGP which can be inferred to have formed at lower-greenschist facies temperatures. The most prominent differences between the two sets of data are the lower Pb and Zn concentrations in the fluids at Brusson. In this respect it is noted that the Brusson deposits are Au-only, and lack either elevated concentrations of the base metals or base metal bearing sulfide minerals, as are present in many deposits in the TGP.

Comparisons with sedimentary and low-grade metamorphic fluids

Most reported analyses of fluids from these two environments are of high-salinity brines, and are hence of little comparative value here. Almost all analysed fluids of low- to moderate salinity from sedimentary basins are aqueous, and have significantly higher Ca contents (1000's ppm), and significantly lower contents of Mn, Fe, Zn and Pb (as low as sub ppm concentrations) than the TGP fluids. In addition they have lower Na/K ratios, as expected from equilibration at basinal temperatures.

Yardley (2005, from Meere and Banks, 1997) presented multi-element compositional data of moderate salinity aqueous fluid inclusions in syn-deformational veins in a sub-greenschist-facies clastic metasedimentary terrain. Most components in the fluids are of similar concentrations as recorded in the TGP. The most significant exception is Ca (and Sr), which is at order of magnitude higher concentrations. It is noted, however, that halogen ratios indicate that the fluids analysed by Meere and Banks (1997) were modified seawater (connate fluids?) rather than fluids derived through metamorphic devolatilisation reactions.

What hydrothermal ore fluids were present in the Tintina gold province during the mid-Cretaceous time period of gold mineralization?

The results of this project imply that all fluids that circulated in the TGP at the time of mid- to late-Cretaceous gold mineralisation can be considered to belong to a single compositional suite. The dominant primary and pseudosecondary fluid inclusions in veins in all settings are low- to moderate-salinity aquo-carbonic fluids. Some aqueous fluids of similar salinity were present. The ratios of the major elements (Na > K > Ca, Mn, Fe) are consistent in all fluids, both aqueous and aquo-carbonic. A distinct suite of trace elements (B, As, Sb, Pb) is present at high concentrations relative to crustal abundances. Where these elements are not detected in the fluid inclusions, they are present at elevated concentrations in vein quartz.

Implication for gold mineralisation models and prospectivity in the Tintina gold province

The dominance of low- to moderate salinity aquo-carbonic fluids and the uniformity of their compositions in hydrothermal systems of post-metamorphic, syn-intrusion (104 – 88 Ma) age in the TGP, irrespective of setting and distance from co-eval intrusions is consistent with the IRGD model for the terrain. The suite of elements that can be considered enriched in the fluids (relative to crustal abundance ratios) overlaps the suite of elements at high concentrations within one or more of the different ore types of the Province (As, Sb, Bi, Pb, Zn, Ag, W, Mo).

There is some support in the fluid compositional data for zoned ore fields. For instance, the concentrations of Sb and As are as high in fluids at the granite hosted Fort Knox deposit (despite low contents of these metals in the ore) than in fluids in Sb-As rich fissure veins in metamorphic hostrocks that are proposed to be distal ores. Conversely, fluid concentrations of Bi are highest at Fort Knox. This element is enriched in ore at Fort Knox, but is not recorded in the proposed distal deposits.

Within the context of an IRGD ore system, the variability of fluid compositions at single localities implies temporal evolution of fluid composition within the hydrothermal systems. The variable K:Cs ratios of the inclusion assemblages imply that fluids may have originated at different stages of magmatic fractionation.

Support for the IRGD model would be strengthened if the low Mn, Fe and Cu contents of the fluids could be reconciled with a magamtohydrothermal origin. Iron is critical in this respect in that significantly higher fluid concentrations of Fe in equilibrium with Fe-bearing magmatic minerals have been measured in experimental studies (e.g. Simon et al., 2004). In addition, the likelihood of ore formation in the context of limited fractionation of source plutons, compared to the extreme fractionation recorded in porphyry style ore systems (e.g. Audetat et al., 2008), needs to be addressed.

The results of this project would, however, be reconcilable with proposals for multiple (magmatic and metamorphic) gold-ore fluid sources in the terrain (Goldfarb et al., 2005), if the distinct geochemical signature of the fluids could be defined as a regional geochemical signature that was imposed by terrain architecture. Fluids derived through metamorphic devolatilisation will carry geochemical signatures of their, presumed crustal, source rocks. Magmatohydrothermal fluids can carry signatures of crustal components incorporated into the magmas. Based on a combination of Pb, Nd, Sr and O isotope systems, Aleinikoff et al (2000) proposed that the Cretaceous granitoids of the terrain were derived from the Paleozoic country rocks (the same country rocks that are potential sources of metamorphic fluids) and an admixed non-radiogenic source, most likely either mantle or mafic crustal rocks. This project has defined a suite of trace elements that is enriched in the hydrothermal systems of the province. A study of mass balance and the behaviour of this element suite, both in the Cretaceous magmatic systems and during metamorphism of the Paleozoic country rock, might provide support to the model of proposed multiple ore fluid sources.

Publications resulting from this award

Ridley J and Gibson J, 2008, Au-bearing Bi-Sb melt (?) inclusions in vein quartz at the Fort Knox Intrusions Related Gold deposit, Alaska. In HE Belkin (ed), Ninth Pan-American Conference of Research on Fluid Inclusions, Program and Abstract, June 22-5 2008, USGS Reston VA, p 51.
(copy attached in Appendix D).

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Appendix A: Quantification strategy for LA-ICP-MS analysis of fluid inclusions

Data reduction used AMS software (http://www.geochem.geos.vt.edu/fluids/laicpms/images/PosterWeb.pdf). Following established procedures, the quantification of LA-ICP-MS fluid inclusion analyses used estimates of total salinity (expressed as wt % eq. NaCl) that had been determined by microthermometry. The interval of inclusion ablation was estimated from inspection of time traces of element counts.

Typically six to eight inclusions from a fluid inclusion assemblage were analysed to enable improved confidence in the detection and quantification of elements near detection limits.

To date there have been few systematic studies of the compositions of relatively low salinity fluids inclusions using LA-ICP-MS. In addition to known complexities that affect LA-ICP-MS fluid inclusion analyses (sub-microscopic to microscopic solid inclusions, statistical integration over limited numbers of element scans), unexpected difficulties were encountered in this study from:

- Contamination from surfaces of the polished thin section. This source of contamination was in particular apparent in samples with high modal contents of sulfides or secondary hydroxide and oxide minerals
- Analytical interference from trace (ppm) levels of elements of critical interest in the host quartz, in particular Li, B, Fe, As, and Sb. The present analytical and data reduction protocols do not provide a routine method to separate these components. The technique adopted here is: (1) Reduction using blank background. This is equivalent to assuming quartz contains only SiO_2; (2) Visual inspection of time traces of element counts to assess confidence in the calculated trace-element concentrations of inclusions, (3) In cases where inspection indicated that a trace element is present in host quartz, recalculation of the fluid inclusion composition using analysis of adjacent quartz as background. This procedure leads is not ideal as it leads to higher than necessary limits of detection.

Appendix B

Fluid inclusion Laser-Ablation ICP-MS analyses.

The attached Excel file (AppendixB.xls) gives representative single fluid inclusion analyses of each sample. The analyses in this file have been chosen as example analyses that are largely free of interference from surface contamination and from simultaneous ablation of solid inclusions in the host quartz, and are therefore representative of the best analyses obtained. Each analysis is given two columns. The first column is the calculated composition in ppm. (The symbol '-' indicates a value below the limit of detection). The figures in the second column (in italics) give the limits of detection for each element in that analysis.

The rows at the top of each Table are:
1. Sample number – see Tables 1 and 2 for locality and microthermometric data on the inclusions.
2. Fluid inclusion salinity assumed for normalisation.
3. The inclusion number is given in the form: 'chip' (=fragment of thin section)-assemblage-number of inclusion in assemblage, e.g. 1-b-2. A slash '/' after the number indicates that multiple trials were made of data reduction.
4. Na(cps) = the average counts per second of Na over the inclusion time interval of inclusion ablation. This, in combination with the time period of signal integration, is a measure of the volume of the inclusion, and hence of the quality of the analysis.
5. The time period of integration in seconds of the ICP-MS signal over which calculation of inclusion composition was made.

Rows in the data tables that are blank indicate that this element was not analysed for this sample.

Appendix C

Laser-Ablation ICP-MS analyses of host quartz of inclusions.

Excel file (AppendixC.xls) gives representative multi-element analyses of host quartz from ten of the analysed samples. The quartz analyses were of the same element suite as fluid inclusions. Each analysis is given two columns. The first column is the calculated elemental composition in ppm. (The symbol '-' indicates a value below the limit of detection). The figures in the second column (in italics) give the limits of detection for each element in that analysis.

Rows in the data tables that are blank indicate that this element was not analysed for this sample.

Appendix D
Copy of:
Ridley J and Gibson J, 2008, Au-bearing Bi-Sb melt (?) inclusions in vein quartz at the Fort Knox Intrusions Related Gold deposit, Alaska. In HE Belkin (ed), Ninth Pan-American Conference of Research on Fluid Inclusions, Program and Abstract, June 22-5 2008, USGS Reston VA, p 51.

Au-bearing Bi-Sb melt (?) inclusions in quartz veins at the Fort Knox Intrusion Related Gold Deposit, Alaska

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Fort Knox in interior Alaska is a type example of a RIRG (Reduced Intrusion Related) gold deposit. Gold mineralisation, with associated concentrations of Bi, W, Mo etc, is in and along rims of sheeted to stockwork narrow quartz and quartz-K-feldspar (‘pegmatitic’) veins in the cupola of a mid-Cretaceous granodiorite to granite stock that intruded at a late stage of regional metamorphism into the Fairbanks Schists. A close timing and genetic relationship between the host granitic suite and mineralisation is argued from a number of lines of evidence: There is no pervasive hydrothermal alteration in the stock, but weakly developed potassic to phyllic haloes around quartz veins; Zircon U-Pb ages of the stock are indistinguishable from Re-Os in molybdenite ages of samples from the Au-mineralised veins.

Earlier works determined that fluid inclusions in the mineralised quartz veins are dominantly low to medium salinity aqueous-carbonic fluids, with overall characteristics similar to the interpreted ore fluids of orogenic gold deposits. Here we report on the local presence of a second ‘fluid’ phase in the veins of the deposit. This phase is preserved in opaque, now solid inclusions in quartz of quartz – K-feldspar veins. The inclusions are sub-rounded to negative crystal in shape, of a same range of sizes as the fluid inclusions (< 20 μm), and occur in planes with petrogenetic relations indistinguishable from those of the aqueous-carbonic inclusions. Some inclusions have co-entrapped small amounts of a transparent low-relief liquid, presumably the aqueous-carbonic fluid. The opaque inclusions are homogeneous in reflected light with high reflectivity. LA-ICP-MS analyses show the inclusions to be Bi-Sb dominated, with Au at concentrations of order 10’s of ppm.

The inclusion composition is consistent with being a melt at likely temperatures of vein formation of above about 500 ºC, and the inclusions are thus interpreted as being solidified Au-bearing Bi-Sb rich melt that was present in the vein space during the main stage of gold mineralisation, potentially sharing the vein space with aqueous-carbonic fluid. Most gold in the deposit is free milling, but Au-bearing Bi rich alloys were reported from associated placer workings. Hanley et al. (2007) have argued for the importance of a Fe-S melt phase within the

host granite during its crystallisation. An Au-bearing Bi-Sb melt may have exsolved directly from the granite, or indirectly, through fractionation of a sulfide melt phase. However, it is also feasible that the melt was produced within the deposit as a 'remelt' of hydrothermally precipitated sulfides. In either case, the melt would have been a carrier for gold in the magmato-hydrothermal system, and its formation may explain some of the distinct geochemical features of gold ore at the Fort Knox deposit.

Hanley JJ, Spooner ETC, Hart CJ, Heinrich CA and Guillong M, 2007, Evidence for sulfide melt oxidation and metal-rich aqueous-carbonic fluid exsolution in the intrusion-related Au system at Fort Knox. ECROFI Abstract Volume, p 66.