GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7852

Targeted Geoscience Initiative 4: Contributions to the Understanding of Precambrian Lode Gold Deposits and Implications for Exploration

Synorogenic gold mineralization in granite-greenstone terranes: the deep connection between extension, major faults, synorogenic clastic basins, magmatism, thrust inversion, and long-term preservation

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2015

Recommended citation

Bleeker, W., 2015. Synorogenic gold mineralization in granite-greenstone terranes: the deep connection between extension, major faults, synorogenic clastic basins, magmatism, thrust inversion, and long-term preservation, *In:* Targeted Geoscience Initiative 4: Contributions to the Understanding of Precambrian Lode Gold Deposits and Implications for Exploration, (ed.) B. Dubé and P. Mercier-Langevin; Geological Survey of Canada, Open File 7852, p. 25–47.

Publications in this series have not been edited; they are released as submitted by the author.

Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 4 (TGI-4) Program (2010–2015)

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ABSTRACT

Structurally controlled "lode gold" systems within or in proximity to major fault zones (colloquially known as "breaks") represent a dominant deposit type in Canada, particularly in the Archean cratons of the Canadian Shield. This paper describes some of the critical characteristics of these deposits, specifically their relationship to the major faults and the complicated kinematic history of these faults, and to the panels of synorogenic clastic (±volcanic) rocks that occur along these faults. The synthesis that emerges is mainly based on the Timmins area, Canada's most prolific gold camp, but critical elements apply equally to and have been ground-truthed in other gold camps, i.e., Kirkland Lake, the Abitibi more generally, the Rice Lake belt, Yellowknife, and the Agnew camp of the Yilgarn craton. In all of these areas, the key faults cut early fold-and-thrust structures and were likely initiated as crustal-scale, synorogenic extensional faults in association with a flare-up in synorogenic, typically more alkaline magmatism. Extension, the associated mantle-derived magmatism, and the resulting thermal pulse into the lower crust were likely the ultimate drivers of the gold mineralizing events. Synorogenic extension also minimized post-orogenic uplift, thus playing an important indirect role in preservation of the upper crustal depositional environments. Following synorogenic extension and the initiation of the magmatic and hydrothermal processes that produced the gold systems, the crustal-scale faults were invariably inverted as thick-skinned thrusts, burying synorogenic basin remnants and gold deposits in their structural footwall, while deposits were removed or largely eroded from the structural hanging wall of these thrusts. This thrust inversion thus plays a critical role in the preservation of the gold endowment and explains the fundamental asymmetry across most of these camps. Gold mineralization appears to have peaked during the thrust-inversion stage and subsequent shortening, but had waned prior to final strike-slip overprinting of the fault zones. The integrated model provides a coherent guide for identifying and analyzing similar settings in more remote settings of northern Canada.

INTRODUCTION

The majority of gold produced in Canada has come from Archean cratons embedded within the Canadian Shield, principally the Superior and Slave cratons. Within these Archean cratons[1] economic gold mineralization is known to occur in several different settings (e.g. Poulsen et al., 2000):

1. Volcanogenic base metal mineralization with above average gold tenor (e.g. the Doyon-Bousquet-LaRonde camp: Mercier-Langevin et al., 2007).
2. Disseminated gold and gold-bearing veins within and around high-level intermediate to felsic plutons (e.g. Coté Gold: Katz et al., 2015).
3. Gold associated with metamorphism and sulphide replacement of iron formations (e.g. Lupin, Meadowbank, and Musselwhite: Lothka and Nesbitt, 1989).
4. Structurally controlled vein systems within or in proximity to major fault zones (e.g. Hollinger, Dome, Pamour, Giant Yellowknife: Hodgson, 1993).
5. Paleoplacer deposits (e.g. some basal conglomerate beds within the Huronian Supergroup, of earliest Proterozoic age: Roscoe and Minter, 1993).

Paleoplacer deposits (type 5 above), resulting from uplift, erosion, and epiclastic concentration of vein-hosted free gold (type 4), are rare in Canada but worldwide form perhaps the single largest known gold resource, the Witwatersrand gold-bearing conglomerate of South Africa (Frimmel et al., 2005). Together, the five types of gold deposits represent, in essence, the

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complete orogenic cycle from initial juvenile crust formation, to partial melting and formation of evolved felsic magmas, to metamorphism and polyphase deformation and faulting of heterogeneous crust, and finally to uplift and erosive reworking of that crust. Gold concentration thus occurs in different settings and as a consequence of a number of different processes. Nevertheless, structurally controlled vein systems within or proximal to major faults zones ("lode gold deposits"[2]) represent a dominant deposit type in Canada, both in number of deposits and in historic production (e.g. Hodgson, 1993). They include the major deposits in classical mining camps such as Val-d'Or, Kirkland Lake, Timmins, Red Lake, and Yellowknife. It is this deposit type that is being illuminated in this study. It will be shown that the majority of these deposits are the result of a complex but largely predictable sequence of processes:

- Volcano-sedimentary deposition, possibly on the edge of thinned, somewhat older crust.
- Significant early deformation and imbrication.
- Uplift and onset of synorogenic extension.
- Initiation of the major faults, as crustal-scale extensional faults.
- A coeval flare-up of extension-related alkaline magmatism.
- Heating of the lower crust and transport of fluids and magmas up the main faults.
- Formation and deepening of synorogenic clastic basins (±volcanic rocks).
- A tectonic switch back to regional shortening.
- Inversion of main extensional faults into thick-skinned thrust.
- Rapid filling and deformation of synorogenic clastic basins.
- Burial of synorogenic clastic basin remnants, and gold deposits, in the footwalls of the major inverted faults.
- Long-term preservation of gold deposits (contingent on sufficient tectonic burial).
- Slow but significant post-orogenic uplift (~10–15 km), exposing gold deposits at the present surface or bringing them to within minable depth (i.e. within ~1–3 km of the present surface).

The list above represents a "process chain" of essential processes, i.e., one is missing and economic gold deposits either failed to form or are no longer preserved. Although this general concept has been recognized before to various extents (e.g. Poulsen et al., 1992; Cameron, 1993; Hodgson, 1993), the synthesis presented here argues more explicitly for many of the critical steps, particularly the role of synorogenic extension in initiating the key faults; extension-related magmatism as a likely gold transport mechanism and a critical determinant of overall gold endowment; and thrust inversion of the main faults as essential to tectonic burial and successful preservation. Conversely, it downplays the role of some other factors that have long been thought to be important, for instance the presence of ultramafic rocks (komatiite). The model presented (see also Bleeker, 2012) is the first coherent attempt to explicitly recognize the role of synorogenic extension in an area such as the Abitibi greenstone belt in a way that is consistent with field evidence and first-order structural and stratigraphic constraints. It also brings the model for large Archean lode gold deposits closer, in terms process understanding, to models for major gold mineralization in younger tectonic environments. Finally, the model makes strong predictions for how to search for this class of deposits in less explored parts of the Canadian Shield.

STRUCTURALLY CONTROLLED VEIN SYSTEMS WITHIN OR IN PROXIMITY TO MAJOR FAULT ZONES

Gold deposits hosted by structurally controlled quartz±carbonate vein systems and their alteration envelopes, known as lode gold deposits, show a wide variation in size and styles and occur throughout the geological record (Goldfarb et al., 2001). They are particularly prolific in Archean granite-greenstone terranes, at least those that are not too deeply eroded. As the quartz veins that host much of the gold represent structural damage to the host rocks, these deposits are invariably associated with deformation of the host terranes, and commonly specific phases of deformation (e.g. Groves, 1993; Hodgson, 1993; Kerrich and Cassidy, 1994; Groves et al., 1998; Kerrich et al., 2000). Some of the smaller deposits can be scattered throughout a deformed host terrane, and represent local dilations in fold hinges or along minor faults. Hence, not all deposits of this type are necessarily associated with major fault corridors. However, in many terranes, a century of exploration, geological mapping, and mine production has shown a distinct clustering of deposits

[1]Long stabilized, ancient, heterogeneous crustal fragments composed of various granitoid rocks and deformed remnants of volcanic and sedimentary rocks, i.e., "granite-greenstone terrains", and locally deeper exhumed plutonic infrastructure, i.e., "gneiss terrains".

[2]Lode: an old English miner's term for a mineralized vein, vein system, or zone "leading"' them through unmineralized waste rocks, i.e., "a lead".

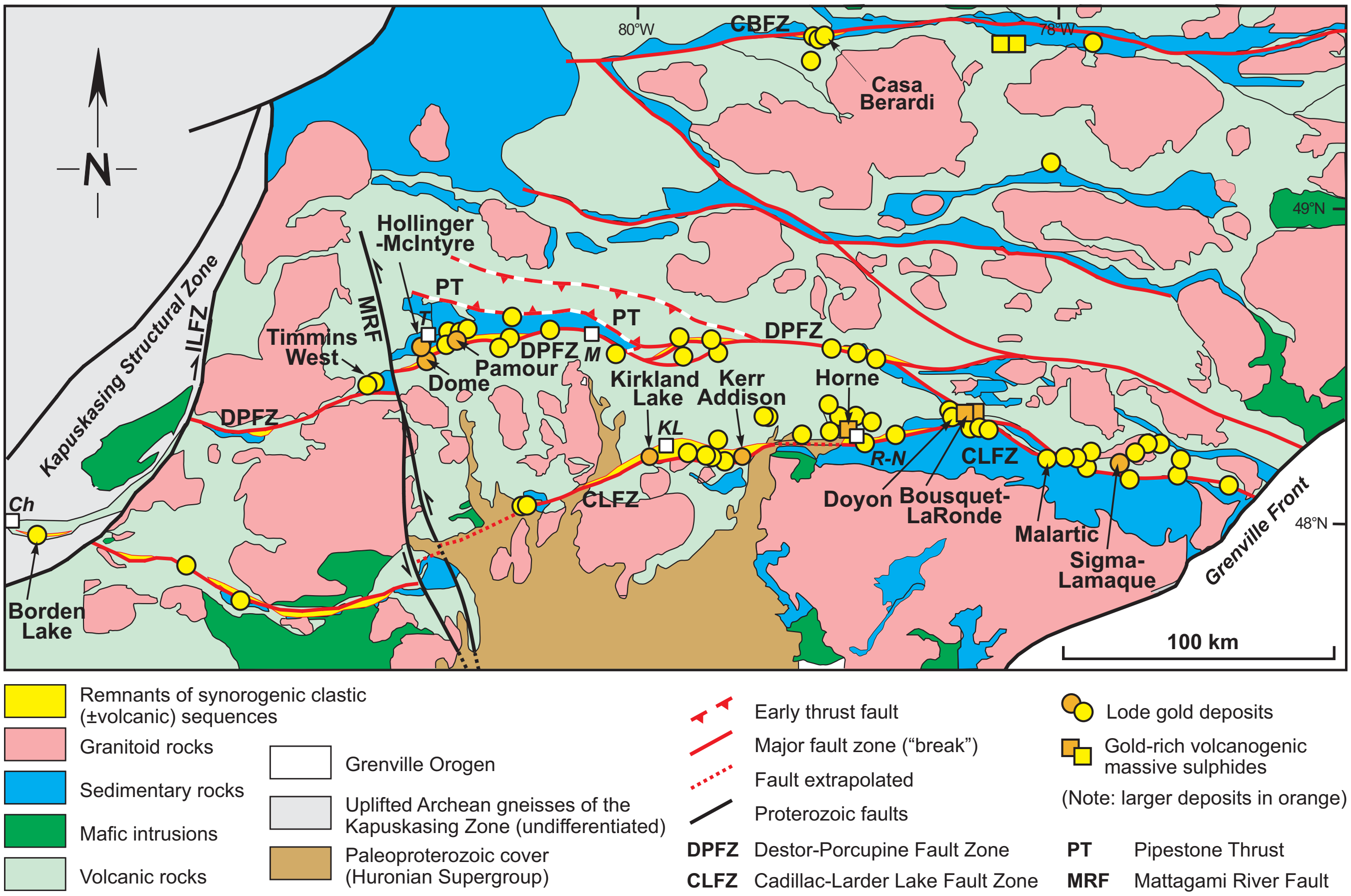


Figure 1. Simplified geological map of the central and southern Abitibi greenstone belt, highlighting the major faults and the distribution of gold deposits (modified after Poulsen et al., 2000; and Dubé and Gosselin, 2007). Abbreviations: CLFZ, Cadillac-Larder Lake Fault Zone; CBFZ, Casa Berardi Fault Zone; DPFZ, Destor-Porcupine Fault Zone; ILFZ, the Ivanhoe Lake Fault Zone; MRF, the Paleoproterozoic Matagami River Fault; and PT, the Pipestone Thrust. Towns: Ch, Chapleau; KL, Kirkland Lake; M, Matheson; R-N, Rouyn-Noranda; T, Timmins. Specifically note the two major fault zones, DPFZ and CLFZ, and the strong spatial association with gold deposits, as well as with thin panels of synorogenic clastic rocks (in yellow).

along structural corridors that are the locus of one or several major faults or fault strands (Fig. 1, Hodgson, 1993; Robert et al., 2005, and references therein). It is this important subclass of lode gold deposits, and their spatial and genetic association with the major fault corridors, that is the specific focus of this paper.

MAJOR FAULT CORRIDORS: THE "BREAKS"

Early mappers named the dominant fault traces "breaks", explicitly recognizing that they represent major discontinuities in map patterns (e.g. Knight, 1924; Gunning, 1937; Gunning and Ambrose, 1939). In the Abitibi greenstone belt of northern Ontario and Quebec, the importance and longevity of these "breaks" is demonstrated by the simple observation that few Archean rock units, not even late granites, are seen to crosscut these faults—i.e., there are few obvious "stitching plutons". In the Abitibi belt, the first rock unit to cut across the "breaks" are approximately north-trending Paleoproterozoic Matachewan diabase dykes, the oldest pulse of which has been dated at 2479 ± 4 Ma (Bleeker et al., 2012). In the southern Abitibi greenstone belt, two major "breaks" are recognized (Fig. 1): the Destor-Porcupine Fault Zone (DPFZ), and the Cadillac-Larder Lake Fault Zone (CLFZ). A third major fault zone and possibly others occur farther north and south (e.g. Casa-Berardi Fault Zone, CBFZ, see Fig. 1). Analogous structures are known elsewhere in the Superior craton and in the granite-greenstone terranes of other cratons, in each case associated with significant gold mineralization, e.g., the Yellowknife River Fault Zone of the southern Slave craton (e.g. Bleeker and Hall, 2007), or the Ida Fault Zone and its along-strike equivalents of the eastern Yilgarn craton (e.g. Duuring et al., 2012; Mole et al., 2013).

The kinematic history of these major faults is typically complex, as will be discussed later. Late transpressional deformation has deformed and steepened the faults such that, in their present attitude, they are steep to subvertical. Their map traces are typically 100s of km long and may be somewhat arcuate (Fig. 1). In

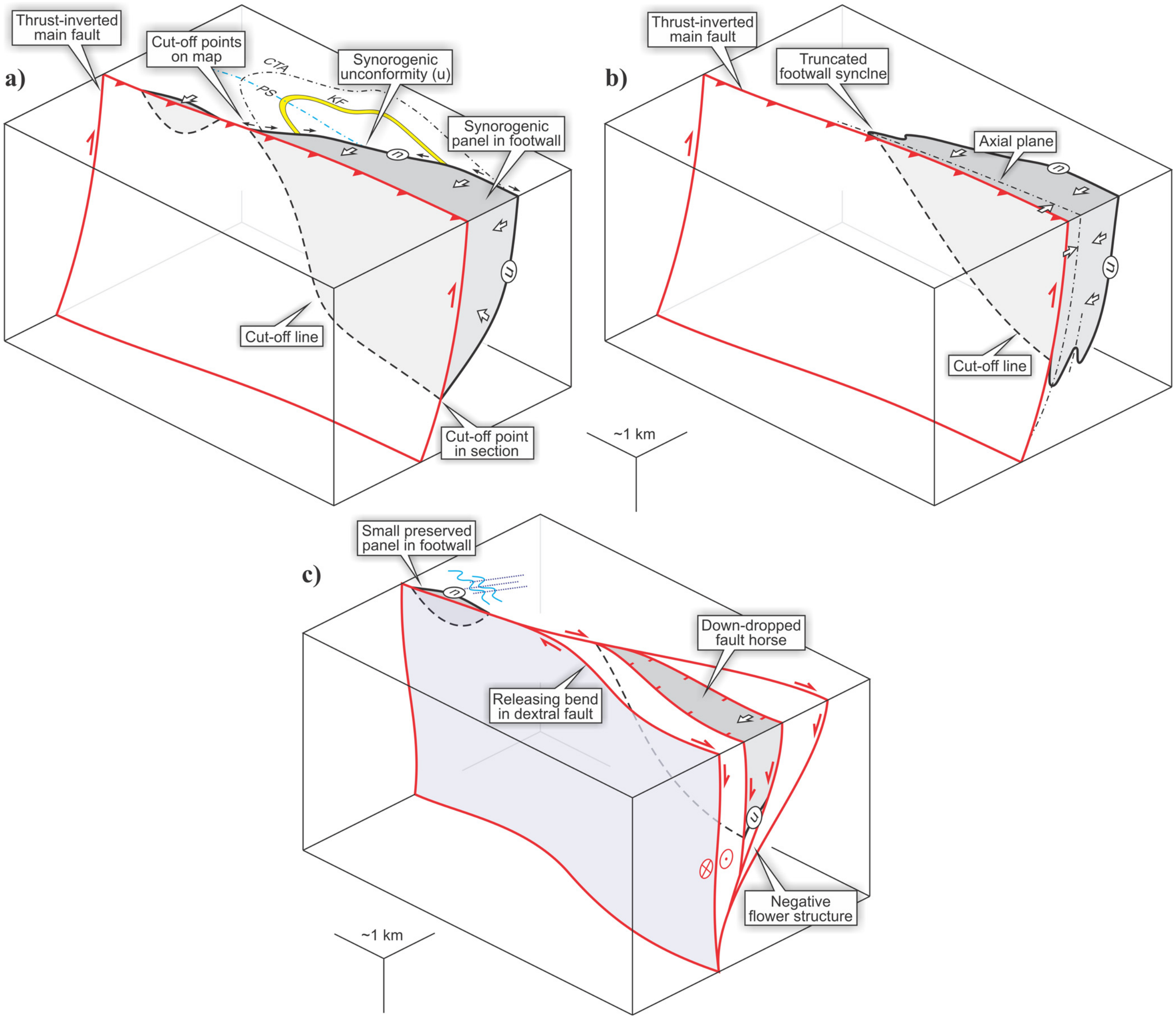


Figure 2. Typical setting of preserved panels of synorogenic clastic rocks in the footwall of a thrust-inverted main fault, either as **(a)** a truncated asymmetric panel younging one-way into the main fault, as modeled on the Timmins area, or as **(b)** a truncated asymmetric footwall syncline with minor preservation of a sheared overturned limb. The main fault is shown in red; bold white arrows show the younging direction in the clastic panel; and the bold black line is the synorogenic unconformity (u) at the base of the clastic panel. This unconformity truncates earlier structures in the stratigraphic footwall. In Timmins, these are: axial planes of early, tight to isoclinal folds (e.g. CTA, Central Tisdale Anticline); and the younger, east-plunging Porcupine Syncline (PS), both limbs of which are also truncated; shown in yellow is the ca. 2688 Ma Krist Fragmental unit (KF). Small black arrows are the facing directions projected onto the base of the synorogenic unconformity, demonstrating that two phases of folding (both the CTA and then the PS) predate the synorogenic unconformity surface (Bleeker, 1995). Note also that the down-dip extent of the synorogenic panel is determined by the "cut-off line" with the fault plane. This intersection line can be irregular, as shown in (a). Where the present erosion level reaches below this cut-off line, much of the diagnostic information on the age and kinematics of the fault is lost. **(c)** Down-dropped fault-bounded panel of synorogenic clastic rocks (grey) in a "negative flower structure", during late-stage strike-slip movement on the major fault system. This is a potential mechanism how strike-slip may have contributed to preservation.

some cases the main fault traces have been so distorted by late deformation that they may not be easily recognized as the key faults (e.g. the Rice Lake belt).

In addition to their association with gold mineralization (e.g. Hodgson, 1993), another first-order attribute of these major fault corridors is the occurrence of panels of synorogenic clastic rocks (Figs. 1, 2), as first recognized by Knight (1924). A typical occurrence of such clastic rocks consists of steeply dipping, polymict conglomerate and crossbedded sandstone (Fig. 3). At their stratigraphic base, the clastic rocks unconformably overlie previously deformed greenstone rocks (e.g. Burrows, 1924; Hurst, 1939; Wilson, 1962), whereas towards their stratigraphic top they young into the major fault zone. Where the overall structure is not too complex, it can be shown that the synorogenic clastic rocks occur in the structural footwall of the main faults, either as asymmetric truncated panels (Fig. 2a) or as asymmetric, truncated, footwall synclines (Fig. 2b). In other words, the synorogenic clastic rocks have been tectonically buried below the main faults, and these faults must have acted as thrusts during this phase of their evolution. These observations are consistent enough that they cannot be explained as local artefacts of complicated strike-slip deformation (cf. Cameron, 1993). However, it is not uncommon that late deformation has steepened the faults to vertical, or even led to local overturning of the entire geometry, such that a panel of synorogenic clastic rocks, which originally was buried below a main fault, now occupies what appears to be the structural hanging wall of this fault. Some of these typical complexities are illustrated in Figure 4, which is modeled on the structural set-up in Timmins (Bleeker, 1999). An example of highly deformed conglomerate adjacent to the main fault trace of the DPFZ in Timmins, showing dip-slip kinematic indicators, is shown in Figure 5.

THE SPATIAL ASSOCIATION BETWEEN LODE GOLD DEPOSITS AND MAJOR FAULT CORRIDORS: IS IT REAL AND WHAT DOES IT MEAN?

An important question is whether the apparent strong spatial association between lode gold deposits and major fault corridors (Fig. 1) is real? This question may seem naive but is far from trivial. A cycle of gold discovery, additional exploration nearby, drilling and more discoveries may lead to a spatial pattern that is biased simply as a function of where money was spent to drill exploration holes. If the apparent spatial association is real, it puts strong constraints on any model that aims to explain this class of gold deposits. If, on the other hand, the spatial distribution merely reflects where money was spent on drilling, it will falsely inform a possible model. So this question is important.

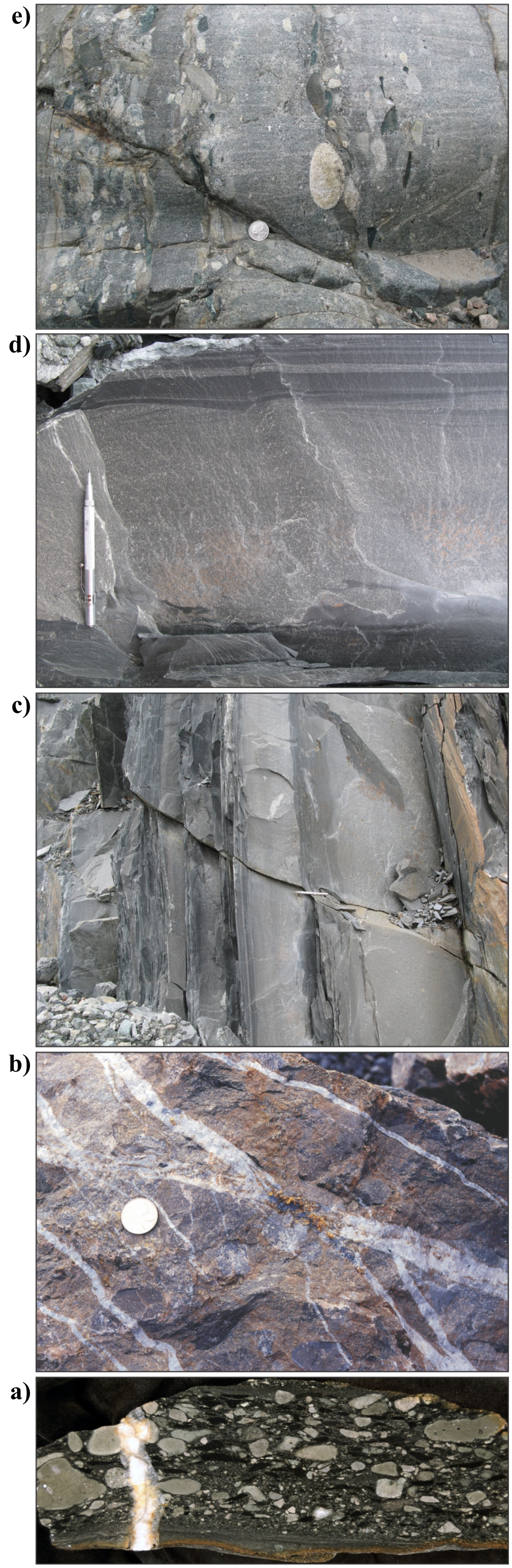
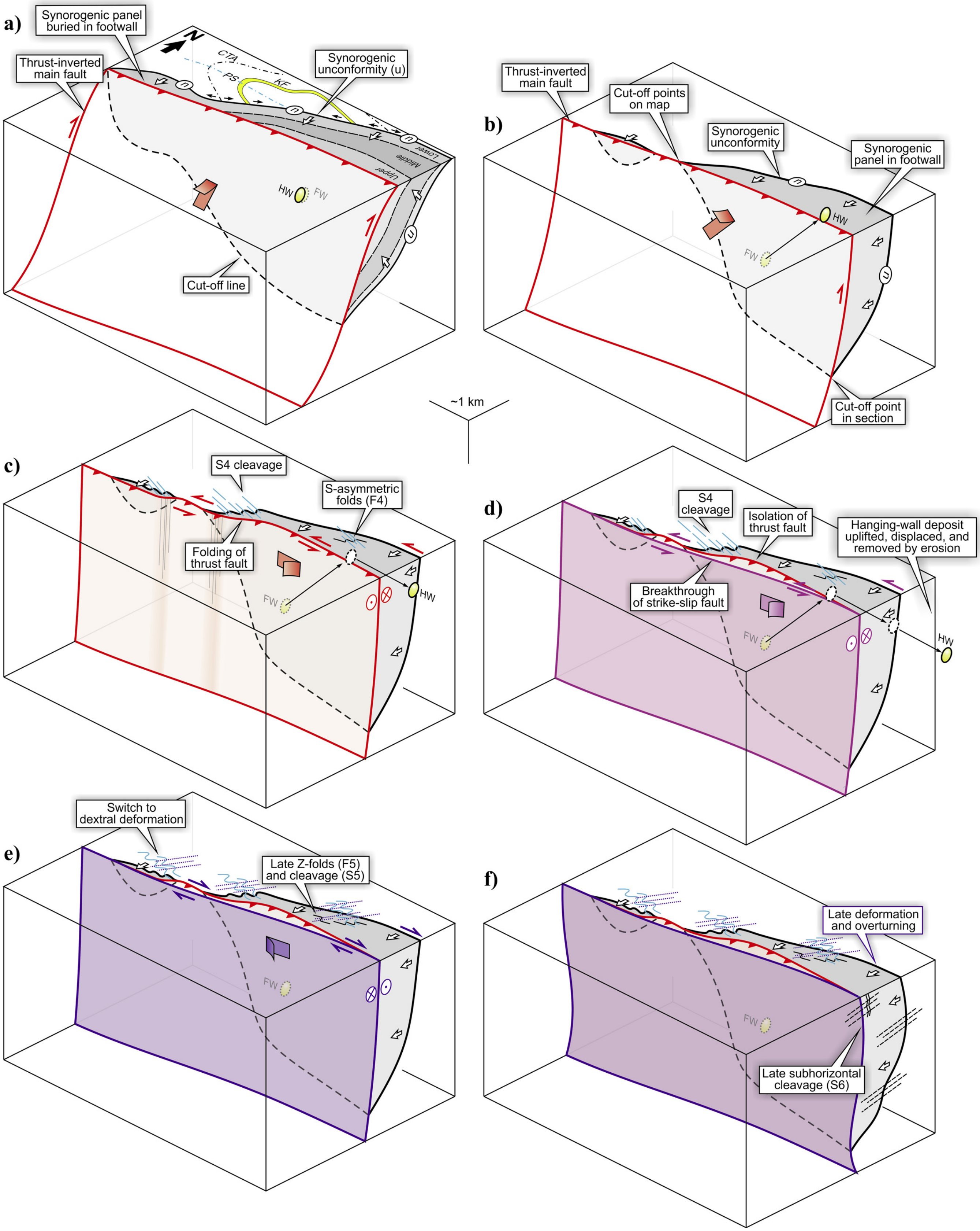


Figure 3. Representative photographs of synorogenic clastic rocks from the Timmins area. Photographs are in stratigraphic order from bottom (a) to top (e). **a)** Oligomict basal conglomerate of the synorogenic sequence in Timmins, Pamour Mine; sample is dominated by angular to subrounded mafic volcanic clasts, representing erosion and moderate transport of metavolcanic rocks from the uplifted volcanic footwall. **b)** Polymict conglomerate (the "Pamour Conglomerate") cut by intersecting quartz veins carrying gold (in the centre of the picture, with minor sphalerite). **c)** Steeply dipping turbiditic greywacke that is representative of the middle part of the sequence in Timmins. **d)** Close-up of graded greywacke-siltstone beds; note load casts at the base of the graded bed and ripple laminations near the top of the sand layer. **e)** Polymict conglomerate and pebbly sandstones, representative of the upper part of the sequence. Note the rounded plutonic clast (near the centre), which contains a pre-depositional deformation fabric.


a)
Synorogenic panel buried in footwall
Thrust-inverted main fault
N
CTA
PS
KF
Synorogenic unconformity (u)
Lower
Middle
Upper
HW
FW
Cut-off line
b)
Thrust-inverted main fault
Cut-off points on map
Synorogenic unconformity
Synorogenic panel in footwall
HW
FW
Cut-off point in section
~1 km
c)
S4 cleavage
S-asymmetric folds (F4)
Folding of thrust fault
FW
HW
d)
S4 cleavage
Isolation of thrust fault
Hanging-wall deposit uplifted, displaced, and removed by erosion
Breakthrough of strike-slip fault
FW
HW
e)
Switch to dextral deformation
Late Z-folds (F5) and cleavage (S5)
FW
f)
Late deformation and overturning
FW
Late subhorizontal cleavage (S6)

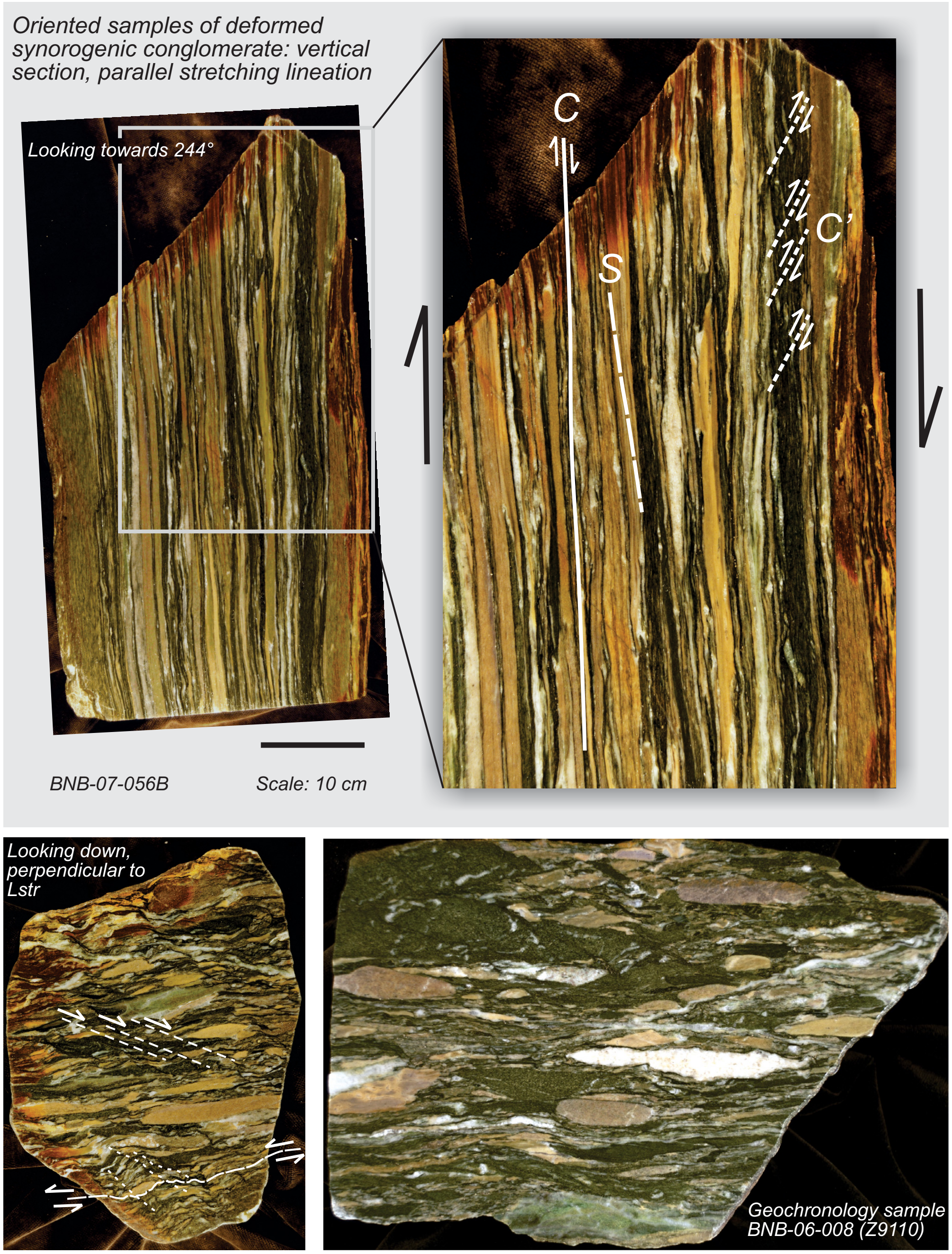


Figure 5. Cross-sectional view of highly deformed conglomerate at the stratigraphic top of the synorogenic conglomerate panel in Timmins (Buffalo-Ankerite open pit), immediately north of the steepened thrust fault. View is towards the west-southwest (244°), in a vertical section parallel to the steeply plunging stretching lineation. Kinematic indicators (low-angle C-S relationships, and late shear bands, C') indicate that the conglomerate moved down relative to the older volcanic rocks to the south of the fault. The initial thrust geometry has been severely steepened and is in fact slightly overturned. In a strict sense, therefore, the deformed conglomerate, which initially was buried in the footwall of the thrust fault, now appears to sit in the structural hanging wall of the fault, confusing the overall interpretation. Lower pictures show subhorizontal sections, perpendicular to the stretching lineation (Lstr), with two generations of strike-slip related minor structures. The picture on the right is from the conglomerate from which synorogenic detrital zircons were extracted that were dated at ca. 2675 Ma (Bleeker and van Breemen, 2011).

Figure 4 (opposite page). Illustration of the complex geometric and kinematic history of the main fault(s), modeled on the Timmins area. The six block diagrams (a to f) are ordered in time, starting with the ca. 2665 Ma thrust inversion of the main fault and burial of the synorogenic clastic sequence below the main fault plane. **a)** Thick-skinned thrust-inversion phase, details as in Figure 2. **b)** Continued thrust burial, possibly oblique, and steepening of fault plane due to north-south shortening. This figure shows a slightly deeper cut through the structure than (a). **c)** Transition to sinistral strike slip, and folding (S-asymmetry) of the steepened thrust plane (red shading). S_4 cleavage development in association with the transpressional deformation. **d)** Break-through of a new, more planar strike-slip fault (purple shading), isolating the older and folded thrust fault to the north. In Timmins, the older thrust fault is the Dome Fault, whereas the new strike-slip fault is the main DPFZ trace. **e)** Late reversal to dextral strike slip and formation of late Z-asymmetric folds and a ubiquitous northeast-trending crenulation cleavage (S_5). **f)** Further deformation of the fault geometry, with local overturning and formation of a subhorizontal crenulation cleavage (S_6). Note that due to this late deformation, the synorogenic clastic rocks now sit in the apparent hanging wall of the steeply north-dipping fault. Figures track the position of a gold deposit (yellow ovals) that forms along the fault during thrust inversion. Whereas the footwall portion (FW) of this deposit is preserved, the hanging-wall portion (HW) is uplifted (b), laterally displaced (c and d), and ultimately eroded.

In the Timmins area, the first discovery of gold at surface was made over a century ago (Doherty, 1986; Barnes, 1991) and since then numerous deposits have been found (Table 1), some highly profitable whereas others had marginal economics and were abandoned. The entire area has been intensely prospected, for tens of kilometres away from the main faults. Tens of thousands of test holes have been drilled, and numerous test shafts have been sunk. Hence, for the wider Timmins area, there has been enough random testing away from the faults that the pattern that has emerged is likely to reflect underlying processes. The same can probably be said for much of the southern Abitibi and probably also the Eastern Goldfields of the Yilgarn craton. Elsewhere the picture may be less mature or "saturated". It is thus concluded that for highly endowed belts, such as the southern Abitibi, the main faults must play a key role in any comprehensive model for the gold mineralization.

Another important observation serves to amplify this conclusion. To the north of Timmins, ~20 km north of the trace of the DPFZ, there occurs another major fault—the Pipestone fault (Fig. 1). This fault has often been portrayed as a splay fault of the DPFZ and for this reason, and for its relative proximity to Timmins, has seen equally intense prospecting and exploration. Yet no major correlation with productive gold deposits has emerged, although there are some minor deposits in the area. The reason for this distinct difference in gold endowment of the two fault zones is that they have radically different origins. The Pipestone fault, renamed the Pipestone Thrust by Bleeker and van Breemen (2011), represents an early high-level thrust fault that was subsequently folded, whereas the DPFZ was initiated somewhat later as a deep-reaching crustal-scale extensional fault, which was then inverted as a thick-skinned thrust. Although the folded Pipestone Thrust (see structural cross-section in Bleeker and van Breemen, 2011) may have seen some reactivation at critical times, it lacks the extensional history and the associated gold endowment. These important differences, despite both faults having seen a century of prospecting and drilling, underscore that the spatial pattern of Figure 1 is sufficiently saturated to be meaningful.

As part of this discussion on the reality of the spatial distribution, it is useful to introduce yet one other key observation, one which is not immediately apparent from Figure 1 because of scale. If one tabulates all the gold deposits and their production along the DPFZ, at least for that portion that occurs in Ontario, and one classifies the deposits as being situated north, within (or ambiguous), or south of the principal fault trace(s), it turns out that >>95% of all gold produced has come from one side of the fault—i.e., the north side (Table 1). For the Porcupine camp proper, essentially ~25–30 km along the DPFZ on either side of Timmins, this statistic is >99% (Bleeker, 1995). In other words, not only is the overall spatial association with the major fault zone robust, but essentially all historic and on-going gold production has come from one side (north side), or from within, the fault zone. Combining this key observation with knowledge of the initial fault geometry leads to the conclusion that essentially all gold production has come from the structural footwall of the main fault(s), i.e., from the side that also preserves the tectonically buried panels of synorogenic clastic rocks (Fig. 4).

At the time that the gold-bearing quart±carbonate veins were emplaced, there is no obvious reasons why hydrothermal fluids, or the fluid-assisted opening of veins, would be able to differentiate between footwall and hanging wall of a major fault zone and fluid conduit. The robust observation above, that essentially all gold was produced from the footwall, therefore must mean that (1) veins emplaced in the hanging wall were preferentially uplifted and eroded; and (2) thrust displacement on the principal faults must have outlasted the peak of gold mineralization. This in turn must lead to a third conclusion: (3) the transition to late-stage strike-slip dominated movement, on a steepened fault trace, largely post-dated gold emplacement. In other words, the major strike-slip displacement and transpressional deformation that is easily demonstrated on the faults (in the case of the DPFZ and CLFZ: first sinistral and then dextral; Bleeker, 1995, 1999) is late and of little bearing on a detailed genetic model for the mineralization. Strike-slip deformation is important, however, in redistributing remaining mineralization on either side of the faults by possibly tens of kilometres. In other words, the uplifted and partly eroded roots of a major mineralized gold system, if still partially preserved on the hanging-wall side of a major fault, may be displaced ~10 to 100 km laterally relative to the main part of the deposit that is preserved in the footwall. Understanding and quantifying the late strike-slip history on the faults is thus important for exploration and for finding possible complements of known deposits, but it is less important in terms of understanding the genetic aspects of the lode gold hydrothermal systems.

SYNOROGENIC BASINS AND THEIR ROLE

The typical setting of a preserved panel of synorogenic clastic rocks was introduced in Figures 1, 2, and 4. A reconstructed and generalized stratigraphy of these preserved panels is shown in Figure 6, largely based on observations in Timmins, but augmented by critical aspects from other localities in the Abitibi greenstone belt, particularly the Kirkland Lake area (Thomson,

Table 1. Gold production, to the end of 2013, in the vicinity of the Destor-Porcupine Fault Zone; modified after Bleeker et al. (2014).

Mine	Township	Years of Production	Tons Milled	Production (ounces gold)	Grade[1] (oz/ton)	Position relative to the DPFZ[2]
Aljo	Beatty	1940	2333	42	0.02	N
American Eagle	Munro	1911	60	40	0.67	N
Ankerite/March	**Deloro**	**1926–1935**	**317 769**	**61 039**	**0.19**	**N**
Aquarius	**Macklem**	**1984, 1988–1989**	**139 634**	**27 117**	**0.19**	**S**
Argyll	Beatty	1918	12 455	851	0.07	N
Aunor (Pamour #3)	**Deloro**	**1940–1984**	**8 482 174**	**2 502 214**	**0.30**	**N**
Banner	**Whitney**	**1927–1928, 1933, 1935**	**315**	**670**	**0.13**	**N**
Bell Creek	**Hoyle**	**1987–1991, 1992–1994,** **2011-2013**	**576 017** **609 670**	**112 739** **74 825**	**0.20** **0.13**	**N**
Black Fox (Glimmer)	Hislop	1997–2001, 2009–2013	5 020 823	561 645	0.11	Within
Blue Quartz	Beatty	1923, 26, 28, 34	500	81	0.16	N
Bonetal	**Whitney**	**1941–1951**	**352 254**	**51 510**	**0.15**	**N**
Bonwhit	**Whitney**	**1951–1954**	**200 555**	**67 940**	**0.34**	**N**
Broulan Porcupine	**Whitney**	**1939–1953**	**1 146 059**	**243 757**	**0.21**	**N**
Broulan Reef Mine	**Whitney**	**1915–1965**	**2 144 507**	**498 932**	**0.23**	**N**
Buffalo Ankerite	**Deloro**	**1926–1953, 1978**	**4 993 929**	**957 292**	**0.19**	**N**
Buffonta	Garrison	1981, 91–92	117 013	12 139	0.10	S
Canadian Arrow	Hislop	1974–76, 1980–83	303 449	19 140	0.06	S
Canamax Matheson Project	Holloway	1988	38 675	5391	0.14	Within
Centre Hill	Munro	1967–70	327 007	422	0.001	N
Cincinnati	**Deloro**	**1914, 1922–1924**	**3200**	**736**	**0.23**	**N**
Clavos	**Stock**	**2005–2007**	**188 743**	**24 609**	**0.13**	**N**
Concordia	**Deloro**	**1935**	**230**	**16**	**0.07**	**S**
Coniarum/Carium	**Tisdale**	**1913–1918, 1928–1961**	**4 464 006**	**1 109 574**	**0.25**	**N**
Croesus	Munro	1915–18, 23, 31–36	5333	14 859	2.79	N
Crown	**Tisdale**	**1913–1921**	**226 180**	**138 330**	**0.61**	**N**
Davidson–Tisdale	**Tisdale**	**1918–1920, 1988**	**53 221**	**9739**	**0.18**	**N**
Delnite **(open pit)**	**Deloro**	**1937–1964** **1987–1988**	**3 847 364** **56 067**	**920 404** **3602**	**0.24** **0.06**	**N**
DeSantis	**Ogden**	**1933, 1939–1942,** **1961–1964**	**196 928**	**35 842**	**0.18**	**N**
Dome	**Tisdale**	**1910–2013**	**114 624 858**	**16 361 420**	**0.14**	**N**
Faymar	**Deloro**	**1940–1942**	**119 181**	**21 851**	**0.18**	**S**
Fuller (Vedron)	**Tisdale**	**1940–1944**	**44 028**	**6566**	**0.15**	**N**
Gillies Lake	**Tisdale**	**1921–1931, 1935–1937**	**54 502**	**15 278**	**0.28**	**N**
Goldhawk **(open pit)**	**Cody**	**1947** **1980**	**636** **40 000**	**53** **3967**	**0.08** **0.10**	**S**
Goldpost	Hislop	1989	9403	2913	0.31	S
Gold Pyramid	Guibord	1911	175	36	0.21	N
Hallnor (Pamour #2)	**Whitney**	**1938–1968, 1981**	**4 226 419**	**1 645 892**	**0.39**	**N**
Hislop (Hislop East)	Hislop	1990–91, 1993–95, 1999–2007, 2010–13	1 992 346	124 373	0.062	?
Hollinger–Schumacher	**Tisdale**	**1915–1918**	**112 124**	**27 182**	**0.24**	**N**

Table 1 continued.

Mine	Township	Years of Production	Tons Milled	Production (ounces gold)	Grade[1] (oz/ton)	Position relative to the DPFZ[2]
Hollinger	**Tisdale**	**1910–1968**	**65 778 234**	**19 327 691**	**0.29**	**N**
Pamour Timmins Property		**1976–1988**	**2 615 866**	**182 058**	**0.07**	
Holloway	Holloway	1993, 95, 96–2006, 2011–13	6 091 733	946 384	0.16	Within
Holloway-Holt	Holloway	2007–2010	601 778	89 703	0.15	Within
Holt	Holloway	1988–2004, 2011–13	9 191 442	1 409 473	0.15	Within
Hoyle–Falconbridge	**Whitney**	**1941–1944, 1946–1949**	**725 494**	**71 843**	**0.10**	**N**
Hoyle Pond	**Hoyle**	**1985–2013**	**9 215 939**	**3 233 793**	**0.35**	**N**
Hugh–Pam	**Whitney**	**1926, 1948–1965**	**636 751**	**119 604**	**0.19**	**N**
Marlhill	**Hoyle**	**1989–1991**	**156 800**	**30 924**	**0.20**	**N**
McIntyre Pamour	**Tisdale**	**1912–1988**	**37 634 691**	**10 751 941**	**0.29**	**N**
Schum. (ERG tailings recovery)		**1988–1989**	**2 549 189**	**18 260**	**0.01**	
McLaren	**Deloro**	**1933–1937**	**876**	**201**	**0.23**	**N**
Moneta	**Tisdale**	**1938–1943**	**314 829**	**149 250**	**0.47**	**N**
Naybob (Kenilworth)	**Ogden**	**1932–1964**	**304 100**	**50 731**	**0.17**	**N**
Newfield	Garrison	1996	55 000	9680	0.18	Within
Nighthawk	**Macklem**	**1995–1999**	**1 479 607**	**175 803**	**0.12**	**S**
Owl Creek	**Hoyle**	**1981–1989**	**1 984 400**	**236 880**	**0.12**	**N**
Pamour # 1 (incl. pits 3, 4 and 7 and Hoyle)	**Whitney**	**1936–1999**	**45 795 863**	**4 078 525**	**0.09**	**N**
		2005–2011	**17 750 312**	**698 771**	**0.04**	
Pamour (other sources)	**Whitney**	**1936–1999**	**7 416 634**	**676 645**	**0.09**	**N**
Paymaster	**Deloro**	**1915–1919, 1922–1966**	**5 607 402**	**1 192 206**	**0.21**	**N**
Porcupine Lake (Hunter)	**Whitney**	**1937–1940, 1944**	**10 821**	**1369**	**0.13**	**S**
Porcupine Peninsular	**Cody**	**1924–1927, 1940, 1947**	**99 688**	**27 354**	**0.27**	**S**
Preston	**Tisdale**	**1938–1968**	**6 284 405**	**1 539 355**	**0.24**	**N**
Preston NY	**Tisdale**	**1933**	**2800**	**153**	**0.05**	**N**
Preston/Porcupine Pet	**Deloro**	**1914–1915**	**1000**	**314**	**0.31**	**N**
Preston/Porphyry Hill	**Deloro**	**1913–1915**	**46**	**312**	**6.78**	**N**
Ross	Hislop	1936–1989	6 714 482	995 832	0.15	S
Stock	**Stock**	**1989–1994, 2000**	**821 304**	**129 856**	**0.16**	**Within**
Taylor	**Taylor**	**2007**	**19 259**	**2043**	**0.11**	**Within**
Timmins West	**Bristol**	**2009–2013**	**2 108 651**	**308 298**	**0.15**	**N**
Tisdale Ankerite	**Tisdale**	**1952**	**14 655**	**2236**	**0.15**	**N**
Tommy Burns/Arcadia	**Shaw**	**1917**	**21**	**14**	**0.66**	**S**
Triple Lake	McArthur	1932	155	121	0.78	N
Vipond	**Tisdale**	**1911–1941**	**1 565 218**	**414 367**	**0.26**	**N**
White-Guyatt	Munro	1911	50	10	0.20	N
		Total	**388 599 637**	**72 537 028**	**0.19**	

[1]Grade: ounces of gold per ton; all tonnages have been converted to imperial units using a conversion factor of 1.1023113.
[2]Position relative to the Destor-Porcupine Fault Zone (DPFZ): N, north of fault; S, south of fault; Within, within fault zone; ?, ambiguous position or unknown.
Deposits shown in bold font are within the Porcupine Camp proper, where 99.6% of the ounces produced have come from north of or within the DPFZ. Including deposits further east (i.e. east of Matheson), ~95% of all gold produced has come from north of or within the DPFZ.
Deposits shown in red occur along the Nighthawk Lake Fault trend, a poorly understood fault trend south of the main DPFZ, and likely a splay thereof.
For the Faymar deposit (shown in blue, Deloro Twp and south of the DPFZ) there is some uncertainty of the true provenance of the quoted production.

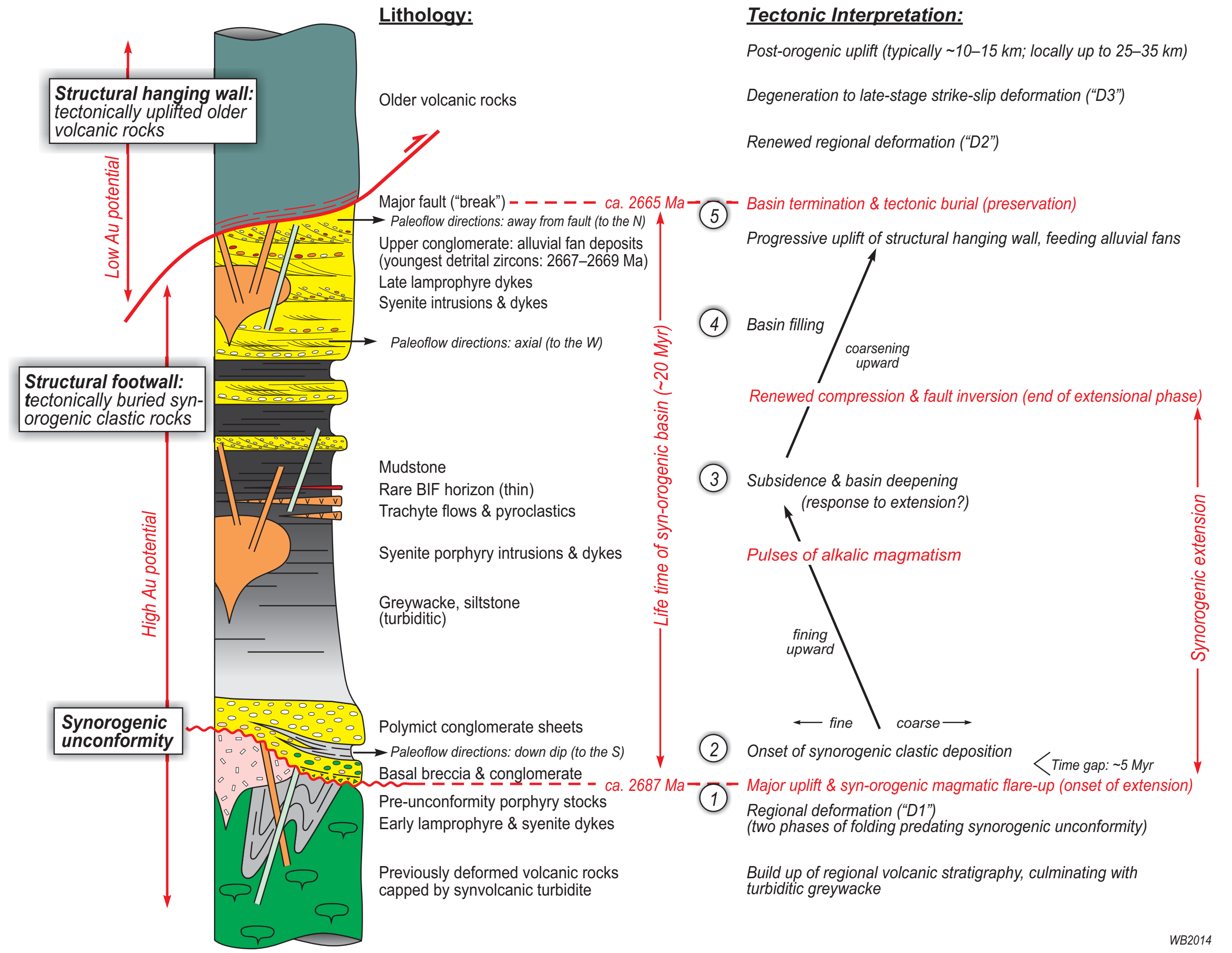


Figure 6. Stratigraphic reconstruction of the preserved panels of synorogenic clastic (± volcanic-plutonic) rocks below the main thrust-inverted faults, synthesized from both the Timmins and Kirkland Lake areas. Stratigraphic column and main lithologies are shown on the left, and tectonic interpretation is given on the right. The overall evolution or "life time" of the synorogenic basin remnants can be divided into five phases, with a total duration of approximately 20 Myr (see text for discussion). The basin remnants overlie a synorogenic unconformity at their base, and young up into a thrust-inverted main fault at their stratigraphic top. The synorogenic processes started with uplift, significant erosion, and the onset of alkaline magmatism. This phase is only recorded by early alkaline intrusions that predate the unconformity surface. The depositional record started significantly later, probably when extension-driven subsidence took over. The basin remnants then recorded a cycle of deepening, and then shallowing and basin filling, the latter indicating the onset of thrust inversion. Final thrust inversion terminates the basin and places deeper volcanic footwall rocks on top of the tectonically buried basin remnant. Gold deposits were largely uplifted and eroded from the hanging-wall side of the system, explaining the overall asymmetry in gold distribution (in Timmins >99% of gold produced from the footwall environment).

1950).[3] In the Abitibi, the total "life time" of the synorogenic basins is about 20 million years, from ca. 2686 Ma to ca. 2665 Ma. Their evolution was initiated immediately following intense folding and imbrication of the underlying greenstones, deformation that culminated at about 2688–2687 Ma ("D1" deformation phase). In more detail, the evolution of the synorogenic basin(s) can be divided into five distinct phases (see Fig. 6):

1. Following "D1" deformation: uplift and a flare-up of synorogenic alkaline magmatism.
2. Subsidence and initial deposition (and preservation) of basal clastic rocks.
3. On-going extension: basin deepening and episodic synorogenic magmatism (and volcanism).
4. Switch to renewed shortening, leading to fault inversion and basin filling.
5. Basin termination and tectonic burial.

[3] In the Abitibi greenstone belt, the synorogenic conglomerates have long been referred to as "Timiskaming conglomerates", in reference to a type locality west of Lake Temiskaming. In the present paper, these rocks are described in terms of more general processes and hence preference is given to the adjective "synorogenic" rather than a locality (and time) specific term.

Phase 1: Uplift and Flare-Up of Alkaline Magmatism (ca. 2687–2685 Ma)

The first major deformation of the volcanic stratigraphy resulted in two responses: 1) major uplift and emergence of deformed and imbricated greenstones and overlying turbidites; and 2) a switch to and sudden flare-up of alkaline magmatism. These processes are also seen in modern mountain belts following major orogenic phases. The uplift and ensuing subaerial erosion created an unconformity surface that cuts through the early fold structures. The earliest clastic deposits that overlie this unconformity surface were probably ephemeral and were removed by additional uplift and erosion. The depositional record, therefore, did not start until about 5 million years later (see Phase 2 below). The flare-up of alkaline magmatism is expressed as early lamprophyre and syenite dykes and high-level stocks, the earliest of which have been dated at 2687–2686 Ma (Frarey and Krogh, 1986; Barrie, 1990). In Wawa, along strike to the west of Timmins, ultramafic lamprophyre produced vent-facies rocks and brought mantle xenoliths and diamonds to the surface (Stachel et al., 2006; Wyman et al., 2006). South of Timmins, a major pluton of quartz syenite to alkali granite, dated at 2686 Ma (Frarey and Krogh, 1986) intrudes across early folds (Fig. 7a). Although verification of this age is in progress, the aggregate of existing ages indicates without much doubt that the transition to synorogenic processes had occurred by 2687–2686 Ma. As pre-folding rocks are known to be as young as 2690–2688 Ma (e.g. Corfu et al., 1989; Corfu, 1993; Ayer et al., 2003), this leaves a remarkable short time span (~1 million years) for the intense folding of the volcanic stratigraphy.

Phase 2: First Deposition and Preservation of Basal Clastic Rocks (ca. 2680 Ma)

Following uplift and erosional down-cutting of the synorogenic (angular) unconformity surface, the depositional record started at ca. 2680 Ma, typically with local lenses of regolithic breccia or oligomict angular conglomerate, followed by polymict conglomerate (Fig. 3a,b). In Timmins, these basal conglomerate units are only on the order of 10–20 m thick, giving way quickly to fine-grained, thinly bedded siltstones. This must reflect basin widening (e.g. from a river to a larger basin or delta), a receding shoreline, and possibly basin deepening.

Phase 3: Ongoing Extension, Basin Deepening, and Episodic Magmatism (ca. 2680–2672 Ma)

The middle part of the synorogenic sequence is dominated by greywackes and mudstones with turbiditic layering (Fig. 3c,d). Evidently, these sedimentary rocks were deposited in a more extensive and deepening basin, below wave base (~100 m, dependent on the size of the basin and wave amplitude). This stratigraphic signal is interpreted in terms of relatively rapid deepening in response to ongoing extension. This interpretation may also explain the ongoing alkaline magmatism, which in the Kirkland Lake area produced trachyte lava and pyroclastic rocks (e.g. Mueller et al., 1994). Farther east, near Larder Lake, a thin laminated iron formation is deposited at this stage of basin evolution, intercalated in dark green siltstone and intruded by synorogenic mafic dykes. In Timmins, this middle part of the sequence culminates in several metres of black mudstone.

Phase 4: Switch to Renewed Shortening, Leading to Fault Inversion and Basin Filling (ca. 2672–2669 Ma)

Following the deposition of siltstones and mudstones in the middle part of the sequence, a coarsening-upward trend is observed with a return of pebbly sandstone and polymict conglomerates (Fig. 3e), and also well developed crossbedded sandstones (e.g. the Three Nations Formation in Timmins). This coarsening-upward trend is interpreted as the end of extension and a switch to renewed compression, which led to rapid filling of the basin with coarser polymict and quartz-rich detritus. It seems likely that the major faults were being inverted as thrusts, leading to uplift of a mountain front to the south of Timmins (and also to the south of Kirkland Lake). In Timmins, paleocurrents in these upper sandstone and conglomerate units are unidirectional, from east to west, and suggest axial transport in front of the rising mountain front. In Kirkland Lake, spectacular polymict conglomerates and crossbedded sandstones at the top of the section, interpreted as alluvial fan deposits, show paleocurrents up the dip from south to north, away from the main fault trace of the CLFZ that lies to the south (i.e. transverse). Both in Timmins and in Kirkland Lake, the youngest detrital zircons that make it into these uppermost clastic rocks are 2669 Ma (e.g. Ayer et al., 2005; Bleeker and van Breemen, 2011; see also Krogh, 1993).

Phase 5: Basin Termination and Tectonic Burial (shortly after 2669 Ma)

The uppermost alluvial fan deposits are overlain, structurally, by the main fault planes, the DPFZ in Timmins and the CLFZ in Kirkland Lake, respectively. This relationship, now steep and "on end", is interpreted as inverted faults having overridden the synorogenic basin remnants, from south to north, and thus terminating their depositional history. The exact timing of this basin termination is not known in detail but the excellent agreement of youngest detrital zircon ages, at ca. 2669–2667 Ma, from several basin remnants across the

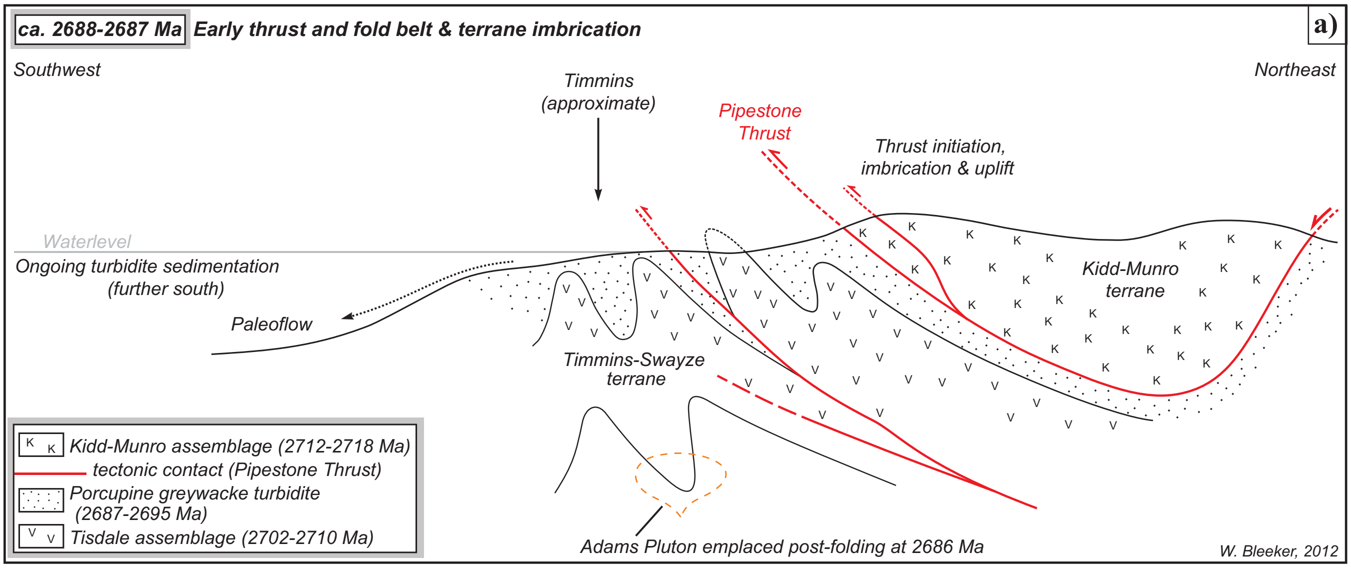


Figure 7 (above and on the following pages). Six time-sequential structural-stratigraphic sections across the southern Abitibi belt and the main fault planes, illustrating the inception of the main faults as synorogenic extensional faults, and their subsequent inversion as thick-skinned thrust faults. Only critical elements are shown, and details are not to scale. Overall view is towards the west (modified from Bleeker, 2012). Abbreviations: Au, gold; CLFZ, Cadillac-Larder Lake Fault Zone; DPFZ, the Destor-Porcupine Fault Zone; u, the synorogenic unconformity at the base of the clastic panels. **a)** Simplified section showing the early fold-thrust belt architecture affecting the south-central Abitibi greenstone belt, Timmins area, at ca. 2688–2687 Ma, just prior to the flare-up of alkaline magmatism. Porcupine Group greywacke turbidites are being fold- and thrust-imbricated with older volcanic rocks. Major thrust slices, such as the Kidd-Munro terrane, are emplaced on top of the structural pile. Overall vergence of these early folds is towards the west (southwest). There is no indication at this stage that the major "breaks", such as the DPFZ, were present. Timing is constrained by the 2686 Ma Adams pluton south of Timmins (shown in dashed outline) cutting across tightly folded stratigraphy deeper in the section.

Abitibi, suggests that it occurred shortly thereafter. Alternatively, no plutonic zircons younger than ca. 2669 Ma were available to provide a monitor of even younger depositional ages and a later timing of basin termination. The faults that terminated the synorogenic basins, and tectonically buried small basin remnants in their structural footwall, must have acted as major thrusts at this stage of their evolution. They emplaced deeper, older, and previously deformed volcanic rocks on top of the uppermost alluvial fan conglomerates.

The key faults were probably moderately steep, thick-skinned thrusts that were inverted from earlier extensional faults. These characteristics make them ideal deep-reaching fluid conduits for the advection of gold-bearing hydrothermal fluids. The thick-skinned thrust inversion had two important, and linked, consequences: 1) major thrust movement deeply buried the synorogenic basin remnants in their footwall, preserving them against substantial post-orogenic erosion; and 2) at the same time, substantial uplift of the hanging wall brought deeper rocks, and gold deposits, to the surface and exposed them to erosion. It is this footwall (preservation) versus hanging-wall (uplift and erosion) asymmetry that explains the distribution of gold deposits in Timmins (and Kirkland Lake) with >99% of all the gold having been produced from the northern footwall side of the principle fault systems.

SYNTHESIS: AN INTEGRATED MODEL

Here the main elements of an integrated model are outlined that explains essentially all the key observations. This is done most easily by means of a time sequence (from old to young) of six schematic sections (Fig. 7a-f). This sequence starts at ca. 2688 Ma (Fig. 7a) with the onset of major deformation in the volcanic stratigraphy and immediately overlying Porcupine Group turbiditic greywackes (Bleeker and Parrish, 1996). There is no indication, either from the distribution of stratigraphic rock units and facies, or from structures, that the principal faults (DPFZ and CLFZ) were present at this time. The sequential sections then illustrate the onset of extension and the inception of the main faults (Fig. 7b); uplift and somewhat later formation of the synorogenic clastic basin(s); a subsequent switch back to regional shortening and inversion of the main faults as thick-skinned thrusts (Fig. 7c); tectonic burial of synorogenic basin remnants below the faults (Fig. 7d,e); and final degeneration of the fault system to late-stage strike slip (Fig. 7f).

In some of the later structural sections, the distribution of gold deposits (yellow stars in Fig. 7) and the overall envelope to gold mineralization (bold yellow outline in Fig. 7) are shown. The envelope to gold mineralization is simply a function of two key parameters: 1) vertical: gold deposition is concentrated in the near-

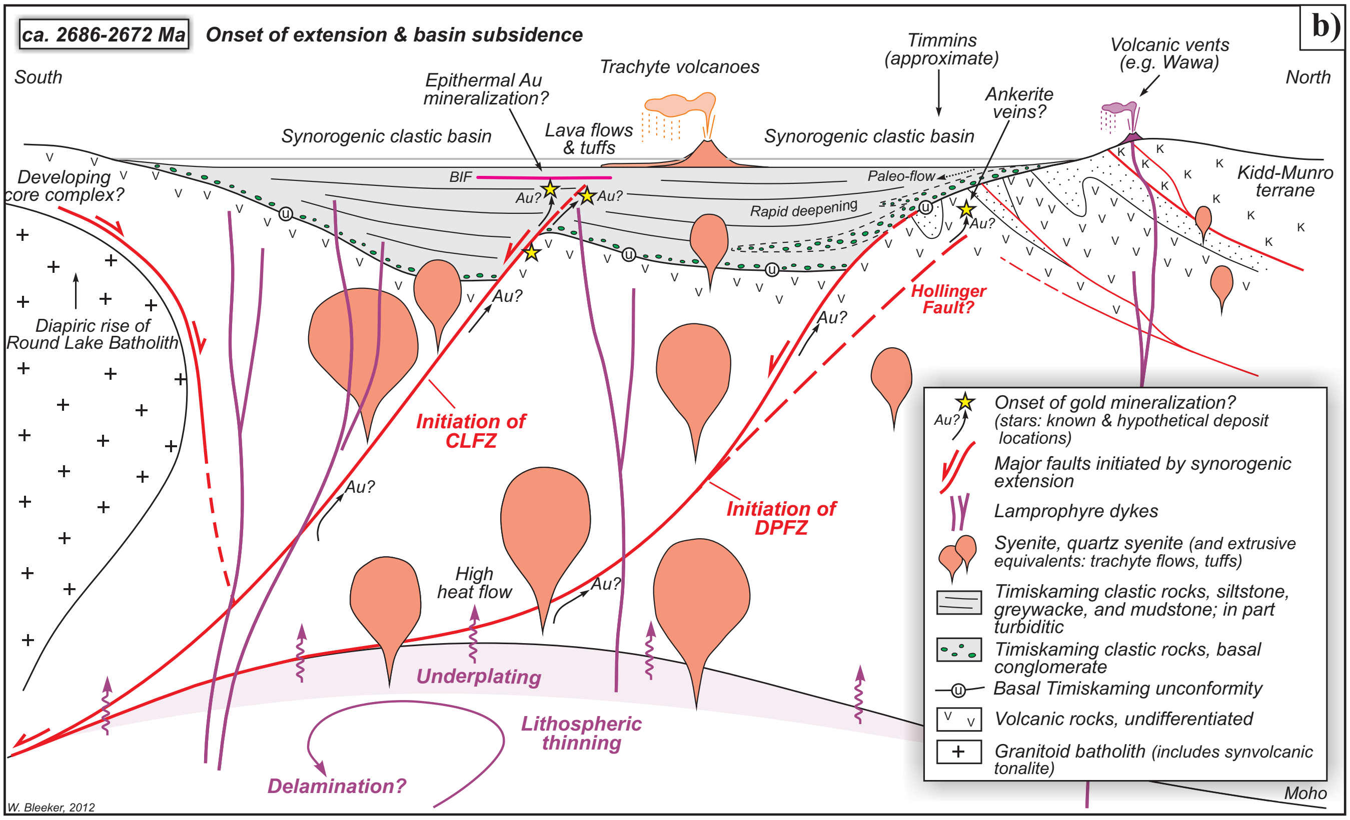


Figure 7 continued. b) Formation of synorogenic clastic basins at ca. 2680 Ma. Rapid deepening of these basins, as well as the sudden flare-up of alkaline magmatism, suggests a link with extension and upper mantle processes (delamination?). The major "breaks", i.e., the DPFZ in the north and the CLFZ further south, were likely initiated at this time as crustal-scale extensional faults, listric to the south. Numerous syenitic plutons were emplaced and lithospheric thinning increased the heat flow into the lower crust. During this extensional deformation, composite granitoid batholiths, such as the Round Lake batholith, rose diapirically, their ascent aided by additional extensional shear zones.

surface environment where pressure and temperature gradients were highest, and low confining pressures allowed the dilation and opening up of veins systems; and 2) horizontal: because the faults acted as principal conduits for hydrothermal fluids from deep reservoirs, gold mineralization peaks in proximity to the fault traces. The resulting envelope is fundamentally asymmetric because the fault system is asymmetric; and this asymmetry increased during thrust inversion, with uplift of the structural hanging walls. In the final section, now also incorporating the complications imposed by significant strike-slip, the distribution of gold deposits (yellow stars in Fig. 7f) is projected as accurately as possible and reflects the statistic that >99% of gold has been produced from within or north of the principal faults, i.e., from the structural footwalls.

The schematic sections also highlight the distribution of synorogenic magmatic rocks, both syenite suite intrusions (and minor extrusives) and lamprophyre dykes, with an origin that was likely tied to extension and perturbations of the mantle lithosphere (delamination?). Prolific syenite suite magmatism likely played a critical role, at some level, in overall gold transport from the upper mantle and deep crust; although final fluids likely represented mixtures of both magmatic fluids and metamorphic fluids (see also Cameron, 1993). At the camp scale, overall gold endowment probably scales with the intensity (or volume) of synorogenic magmatism.

DISCUSSION

Why is Extension so Important?

It is useful to return to this question, because the answer is complicated. Empirically, as well as from an understanding of younger gold deposits, there is often a direct or indirect connection with synorogenic alkaline magmatism (e.g. Richards, 1995). Furthermore, the switch to more alkaline synorogenic magmatism represents a change in overall tectonic regime, from steady-state subduction or accretion to a regime of extension. The onset of extension is often linked to perturbations of the mantle lithosphere, and it is these perturbations that are fuelling the alkaline magmatic flare-up (Fig. 7b). Although far from a perfect analogue for Archean lode gold deposits, the very large Carlin gold province of the western USA (Cline et al., 2005) is important in this respect. This province has a long tectonic pre-history of 1–2 billion years, but gold miner-

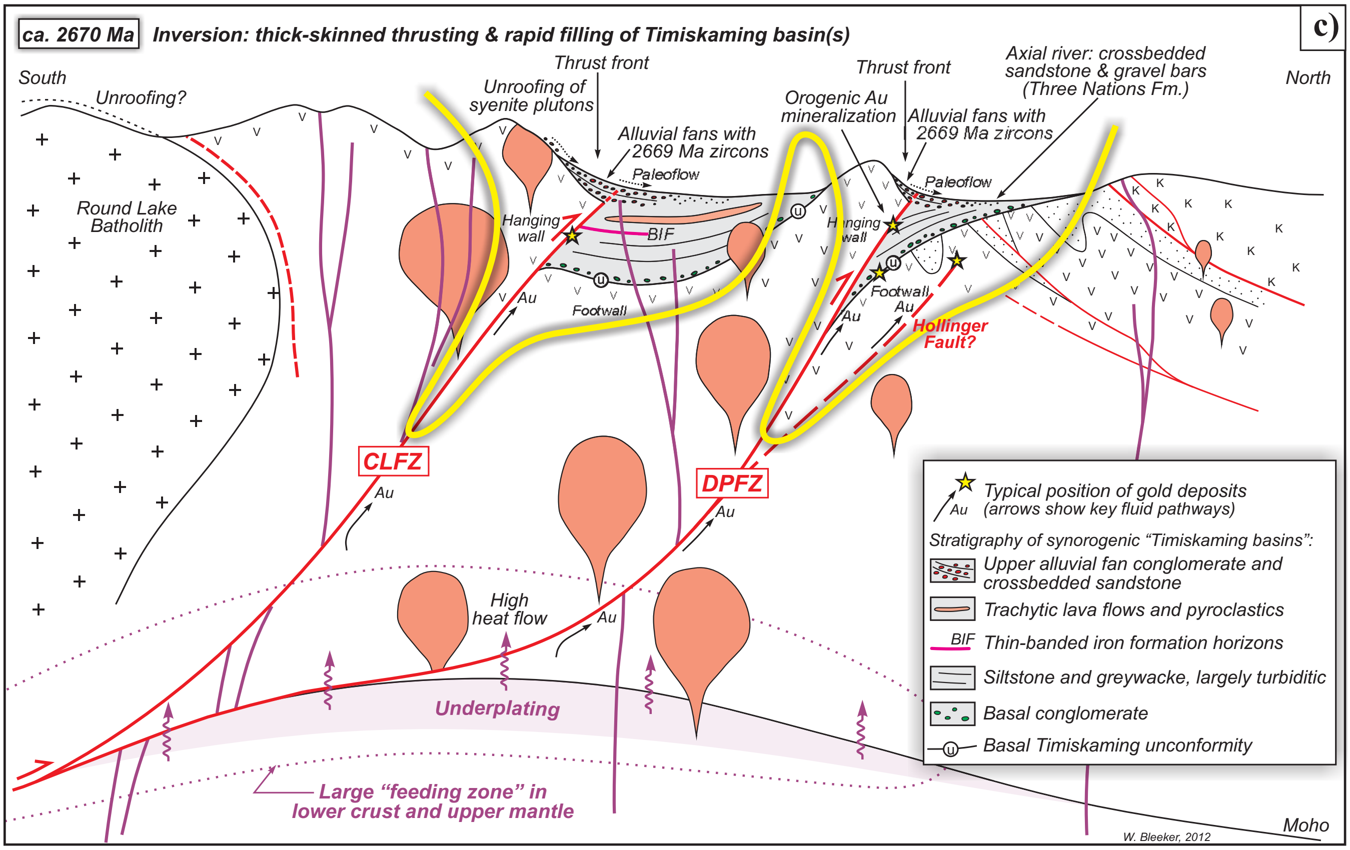


Figure 7 continued. c) Transition from extension to renewed north-south shortening at ca. 2670 Ma, with the major breaks being inverted as thick-skinned thrusts, overriding and burying remnants of the synorogenic clastic basin in their footwalls. Rising mountain fronts were flanking the basin remnants on their south side, shedding alluvial fans to the north. Conglomerate and crossbedded fluvial sandstone filled the basin. This stage is dated by precise ages (2669 Ma) on detrital zircons that were captured in the uppermost alluvial fan conglomerates. Yellow stars show the position of gold deposits forming along the faults, which acted as the principal fluid conduits. The bold yellow envelope outlines the favourable ground for gold mineralization, its asymmetry being a function of the intrinsic asymmetry of the fault system. Gold deposits formed near the synorogenic surface and in proximity to the inverted extensional faults.

alization only initiated in the Paleocene when extension and coeval magmatism overprinted the broad active margin of western North America (e.g. Cline et al., 2005). Extension is also critical because it creates or reactivates relatively simple, deep-reaching faults that provide ideal conduits for advection of gold-bearing hydrothermal fluids from large fluid-generation zones in the deep crust or even upper mantle (e.g. Bierlein et al., 2006). Furthermore, extension leads to thinning of the crust and lithosphere, rapidly increasing the geothermal gradient. This leads to fluid generation in the lower crust. Finally, extension has a subtle but critical link to final preservation. As gold deposition is strongly concentrated in the upper crust (at synorogenic time; Fig. 7b,c), potential deposits are sensitive to the degree of post-orogenic uplift. A scenario of multiple phases of crustal shortening will only thicken the crust and lead to substantial post-orogenic uplift, and thus erosion of the mineralized upper crust. Synorogenic extension counter-balances orogenic thickening and minimizes post-orogenic uplift, thus leading to preservation of the gold depositional sites in the shallow crust.

Thrust Inversion—Why is it Important?

The answer to this question is straightforward and revolves largely around preservation. As gold deposition is strongly skewed towards the upper crust (at synorogenic time), this upper crustal section needs to be preserved. Tectonic burial, with thick-skinned thrust burial of upper crustal sections in the footwall below the main faults, is a very efficient process. The synorogenic clastic rocks can be thought of as a proxy for the surface at synorogenic time (e.g. Fig. 7c). Their presence indicates successful burial of the mineralized upper crustal section and thus long-term preservation. The synorogenic conglomerate and the underlying unconformity, long recognized empirically as being important (e.g. Hodgson, 1993; Robert, 2001), do not play any more significant, deeper, process role; they simply indicate (1) preservation of the optimum crustal level; (2) proximity to a major fault that achieved this

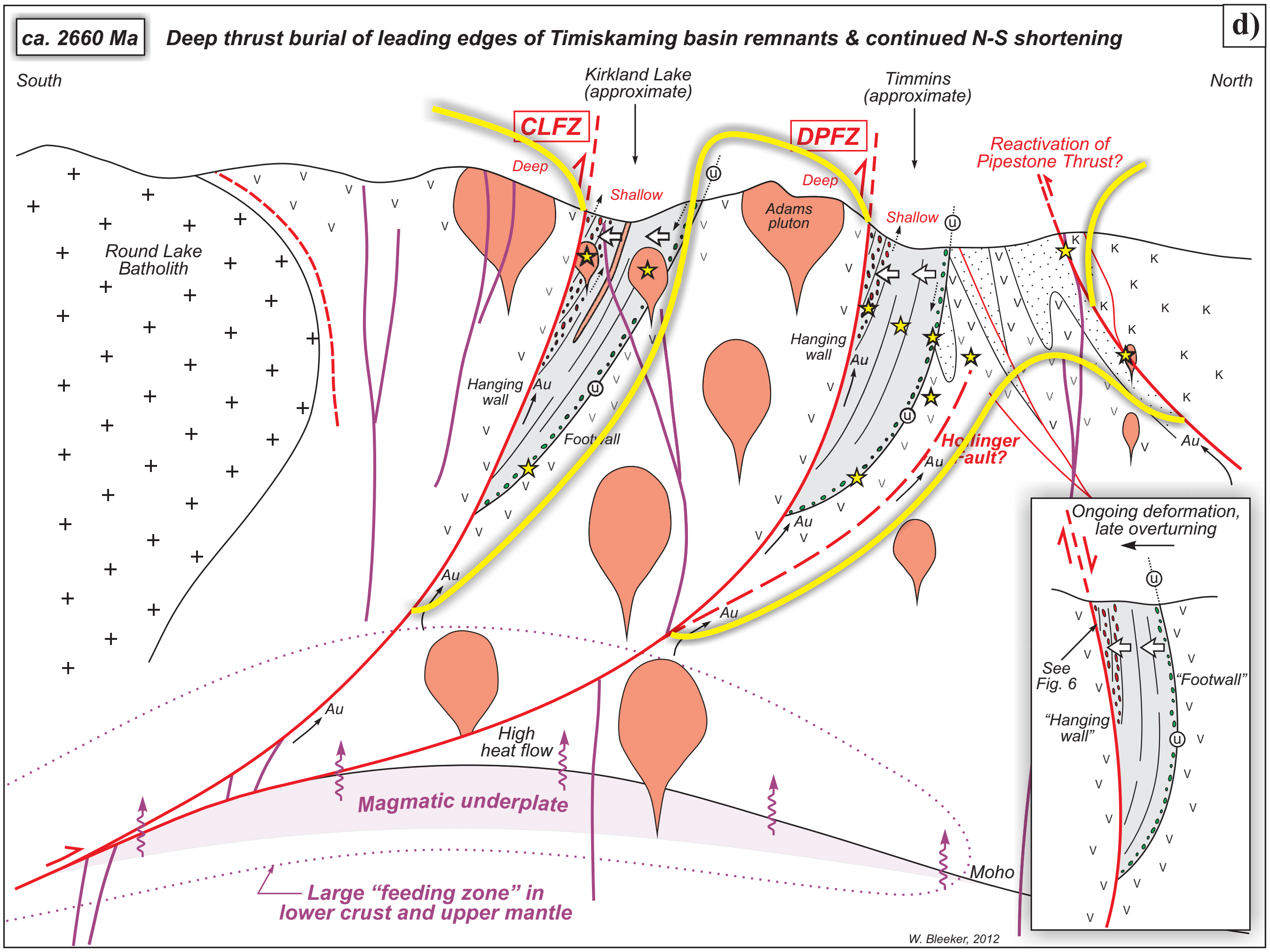


Figure 7 continued. d) Deep burial and steepening of the basin remnants underneath the thick-skinned thrusts. Deeper exhumation of the southern structural hanging walls is indicated by generally deeper tectono-stratigraphy and larger plutons being exposed south of the faults. Substantial thrust motion has now also offset the mineralization envelope (see bold yellow lines), increasing the asymmetry across the faults system. Continued north-south shortening steepened all structures to near vertical, and likely also reactivated other discontinuities (e.g. the earlier Pipestone Thrust). Locally the basin remnants and bounding structures were overturned, leading to confusing kinematics (see inset; see also Figs. 4 and 5). Approximate positions of gold deposits are again indicated by yellow stars. Note their strong asymmetry with respect to the main faults. Bold arrows (white) indicate the overall younging direction in the fundamentally asymmetric panels of synorogenic clastic rocks captured below the faults (i.e. structural footwall).

preservation—i.e., a major fault with significant late-stage thrust motion, and likely an inverted extensional fault; and (3) the overall asymmetry of the fault system—i.e., preserved footwall versus uplifted hanging wall (Fig. 7c,d,e).

Diapirism?

Late-stage diapirism and rapid sinking of intervening greenstone keels between composite granitoid domes is another process that could achieve efficient tectonic burial and thus long-term preservation of upper crustal synorogenic environments (Bleeker, 2002a,b; Lin et al., 2013). Indeed some gold deposits may owe their fluid generation and subsequent preservation to this process. In general, however, the diapir model would predict that synorogenic clastic sections young away from rising diapirs, whereas in the Abitibi greenstone belt, where diapirs are present (e.g. Round Lake batholith, Fig. 7), the opposite is observed. Also, diapiric granitoid domes are lacking in many localities along the laterally extensive principal fault traces. Thrust inversion and associated tectonic burial is therefore the more general mechanism.

When Did Gold Mineralization Peak and the Relevance of Strike Slip?

Although many gold camps show a diversity of deposits, and likely some variation in the timing of gold emplacement, simple crosscutting relationships often argue for a relatively late emplacement of the gold vein systems, from the time of first emplacement of synorogenic plutons hosting disseminated mineral-

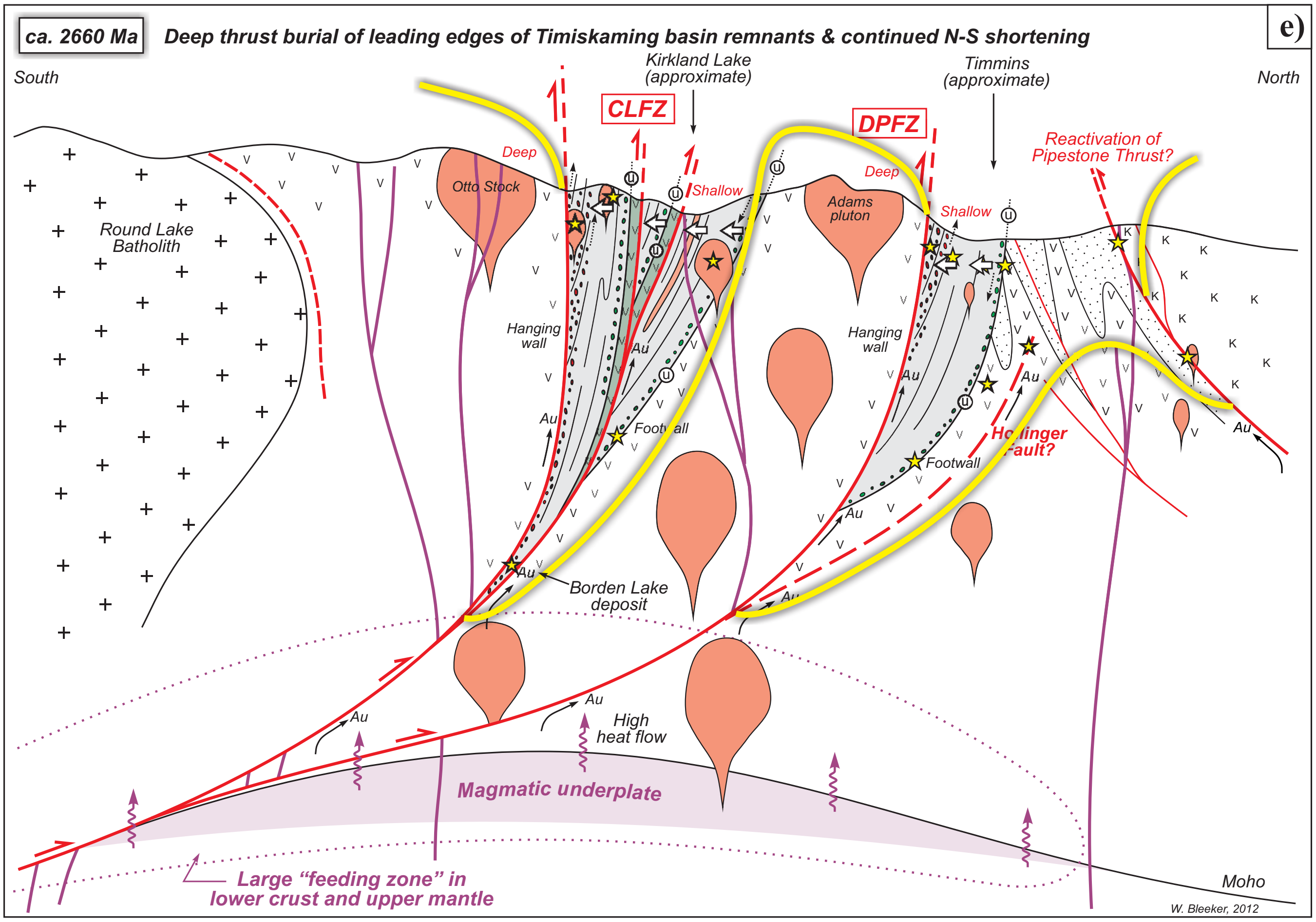


Figure 7 continued. e) This section shows an important variant on the previous section, now incorporating one or more duplex structures within the thrust architecture of the overall synorogenic basin panel below one of the faults (CLFZ). Duplex structures, or stacked thrust slices, are a common consequence of thrust faulting. Slivers of footwall volcanic rocks (highlighted in green) have been incorporated in these thrust slices, creating the observed interleaving of altered mafic-ultramafic volcanic rocks (e.g. Piché Group in Quebec) and synorogenic clastic rocks along some of the faults. Note also the deep tectonic burial of the leading edge of the synorogenic basin panel (and associated gold deposit) below the southern fault. This is essentially the position of the newly discovered Borden Lake gold deposit in the deeply exhumed Kapuskasing Zone near Chapleau (see Fig. 1).

ization to late sub-horizontal veins systems that must post-date much of the steepening of the synorogenic clastic sequences. At the scale of the Abitibi greenstone belt, however, the critical statistic that >95% of all gold comes from one side of the fault systems must mean that most of the gold was emplaced prior to the cessation of the thrust inversion and well prior to the final transition to strike-slip dominated fault motion.

Hydrothermal fluids coming up along a steep fault conduit do not differentiate between footwall and hanging wall, and gold distribution would likely occur on either side. If the fault zone is mainly one of strike slip, gold mineralization would merely be translated sideways and there is no mechanism to favour preservation largely on one side of the fault systems. In fact, strike-slip faulting does not have any preservational aspect and does not explain the systematic deep burial of the synorogenic clastic rocks.

Given that the historical production figures are so strongly skewed (>95% from footwall or within faults), most if not all the gold must have been emplaced either during the extensional phase or during the subsequent thrust-inversion phase, with very little additional gold emplacement during the strike-slip phase. Late-stage strike-slip fault offsets just rearranged the remaining gold endowment laterally—thus complicating the overall picture—but cannot have contributed to overall gold endowment. One exception may involve the formation of "negative flower structures" along some of the major faults, dropping down fault slices during late strike-slip movement, and thus possibly contributing to preservation of higher structural levels (Fig. 2c).

Delayed Gold Mineralization Relative to Extensional Drivers?

Although the detailed timing of gold-bearing quartz vein systems is incompletely known, even in places like Timmins, it seems likely that most of the vein sys-

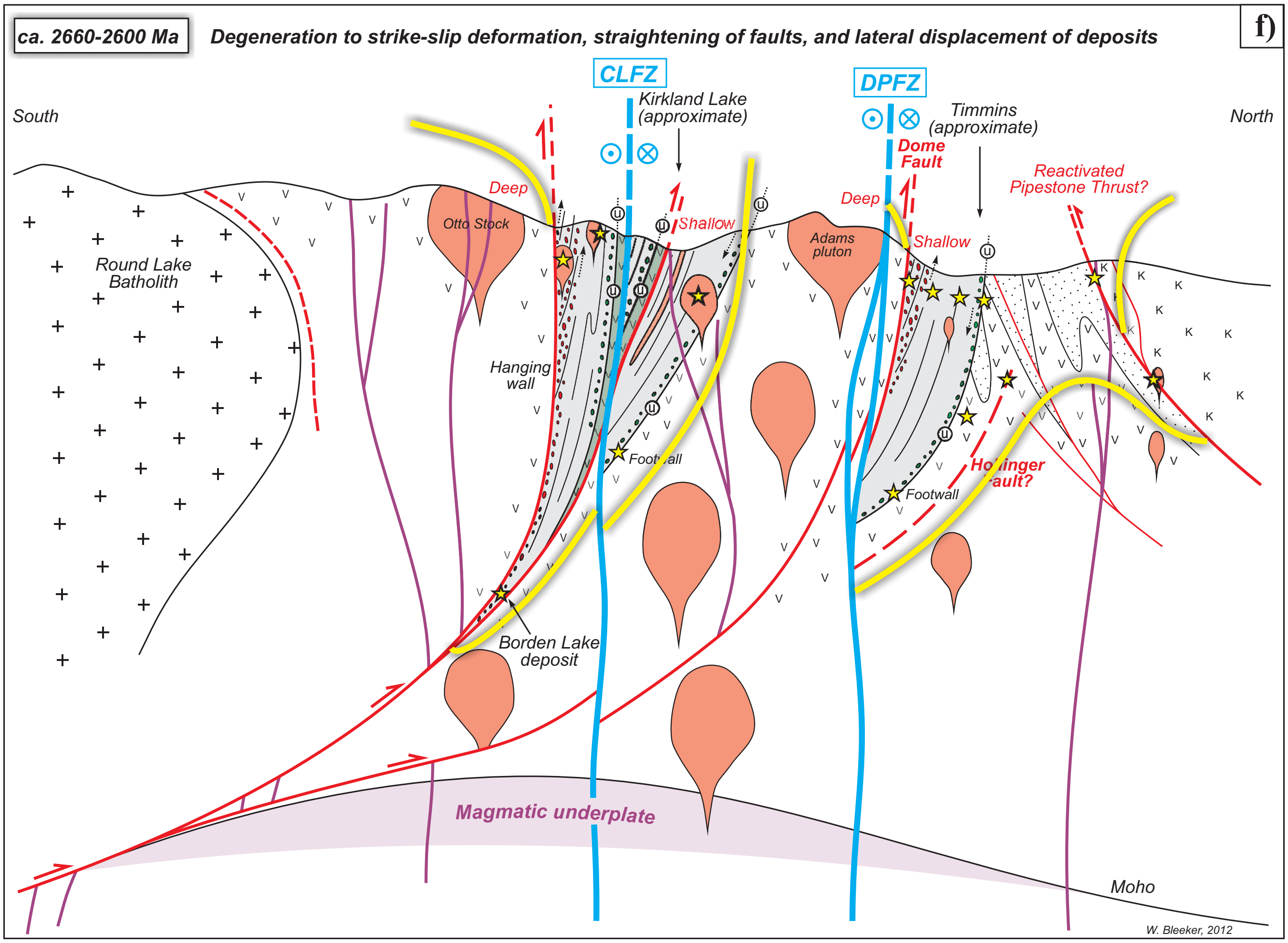


Figure 7 continued. f) Degeneration of the fault systems to strike-slip fault zones. Major strike-slip fault planes (in blue), now typically mapped as "the breaks", broke through to minimize local asperities. Locally the fault planes may follow and overprint the earlier steepened thrust structures, but elsewhere they deviate from and isolate the main thrust faults in separate slices, such as the Dome Fault in the Dome Mine, Timmins. Hence, in some cases the fault trace referred to as "the break" is actually not the most important fault of the system. Staying with the example of the Dome Mine near Timmins (illustrated above), it is the Dome Fault (red) that is the key structure and it is mineralized. In contrast, the DPFZ (in blue) broke through later, further to the south, and is a barren strike-slip fault zone. Both in Timmins and Kirkland Lake there is evidence for early sinistral strike-slip, followed by a latest phase of dextral strike-slip deformation (not shown here, but see Fig. 4e). Net offsets, determined by matching pairs of the most likely piercing points on either side of the principal faults, indicate large sinistral net displacements (e.g. ~10–100 km).

tems came in during the thrust-inversion phase given the ubiquitous observation of shear veins with reverse kinematics (e.g. Colvine et al., 1988). Yet, the overall engine driving the gold mineralization—i.e., extension, faulting, extension-related magmatism, and the ensuing thermal pulse—was initiated earlier. Why this apparent delay of approximately 10 to 15 million years? The most likely answer to this important question is that thermal processes, particularly at somewhat larger distance scales, have a time delay due to the slow thermal conductivity (or diffusivity rather) of silicate rocks. Thermal effects of the extension-related magmatism and initial thinning of the lithosphere may only have reached their maximum at a time when the tectonic regime had already switched back to compression. So, while significant volumes of fluid were still being generated deep in the crust, the main faults were already being reactivated as thick-skinned thrusts. Hence the observed time delay. Nevertheless, there likely were some early high-level epithermal deposits, or late-stage magmatic deposits in syenite suite plutons, that formed during the peak of extension (Fig. 7b). The delicately banded ankerite veins of the Dome Mine, i.e., the "Kurtz veins" with colloform growth forms indicating open-space filling (e.g. Rogers, 1982), were likely part of an early, synextensional mineralizing phase. Being emplaced early during the extensional phase, the veins experienced the initial uplift and were partially eroded into the synorogenic debris of the basin. Clasts of ankerite veins have been reported from the overlying conglomerate at the Dome Mine (Dubé and Gosselin, 2007).

CONCLUSIONS

A comprehensive model has been developed that explains the intricate relationships between major faults, remnants of synorogenic basins, the distribution of major gold deposits, and the fundamental asymmetry in this distribution relative to the fault traces. In detail, the model is based on extensive observations in the classic Timmins and Kirkland Lake gold camps, Ontario, but it has been tested in other areas such as the Yellowknife belt, Northwest Territories, and the Agnew-Wiluna belt, Western Australia. The model explicitly recognizes the role of synorogenic extension in an area such as the Abitibi greenstone belt in a way that is consistent with field evidence and first-order structural and stratigraphic constraints.

Synorogenic extension initiated the major faults, and was intimately linked to upper mantle processes, a flare-up in alkaline magmatism, increased heat flow into the lower crust, and synorogenic basin development. Synorogenic extension also helps to minimize post-orogenic uplift, thus contributing to preservation of upper crustal environments where gold mineralization is concentrated. Later inversion of the deep-reaching extensional faults, as thick-skinned thrusts, tectonically buried and preserved the upper crustal sections, including gold deposits and synorogenic basin remnants, in the structural footwall of the principal faults. Significant uplift of the hanging walls of these faults removed synorogenic rocks and gold deposits from that side of the faults. This explains the fundamental asymmetry in the distribution of gold deposits, with >99% of the gold having been produced from the footwall side in an area such as Timmins. Similarly, in Yellowknife and the Agnew camp, all gold production has come from the footwall side. Preservation of this marked asymmetry across the principal fault traces must mean that gold mineralization likely was initiated during extension and then peaked before the end of the thrust inversion phase. Late-stage strike-slip, although important in all these areas, has no mechanism to explain this asymmetry in gold distribution. It merely complicated the overall picture by having redistributed remaining mineralization laterally.

Extension, mantle-related magmatism, increased heat flow, and the formation of major faults as crustal-scale fluid conduits, probably represent the overall engine that drove the gold mineralization events. At the belt scale, gold endowment probably scales with the volume of synorogenic (alkaline) magmatism (see also Spooner, 1991). As many of the vein systems were emplaced during thrust inversion, the apparent delay between peak extension and peak gold mineralization (~10–15 Myr) was likely caused by the slow thermal diffusion in the lower crust.

How can these new insights be used to more effectively explore more remote parts of the Canadian Shield? A straightforward approach would assess all the conglomerates and major faults across the north against the model describe herein. Where the occurrence of demonstrable synorogenic conglomerates "intersects" (in a Venn diagram sense) with major faults: what is the local asymmetry of the system? What is the footwall versus hanging wall? Next, the granitoid rocks in promising areas would need to be re-evaluated. Are there any mantle-derived synorogenic plutons (e.g. syenite, monzonite, quartz-monzonite)? Are there any coeval lamprophyre dyke swarms? And what is the overall degree of post-orogenic uplift? Areas that pass all these test should then be reassessed in terms of the gold content in surficial materials (stream and lake sediments, and till). With a more complete understanding of these systems, advanced exploration will be able to focus on the most productive part of the systems, i.e., the structural footwalls.

ACKNOWLEDGEMENTS

Observations and ideas presented in this paper have been assembled over many years, with much of the funding provided by the Geological Survey of Canada through its TGI-3 Abitibi and TGI-4 Lode Gold projects. Support from several mining companies in the Abitibi is acknowledged. Access to their properties, and drill core, as well as in-depth discussions with their geological staff, has been critical in elucidating the full complexity of the fault systems. I would like to acknowledge numerous discussions with colleagues at the GSC and OGS, particularly Benoît Dubé (GSC). Thanks also to Brian Atkinson, long-time Resident Geologist of the Ontario Geological Survey in Timmins. Brian's enthusiasm and readiness to co-lead yet another field trip in the Timmins area will be sorely missed now he has retired. Patrick Mercier-Langevin and Valérie Bécu contributed comments and corrections to this paper on a short time frame. Elizabeth Ambrose handled the final editing and lay-out of the manuscript.

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