Synchronous vertical and horizontal tectonism during the late stage of Archean cratonization: An important process in gold mineralization?

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Abstract. Both vertical and horizontal tectonism played an important role in Archean tectonic evolution. These two processes have independent driving forces and should not be mutually exclusive. In the Superior Province in Canada, there is convincing evidence for synchronous vertical and horizontal tectonism at the late stages of Archean cratonization, and horizontal shearing (a result of horizontal tectonism) is concentrated in synclinal keels (a result of vertical tectonism). The Timiskaming-type sedimentary rocks were deposited in the keels during this process. The synclinal keel-shear zone association provided a link between the upper crust and the lower crust or mantle, and might have served as a conduit for mineralizing fluids and magma that were generated in the crust and/or mantle during the process. Such a process in the late stage of Archean cratonization can readily explain the common association of gold deposits with greenstone belts in synclinal keels, shear zones, late felsic to intermediate intrusions and Timiskaming-type sedimentary rocks.

Keywords. Vertical tectonics, horizontal tectonics, gold mineralization, Archean, cratonization, Superior Province

1 Introduction

Two contrasting processes have been proposed for Archean tectonics: "vertical tectonism" driven by density inversion and "horizontal tectonism" driven by regional horizontal tectonic stress. Many Archean geologists now accept that processes similar to present-day plate tectonics (a form of horizontal tectonism) existed in some form in the Archean, particularly in the Neoarchean (van Kranendonk 2004 and references therein). On the other hand, detailed field-based studies have continued to document convincing evidence for vertical tectonism (van Kranendonk et al. 2004 and references therein). Considering that the driving forces for vertical and horizontal tectonism are independent, the two processes should not be mutually exclusive. It is therefore conceivable that at some point in time and space, the two processes might operate synchronously (and potentially interactively), although direct (as opposed to circumstantial) evidence has rarely been reported. In this paper, we summarize evidence for synchronous vertical and horizontal tectonism in the Superior Province in Canada and suggest that such a process in the late stage of cratonization played a very important role in gold mineralization.

2 Synchronous vertical and horizontal tectonism in the northwestern Superior Province

As part of a multidisciplinary program to better understand the tectonic evolution of the Superior Province, detailed studies have been conducted in major greenstone belts in the northwestern Superior Province, including the Gods Lake, Knee Lake, Carrot River, Cross Lake and Island Lake belts (Fig. 1a). The results show that both horizontal tectonism (in a form similar to present-day plate tectonics) and vertical tectonism have played a significant role in the tectonic evolution of this part of the Superior Province, and there is convincing evidence for synchronous vertical and horizontal tectonism at the late stages of cratonization. The geological evolution of the Cross Lake greenstone belt is typical of the greenstone belts in the area and is described here as an example (based on Parmenter 2002).

Supracrustal rocks of the Cross Lake greenstone belt consist of two main groups: the >2760 Ma Pipestone Lake Group and the unconformably overlying <2704 Ma Cross Lake Group. The former consists of mafic volcanic and minor sedimentary rocks, and the latter is a fining-upward fluvial to marine sedimentary sequence consisting of polymictic conglomerates, sandstones, argillite-rich horizons and turbidites.

Detailed structural analysis revealed four major generations (G1-G4) of structures in the Pipestone Lake Group and three generations (G2-G4) in the Cross Lake Group. Clasts in the latter contains a pre-depositional foliation (interpreted as S1). The main features of the four generations of structures and their tectonic interpretations are schematically shown in Figure 2. The nature of G1 is enigmatic due to poor preservation. It might represent the major phase of collisional deformation, thrusting, and greenstone belt amalgamation proposed based on data from other greenstone belts in the area. G2 is characterized by the development of a belt-scale synclinorium cored by supracrustal rocks and flanked by granitoid domes (Fig. 2b-c). During G3, large-scale shear zones were developed along supracrustal-pluton contacts, under amphibolite-facies conditions. Movement along these shear zones was oblique with dominant pluton-side-up dip-slip component and minor dextral strike-slip component (Fig. 2d). During G4 deformation, these shear zones were reactivated under greenschist facies conditions and exhibited similar kinematics as G3 (Fig. 2e). Although the pluton-side-up dip-slip movement component continued, dextral strike-slip movement component was much more significant.

The G2 structures and the dip-slip components of G3-G4 are best explained by gravity-driven vertical tectonism, with subsidence of the dense volcanic sequence (sagduction) and concurrent diapirism of underlying sialic material (Fig. 2b-e). On the other hand, the dextral strike-slip components during G3-G4 are consistent throughout the Superior Province and are best explained by horizontal tectonism related to regional dextral transpression. During most part of the G2-G4 deformation history,vertical and horizontal tectonism was synchronous. During G2 and at least the early stage of G3, vertical tectonism was dominant, whereas during G4 horizontal tectonism prevailed. These relationships indicate that G2-G4 may represent a transition from dominantly vertical tectonism, in the form of diapirism and sagduction, to dominantly horizontal tectonism, in the form of regional transcurrent shearing.

The overall map pattern of the northwestern Superior Province (Fig. 1a-b) is consistent with the presence of both vertical and horizontal tectonism. In areas where vertical tectonism is dominant, the granitoid domes tend to be rounded with greenstone belts occurring in-between in synclinal keels, for example, in the interior of the Sachigo subprovince (lower right corner of Fig. 1a-b). In areas where horizontal tectonism is more significant, both the domes and the greenstone belts are elongated and the general geometry is more "linear" (Fig. 1a-b). Deformation related to horizontal tectonism tends to be localized in shear zones coincident with elongated synclinal keels (Fig. 1a).

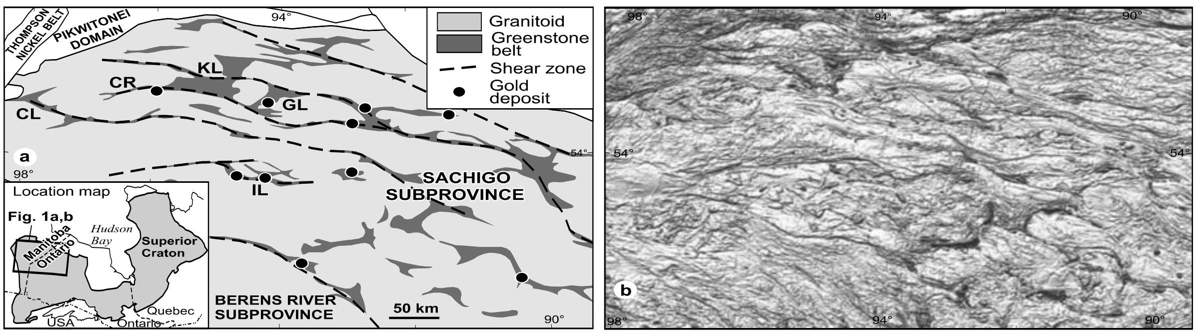

Figure 1: (a) Map showing the distribution of greenstone belts, granitoids and gold deposits and the general geometry of the northwestern Superior Province. (b) A shaded relief image of the total magnetic field of the same area. CR: Carrot River; CL: Cross Lake; GL: Gods Lake; IL: Island Lake; KL: Knee Lake. Magnetic map from the Geological Survey of Canada

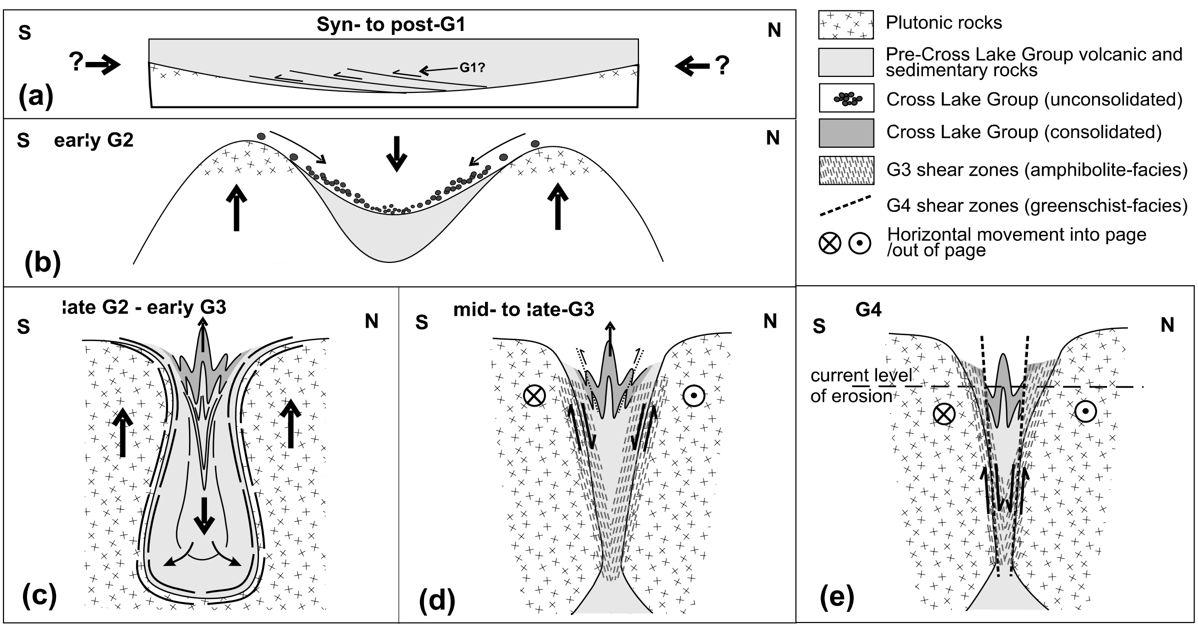

Figure 2: Schematic diagrams showing the structural evolution of the Cross Lake greenstone belt (modified from Parmenter 2002). See text for explanation. Note that movement along G3 and G4 shear zones in (d) and (e), respectively, have both dip-slip and strike-slip components, with the dip-slip component being dominant during G3 and the strike-slip component more important during G4. (c) is modified from Dixon and Summers (1983).

2.1 Deposition of Timiskaming-type sedimentary rocks during vertical tectonism

In many greenstone belts in the Superior Province (and other Archean cratons), a sequence of sedimentary rocks similar to the Cross Lake Group lie unconformably on older greenstone sequences. These “Timiskaming-type” sedimentary rocks show sedimentary features for a structurally controlled basin (Thurston and Chivers 1990). They are commonly spatially associated with, and have traditionally been interpreted as deposits in pull-apart basins genetically related to, late strike-slip shear zones (equivalents of G4 shear zones here). However, data from various greenstone belts in the northwestern Superior Province indicate that basin development and sedimentation were most likely penecontemporaneous with G2 and the onset of vertical tectonism (Fig. 2b; Parmenter 2002). Greenstone-belt subsidence (sagduction), concurrent with diapirism and uplift, provides an ample mechanism for the development of tectonic basins in the synclinal keels between the flanking granitoid domes. A similar interpretation has been proposed for similar sedimentary sequences in the east Pilbara in Australia (e.g. van Kranendonk et al. 2004) and in the Slave Province in Canada (Bleeker 2002). Parks (unpublished data) dated ~400 detrital zircon grains from samples collected at various stratigraphic positions of such a sedimentary sequence in the Island Lake greenstone belt (Fig. 1a) by the LA-MC-ICP-MS method. The results indicate an unroofing pattern in the flanking domes that is consistent with such an interpretation.

3 Implications for Archean gold mineralization

Archean gold deposits dominantly occur in greenstone belts and are spatially associated with major deformation zones that are believed to have served as conduits for mineralizing fluids (e.g. Fig. 1a). There is also a close spatial relationship of gold deposits with post-volcanic, syn- to late-tectonic, felsic to intermediate intrusive rocks and Timiskaming-type sedimentary rocks (Colvine et al. 1988 and references therein). In addition to displaying a spatial association with gold deposits, these syn- to late-tectonic intrusions and sedimentary rocks seem to occur more frequently or dominantly in the deformation zones that host gold mineralization. The latter indicates that their emplacement/deposition might also have been controlled by the deformation zones (Colvine et al. 1988 and references therein). In some deposits, it can be demonstrated that there is a genetic link between these intrusions and gold mineralization. In others, such a direct link cannot be demonstrated and may not exist.

Synchronous vertical and horizontal tectonism at the late stages of cratonization can readily explain the above spatial associations and potential genetic links, and is potentially a very important process in Archean gold mineralization. At the beginning of the process, the greenstone sequence overlaid and insulated the sialic crust, while the crust was likely being “underplated” or intruded by mantle-derived magmas (see Colvine et al. 1988 and references therein; Beakhouse 2003). As a result, the crust below the greenstone sequence was significantly heated and its viscosity significantly lowered creating a gravitational instability and initiating vertical tectonism. This resulted in subsidence of the dense volcanic sequence in the synclinal keels concurrent with diapirism of underlying sialic material in the flanking domes. The Timiskaming-type sedimentary rocks were deposited in the synclinal keels, unconformably overlying the volcanic sequence. The synclinal keels, with steep contacts, are favourable locations for localized horizontal shearing associated with regional transpression, resulting in elongated synclinal keels in which the supracrustal rocks are strongly deformed and foliated. These rocks are thus much more permeable than the granitoids in the flanking domes. Meanwhile, mineralizing fluids and felsic to intermediate magma were generated in the crust and/or upper mantle. They followed these deformation zones up to the upper crust, forming gold deposits and intrusions in the supracrustal rocks, including in the Timiskaming-type sedimentary rocks and in the intrusions emplaced during the process. An important feature of this model is that the mineralizing fluids and the fluid conduits are genetically related, both being generated as a result of Archean cratonization.

3.1 Potential examples

The features summarized above are shared by many gold deposits in both the northwestern and southern Superior Province, implying a common tectonic process for gold mineralization. The spatial association of Timiskaming-type sedimentary basins with major auriferous shear zones such as the Destor-Porcupine fault and the Cadillac-Larder Lake fault is well documented.

The Dome Mine is a potential example of gold deposits formed during synchronous vertical and horizontal tectonism. The deposit is spatially associated with the Dome Fault (a branch of the Destor-Porcupine fault), quartz porphyry intrusions and the Timiskaming Group (conglomerate and slate; Fig. 3). The last unconformably overlies older metavolcanic and metasedimentary rocks, including metabasalt (greenstones). The supracrustal rocks are folded and sheared, and the geometry of the conglomerate layer defines an overall syncline, with a second-order central anticline flanked by two synclines (Fig. 3). The overall kinematics and geometry are very similar to that of Figure 2c-e. Gold mineralization mainly occurs near the crest of the anticline, in stockworks in the conglomerate and in zones parallel to the foliation and lithological contacts in the greenstones. It occurred during folding and shearing, and its location is apparently con-

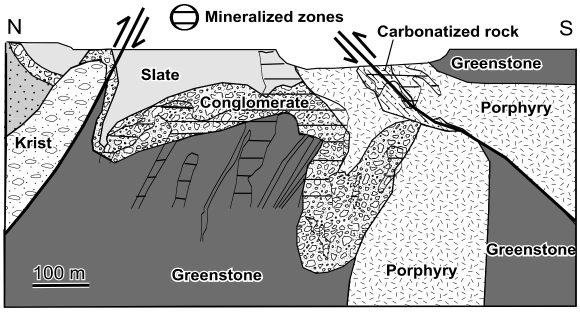

Figure 3: A section of the Dome mine, Timmins, Ontario (modified from a field trip handout supplied by, and published with permission of, the Dome Mine). See text for discussion.

trolled by the (permeable) conglomerate and the geometry of the anticline. The steep foliation and lithological contacts might have served as fluid conduits, the conglomerate as a fluid trap and the slate (shale) as an impermeable cap.

The Hemlo gold deposit is another potential example. Here, gold mineralization, Timiskaming-type sedimentation, shear zone deformation and late-tectonic magmatism are spatially associated and were synchronous (Lin 2001). They occurred at ca. 2677 Ma, probably synchronous with diapirism in a major granitoid dome to the south.

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