Structural controls on proterozoic nickel and gold mineral systems identified from geodynamic modelling and geophysical interpretation, east Kimberley, Western Australia

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A R T I C L E   I N F O

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Numerical modelling
Fluid pathways
Gold deposits
Nickel mineralisation

A B S T R A C T

Major structures considered important for controlling mineralisation in the Halls Creek Orogen, east Kimberley are identified via integrated interpretation of geophysical and geological data combined with geodynamic numerical modelling. In the numerical geodynamic models, the second invariant of strain rate (εII) is used to investigate the shearing processes that led to the development of major faults or shear zones and assessing their role as lithospheric-scale conduits and pathways for the movement of magmatic and hydrothermal fluids into the upper crust. The influence of these deep structures interpreted from the geodynamic models is evaluated through structural interpretation of geophysical, remotely-sensed and geological data. When compared to the location of Ni and Au mineral deposits the deep-crustal scale structures delineated in the models and compared to those mapped in the region contain a close spatial relationship with mineral deposits. It is apparent that 1st order crustal-scale structures acted as fluid conduits in the deep crust resulting in the formation of Ni-Cu-PGE deposits and are associated with Au mineralisation. However, 2nd and 3rd order structures manifesting in the upper crust as deformation focused mineralising fluids and magma resulting in the formation of gold deposits. Large-scale structures developed early in the genesis of the Halls Creek Orogen, appear to be long-lived and have been reactivated. These form the margins of Kimberley Craton domains and influence the location of Ni-Cu-PGE mineralisation, whereas the lower-order structures acted as structural traps for the subsequent deposition of Au mineralisation.

1. Introduction

Deep-crustal or lithospheric-scale structures are understood to influence the development of a wide range of mineral deposits (McCuaig and Hronsky, 2014). At the lithospheric scale, deep imaging techniques have demonstrated the close spatial association of deposits to deep-mantle tapping structures coincident with lithospheric boundaries (Goldfarb and Santosh, 2014; Groves et al., 2016; Groves and Santosh, 2015; Hronsky et al., 2012; Titley, 2001). Most significant mineral deposit in convergent margin settings are spatially associated with crustal- to lithospheric-scale structures, especially the intersection of ore sub-parallel with structures at high angles to the orogen trend (O’Driscoll, 1986; Richards et al., 2001). Such intersection zones are likely to provide localised permeable connections between the mantle and upper crust, supplying metal rich fluids to the crust (Cox et al., 2001; Glen and Walshe, 1999; Gow and Walshe, 2005; Hill et al., 2002; Lund, 2008; Neubauer et al., 2005). In addition, lower-order structures and geological complexities in the middle to upper crust can act as physical traps for fluid (Breeding and Ague, 2002; Cox et al., 2001; Goldfarb and Santosh, 2014; Groves et al., 2006; Groves et al., 2016; Groves and Santosh, 2015; Hyndman et al., 2015) and are therefore important for prospectivity analysis at the camp and deposit scale. Several studies have highlighted the benefits of multidisciplinary approaches in order to constrain the relationship of metallogenesis of a region to regional structures. For example, Crawford and Grauch (2002) and Bierlein et al. (2006) used geological, geophysical and geochronological data to identify fundamental links between the location of gold deposits and deep crustal-scale structures.

Orogenic gold deposits are thought to mainly form during compressional to transpressional tectonics late in an orogenic cycle (Goldfarb et al., 2005, 2001), thus display strong structural controls (Cox et al., 2001; Groves et al., 2000; Groves et al., 2006; Sibson et al., 1988). Therefore, it is important to understand if particular geometries control gold deposits in specific terrains (Cox, 1999; Hodgson, 1989; Sibson et al., 1988). A number of major gold provinces with a variety of deposit styles of different ages occur at the margins of cratonic domains or...
2. Regional geology

The Halls Creek Orogen includes the 1910–1805 Ma Lamboo Province that developed between the Kimberley and North Australian Cratons (Figs. 1 and 2). In the east Kimberley, the Lamboo Province comprises three parallel, north-northeast trending zones (the Western, Central, and Eastern zones) that have been interpreted as distinct tectonostratigraphic terranes (Tyler et al., 1995). These three zones separate tectonostratigraphic terranes containing distinct Paleoproterozoic geological units and were juxtaposed by the 1870–1850 Ma Hooper Orogeny and 1835–1805 Ma Halls Creek Orogeny (Griffith et al., 2000; Griffin and Tyler, 1992; Page et al., 2001; Page and Hoatson, 2000). These terranes are separated by major faults. The Central Zone of the Lamboo Province is separated from the Eastern Zone by the northeast striking Angelo, Halls Creek, and Osmond faults; and from the Western Zone by the northeasterly trending Ramsay Range and Springvale faults, and the northern part of the Halls Creek Fault (Fig. 3). The Lamboo Province hosts a variety of mineralisation types that have been documented by Sanders (1999), Hassan (2000), Occhipinti et al. (2016). Meta-sedimentary and felsic volcanic rocks of the Halls Creek Group in the Eastern Zone are known to contain Au (Fig. 1) that probably formed in the later stages of deformation during the Halls Creek Orogeny (Griffin and Tyler, 1992; Occhipinti et al., 2016; Sanders, 1999). Significant Ni-Cu-PGE mineralisation is mainly restricted to layered mafic-ultramafic intrusions in the Central Zone of the Lamboo Province (Fig. 1) (Occhipinti et al., 2016; Sanders, 1999).

The oldest exposed rocks in the Eastern zone are c. 1910 mafic and felsic rocks of the Ding Dong Downs Volcanics and c.1910 Ma gravitoids of the Sophie Downs Suite. The 1880–1840 Ma Halls Creek Group is unconformable on the Sophie Downs Suite and contains the Saunders Creek, Brim Rockhole, Biscay, and Olympio formations (Griffin and Tyler, 1992; Phillips et al., 2016). Sills of Woodward Dolerite intruded the Halls Creek Group at c. 1855 Ma (Griffin and Tyler, 1992; Tyler et al., 1998). All these rocks were metamorphosed, and variably deformed, to greenschist facies (Occhipinti et al., 2016).

The oldest rocks in the Central Zone are the c. 1865 Ma mafic volcanic and turbiditic sedimentary rocks of the Tickalaria Metamorphics which were metamorphosed at greenschist to granulite facies (Tyler et al., 1995) and intruded by the sheet-like tonalite and trondhjemite Dougalls Suite at 1850 Ma. The Koongie Park Formation is exposed in the southern part of the Central Zone and is a sequence of folded and metamorphosed turbidites, carbonate, mafic and felsic volcanioclastic rocks that were deposited between 1845 and 1840 Ma during rifting of the Tickalaria Metamorphics (Tyler et al., 2012). The Central Zone was extensively intruded by felsic to mafic magmas of the 1835–1805 Ma Sally Downs Supersuite during the Halls Creek Orogeny (Blake, 2000; Bodorkos et al., 2000; Page et al., 2001; Sheppard et al., 2001; Tyler et al., 1995; Tyler and Page, 1996). The granitic intrusions mostly occur in the Central Zone, although they intrude the Western and Eastern zones. The Central Zone also contains most of the layered mafic-ultramafic intrusions observed in the Lamboo Province. These include the large gabbroic and layered mafic-ultramafic bodies of the c. 1856 Ma Panton, c. 1845 Ma Sally Malay, and c. 1830 Ma McIntosh suites (Page and Hoatson, 2000; Page and Sun, 1994).

The Western Zone of the Lamboo Province is exposed around the southwest and southeast margins of the Kimberley Craton (Fig. 1) (Tyler et al., 1995). The main components of the Western Zone are the c. 1870 Ma Marboo Formation, 1865–1850 Ma Paperbark Supersuite, c. 1855 Ma Whitewater Volcanics, and c. 1855 Ma layered mafic-ultramafic intrusions (Page and Hancock, 1988; Tyler et al., 2012; Tyler et al., 1999), which are metamorphosed at low to medium grade (Occhipinti et al., 2016). The Marboo Formation consists of turbiditic sandstone, siltstone, greywacke, and quartz wacke deposited along the rifted paleomargin of the Kimberley Craton (Griffin et al., 2000; Tyler et al., 1999). The c. 1855 Whitewater Volcanics unconformably overlie the Marboo Formation and consists of volcanioclastic rocks interlayered with felsic to intermediate volcanic rocks (Griffin et al., 1994). The Marboo Formation was intruded by potassic I-type granitic and gabbroic intrusions of the Paperbark Supersuite, as well as layered mafic-ultramafic intrusions, between 1865 and 1850 Ma (Tyler et al., 2012). Sedimentary and mafic volcanic rocks of the Spewah and Kimberley groups were deposited unconformably on rocks of the Western Zone between 1835 and 1740 Ma (Sheppard et al., 2012).
trending dextral faults that appear to separate the Western, Central and Eastern zones (Fig. 3) (Dow and Gemuts, 1969; Tyler et al., 1995). Tyler et al. (1995) suggested that this pattern of strike-faulting was controlled by deep-seated, northeasterly trending structures developed during the Paleoproterozoic that formed terrane boundaries within the Lamboo Province (Fig. 1). The Central Zone of the Lamboo Province is separated from the Eastern Zone by the Angelo, Halls Creek, and Osmond faults; and from the Western Zone by the Ramsay Range, Springvale and the northern part of the Halls Creek faults (Tyler et al., 1995). Most of these major structures are thought to have developed in the Paleoproterozoic during the Hooper and Halls Creek orogenies and have experienced multiple periods of reactivation through time (Thorne and Tyler, 1996).

Seven deformation events have been recognized in the Halls Creek Orogen (Fig. 2). The two oldest (D1 and D2) are related to the 1865–1850 Ma Hooper Orogeny (Griffin et al., 1998; Tyler et al., 1998) in the Central and Western zones. These deformation events have not
<table>
<thead>
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<th>Western Zone</th>
<th>Central Zone</th>
<th>Eastern Zone</th>
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<td><strong>Yampi Orogeny (D5)</strong></td>
<td><strong>Strike-slip movement</strong></td>
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<td><strong>Halls Creek Orogeny (D3/D4)</strong></td>
<td><strong>Compression</strong></td>
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<td>1950</td>
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Fig. 2. Time-space plot illustrating the major lithological units, orogenies and deformation events of the Eastern, Central and Western zones of the Halls Creek orogen (modified after Lindsay et al., 2016).
been recognized in the Eastern Zone. In the Central Zone, the oldest deformation event (D1) produced small-scale layer-parallel isoclinal folds in the metasedimentary rocks, followed by tight to isoclinal deformation event (D1) produced small-scale layer-parallel isoclines. Further deformation events (D2 and D3) associated with the 1835–1805 Ma Halls Creek Orogeny (Phillips et al., 2016; Sheppard et al., 1997). In the Central Zone, D3 and D4 produced, respectively, tight to isoclinial, upright northeast-trending folds in Group I of mafic-ultramafic intrusions and ductile shear zones (Griffin et al., 1998; Tyler et al., 1995). In the Eastern Zone, the earliest deformation event (D3) produced a non-pervasive, layer-parallel foliation (Griffin and Tyler, 1992) that postdated deposition of the Olympic Formation and was followed by pervasive, large-scale, northeasterly to east-northeasterly trending folds (D4). In the Western Zone, deformation equivalent to D3 and D4 in Central and Eastern zones has not been documented (Tyler et al., 1995).

The 2D geodynamic numerical experiments by Kohanpour et al. (2017) conducted a series of geodynamic numerical experiments using the I2VIS code (Gerya, 2010; Gerya and Yuen, 2003) to determine the tectonic evolution of the Halls Creek Orogen. The second invariant of strain rate ($\varepsilon_2$) was used to recognise the major shear zones during the evolution of the experiments. In this study, $\varepsilon_2$ is applied to understand how deep-crustal and lithospheric-scale structures may develop, and how they may have controlled fluid flow. These structures then linked to the structural-geophysical interpretation of the area.

The large-scale structural architecture of regions can be derived from structural interpretation of aeromagnetic data (Aitken et al., 2013; Aitken and Betts, 2009; Lindsay et al., 2016; Stewart et al., 2009; Occhipinti et al., 2016). In this study, integration of gravity, aeromagnetic, and Landsat data, with geological maps is used for identification of geological structures associated with gold and nickel mineralisation. Total magnetic intensity (TMI) data were obtained from the Geological Survey of Western Australia (GSWA). Most of the airborne magnetic surveys in the region were conducted with a line spacing of 400 m, although some were flown at 200 m line spacing. Each survey was gridded using minimum curvature with 80 m cell size. A differential reduced to pole (drTDP) transform was applied to the stitched TMI.

2.2. Gold and nickel mineralisation

Gold mineralisation is widespread in the Halls Creek Orogen, but is mainly located in the Eastern Zone and the southern part of the Central and Western zones (Fig. 1). In the Eastern Zone, gold mineralisation is concentrated in the lower part of the Olympic Formation and the upper part of the Biscay Formation, or within felsic rocks of the Butchers Gully Member (Sanders, 1999). Gold mineralisation is typically restricted to shear zone-hosted quartz veins and stockwork within trachyandesites or within the axial plane of anticlines (Sanders, 1999). Some gold deposits are within a few kilometers of the exposed youngest granite of the Lamboo Province, the 1788 Ma San Sou Monzogranite, which is located in the southern part of the Eastern Zone (Sanders, 1999).

Warren (1997) suggested that gold may have been derived from the mafic volcanics of the Biscay Formation, lower Olympic Formation, or Maude Headly Member, and remobilized into late faults. Tyler et al. (1998) suggested that gold mineralisation is related to a low-grade metamorphic and deformation event associated with the c. 1000–800 Ma Yampi Orogeny. The geometry of faults and mineralised quartz veins is consistent with formation in a sinistral wrench regime, coeval with late brittle to brittle-ductile movement on the Halls Creek Fault (Griffin and Tyler, 1992). Gold prospectivity analysis by Occhipinti et al. (2016) outlined that areas of structural complexity, or those around fault jogs in the Biscay and Olympic formations of Eastern Zone and greenschist facies rocks of the Koongie Park in the Central Zone may be the most prospective for gold mineralisation.

Nickel-copper-PGE sulphide occurrences are hosted in layered mafic-ultramafic rocks, which are confined to the Central and Western zones. The 1857 ± 2 Ma Panton (group I of Hoatson and Blake (2000), 1844 ± 3 Ma Sally Malay (group V of Hoatson and Blake (2000)) intrusions are understood to be the most important prospective intrusions for Ni-Cu-PGE mineralisation (Sanders, 1999). Hoatson and Blake (2000) recognized that the major mineralised layered mafic and ultramafic intrusions are located in two northeast-trending corridors; one characterised by a chromite association (Cr-PGEs-Ni-Cu ± Au) and the other to the northwest by a sulphide association (Ni-Cu-Co-PGEs ± Cr). These intrusive rocks and mineralisation are spatially controlled by the intersection of deep crustal structures parallel with and orthogonal to the orogeny (Lindsay et al., 2016), suggesting these structures acted as magma conduits (Occhipinti et al., 2016), suggesting these structures acted as magma conduits.
grid. Terrain-corrected spherical-cap Bouguer gravity data with an average 2.5 km station spacing were obtained from the GSWA. Grids were produced with a cell size of 400 m to provide detailed coverage over the Halls Creek Orogen.

Geological structures were primarily interpreted from dRTP data, its first vertical derivative and overlays of tilt derivative and dynamic range compression. Landsat data presented as colour composites were used to delineate surface geological features, especially shallow linear features. Bouguer gravity data (Fig. 4), its first vertical derivative, upwards continuation, and multi-scale edge detection or gravity worms (Fig. 5) were used to provide additional insights to large, presumably deep-seated structures. For this project a structural interpretation was completed based on the assumption that lithological contrasts within the relatively shallow crust can produce discontinuities in the measured geophysical data (Stewart et al., 2009). These discontinuities may represent contacts between different geological units, or alteration zones within geological units, resulting in changes in their petrophysical properties. Therefore, truncation or deflection of magnetic or gravity anomalies may indicate the location of faults or shear zones. Fold axes can be recognized based on the closure of the trend of magnetic lineaments. Rotation or offset of marker anomalies may indicate strike-slip movement. Large-scale structures can represent the boundaries between tectonic terranes, identified from long truncations of anomalies and changes in the strike of linear features in aeromagnetic data, Landsat images and gravity data, particularly where different geophysical-geological domains are delineated across them.

Our analysis focuses on the depth extent of structures within the Halls Creek Orogen, the relationship of first and lower order structures and the mechanisms by which these structures formed and then acted as conduits for fluid and magma responsible for gold and nickel mineralisation in the region. In order to ascertain the depth extent of structures mapped from the geophysics, digitally generated “worms” produced by the GSWA were derived from gravity grids, using edge detection software (Intrepid Geophysics Ltd). Worming can be applied to automatically define the positions of gradients at successive upward continued heights (Archibald et al., 1999; Hornby et al., 1999) and represent a 3D spatial position of horizontal gradients in the gravity data projected upward to different heights above the ground surface (FitzGerald and Milligan, 2013).

4. Results and discussion

4.1. Structural evolution; insight from geodynamic numerical modelling

Plausible tectonic scenarios for the Halls Creek Orogen were examined through 2D thermo-mechanical-petrological numerical experiments using I2VIS code (Gerya and Yuen, 2003) by Kohanpour et al. (2017). Their results indicate that the geology of the Halls Creek Orogen is best represented by west-dipping subduction at the margin of Kimberley Craton (Model I and II; Figs. 6 and 7). Analysis of the two most feasible geodynamic numerical models identified by Kohanpour et al. (2017) reveal tectonic events which may have led to the generation of major structures during the tectonic evolution of the Halls Creek Orogen which eventually formed terrane boundaries.

In Model I, the onset of lithospheric-scale deformation occurs in a region of high strain rate in response to the fluid-induced weakening of the upper lithosphere during ocean subduction (Fig. 6a). The development of this zone of high-strain rate is interpreted to be associated with volcanism suggesting this shear zone acted as a magma conduit. During extensional basin development, the high strain zone maintains connectivity to the basin in which volcanic activity continues due to mantle decompression and slab melting (Fig. 6b and c). After collision and basin closure, the depth extent of deformation zones increase, leading to formation of lithospheric-scale shear zones and faults (Fig. 6d). Formation of major shear zones is linked to basin closure and upwelling of the serpentinized mantle (Fig. 6d). The shear zones are deep-seated and may be responsible for melt transfer from the mantle to the surface. In the final stages of this numerical experiment (Fig. 6e and
two major lithospheric-scale shear zones formed by closure of the extensional basin (presented in Fig. 6f with dashed lines). Second invariant of strain rate illustrates how major shear zones act as conduits for fluid and magmas derived from the slab subduction and molten peridotite (Fig. 6e and f).

In Model II, the major deformation zone is a residue of suturing of a subduction zone during collision (represented with dashed line in Fig. 7). During the early stages, the onset of lithospheric faulting occurs
in a region with a high strain zone resulting from compression and weakening effects of fluids (Fig. 7b). Fig. 7b and c represent how the major deformation zones act as magma conduits to the surface. Lithosphere upwelling and collisional magmatism result in high strain rate zones occurring in the centre of the orogen (Fig. 7d–f).

Both Models I and II show trans-lithospheric emplacement of magmatic bodies into the crust with associated magmatism at the surface. In the first steps of the numerical models, magmatic channels may originate due to localised upward percolation of hot mobile fluid or magma, which are derived from the slab during the subduction of oceanic crust. An important point is that fluid percolation and resulting pore fluid pressure decrease the plastic strength of rocks, which in turn allow massive ascent of molten rocks through the lithosphere. This process will then lead to further localised deformation along weakening faults (Gerya, 2010).

The numerical models show how the major fault systems of the Halls Creek Orogen may have developed during the extensional and compressional tectonic regimes that operated during collision of the North Australian Craton and Kimberley Craton in the Paleoproterozoic (Figs. 6 and 7). These first-order shear zones act as lithospheric-scale conduits and pathways for magma and fluids. They simulate connectivity between the lithosphere and surface, and thus appear to control the emplacement of volcanic rocks, and also regional-scale fluid flow. In addition, the major shear zones are considered to represent current boundaries to the zones of the Halls Creek Orogen: i.e., Angelo-Halls Creek and Ramsay Range-Springvale fault systems which can be recognized with geophysical data (Fig. 3). The results outlined in these models have implications for our understanding of how terrane boundaries transect the lithosphere into the asthenosphere and tap mantle-derived fluid reservoirs.

4.2. Structural controls on nickel and gold mineralisation

The relationship of regional-scale discontinuities to mineralisation has been established by Hobbs et al. (2000) and Archibald et al. (2001) who drew attention to deep-seated gravity gradients and location of
large deposits. For this project a series of upward continued images and their first vertical derivatives from the Bouguer gravity data of the Halls Creek Orogen were produced and used (Fig. 5). Gravity data were processed to an upward continuation of 1, 5, 10, and 20 km which calculates the response from sources deeper than depths of approximately half the upward continuation level namely 500 m, 2.5, 5, and 10 km respectively (Fig. 4; Dufréchou and Harris, 2013; Jacobsen, 1987). It is worth noting rigorous mathematical solution for interpretation of field potential data can lead to erroneous interpretation (Saltus and Blakely, 2011), so we consider an a priori constraint includes having steep structures in the Halls Creek Orogen (Lindsay et al., 2016). Therefore, as the geology is mostly steeply-dipping, long wavelength anomalies are more likely to be deep, as opposed to a flat-lying basin setting, where there is a higher likelihood to encounter broad anomalies responding to shallow features. Analyses of gravity worms generated from continuation levels of 636 m to 44,188 m (Fig. 5) assumed that worms calculated from larger continuation values represent deeper structures, while smaller values represent those nearer the surface (FitzGerald and Milligan, 2013). The true depth of the worm maps is based on Jacobsen (1987) and Hornby et al. (1999) taken as half the level of the upward continuation as the depth.

These analyses provide information on the apparent dip direction through lateral shifts of worms (Godin and Harris, 2014) and the depth persistence of contacts that have a detectable density contrast across them. The structural feature of major faults in the Halls Creek Orogen based on the geophysical data are presented in Table 1. Two main groups of structures are observed: Parallel to subparallel to the trend of the Halls Creek Orogen, and linear cross-strike features (Fig. 8). The major crustal-scale structures are north-northeast trending terrane boundaries (Tyler et al., 1995, 2012). Subsidiary east-northeast trending cross-faults are also interpreted (Fig. 8a). Several northeast trending orogen-normal deep structures, in addition to orogen-parallel structures have been interpreted from Bouguer gravity data (Fig. 8b). Long traverse structures cross-cut the Lamboo Province and extend to the Kimberley and Speewah Basins, and extend further east into the Ord and Wolfe Creek basins (Fig. 8c). They are sub-parallel to the strike of dykes in the Lamboo Province and further west in the Kimberley Craton (Fig. 8c). These orogen-normal structures are not associated with any continuous lineament at the surface, and in some cases their expression on the surface is difficult to distinguish. Nonetheless, they can be recognized using a tilt derivative of upward continued aeromagnetic data (Fig. 8d). Orogen-normal structures are also documented in other orogens and continental/island arcs such as the New Guinea Orogen.

### Table 1

<table>
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<th>Major faults</th>
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<th>Dip</th>
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<th>Depth extent (km)</th>
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<td>Steep</td>
<td>SE</td>
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<td>SE</td>
<td>2.5–5</td>
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<td>Steep</td>
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N: North; S: South; E: East; W: West. Dip > 45° considered as steep.
Fig. 8. Deep structures of the Hall Creek Orogen identified through interpretation of gravity data: (a) orogen-parallel to sub parallel structures and (b) orogen-normal structures superimposed on first vertical derivative of gravity data. (c) Extension of orogen-normal structures into basins around the Halls Creek Orogen and parallel to the strike of dykes mapped on the tilt derivative of aeromagnetic data; (d) deep structures superimposed on tilt derivative of 1 km upward continued image of aeromagnetic data.
(Corbett, 1994; Garwin et al., 2005; Hill et al., 2003, 2002), Indonesia (Garwin et al., 2005), the Andean margin in Argentina (Chernicoff et al., 2002), Lachlan Orogen, Australia (Glen and Walsh, 1999), and the Grenville Orogen in Canada (Dufréchou and Harris, 2013; Dufréchou et al., 2014).

The most prominent orogen-parallel structures correspond to the Ramsay Range-Springvale and Halls Creek-Angelo fault systems or terrane boundaries (Tyler et al., 1995, 2012) (Fig. 3). The major orogen-parallel structures are interpreted as lithospheric-scale structures developed in the Paleoproterozoic during arc basin development and lithosphere upwelling in the margin of Kimberley Craton by geodynamic numerical modelling (Fig. 6). Northeast-trending structures are strike subparallel to crustal extensional faults that have subsequently reactivated as sinistral strike-slip faults (Tyler et al., 1995). In addition, several transverse northwest-southeast normal structures to the orogen do not correspond to the mapped features. Association of these deep structures with mafic to ultramafic intrusions, and associated mineral deposits (Lindsay et al., 2016; Occhipinti et al., 2016), and their parallelism with late dykes that cut the Kimberley Craton suggest that pre-existing deep fracture zones roughly parallel to the convergence direction may have been multiply reactivated, for example during the collisional orogenesis or post-orogenic magmatism.

4.2.1. Magmatic nickel sulphide mineralisation

Nickel occurrences are mainly present in the Central Zone of the Halls Creek Orogen, which is surrounded by two trans-crustal structures developed during rifting of the margin of the Kimberley Craton prior to the 1835–1805 Ma Halls Creek Orogeny (Fig. 9). At the regional scale, the nickel occurrences in the Halls Creek Orogen occur adjacent to major deep structures (Fig. 10a) and are associated with relatively deep worms (4744 m upward continued height) (Fig. 10b). These deep lineaments are interpreted to represent deep faults or shear zones through which large amounts of mantle-derived magma can ascend.

The association of most Ni-Cu-PGE sulphide deposits at or near the margins of lithospheric blocks and more generally near the margins of cratons (Begg et al. 2010; Maier and Groves, 2011) related to channelling of mantle plumes into the thinnest lithosphere at craton margins (Barnes et al., 2016; Begg et al., 2010) is supported by the geodynamic models of Kohanpour et al. (2017). These models illustrate the possible development of an environment at the Kimberley Craton margin containing a high flux of mantle-derived magmatism, facilitated by mantle-tapping structures was channeled into the upper crust, or onto the surface (Figs. 6 and 9b). Magma is focused by shifting extensional-compressional tectonic regimes, and was modelled to ascend via major trans-crustal structures (Fig. 6). The mineralised mafic-ultramafic rocks (such as the Panton Suite) would have their metals and immediate host rocks derived from the same magma, usually ascribed to originate from the mantle source (Barnes et al., 2016). The geodynamic models represent two kinds of mantle-derived melts in the evolution of the Halls Creek Orogen, which can be the source of mafic-ultramafic rocks.

Fig. 9. (a) Regional distribution of nickel occurrences in the Central Zone constrained between two major faults system as terrane boundaries; (b) some snapshots of the geodynamic numerical model showing development of major fault systems and mantle-derived melts during extensional and compressional regimes in the margin of Kimberley Craton.
observed at the surface: (a) decompression melt resulting from rifting at the margin of the Kimberley Craton (b) hydrated mantle melt derived from the slab subduction (Fig. 9b).

The geodynamic numerical models suggest asthenosphere upwelling, marginal basin development, and syn-to post-collisional mantle plume activity resulting in crustal extension, and trans-crustal faulting facilitated magma generation and ascent (Figs. 6 and 9b). The second invariant of strain rate suggests a relatively high value in a rift setting and at the edge of cratons during active tectonic regimes (Fig. 6). Therefore, in a rift environment along cratonic margins, deformation can be localised or focused, facilitating the upwelling of magma into fairly narrow zones. Mineralised provinces are commonly associated with the large flux of magmas into deep crust, giving rise to regional positive gravity anomalies (e.g. West Musgrave Province; Smithies et al. (2011)). In the Halls Creek Orogen, mineralised mafic-ultramafic intrusions are associated with a regional positive gravity anomaly (Fig. 10a), likely resulting from the large flux of decompression mantle melt into deep crust during marginal basin development (Fig. 9b).

Further details of interpreted structures within the Central Zone are presented in Fig. 11. Major deformation events that control the current architecture of this region are mostly related to the Halls Creek Orogeny when the rocks of the Central Zone deformed during D3 and D4. D3 is characterized by large-scale northeasterly trending shallow plunging folds. The major example of this folding event can be recognized in the Group 1 mafic-ultramafic intrusions (the c. 1856 Ma Panton) which were folded into tight to isoclinal NE plunging D3 folds. D4 resulted in development of steep northeasterly shear zone that cut the Sally Downs Supersuite (Griffin and Tyler, 1992), and deformed the c. 1845 Ma Sally Malay granite. Deformation of two groups of mineralised mafic-ultramafic intrusions during D3 and D4 suggests that intrusion of ultramafic rocks and nickel mineralisation took place prior to the 1835–1805 Ma Halls Creek Orogeny, likely during the extensional tectonic regime related to marginal basin development over the Central Zone (Fig. 9b).

4.2.2. Orogenic gold mineralisation

Deep-crustal to lithospheric-scale structures provide the main first-order regional controls on the distribution of gold deposits in the Halls Creek Orogen (Fig. 12a). A series of tectonic events including basin development, and subsequent closure and then inversion (Fig. 6) resulted in the development of favourable structural architecture with the formation of many orogen-parallel, deep-crustal scale shear zones. The gold deposits are mainly focused along major structures, which initiated during an extensional phase of tectonism and their development continued during subsequent compressional tectonism and strike-slip movement (Fig. 12a). These lithospheric- to crustal-scale faults or shear zones may have been the focus site for initial deformation during the development of the terranes, and late kinematic deformation during strike-slip motion between the terranes. A deep lithospheric connection is inferred by the preferential distribution of gold occurrences adjacent to major deep-penetrating structures. The proximity of orogen-normal structures to the gold deposits suggests that intersection of these orogen-normal structures with orogen-parallel structures may control the location of magmatism and presumably act as dilational zones and magma or fluid conduits that transported metals into the middle to upper crust (Lindsay et al., 2016).

There is a corridor of gold occurrences in the Eastern Zone associated with a high gravity gradient (Fig. 12a). In the intersection of cross-orogen and orogen-parallel structures, there are some low gravity anomalies proximal to the gold mineralisation, which create low first vertical derivative values. These ellipsoid low first vertical derivative figures (indicated by the stars in Fig. 12a), showing a similar value to the Ding Dong Downs Volcanics, Sophie Downs Granite, San Sou Monzogranite, and Junda Microgranite in the Eastern Zone, or the Loadstone Mozogranite in the Central Zone (Fig. 12a). The figures of low first vertical derivative of gravity data under the sites of gold camps
Structural traps which host a group of gold deposits (Fig. 12c), within the Eastern Zone are mainly sited on second- or third-order faults or shear zones which are in northeast trending, located proximal to first-order major structures (Fig. 12c). Anticlinal hinges and orogen-normal structures are important features of most gold deposits in the region (Fig. 13), and may be important for trapping mineralising fluids. The Woodward Dolerite is a known feature in proximity of some of gold deposits (Fig. 13a–c), and may have acted as a chemically reactive host rock that caused gold precipitation (Groves et al., 2000).

Fig. 13a and b presents pervasive northeasterly trending shallow plunging folds which can attributed to the second deformation in Eastern Zone (D4). The orientation and intensity of D4 folding varies considerably. Folds are tighter adjacent to the Anglo-Halls Creek fault system, with upright to steeply inclined axial surface oriented sub-parallel to the main fault system (Fig. 13a). Gold deposits are mostly located proximal to mapped or interpreted fold hinges. In Fig. 13a, the most obvious D4 folds are a series of anticlines forming the Biscay Anticlinorium (Dow and Gemuts, 1969). A group of gold deposits in Fig. 13a located near to a cross-orogen structure with an anticline marked by outcrop of a north-northeast plunging antiform synform pair deforming the Biscay and Olympio formations. Further to the northeast, outcrop of Woodward Dolerite and a magnetic lineament defines a sheared antiform structure associated with gold deposits within the Biscay Formation.

Fig. 13c and d shows gold deposits situated along northeast trending shear zones between first-order strike-slip faults, where strike-slip movement has resulted in the development of dilational jogs. This scenario is well-known in transpressional regimes, where deposits can occur in predictable dilational sites such as fault jogs or overstepping faults (Hagemann et al., 1992; Hodgson, 1989). These shear zones are related to the third deformation event in the Eastern Zone (D5) which caused intensive deformation between the Angelo and Halls Creek faults during sinistral strike-slip movement (Tyler et al., 1998). The main D5 faults are the north-northeasterly Dockrell and Woodward faults (Tyler et al., 1998). Associated with these faults are open to tight folds that trend easterly and northwesterly to northerly (Fig. 13c and d). The large open and steep plunging antcline-syncline structure between the Angelo and Halls Creek faults (Fig. 13c) is closely associated with gold mineralisation. The Juda and Talor Lookout anticlines (Fig. 13d) were produced by interference of northeasterly trending D4 anticline and north-northwest trending D5 folding (Tyler et al., 1998). Deformation that can be related to D6 in the Eastern Zone involved sinistral strike slip movement of easterly trending Haughton Range Fault where both the Woodward and Dockrell faults and other shear zones were offset (Fig. 13d).

It is apparent that gold mineralisation is confined to a series of the northeasterly trending folds and shear zones which are mainly related to the D4 and D5 deformation events (Fig. 13) that occurred during the accretion of the Eastern Zone to the Central Zone and subsequent strike-slip movement. Therefore gold mineralisation could be coincident with either plate convergence during the 1835–1805 Ma Halls Creek Orogeny or during the subsequent sinistral northeasterly trending strike-slip movement of c.1000–800 Ma Yampi Orogeny, or both. If the gold mineralisation occurred during both the Halls Creek and Yampi orogenies, the association of gold mineralisation with greenschist facies conditions (Occhipinti et al., 2016) implies that Eastern Zone was not exhumed between the c. 1800 and 1000 Ma. Alternatively if gold mineralisation occurred during the 1835–1805 Ma Halls Creek Orogeny, it involved collision and also late orogenic sinistral strike-slip faulting. In this case, the c. 1000–800 Ma Yampi Orogeny may have caused re-activation of earlier formed sinistral strike-slip faults. Further study including age dating of hydrothermal minerals formed during gold mineralisation may reveal the precise relationship between gold mineralisation and tectonic-deformation events.

could represent unexposed granitoid bodies which may release the gold-bearing fluid or energy. A localised zone of dilation resulting from the intersection of orogen orthogonal features with the extensional faults, may have facilitated igneous intrusion and fluid ascension (Fig. 12a).

The results of worming of gravity data technique indicate an association of gold deposits with relatively shallow worms, although they are localised around the deepest worm in the region (Fig. 12b). Deep-seated gravity worms reflect deep-crustal structures that could provide connectivity from the mantle to the middle or upper crust, providing a fluid transport path into the structural traps represented by the relatively shallow worms. The results are consistent with observation that structural traps are vital ingredient of orogenic gold deposits as they are mainly sited in lower-order structures within geologically complex areas adjacent to the first-order deep structures (Fig. 12c; Groves et al., 2000, 2016).

The gold deposits in the HCO are mostly located in fold hinges that are oriented at a high angle to the direction of terrane convergence.
5. Conclusions

In this multiscale study, geophysics and interpreted structures combined with geodynamic numerical modelling were used to simulate the behavior of crustal- to lithospheric-scale structures acting as pathways for fluids and physical traps of nickel and gold mineralisation in the Halls Creek Orogen. This study confirms the importance of the deep crustal-scale structures which are formed during extension and plate convergence in the development of mineral systems and the emplacement of mineralisation. Gold and nickel deposits appear to develop proximal to first-order deep structures, particularly where they intersect orogen-normal structures. This implies that proximal to the orogen-parallel deep-seated structures, particularly those that are orientated normal to the orogen, there is a greater potential for mineralisation. Gold and nickel deposits appear to develop in or near lower-order structures that themselves are proximal to first-order deep structures, and structural interpretation and further supports the role of lithospheric-scale structures acting as structural traps for gold mineralisation, are all important constituents of gold mineralisation system for the east Kimberley.

Key features that control the localization of nickel mineralisation at the regional scale are proximity to ancient cratonic boundaries, long-lived, lithospheric-scale faults and are spatially related to voluminous mafic-ultramafic intrusions. The parental magma for nickel mineralisation can be generated through decompression melt below the marginal basin or melting of sub-crustal lithospheric mantle during the collision of North Australian Craton and Kimberley Craton. It is possible that mafic melts intruded into the upper crust by deep-crustal structures during the numerically modelled extensional and compressional regimes. Deformation of the c. 1856 Ma Panton and c. 1845 Ma Sally Malay by D3/D4 shows that nickel mineralisation and host ultramafic rocks intruded during extensional events prior to collision between the North Australian and Kimberley cratons (Halls Creek Orogen). The association of mineralised mafic-ultramafic intrusions with regional positive gravity anomalies can be indicative of probable large fluxes of modelled decompression melt and associated deep–crustal magmatism during marginal basin development. The regional distribution of gold mineralisation is interpreted to be controlled by shallow second- and third-order structures that splay from the larger and deeper first-order structures. Furthermore, traps in lower-order structures could have resulted from plate convergence and following sinistral strike-slip movements during the 1835–1805 Ma Halls Creek Orogeny (D3/D4) and later strike-slip movement during the c. 1000–800 Ma Yampi Orogeny (D5). Further studies may determine the age of gold mineralisation, and thus reveal the relationship between major tectonic events and gold mineralisation. The high spatial density of faults and folds, proximity to anticlinal structures, fold hinges, the presence of reactive host rocks (e.g. the Woodward Dolerite), and proximity to dilational sites such as fault jogs between first-order strike-slip faults acting as structural traps for gold mineralisation, are all important constituents of gold mineralisation system for the east Kimberley.

Fig. 12. Regional distribution of gold deposits in the Eastern Zone of the Halls Creek Orogen: (a) a corridor of gold deposits mainly focused along the first-order deep-crustal structures; relationship between gold sites and intersection of orogen-normal and parallel to subparallel structures; ellipsoid figures of low first vertical derivative of gravity value near to gold deposits (stars) similar to known granitoids in the Eastern Zone. (b) Distribution of gold deposits shown with a “gravity worm” image illustrating gold deposits are located in or near lower-order structures that themselves are proximal to first-order deep structures, and (c) structural interpretation of the Halls Creek Orogen overlaid on a blend of the first vertical derivative of gravity data and tilt derivative of aeromagnetic data and.
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Fig. 13. Interpreted structural traps of gold deposits: anticline hinges; shear zones between first-order strike-slip faults and; orogen-normal structures. Gold deposits are sited in: (a–a’) northeast trending folds attributed to D4 cross cut by orogen-normal structures; (b) high spatial density of folds and faults adjacent to the Halls Creek Fault; (c) shear zones between first-order strike-slip faults related to D5; (d) deep faults with sinistral strike-slip movement related to D5 and D6.
References


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