TAG: Thermal Aureole (pluton- related) Gold systems

V. J. Wall (Presented by Greg Hall)

Introduction

Gold deposits accorded giant status in view of their tonnage-grade characteristics occur in a variety of geological environments. These associations are commonly termed "epithermal", "porphyry", "Carlin" and "orogenic", etc. Although links between felsic plutonism and some large gold deposits have long been recognised in Eastern Block literature (eg, Moravek, 1979), the significance of a distinctive class of pluton-related gold deposits is less appreciated in the West (cf. Sillitoe & Thompson, 1998; Groves and others, 2003). This article examines the nature and evolution of thermal aureole gold (TAG; pluton-related) ore-forming systems and key factors in the localisation of some giant deposits in such systems. As the forerunner to a more comprehensive manuscript it is short on detail and long on assertion.

The TAG Association

TAG deposits (Wall, 1989; Wall & Taylor, 1990; Wall, 1999) are localised in the roof zones and tops of felsic plutons and are temporally related to the emplacement and cooling of such plutons (Figure1).

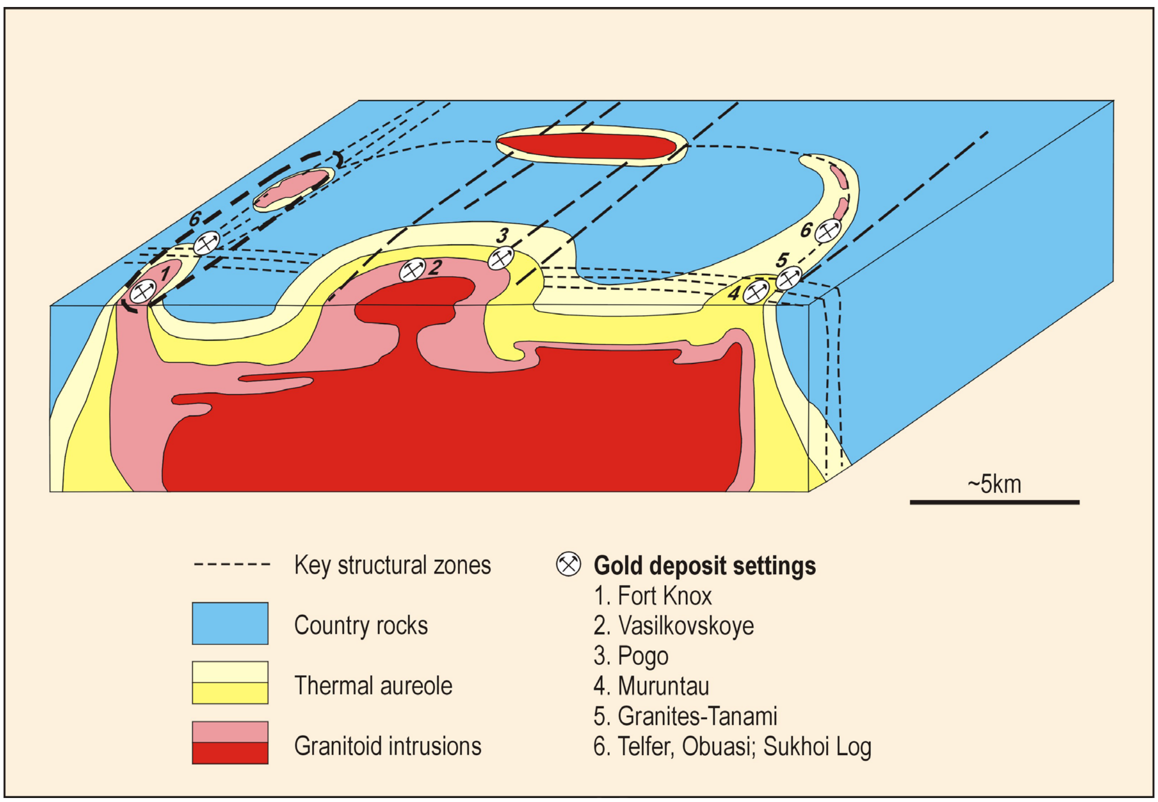


Figure 1 Conceptual 3D geological model for TAG systems showing the locations of some major gold deposits in the roof zone thermal aureoles and tops of granitoid plutons.

TAG deposits comprise vein networks and/or disseminations as well as replacements in reactive rocks. Vein mineralogies and alteration assemblages range from high temperature (pluton proximal) parageneses to relatively low temperature – the latter reflecting pluton-distal or retrograde thermal metamorphic environments.

The key evidence for the association of TAG deposits with felsic plutonism and related thermal metamorphism includes:

- mutually cross-cutting relations of mineralisation and minor, pluton-related intrusions;
- radiometric ages of mineralisation and related alteration which overlap with those of associated plutons;
- localisation of hydrothermal mineralisation and alteration by structures active during pluton emplacement and cooling (eg Matthai et al., 1995). These structures postdate and/or commonly reactivate structures developed during regional deformation. Associated plutons are typically late- or post orogenic, emplaced after the bulk of regional deformation-related strain;
- hydrothermal alteration and vein mineral assemblages and fabrics ranging from low to high temperature and consistent with the thermal metamorphic grade of their hosts during mineralisation (eg Matthai et al., 1995);
- systematic mineralogical and geochemical zoning patterns (eg in Bi, As, Sb, W, Sn and base metals) of mineralisation and related alteration, focused on temporally and spatially associated plutons (Wall, 1989).

TAG systems form in environments which are distinct from, but may be transitional to, those characteristic of "epithermal-", "porphyry-", "orogenic-" and "Carlin-style" gold, and overlap with iron oxide copper-gold associations, viz:

- the tops and roof zones of plutons which were typically at depths of 5-10km during TAG mineralisation (eg Matthai et al., 1995; Kotov and Poritskaya, 1992;). These settings are substantially deeper than the epithermal environment, but may overlap with the roots of porphyry systems. The depths at which TAG systems operate have significant consequences with regard to thermal gradients, mechanical conditions and fluid processes attending mineralisation, which contrast with those of epithermal and porphyry environments.
- TAG deposits exhibit a broader range of magmatic affiliations (ranging from ilmenite series "S" and "I" type to magnetite series felsic plutonism) than the high-temperature, oxidised magmas with which porphyry copper-gold (Burnham & Ohmoto, 1980) and iron oxide copper-gold systems (Wall and Gow, 1995) are associated. TAG systems are more common in belts floored by sialic crust than in less evolved magmatic arcs.
- some pluton-distal TAG occurrences resemble Carlin-style deposits, but most formed at higher temperatures and may lack the Carlin-style geochemical signature. TAG deposits do occur in extensional settings, but are most common in compressional fold belts.
- unlike some mesothermal or "orogenic" gold associations (eg slate belt styles: Cox et al., 1991), TAG mineralisation is associated in time and space with plutonism which postdated or was late in regional deformation and metamorphism histories. However there may be substantial overlap of plutonism and regional deformation/metamorphism.

Pluton-distal TAG deposits may be difficult to recognize as such because of equivocal characteristics and timing relations, and commonly have been grouped with 'orogenic' gold deposits.

TAG Distribution

Defined as above, the TAG association is broadly distributed in space and time, examples ranging from Archaean (Brisbin, 2000) through the Phanerozoic (eg Thompson and others, 1999) and is (arguably) represented in a number of significant auriferous belts. These host several giant and numerous large (>5Moz contained gold) deposits. Table 1 is a far from comprehensive list of deposits for which there is evidence of TAG affinities.

Table 1: Some examples of TAG deposits

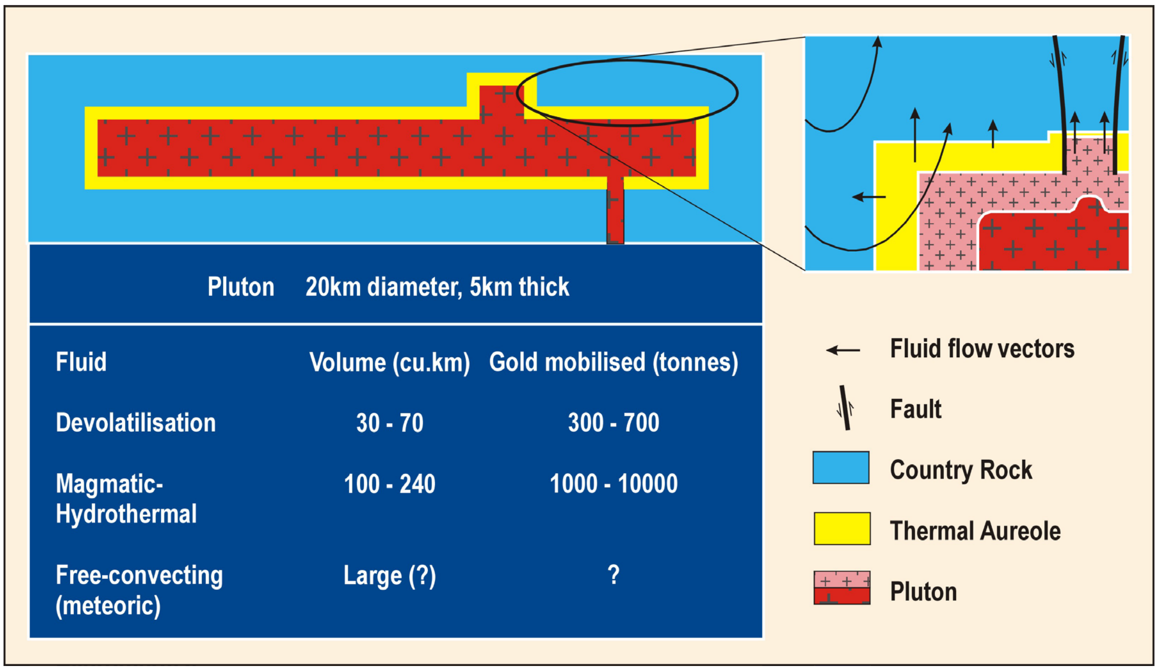
Deposit	Location	Age	Host Rocks	Gold Resource and Comments
Fort Knox	Alaska	Cretaceous	granitoids	>5.6Moz; pluton margin hosted
Pogo	Alaska	Cretaceous	gneisses	5.7Moz @ 17.8g//t; pluton proximal
Muruntau	Uzbekistan	Permian	metasediments	>100Moz @ 2-3g/t; medium temperature mineralisation
Kumtor	Kyrgyzstan	Permian	metasediments	9.3Moz @ 3.6g/t; pluton distal
Vasilkovskoye	Kazakhstan	Early Palaeozoic	granitoids	13.3Moz @ 3g/t; pluton margin hosted
Telfer	Australia	Late Proterozoic	mainly metasediments	>31Moz; pluton distal
Granites-Tanami	Australia	Early Proterozoic	metasediments	>13Moz; medium-high gold grades pluton proximal to distal
Obuasi	Ghana	Early Proterozoic	metasediments	>49Moz production + resources; pluton distal
Morila	Mali	Early Proterozoic	metasediments	>7.0Moz; pluton proximal
Wallaby	Australia	Late Archaean	metasediments	7Moz; pluton distal
Campbell-Red Lake	Canada	Late Archaean	mafics-ultramafics	>25Moz @ >15g/t; pluton proximal

Host terranes vary from Achaean granite-greenstone to Mesozoic, metasediment-dominated fold-thrust belts. Examples include large, bulk mineable and also high grade resources. TAG deposits contain a significant proportion of the World's gold inventory. For example, it has been estimated (Krivtsov et al., 1992) that metasediment-hosted, but pluton-related, and pluton-hosted deposits in the former Soviet Union contain more than 500 million ounces of (C_1+C_2) gold resources. The largest TAG deposits and the bulk of TAG resources occur in pluton roof zones.

Why pluton roof environs?

The gold fertility of pluton roof zones results from:

- the large volume of hydrothermal fluids liberated by crystallisation of hydrous felsic magmas and thermal metamorphic devolatilisation, or possibly also convectively circulated by the cooling pluton which may infiltrate its roof zone (Figure 2);
- metal and ligand sources in the form of the pluton and its thermally metamorphosed envelope;
- driving forces for fluid migration – heat, fluid overpressurising, dilatancy;
- active structures, resulting from the perturbations of stress and strain patterns during pluton emplacement and cooling, that focus fluid flow (Figures 2, 3);
- a range of thermal, mechanical and chemical environments to effect ore deposition.



Fluid	Volume (cu.km)	Gold mobilised (tonnes)
Devolatilisation	30 - 70	300 - 700
Magmatic-Hydrothermal	100 - 240	1000 - 10000
Free-convecting (meteoric)	Large (?)	?

Figure 2 Simple mass balance model for fluid budgets and gold mobilisation associated with the emplacement and crystallisation of a typical sill-like pluton in metasedimentary host rocks. The model assumes magma water contents of 2.5-4 weight percent and gold contents of mobilised devolatilisation and magmatic hydrothermal fluids averaging 10-50ppb. The inset, a schematic cross section, shows preferred fluid paths, mainly through the plutons. Modified from Wall (1989).

A simple mass balance example may suffice to illustrate the gold ore-forming potential of a system comprising a typical granitoid pluton and its enveloping thermal aureole (Figure 3). This model is drawn roughly to scale and utilises dimensions, magma water contents and devolatilisation fluid balances typical of felsic pluton environments (Wall, 1989). Such models show that magmatic hydrothermal fluids will generally dominate fluid infiltration through the pluton roof zone. It may also be evident that enough hydrothermal fluid and gold are mobilised during the cooling of a typical granitoid pluton to form large, or even giant deposits. The latter, however, require efficient focusing of fluids through effective ore depositional environments in the pluton roof zone.

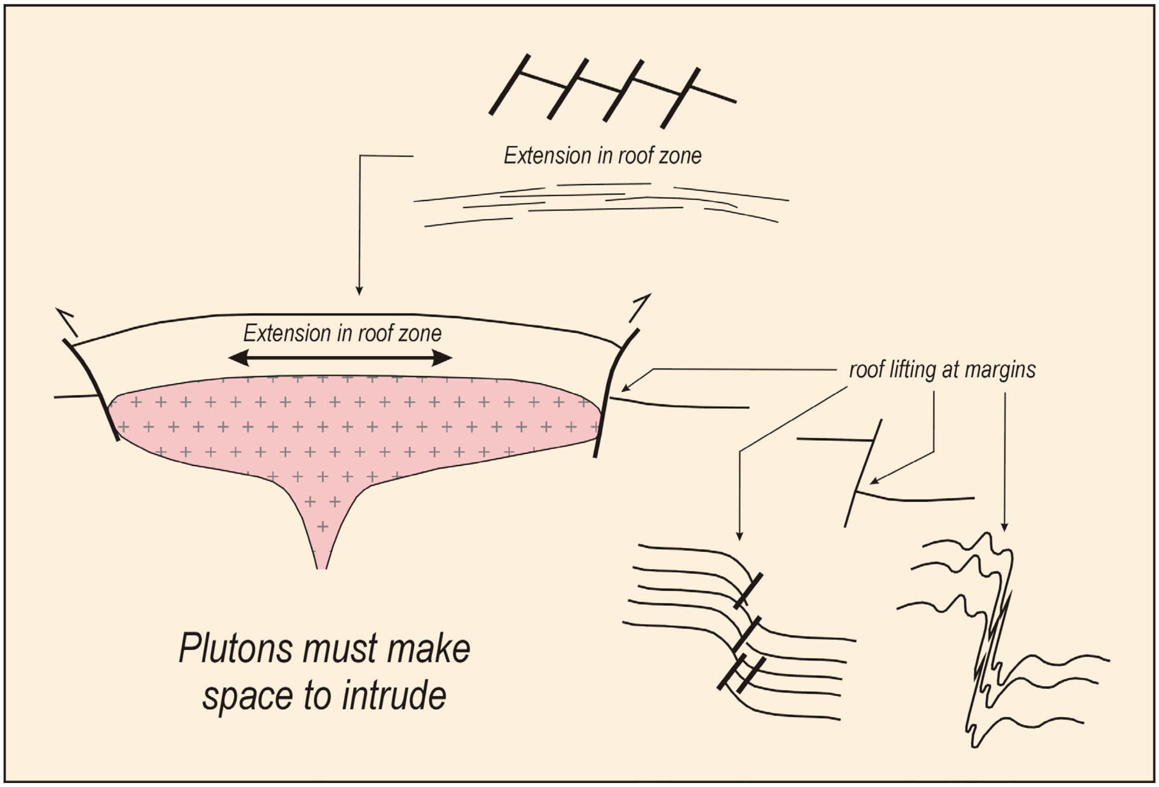


Figure 3 Cartoon showing structures formed or reactivated during pluton emplacement accommodated partly by pluton roof lifting. Such structures are commonly localised around pluton margins or apophyses and may focus fluid flow in the pluton's roof zone as well as providing dilatant zones in which gold deposits may be localised. From Valenta and Wall (1996).

Controls on TAG mineralisation

Hydrous felsic magmas liberate relatively high temperature fluids (>650-700°C) during their crystallisation. At the depths of fluid exsolution (>5-6kms, $\geq$2Kbars pressure) from magmas, and in the TAG ore-forming environment, the fluids may be supercritical and hence weakly to moderately saline (cf. porphyry copper-gold systems; eg Matthai et al., 1995). However, such fluids may contain high H_2S and/or SO_2 contents, depending on the magmatic redox conditions and temperature (Burnham and Ohmoto, 1980), and total hydrothermal fluid sulphur contents may exceed base metal contents. Gold solubilities (as chloride and/or bisulphide complexes) may be very high (ppm range: Matthai et al., 1995) under these conditions. Although the partitioning of gold between melts and aqueous fluids is a function of pressure and temperature, redox conditions, chlorinity and the sulphur content of the magma, it strongly favours the exsolved hydrothermal fluid. Some hydrothermal magmatic fluids may thus be relatively gold-rich, even when sourced from non-specialised magmas, as well as transporting other key hydrothermal components of TAG systems (Heinrich et al., 1999, 2004).

Felsic plutons are commonly of sill-like, laccolithic or lopolithic forms (eg Ameglio et al., 1997) particularly in the compressional tectonic settings of most TAG systems. Loss of magmatic hydrothermal fluid will occur mainly through the roof zone of the pluton, and may be focused through apophyses/cupolas and related structures above the main body of the pluton (Figures 1, 2). The width and thermal history of the thermal aureole enveloping the felsic pluton depends mainly on the ambient country rock temperatures, prior to pluton emplacement (Barton et al., 1991). Broad thermal aureoles (>1km wide, for minimum temperatures $\geq$300°C) characteristic of pluton emplacement depths of >5kms (confirmed by mineral assemblage stability relations) are a feature of TAG environments (e.g. Figures 1, 4a, 4b).

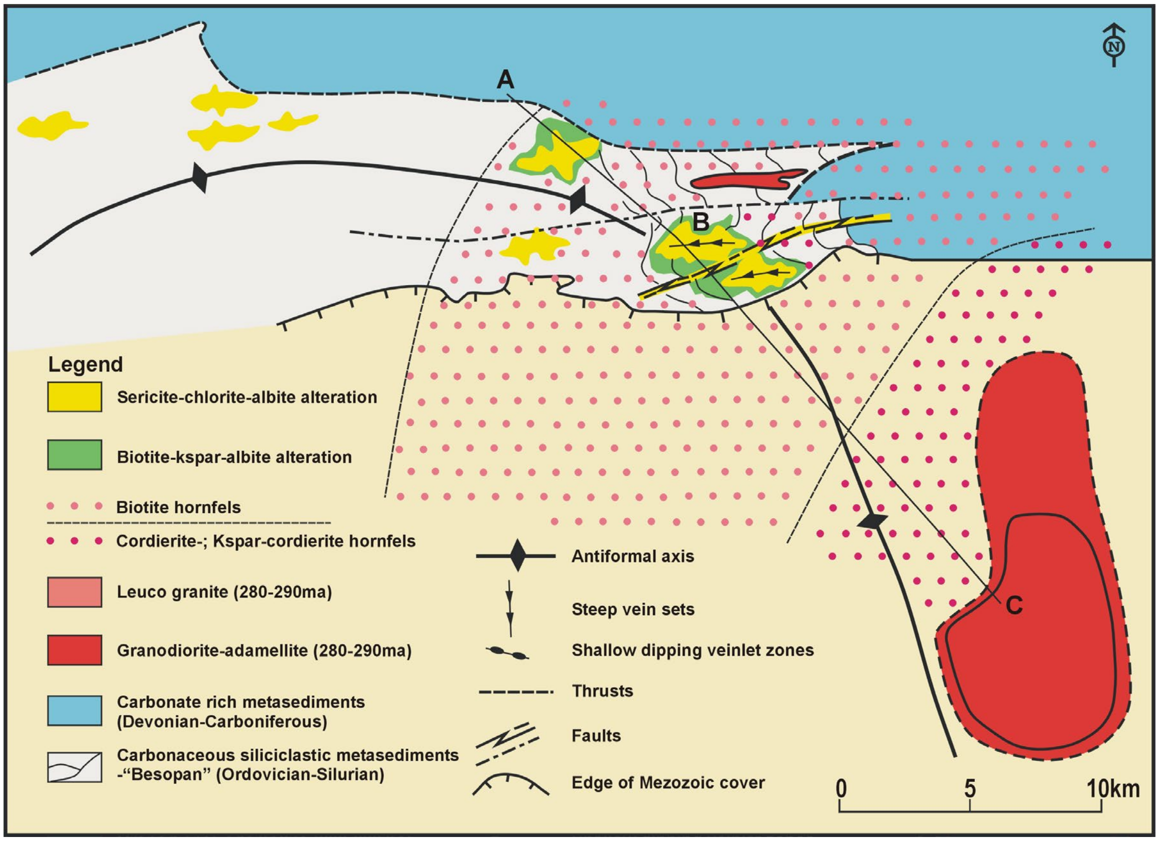


Figure 4 a) Simplified surface geology, thermal metamorphic zones and alteration in the Muruntau area, Uzbekistan. Redrawn from Kotov and Poritskaya (1992).

Because the pluton roof zones contain the largest volume of hornfelses and these zones experience the largest fluxes of hydrothermal magmatic and devolatilisation fluids, these roof zones contain the most numerous and the largest TAG deposits (Figure 1). The tops ("ceilings") of plutons are also included in TAG-forming environments, as these will be largely solid while a significant proportion of magma in the interior of the pluton continues to crystallise and liberate hydrothermal fluids through the solidified pluton carapace.

Plutons must make space to intrude (Hutton, 1997). The emplacement and inflation of sill- and laccolith-shaped plutons may involve several mechanisms including pluton roof lifting and lateral expansion which may effect (Valenta and Wall, 1995; Ameglio et al., 1997; Figure 3):

- extensional zones in the pluton roof zone;
- faulting, ductile shear zones and folding at the margins of the pluton and above pluton cupolas;
- and in some cases, radial as well as pluton-tangential faulting

The interaction of these structures and the reactivation of pre-existing fault and fold systems may produce systematically distributed zones of dilatancy and related permeability, localising fluid flow and providing space for vein formation. Figure 1 is a synopsis of the inferred setting of some major gold deposits relative to plutons and key structures/settings in which such deposits are localised.

After pluton emplacement, related stress and strain perturbations die out, marking a return to regional deformation under the influence of regional far field stresses. At this stage reactivation of pre-pluton and pluton emplacement related and/or modified structures may occur. The partly solid pluton may then become a major mechanical anisotropy even though it continues to liberate heat and hydrothermal fluid. New deposits or later phases of TAG mineralisation may develop in pluton tops, attending retrograde metamorphism in thermal aureoles and localised in different structural settings from those formed during pluton emplacement (Figure 1).

Some giant TAG deposits

Key factors in localisation of some giant TAG systems such as Muruntau (Uzbekistan: Kotov and Poritskaya, 1992; Drew et al, 1996; Wall et al, 2004) were:

- a thick succession of siliciclastic-dominated sediments which exhibits thin- and thick-bedded sedimentary packages and contains carbonaceous lutites;
- fold/thrust deformation and low grade regional metamorphism prior to felsic plutonism). Multiple deformation episodes produced multiply plunging anticlinorial zones and large areas of relatively shallow dipping foliation and bedding, with fold closures localised by the interference of belt parallel and transverse structures (Figure 4a);
- voluminous, late orogenic, hydrous, felsic plutonism involving high temperature, fractionated granitoid suites;
- emplacement of the felsic plutons as sill or laccolith-shaped bodies at depths of 5-10km, producing extensive roof zone thermal aureoles (Kotov and Poritskaya, 1992; Figure 4). The textural changes involved in hornfelsing may also significantly influence the mechanical properties of potential host rock packages and, in turn, the intensity and extents of rockmass fracturing.
- deformation accompanying pluton emplacement and reactivation of earlier formed fold-fault systems in pluton roof zones;
- deformation, post pluton emplacement but syn-pluton cooling, related to regional stress systems but localised in and around structures in the pluton roof zone. Partitioning and focusing of hydrothermal fluids by these structures (Figure 4a);
- cooling and mixing of the throughgoing auriferous hydrothermal fluids with reduced (CH_4-bearing) fluids resulting from interaction with carbonaceous metasediments.

Many other gold productive TAG systems, including the pluton-distal Telfer deposits (Goellnicht et al., 1989; Rowins et al., 1997) and others in Table 1, exhibit some essential features in common with Muruntau. Such features can be systematised into TAG exploration models useful in terranes which at first sight may appear disparate.

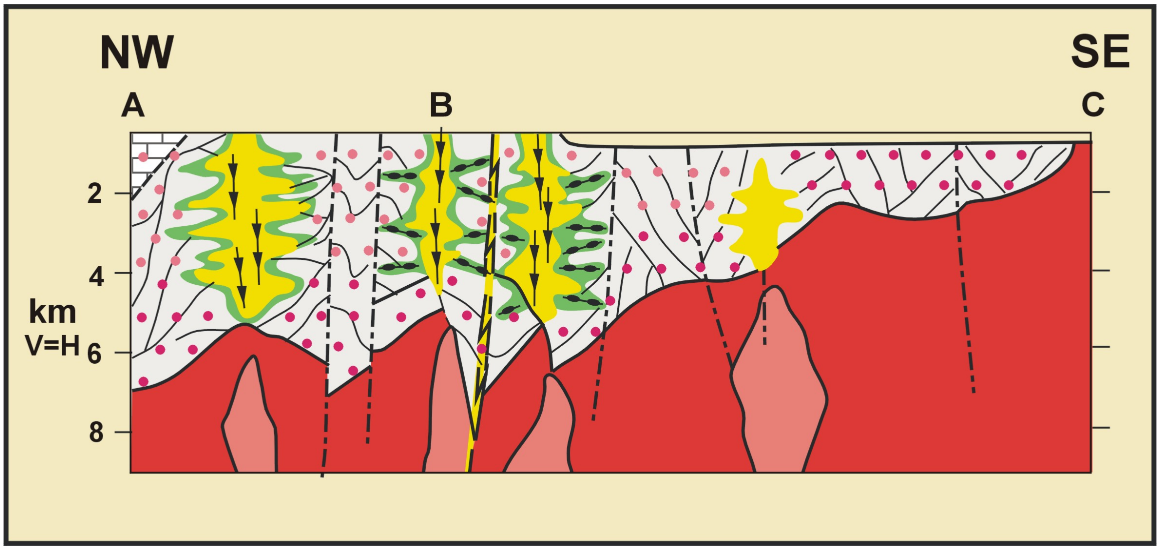


Figure 4 b) Schematic, but partly drill-constrained cross section (line A-B on Figure 4 a) for the Muruntau area, showing geology, structure, alteration and thermal metamorphic zones. Legend as for Figure 4 a). Redrawn from Kotov and Poritskaya (1992). See also Wall et al (2004) for new and more detailed figures.

Implications for exploration

Although TAG deposits are diverse in form and character and TAG systems are hosted by diverse terranes, major deposits occur in a limited range of characteristic geological settings. Recognition of such settings can contribute to more effective targeting through several scales and stages of exploration, including belt, regional and district scale target selection and project assessment.

Pluton roof zones, the key target areas for TAG deposits, can commonly be recognized from geological map patterns, gravity and magnetics data (eg Figure 5), the distributions of metamorphic grade and minor intrusions (eg Figure 1), geochemical zoning patterns, and so on. The more highly gold prospective target zones are situated above pluton margins and cupolas where chemically and mechanically favourable rock packages occur in fault-fold systems subparallel to the underlying pluton margins, particularly at the intersections of reactivated regional structures (Figure 1).

The application and further development of TAG exploration models will enhance the chances of successful project identification and exploration in a variety of gold fertile regions which remain underprospected for TAG deposits. I suggest that as Greg Hall says “act like you believe it” and see where it takes you. I’ve been continually and agreeably surprised.

Acknowledgements

Jeff Taylor and Rick Valenta and then others, particularly Greg Hall and also Stewart Taylor and Mike Etheridge, have contributed to the TAG model. However, they are not to blame for any short-comings in this article which was kindly invited for AIG presentation by Dave Shatwell.

This article was originally published in The Australian Geologist 2005 (February edition).

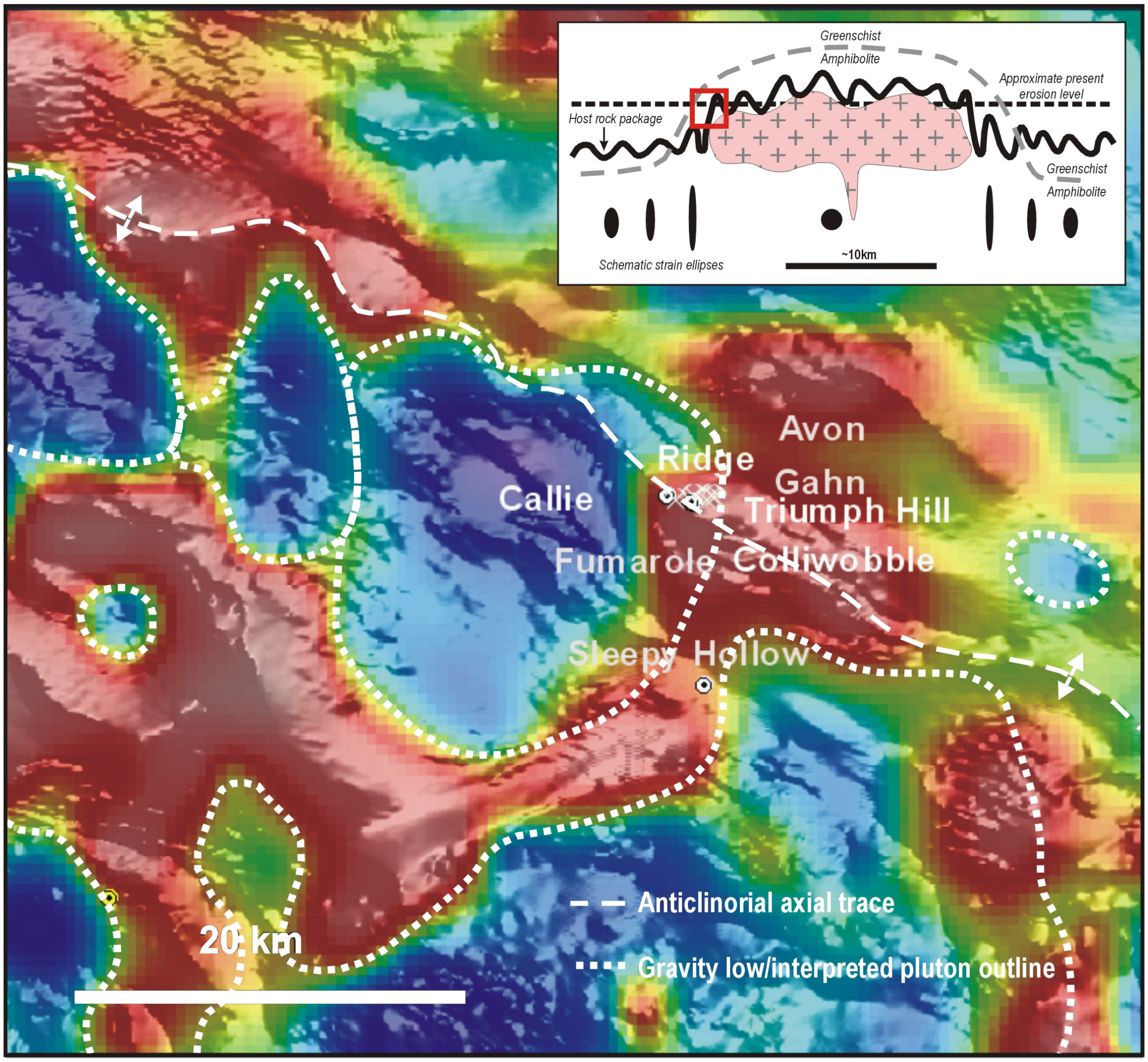


Figure 5 Greyscaled copy of pseudocolour gravity drape over magnetics for the Dead Bullock Soak district, Granites Tanami Province, N.T., Australia. The positions of some significant TAG deposits, mostly localised in a WNW-trending faulted, regional anticlinorial zone, are also labelled. The image also shows the prospective magnetic stratigraphic package in the roof zones of (mainly) concealed felsic plutons manifest as elliptical gravity lows. The major gold deposits are above the margins of such plutons where (reactivated) regional structures strike subparallel to the underlying pluton edge. From Taylor Wall & Western Geoscience, unpublished report to Placer Dome (2000).

REFERENCES

Ameglio, L., Vigneresse, J.L. and Bouchez, J.L.	1997	The Los Pedroches Batholith (Southern Spain): polyphase interplay between shear zones in transtension and setting of granites in Granite: from segregation of melt to emplacement fabrics. Kluwer Academic Publishers, Dordrecht, p199-214
Barton, M.D., Staude, J.M., Snow, E.A. and Johnson, D.A.	1991	Aureole systematics. In Contact Metamorphism, Derril M. Kerrich (ed.). Reviews in Mineralogy V26, p723-847.
Brisbin, D.I.	2000	World class intrusion-related Archean vein gold deposits of the Porcupine gold camp, Timmins, Ontario, in Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F. and Morrise, C.L., eds., Geology and ore deposits 2000: The Great basin and beyond: Reno, The Geological Society of Nevada, p19-35
Burnham, W.C. and Ohmoto, H.	1980	Late-stage processes of felsic magmatism. Society of Mining Geologists of Japan, Special Volume 8, p1-11
Cox, S., Wall, V., Etheridge, M. and Potter, T.	1991	Deformational and metamorphic processes in the formation of mesothermal vein-hosted gold deposits – examples from the Lachlan fold belt in central Victoria, Australia. Ore Geology Reviews, V6, p391-423
Drew, L.J. and Berger, B.R. and Kurbanov, N.K.	1996	Geology and structural evolution of the Muruntau gold deposit, Kyzylkum desert, Uzbekistan. Ore Geology Reviews II, p175-196
Goellnicht, N.M., Groves, D.I., McNaughton, N.J. and Dimo, G.	1989	An epigenetic origin for the Telfer gold deposit: Economic Geology Monograph, V6, p151-167
Groves, D.I., Goldfarb, R.J., Robert, R. and Hart, C.J.R.	2003	Gold Deposits in Metamorphic Belts: Overview of Current Understand, Outstanding Problems, Future Research, and Exploration Significance. Economic Geology, Vol 98, pp 1-29
Heinrich, C.A., Dreisner, T., Stefannson, A. and Seward, T.M.	2004	Magmatic vapour contraction and the transport of gold from the porphyry environment to epithermal ore deposits. Geology, V32, 761-764.
Heinrich, C.A., Gűnther, D., Audétat, A., Ulrich, T.	1999	Metal fractionation between magmatic brine and vapor, determined by microanalysis of fluid inclusions. Geology 27, 755-758
Hutton, D.H.W.	1997	Syntectonic granites and the principle of effective stress: a general solution to the space problem? in Granite: from segregation of melt to emplacement fabrics. Kluwer Academic Publishers, Dordrecht, p189-198
Kotov, N.V. and Poritskaya, L.G.	1992	The Muruntau gold deposit: Its geology, structure, metasomatic mineral associations and origin. International Geology Review, V34, No. 1, p77-87
Krivtsov, A.I., Konstantinov, M.M. and Benevolsky, B.I.	1992	Geology of CIS Gold Deposits. International Center for Information, Inc. Moscow. 56pp.
Lang, J.R. and Baker, T.	2001	Intrusion-related gold systems – the present level of understanding: Mineralium Deposita, V36, p477-489
Matthai, S.K., Henley, R.S. and	1995	Gold Precipitation by fluid mixing in bedding-parallel

Heinrich, C.A.		fractures near carbonaceous slates at the Cosmopolitan Howley gold deposit, Northern Australia. Economic Geology, V90, No. 8, p2123-2142
Matthai, S.K., Henley, R.W, Bacigalupo-Rose, S., Binns, R.A., Andrew, A.S., Carr, G.H., French, D.H., McAndrew, J. and Kananagh, M.E.	1995	Intrusion-related, high temperature gold quartz veining in the Cosmopolitan Howley metasedimentary rock-hosted gold deposit, Northern Territory, Australia. Economic Geology, V90, p1012-1045
Moravek, P.	1979	Primary aureoles and genetic problems of auriferous mineralization. Geologicky Pruzkum 21, 4. p97-99.
Robert, F. and Poulsen, K.H.	1997	World-class Archean gold deposits in Canada: An overview: Australian Journal of Earth Sciences, V44, p329-351
Rowins, S.M., Groves, D.I., McNaughton, N.J., Palmer, M.R. and Eldridge, C.S.	1997	A reinterpretation of the role of granitoids in the genesis of Neoproterozoic gold mineralization in the Telfer Dome, Western Australia. Economic Geology, V92, No. 2, p133-160
Sillitoe, R.H. and Thompson, J.F.H.	1998	Intrusion-related vein gold deposits: Types, tectono-magmatic settings and difficulties of distinction from orogenic gold deposits: Resource Geology, V48, p2137-250
Thompson, J.H.F., Sillitoe, R.H., Baker, T., Lang, J.R. and Mortensen, J.K.	1999	Intrusion-related gold deposits associated with tungsten-tin provinces: Mineralium Deposita, V34, p323-334
Valenta, R.K. and Wall, V.J.	1996	Controls on gold mineralisation at The Granites, Tanami Desert, Northern Territory. 13th Australian Geological Convention, Canberra, Geological Society of Australia, Abstracts 41, p451
Wall, V.J.	1989	Fluids and metamorphism. Unpublished PhD thesis, Monash University, Melbourne, Australia, 234p
Wall, V.J.	2000	Pluton-related (thermal aureole) gold: Taylor Wall and Associates, Alaska Miners Association Annual Convention, Anchorage, October 30-31, 2000, Workshop Notes.
Wall, V.J. and Gow, P.A.	1995	Some Cu-Au ore-forming systems; iron(ic) connections: in Clark, A.H. (ed) Giant Ore Deposits II, Controls on the Scale of Orogenic Magmatic-Hydrothermal Mineralization. Proceedings of the Second Giant Ore Deposits Workshop, Kingston, Ontario, Queens University, p557-582
Wall, V.J. and Taylor, J.R.	1990	Granite emplacement and temporally related gold mineralization. Geol. Soc. Australia, Abstract Series, 25, p264-265
Wall, V.J., Graupner, T., Yantsen, V., Seltmann, R. and Hall, G.C.	2004	Muruntau, Uzbekistan: a giant thermal aureole gold (TAG) system. In J. Muhling et al (eds) SEG 2004: Predictive Mineral Discovery Under Cover; Extended Abstracts. Centre for Global Metallogeny, The University of Western Australia, Publication No. 33, 199-203.