Paper 4

Geology Works: The Use of Regional Geological Maps in Exploration

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ABSTRACT

A review of exploration expenditure by exploration stage over 15 years at Laverton Western Australia has identified a poor conversion rate from the first stage (ground acquisition) to the second stage (drill testing). This poor conversion rate is primarily due to poor target selection. The use of a well described ore deposit model and regional geological and regional geophysical datasets is able to improve target selection. The Thermal Aureole Gold ore deposit model and the relevant geological features that can be detected in regional geological maps are described and some examples are shown for Morila, Sadiola and Muruntau gold deposits.

INTRODUCTION

This paper presents the authors experience in using regional geological maps for defining target areas for mesothermal gold exploration. A target area is defined as a region that could be pegged as an exploration license application. Such a target area would contain a significant metal resource that would be detected by a proposed mineral exploration program. Exploration license applications in many jurisdictions allow maximum areas of 200 km2. A significant mineral resource is defined as +1 million ounces of gold at +2 gm/t grade in an open pit configuration.

Exploration involves two primary objectives. Predict the location of the mineralizing system and involves exploration targeting using an ore deposit model. Detect the existence of a mineralizing system involves an exploration model using geological, geophysical and geochemical exploration techniques. This paper addresses the "Predict the Location" objective and uses the Thermal Aureole Gold (TAG) ore deposit model as described by Wall 1989 and updated in Wall, 2005 as the case study.

THE EXPLORATION PROBLEM

Analysis of past exploration activity for mesothermal gold deposits in the period 1984-2000 at the Granny Smith gold mine in the Eastern Goldfields of the Yilgarn Province in Western Australia (Lord et al 2001) has clearly demonstrated the exploration problem (Table 1). This expenditure totals AUD52 million and includes the discovery of Granny Smith mine itself and subsequent satellite operations. The mine operation is highly successful in that three million ounces were profitably mined in the period under consideration (1990 to 2000). The conversion rate of exploration projects from the target generation phase (Phase 1) to the drill testing phase (Phase 2) is very poor (1 in 6 success rate) and the cost is relatively high at AUD70K per project. Once serious drilling commences the success ratio of successive phases (Phase 3 Resource Delineation, Phase 4 Pre-Feasibility, Phase 5 Feasibility) is very good at greater than 1 in 2 (Figure 1). An alternate view might be expressed as too many projects are selected at the Project Generation phase that fails to generate an effective drilling target. The net impact of this decision making is to slow the discovery rate, increase the cost of discovery and reduce the economic impact of discovery. Improving the exploration target selection process is the focus of this paper.

The economic impact of improving exploration target selection is clearly demonstrated in the Granny Smith mine case. A back analysis of feasibility studies of successful discoveries was completed informally in 2002 and the NPV of each discovery at decision to mine was re-calculated as though the transition from acquisition of ground to serious drilling program was completed within one year. Three projects yielded economic gold deposits (mined in 5 different pits) yet failed to meet this criterion. The opportunity cost of slow discovery within these three projects has not been formally estimated but was informally estimated by the Mine Superintendent as being greater than the net present value of all discoveries at decision to mine (Geoff Fenton pers. comm.). Surprisingly only 25% of the loss of value is attributed to the declining gold price over this period, the bulk of the loss of value derives from not optimizing the gold mining operation. In particular the use of contractor mining in this period is estimated to have cost an additional AUD0.30/tonne and two mines each containing 20mt of ore in 8:1 strip ratio pits were mined. Similarly a saving of AUD1 per tonne of ore is estimated to be lost by not optimizing the milling operation. Additionally significant volumes of ore were sterilized by the slow recognition of the full extent of

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mineralization due to large pre-strips required to expose the deep ore.

Exploration at Granny Smith mine could have achieved a 1 in 3 success ratio if 80 projects had been rejected at the ground acquisition stage over a 15 year period. This decision would likely have saved AUD5.6M of expenditure and have increased the likelihood of progressing early discovery at the projects where discovery took more than one year of exploration activity. Better application of the ore deposit model criteria supporting ground acquisition to geological map pattern analysis could provide a means to achieve this result.

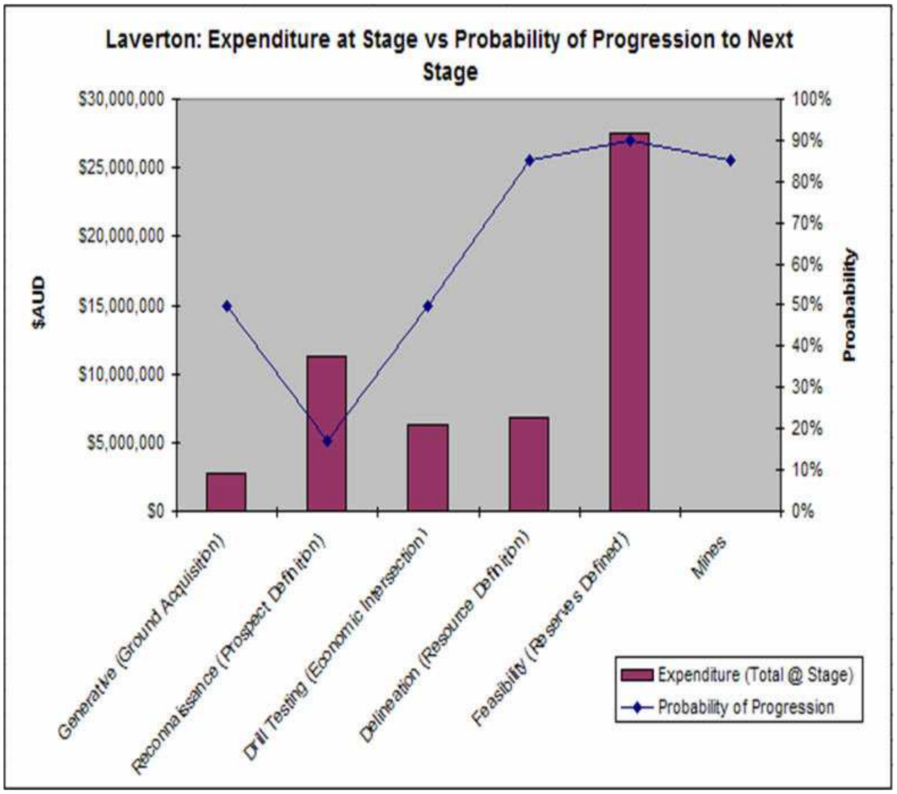

Figure 1: Laverton: Expenditure at Stage versus Probability of Progression to Next Stage. From Lord et al 2001

Table 1: Summary of exploration expenditure at Laverton Western Australia 1984-2000

Stage	Total Expenditure	Number of Prospects	Average Cost Per Project	Probability of Progression
Generative *Ground Acquisition*	2.7M	290	9K	1 in 2
Reconnaissance *Prospect Definition*	11.3M	158	70K	1 in 6 *
Drill Testing *Economic Intersection*	6.3M	27	230K	1 in 2
Delineation *Resource Defined*	6.8M	15	460K	5 in 6
Feasibility *Reserves Defined*	27.5M	13	2100K	9 in 10
Mines		12		10 of 12
Total	54.6M			

THERMAL AUREOLE GOLD ORE DEPOSIT MODEL

The main elements of the TAG model involve the recognition of two key parameters

(i) A roof zone over a large granite pluton buried beneath sedimentary cover, volcanic sequences or basement gneisses and

(ii) The structures associated with pluton emplacement.

Examples of gold deposits in each type of host rock are Muruntau in Uzbekistan (sediment hosted), Red Lake in Canada (volcanic hosted) and Pogo in Alaska (basement gneiss hosted). Gold deposit examples in this class are given in Table 2 and their interpreted location relative to the source pluton and associated structures is shown in Figure 2 (reproduced from Wall 2005).

The plutons are emplaced in post-tectonic settings often at collisional margins during or immediately after basin inversion. These plutons can liberate considerable quantities of gold bearing fluid as shown in Figure 3 which assumes a fluid of 50ppbAu is evolved from the devolatilisation reactions associated with pluton emplacement, the pluton itself or free convecting fluid driven by heat from the pluton.

The granite pluton is often reduced (ilmenite series) thus lacks a magnetic expression but has an expression in gravity data. The pluton is usually fractionated and shows several phases in exposed roof zones (Burnham and Ohmoto 1980). Such roof zones will show distinctive accumulation of radio-elements giving rise to significant radiometric anomalies in airborne data such as at Pogo in Alaska or Boddington in Western Australia if the top of the granite pluton is exposed at surface. Mapped granite outcrop should be significantly less extensive than the sub-surface extent inferred from gravity data. The pluton typically occupies a large sub-surface extent usually greater than 20km by 10km and will have expression in regional gravity datasets even at large grid cell size of data collection. Figure 4 shows the combined gravity and magnetic image for the Callie gold deposit in the Tanami region of Northern Territory in Western Australia (Valenta and Wall 1996). This image of upward continued gravity data highlights the pluton at depth. The lower part of the host basin stratigraphy is magnetic and contrasts with the non-magnetic upper section.

Pluton formation involves magma mixing where a crustal-derived melt mixes with a more mafic magma derived from a depleted mantle source (sanukitoid) (Martin et al 2005). Such plutons show high nickel and chromium values and elevated gold contents (+5ppbAu). The gold-rich nature of vapour-rich fluids derived from similar plutons emplaced at shallow (1 to 3km) depths in porphyry copper deposits has already been demonstrated (Heinrich et al 1999, 2004). The gold content of these fluids is considerably greater (+1ppmAu) than the contents (50ppbAu) assumed in Figure 3.

Pluton emplacement at depths greater than 5km allows wide thermal aureoles to form in the roof zone due to high ambient heat of the wall rocks at such depths. Such plutons do not intrude volcanic edifices and coeval volcanics are not recognized in target areas. Drilling at Muruntau pit intersected granite at 4km depth which allows a +5km thick biotite grade thermal aureole to be inferred. This thermal aureole implies granite emplacement at 10km or greater depths (Wall et al 2004). Recognition of pluton roof zones from pluton sides for outcropping pluton contacts is facilitated by modeling of gravity data and the spatial distribution of thermal aureoles. Thermal aureoles are far more extensive in pluton roof zones than they are laterally extensive from pluton sides.

The pluton is emplaced by roof lifting usually at the basement-cover sequence boundary. Small volume stocks and sills are often emplaced as porphyry phases into the overlying cover sequence. Lifting of anticlines is more easily accomplished than lifting of synclines so large pre-existing anticlines with horizontal fold axes are favored. The lower parts of the stratigraphy are the constant host to a “roof-lifter” pluton in contrast with “cookie-cutter” emplacement where the pluton cuts across stratigraphic units. Extension in the roof zone of such plutons favors the rotation of previously formed cleavage into a horizontal orientation which becomes crenulated when the far-field horizontal stress resumes after pluton emplacement (Figure 5). Foliation trajectory analysis will identify such target areas in air borne imagery as the foliation fabric will become subdued in such areas. Horizontal crenulations are widely developed in the vicinity of Muruntau.

Table 2: 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

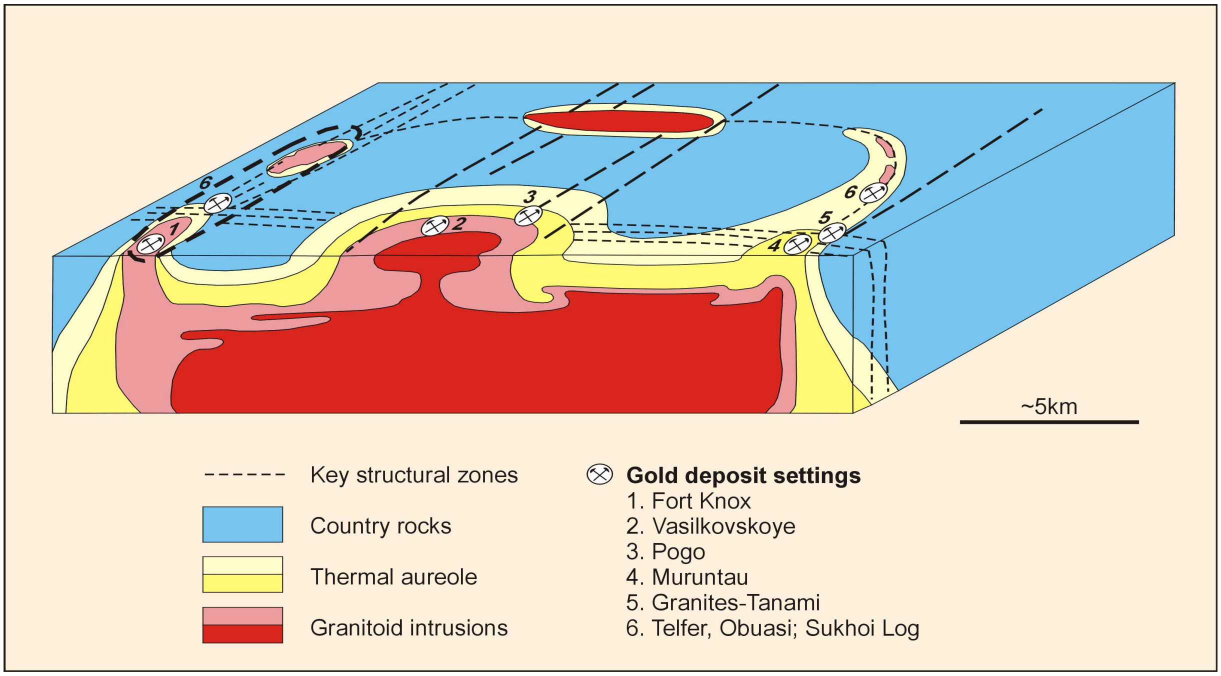

Figure 2: Conceptual 3D geological model for TAG systems showing the locations of some major gold deposits in the roof zone thermal aureoles and tops of granitoid plutons. From Wall 2005

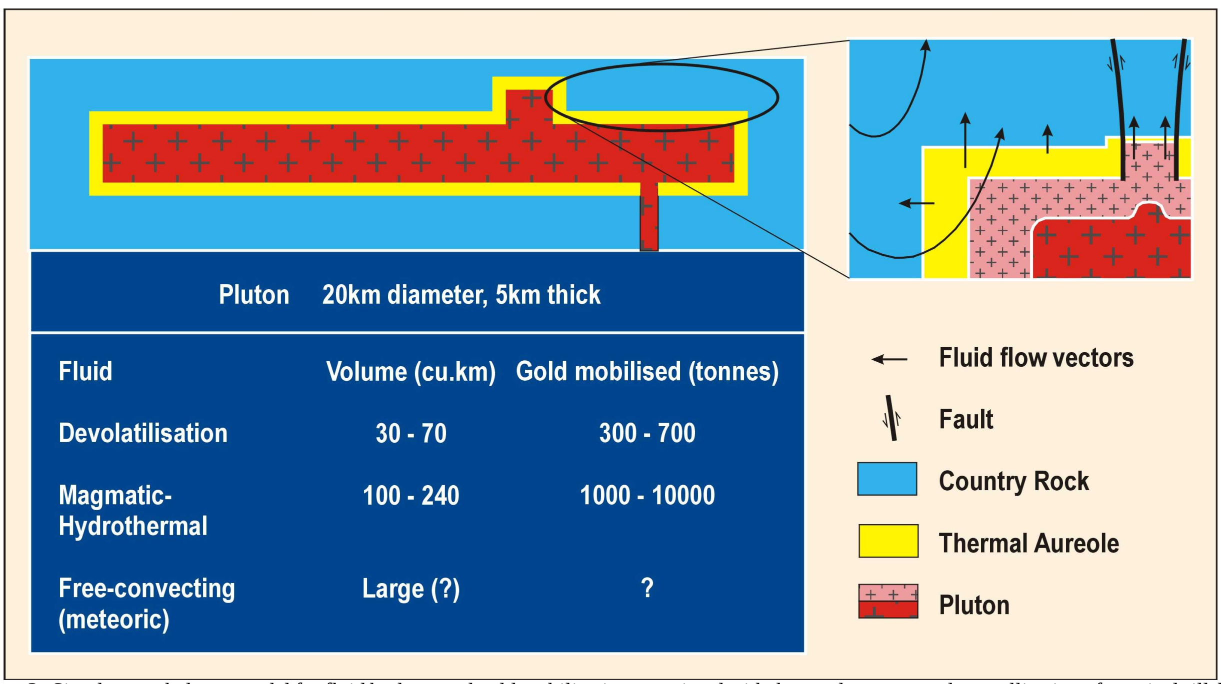

Figure 3: Simple mass balance model for fluid budgets and gold mobilisation associated with the emplacement and crystallisation of a typical sill-like pluton in metasedimentary host rocks. The model assumes magma water contents of 2.5-4 weight percent and gold contents of mobilised devolatilisation and magmatic hydrothermal fluids averaging 10-50ppb. The inset, a schematic cross section, shows preferred fluid paths, mainly through the plutons. Modified from Wall (1989) as shown in Wall, 2005

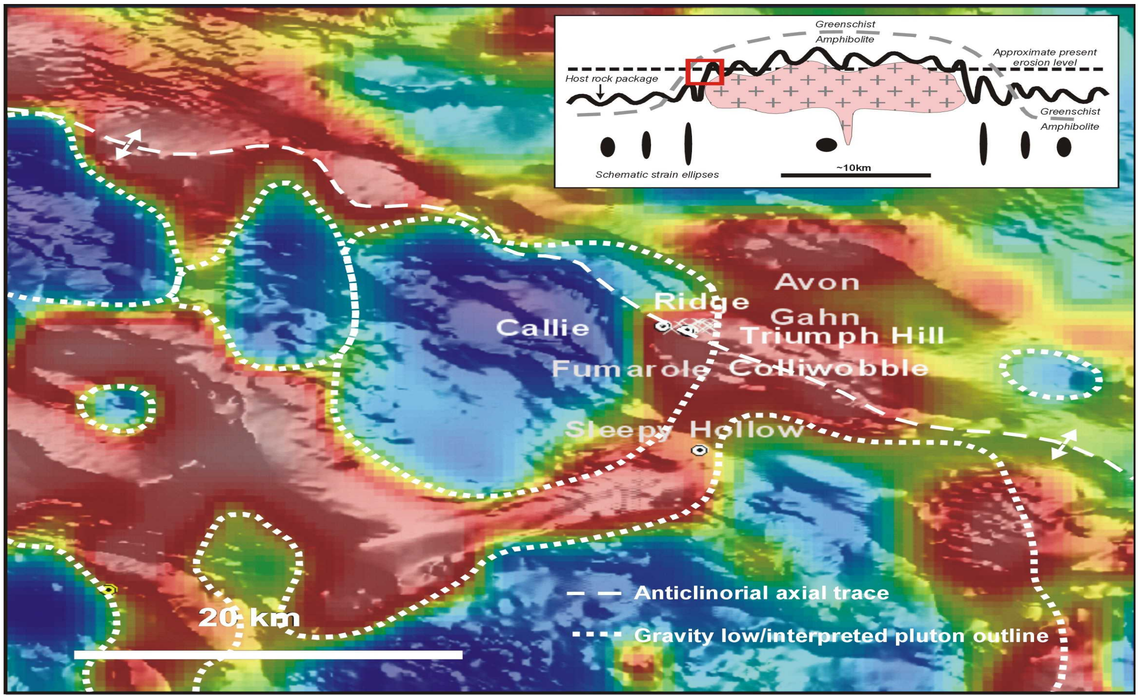

Figure 4: Greyscaled copy of pseudocolour gravity drape over magnetics for the Dead Bullock Soak district, Granites Tanami Province, N.T., Australia. The positions of some significant TAG deposits, mostly localised in a WNW-trending faulted, regional anticlinorial zone, are also labelled. The image also 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).

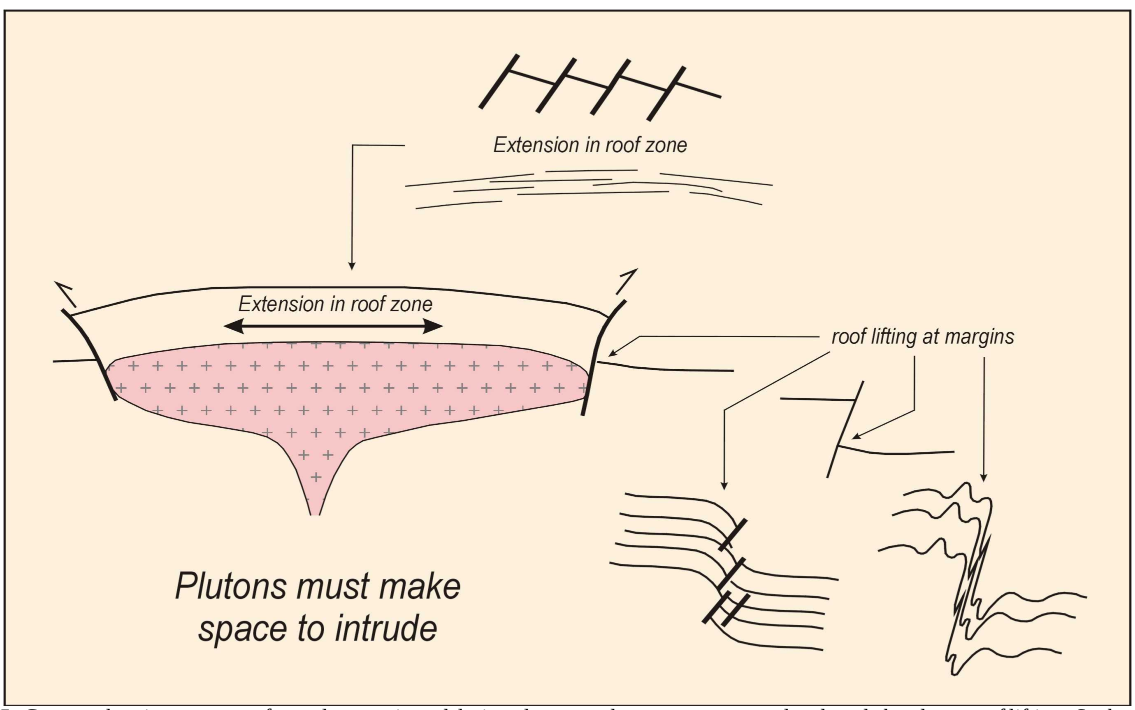

Figure 5: Cartoon showing structures formed or reactivated during pluton emplacement accommodated partly by pluton roof lifting. Such structures are commonly localised around pluton margins or apophyses and may focus fluid flow in the pluton's roof zone as well as providing dilatant zones in which gold deposits may be localised. From Valenta and Wall (1996) as shown in Wall 2005.

Gold deposit formation is developed in regions of maximum fluid flow. Such regions can be cupolas at the "top dead centre" position on an underlying pluton for example Morila in Mali. The other region is in major fault zones that strike tangential and lie above the pluton margin for example Red Lake in Canada or Muruntau in Uzbekistan. In this case recognition of major basement structures at a high angle to the shortening direction is significant. All major gold mineralization in the Muruntau region is aligned along such a NE direction in contrast to the WNW strike orientation of the regional deformation fabric (Figure 6). The basement structure is defined by a corridor of re-oriented folds and faults that encompasses the gold trend in similar pattern to that described by Peters for the Carlin trend in Nevada. The large scale semi-circular drainage pattern of diameter 80km evident in Landsat imagery (Figure 6) at Muruntau is attributed to present day uplift of the intersection point of the rifted continental margin with this basement structure in response to the continued closing of the Indian plate with the Siberian craton in the Himalayan orogeny. This shortening has produced the Patom Dome of similar dimensions surrounding the Sukhoi Log gold deposit in Siberia. In both cases the major gold deposit is located at the centre of the dome and the semi-circular topographic effect is located on the opposite side of the centre to the indentor.

Gold deposit formation is typically located beneath a seal within the host sequence. This seal in sedimentary basins is a regressive sequence, typically black carbonaceous shale and iron formation at Callie gold mine in Australia, micritic limestone at Muruntau in Uzbekistan and Telfer in Australia, late basin unconformities at Obuasi in Ghana, or thrusts in the Carlin district of USA.

Host rocks dictate the nature of the gold distribution in the deposit due to the mechanical fracturing properties of the host rocks during pluton cooling. Gneissic host rocks give rise to massive tension vein-like geometries adjacent to the granite roof zone at Pogo and Tropicana in Western Australia. Siltstone sequences with centimeter scale bedding provide optimal fluid ingress if flat dipping and usually have a carbonaceous component that accentuates a redox gradient promoting gold deposition from the hydrothermal fluid. Muruntau in Uzbekistan is the type example but Morila in Mali and Obuasi in Ghana are other examples of siltstone host rocks. The pluton roof itself can host mineralization in stockworks for example Fort Knox mine in Alaska or as sheeted veins at Booroo mine in Mongolia.

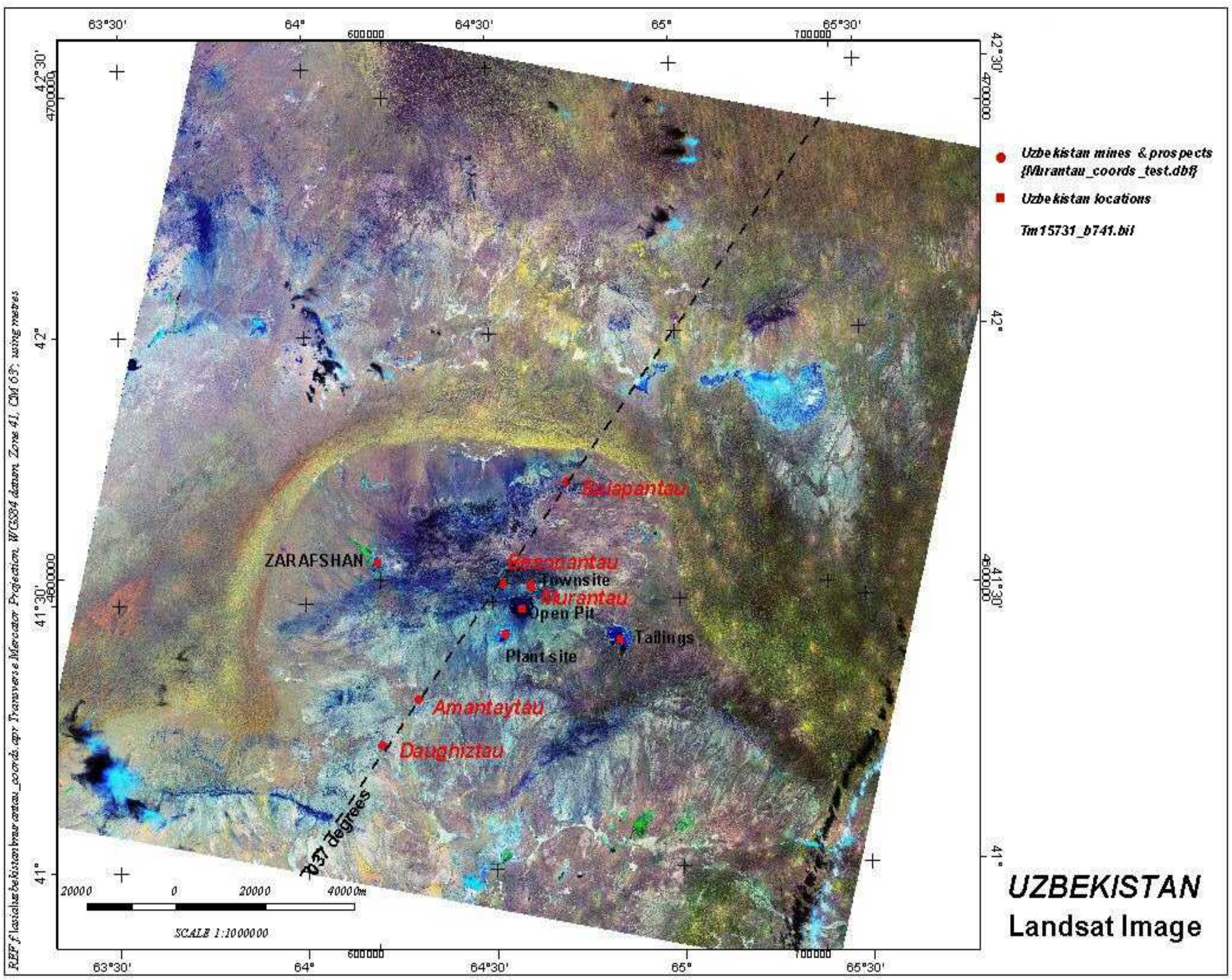

Figure 6: Landsat scene of Muruntau showing location of major gold accumulations within 50km of Muruntau.

GEOLOGIC MAP PATTERN ANALYSIS

The recurring patterns in analyzing regional geological maps for TAG targets reflect basic geological processes and some of these processes are described.

MAGMA PROCESSES

Emplacement

There are two dominant types of mechanisms for granite magma emplacement, termed "Roof Lifter" and "Cookie Cutter" (Wall and Taylor 1990). The characteristic map patterns for each relate to the granite contact with the host sequence. Roof Lifter granites will have a single rock unit in continuous contact with the intrusive. This unit will likely be the lower part of the basin stratigraphy being dragged up into the overlying sequence usually in a monocline pattern but sometimes with accommodating fault movement. The granite magma is emplaced as a ballooning diaper (Figure 7).

Cookie Cutter granites will usually cut straight across stratigraphic units and magma is emplaced as a series of overlapping dykes.

Roof Lifter granites are the target granite type in a TAG model.

Fractionation

The dominant map pattern reflecting crystal fractionation is grain-size variation from euhedral, coarse-grained through medium grained porphyritic to fine-grained aplitic or pegmatitic phases (Burnham and Ohmoto 1980). Concentric emplacement of these phases in a single pluton is a positive feature for TAG related intrusions. Magma composition can vary significantly from quite mafic magmas to granite compositions. The more silicic compositions are common. The granites are often reduced ilmenite series but can vary to oxidised magnetite series compositions.

The presence of tin, tungsten or molybdenum mineralization is supportive of emplacement of a fractionated granite suite and is a favorable feature in TAG target regions. Such mineralization derives from crustal source regions (Hart and Maier).

Magma Mixing

The dominant map pattern is recognition of coeval mafic and crustal melts. The mafic component is usually volumetrically small, for example lamprophyres, diorites etc and may not be recognized in regional geologic maps. Geochemistry of plutons subject to magma mixing of a crustal magma with a component from depleted mantle reservoirs is characterized by high nickel and chromium numbers. These mafic series magmas are classed as sanukitoids (Martin et al 2005).

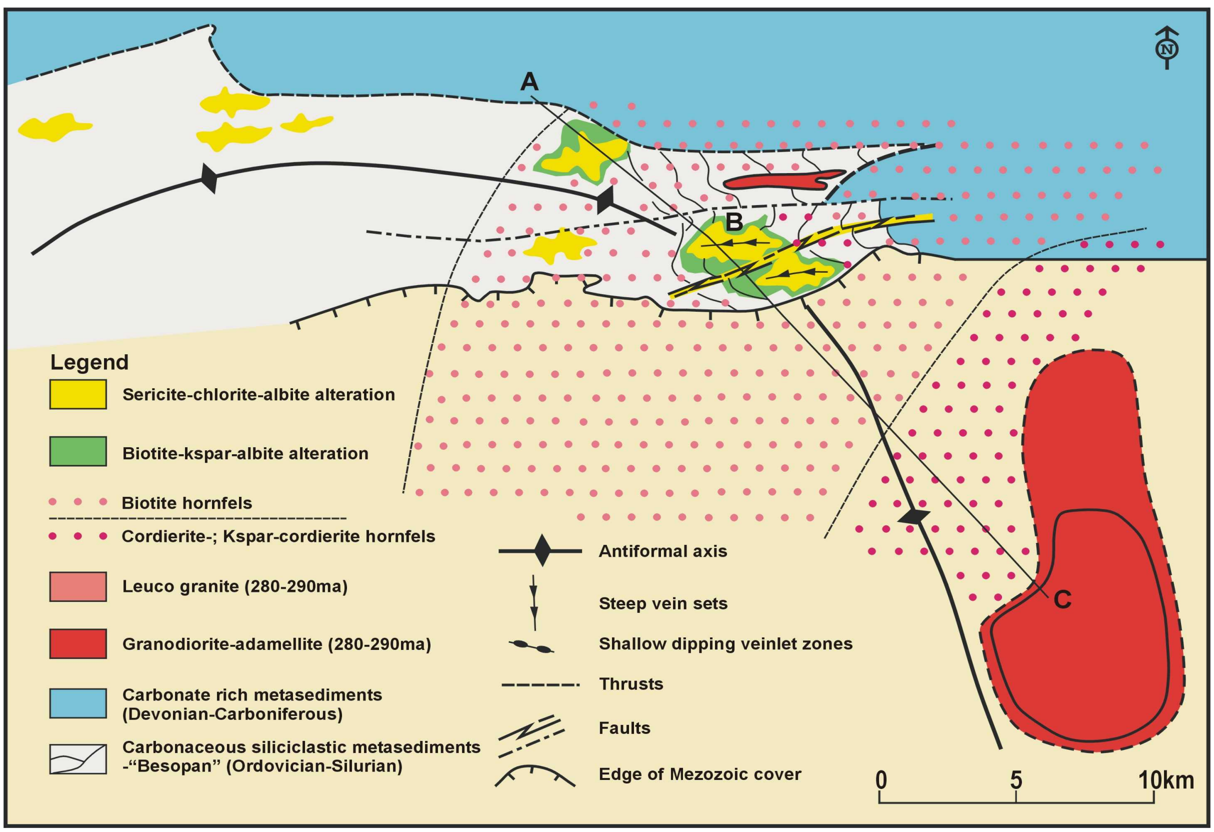

Figure 7: Simplified surface geology, thermal metamorphic zones and alteration in the Muruntau area, Uzbekistan. Redrawn from Kotov and Poritskaya (1992) in Wall 2005

BASIN ANALYSIS

Recognition of stratigraphic tops and bottoms can be aided by the characteristic fill patterns of sedimentary and volcanic basins.

Sedimentary Basins

Sediments infill rift basins in a characteristic manner. Basin floors often show basalt related to initial RIFT phase opening. This basalt is often disrupted by on-going rift related faulting. The basalt is overlain by SAG phase sedimentation, usually coarse clastic in nature and fining upwards as the basin shows progressive deepening. The final FILL phase is often dominated by pelites. Carbonates can also occur in fill phase sedimentation. The fill phase sediments can be very thick sequences.

The preferred target horizons for large open pit targets are the siltstone phases showing centimeter scale layering (turbidites) and hosting carbonaceous shale and banded iron formations. The fill phase sediments are not preferred hosts for open cut targets but are often hosts for fault vein and saddle reef style gold deposits. Sediments within Rift phase basalt sequences can host gold deposits such as at Sabodala in Senegal but such host rocks are rare.

Volcanic Basins

Basic volcanic basins dominate in Archaean settings and are often overlain by very thick sedimentary successions often largely removed by erosion. Basaltic sequences show fractionation patterns from more magnesian composition early phases to iron-rich later phases. Recognition of this variation can aid in interpreting facing and stratigraphic position.

TECTONICS

Basement Faults

Access to the upper mantle magma sources is facilitated by deep crustal faults or plate boundaries. Such zones that are oriented at a high angle to the shortening direction are very favorable. These zones occur in the basement and are not readily transferred to the cover sequence. In the cover sequence they are recognized as zones of re-orientation of fold axes and small scale faults (Muntean et al 2005). They are termed Transfer Faults as they often form during rifting as structures to accommodate different rates of separation during the rifting event. These zones usually define the edges of sub-basins in the overlying sedimentary basin and are denoted by sedimentary facies changes.

These zones also define the propagation points for structures during deformation and basin inversion. Regional scale folds propagate from such zones and they often define domains of different structural style.

Inversion Anticlines

Basement faults with a longitudinal strike are often the site of earlier crusting thinning or rifting. Typically there is a major basin margin fault and several parallel minor faults relating to the thinning of the basement during rifting. Subsequent sedimentation overlaps these faults but often shows sedimentary facies changes from platform to shelf to deep water sedimentation.

During basin closing due to cratonic collision the major faults become loci for anticline development in their hangingwall as the original extensional fault now operates as a reverse fault. Often the anticline development is accentuated by the presence of a pre-existing monocline as sedimentary units often thicken against such a fault. These thickness changes facilitate the development of the anticline (Coward 1994, Coward et al 1991).

The characteristic map pattern for such faults is they dip away from the youngest stratigraphic sequence which is preserved in the footwall to such faults. This pattern is often disturbed by short-cut thrusts that cut into the footwall of the main faults.

EXAMPLES

Muruntau is the type example of a classic TAG deposit and the regional geology is displayed in plan (Figure 7) and section (Figure 8) redrawn from Kotov and Poritskaya 1992 in Wall 2005. The biotite hornfels aureole extends 25km from the subcrop of the underlying host intrusion which itself occupies the axial region of a very large scale anticlinal fold defined by the Devonian limestone contact. This contact acts as the seal in this system. Biotite hornfels and weak mineralization overprint the basal limestone.

Regional geological mapping of the Birrimian sequences in Mali is compiled in a series of map sheets at 1:500,000. This mapping includes metamorphic grade as well as granite and stratigraphic units. These maps have been interpreted using the criteria nominated above to generate TAG target areas.

Morila is a major gold deposit hosting 8 million ounces of gold in a flat-lying open pit configuration. It produced 0.5 million ounces in 2006.

The recognition of a large buried pluton is aided by the mapping of the thermal aureole at biotite and locally amphibolite facies surrounding an extensive area of granite intrusion (Figure 9). This granite locally shows porphyritic phases and these are associated with alluvial tin and tungsten deposits. These porphyritic intrusions are round and small and interpreted as cupolas on the larger intrusion. The basin fill is interpreted as a Rift-Sag-Fill sequence and the top of the SAG phase siltstone is extensively arrayed as the roof zone contact host rock to the intrusion. This sequence is the preferred target host rock.

The interpreted cupola location would constitute a prime TAG target location. Bends in faults located at or near the margin of the underlying pluton would also constitute target zones. These faults strike parallel to inferred pluton margin.

Sadiola is a major gold deposit hosting 15 million ounces of gold in open pit configurations. The mine produced 0.5 million ounces in 2006.

The recognition of a large buried pluton is inferred by the presence of the SAG phase siltstone dominated succession as the main host rock to the exposed granite plutons (Figure 10).

Basement sequences are also exposed as hosting granite plutons. These sequences form a large expanse within extensive pelitic sediment. The recognition of porphyritic phase plutons locally suggest a cupola region to the larger pluton and this region hosts a late conglomerate basin. A NE trending contact between siltstone and shale dominated sequences is adjacent to the cupola region. Locally limestone is described in the siltstone sequence in the cupola region.

The interpreted cupola region constitutes the primary TAG target. Secondary targets are the inferred faulted contacts of the siltstone-shale sequences near Sadiola and Tabakota.

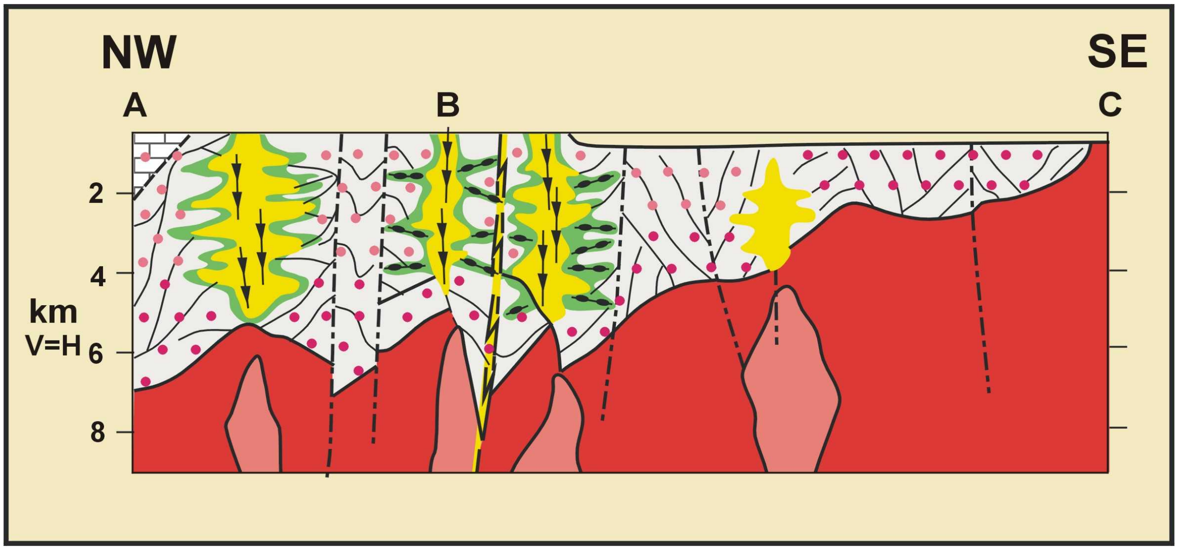

Figure 8: Schematic, but partly drill-constrained cross section (line A-B on Figure 4 a) for the Muruntau area, showing geology, structure, alteration and thermal metamorphic zones. Legend as for Figure 7 Redrawn from Kotov and Poritskaya (1992) in Wall 2005. See also Wall et al (2004) for new and more detailed figures.

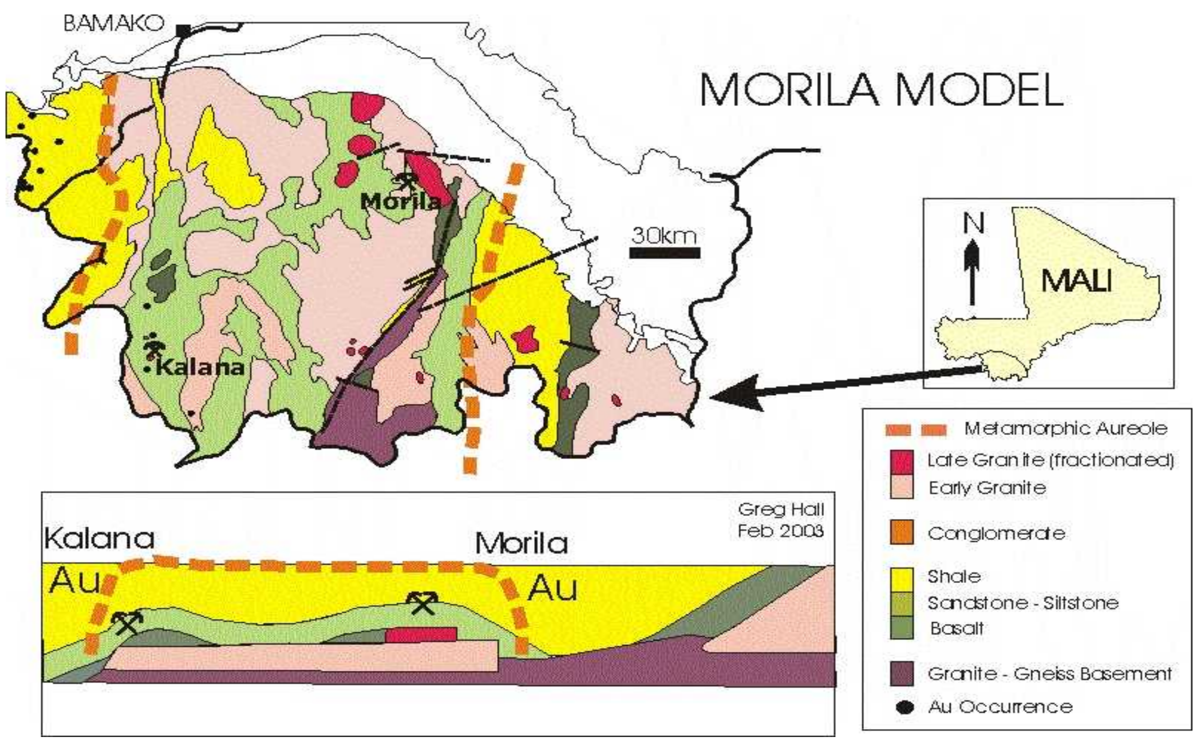

Figure 9: Simplified regional geology of Morila gold mine Mali with inferred cross-section.

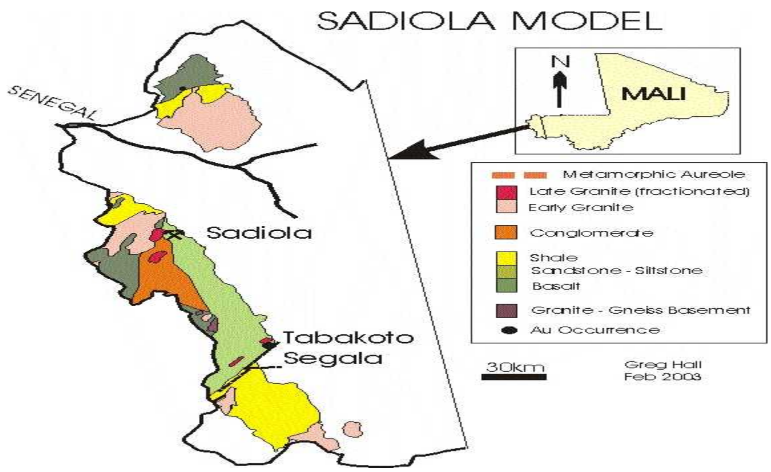

Figure 10: Simplified regional geology of Sadiola gold mine Mali.

CONCLUSIONS

Exploration for gold deposits is often ineffective at the initial stage of target generation even in regions where exploration has proven to be highly effective. The recognition of the main features of an ore deposit model in regional geological and geophysical datasets is considered key to improving the effectiveness at the target generation stage.

The Thermal Aureole Gold ore deposit model has features that allow ready recognition of target areas. These features include roof zones of buried plutons, preferred host rock sequences, stratigraphic seals, major transfer fault corridors and local faults creating accommodation space for pluton emplacement.

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