Progressive fault triggering and fluid flow in aftershock domains: Examples from mineralized Archaean fault systems

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Received 21 October 2005; received in revised form 28 July 2006; accepted 28 July 2006
Available online 1 September 2006
Editor: R.D. van der Hilst

Abstract

In strike-slip fault systems, Coulomb failure stress changes due to mainshocks can trigger large aftershocks or further earthquakes. The combination of static stress changes from mainshocks and large aftershocks potentially has a profound influence on the final distribution of aftershocks and crustal-scale fluid redistribution. Because mineralization acts as a high fluid flux indicator the interaction of static stress changes, fault triggering and fluid flow can be studied from mineralized fossil fault systems. Two examples are presented from separate fault systems in the Kalgoorlie greenstone terrane, Western Australia (the Black Flag and Boulder-Lefroy Fault systems). Using mapped fault geometries, slip directions and the known distribution of fault-hosted gold mineralization we show that the repeated arrest of mainshock ruptures, at both dilational and contractional fault step-overs, controlled aftershock-related fluid flow. Importantly, the largest aftershocks or subsequent triggered earthquakes exerted a very strong control on where the highest fluid fluxes occurred through small-event aftershock fault networks (at distances up to ∼15 km away from the step-overs). Fluid flow through mid-crustal fault systems in crystalline rock is spatially localised in regions where repeated clusters of aftershocks cause permeability enhancement. It is dependent on the seismogenic behaviour of the system, rather than a passive exploitation of the internal structure and fabrics developed by faults or damage zones. Field evidence implies that high pore fluid factors were repeatedly attained in the aftershock-related mineralized faults and that the fluids were derived from deep-level, overpressured reservoirs, rather than local wall rock porosity. It is apparent that high-pressure fluids, possibly released in a pulse after a mainshock, contribute to the rupture of structures already promoted towards failure from static stress changes.

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Keywords: Faults and fluids; Mineralization; Coulomb failure stress change; Aftershocks; Triggering

1. Introduction

Seismogenic processes that operated in ancient mineralized fault systems have long been thought to have a first-order control on fluid flow and gold precipitation [1–3]. On this basis, it has been recognised that the permeability enhancement associated with aftershocks controls the flow of mineralizing fluids after mainshock rupture arrest [4,5]. Significantly, there is potential to gain insights on fault behaviour, plus the impact on crustal-scale fluid redistribution, from studies that link the rock record to fault processes observed in modern, active fault systems.
Active fault processes are notoriously complex. Nonetheless, co-seismic static stress change calculations for fault-slip events have had substantial success at explaining some aspects of earthquake behaviour. Positive static stress changes correlate with 60–80% of aftershocks after an earthquake [6,7] and are consistent with the stepwise triggering of earthquakes along the San Andreas and Anatolian fault systems [6,8]. Faults are modelled in 3D as dislocations with an imposed slip, and the resulting change in Coulomb failure stress is obtained [6,9]. A feature of stress transfer modelling is that it relies on parameters that, in some cases, are accessible from the rock record. Indeed parameters, such as fault geometry or slip direction, can be well constrained.

Outstanding questions remain however, because static stress changes do not explain observations of spatial and temporal evolution in aftershock sequences. Dynamic stress changes, which result from the passage of seismic waves, seem to have a role in triggering failure of unstable faults close to the mainshock rupture plane [10]. It is also possible that asthenospheric and lower crustal stress relaxation following major ruptures transfers stress to the upper crust [11,12]. Finally, fluid redistribution after mainshocks potentially has a profound influence on rupture-related stress changes, which may explain spatial and time-dependent behaviour observed in some aftershock sequences [13–15]. Hydro-mechanical models of this latter behaviour tend to consider the effects of fluid pressure changes on stress states due to fluid redistribution from porosity surrounding a mainshock. Alternative models consider a scenario where high-pressure fluids are released into a fault system from overpressured reservoirs, breached by ruptures [1,14].

Some Archaean greenstone terranes provide an opportunity to investigate fluid flow in fault systems. Gold deposits are commonly hosted on faults and occur in spaced clusters known as goldfields, commonly ∼30 km apart. High fluid fluxes are associated with mineralization [3,16] and the fluids are localised within complex networks of small-displacement faults, shear zones, related veins, plus their alteration haloes [17,18]. Such faults are kinematically related to adjacent, large-displacement, crustal-scale faults. In low porosity, mid-crustal environments the overwhelming control on fluid flow is co-seismic fracture permeability, followed by rapid interseismic hydrothermal sealing and permeability destruction [16]. Thus, with regard to goldfields, those structures that activated the most over the lifetime of a fault system experienced enhanced fluid flow and mineralization. These fault systems represent a novel opportunity to test the long-term cumulative influence of static stress changes on the behaviour of fault–fracture networks and their impact on fluid redistribution between crustal fluid reservoirs.

We describe two ancient mineralized fault networks from near Kalgoorlie, Western Australia (Fig. 1), which are associated respectively with dilational and contractional fault step-overs between large-displacement fault segments. In an earlier work Cox and Ruming [4] and Micklethwaite and Cox [5] demonstrated for the first time that the clustered distribution of gold deposits on small-displacement faults can be understood broadly in terms of static stress changes associated with mainshock rupture events on adjacent large-displacement components of the fault systems. Results supported the hypothesis that aftershocks on small-displacement faults were responsible for extended periods of fracture-induced permeability enhancement, fluid flow and mineralization. However, it was also found that significant areas did not contain mineralization where it may be expected.

Here, we explore the impact that large aftershocks or triggered earthquakes can have on static stress changes generated by the mainshock rupture. In particular we examine how one or two triggered aftershocks or earthquakes, on adjacent medium- to large-displacement faults can modify the static stress change distribution from the

Fig. 1. Schematic map and location of the two case study sites in the Kalgoorlie greenstone terrain, Western Australia. Inset shows location of Yilgarn Craton.
mainshock rupture. We examine the correlation between the modified distribution of static stress change and the distribution of fault-hosted gold deposits, to constrain how fluid pathways are affected by aftershock seismicity and permeability enhancement. Our field observations argue that high-pressure fluids, from breached over-pressured reservoirs, were also involved in inducing failure on those small-displacement faults already promoted to failure by static stress changes.

2. Structural architecture and gold mineralization: case studies

The Mt Pleasant and St Ives goldfields are associated with two fault networks in the Kalgoorlie greenstone terrane, Western Australia [4,5] (Fig. 1). They were mineralized at different times relative to the regional structural sequence but share many similarities in conditions of formation and mineralization style. Mafic volcanic and intrusive rocks comprise the majority of host rock in both goldfields. Alteration assemblages, plus fluid inclusion and isotopic constraints, indicate temperatures during mineralization were 250–300 °C at Mt Pleasant and ∼400 °C at St Ives [19,20], at mid-to upper-crustal depths.

Gold mineralization is hosted by small-displacement faults and shears, with associated breccias and vein arrays (Fig. 2). The faults that are mineralized comprise only small portions of the two fault systems. They are associated with large-displacement, poorly mineralized strike-slip faults, which have irregular and complex fault traces (Fig. 2). Most mineralized faults identified in mines are <1.0 km long, with 1–100 m maximum offsets and tend to be spatially linked with one another. They occur over areas >15 km² and can exhibit a range of orientations relative to the adjacent large-displacement fault segments. Zones of intense hydrothermal alteration surround lode-hosting faults and shear zones.

In the following descriptions the term step-over refers to the region between and around understepping or overstepping fault segments [21] that show evidence of interaction (step-overs are synonymous with fault jogs).

Fig. 2. The Black Flag fault system and Playa–Lefroy fault systems, active during mineralization. (A) Profile of strike separation of stratigraphy along the Black Flag fault (proxy for displacement) vs. fault length; modified from Micklethwaite and Cox [5]. Strike separation measured at any point is normalised over the maximum strike separation measured on the Black Flag fault of 2.4 km. Separation on secondary faults is not integrated in this profile. (B) Map of the Black Flag fault system. The Mt Pleasant goldfield is located adjacent to a 1 km-long dilational fault step (see Fig. 3 for detail), which coincides with a marked minima in the displacement-length profile of the Black Flag fault. (C) Map of the Lefroy and Playa faults. Tick marks along fault traces indicate dip direction. Note, the Lefroy fault is also referred to as the Boulder-Lefroy fault [35].
Accordingly, soft-linked fault segments show evidence of mechanical interaction even though there is no evidence of connecting faults or fractures between the segments. Hard-linked fault segments are connected across the step-over, often by a network of small-displacement faults or fractures. Soft-linked fault segments are expected to evolve to hard-linked fault segments as displacement increases along a fault system [21].

The case study areas enable us to compare an understepping, hard-linked, dilational step-over on the Black Flag fault system (Mt Pleasant), with an understepping, hard-linked, contractional step-over on the Playa–Lefroy fault system (St Ives). At Mt Pleasant two dextral strike-slip fault segments with maximum displacements >2.5 km cut across an open regional anticline and transfer displacement across an extensional step-over [5]. The fault segments are understepping by ∼2.0 km, and hard-linked by faults, narrow strike-slip duplexes, silicified breccias and subvertical, semicontinuous quartz veins (Figs. 2 and 3a). Strike separation of stratigraphy across the step is ∼0.4 km, which represents a minimum in the offset-fault length profile for the Black Flag fault (Fig. 2a; see also Micklethwaite and Cox [5]). A network of synthetic branch faults and a few apparently unlinked faults are developed throughout the goldfield. Quartz–carbonate extension veins (i.e. mode I fractures with quartz–carbonate infill) form dense arrays connected to faults, or en-echelon sets near faults. Extension veins are predominantly subvertical, strike 060° and have mutual crosscutting relationships with fault-fill veins or breccias. The geometric relationships between faults and extension veins confirm a dextral slip on the Black Flag fault system. Silicified wear breccias contain clasts composed of pre-existing breccia and vein fill (Fig. 3b) as well as wall rocks. Development of foliation adjacent to some faults, pressure solution of veins as well as shear zone fabrics record a significant component of non-brittle deformation in the area. There is also an apparent asymmetry present in the fault network, with the
majority of known branch faults splaying off the southern segment of the Black Flag fault and not the northern.

The St Ives goldfield stretches north from a contractional step on the Playa fault, which links to the regional Lefroy fault system. The Playa–Lefroy fault system is a sinistral-reverse strike-slip system, spatially associated with a complex network of small-displacement faults at a contractional step [4,18]. Imbricate thrusts connect across the contractional step and are associated with spectacular arrays of mutual cross-cutting, subhorizontal extension veins and fault-fill veins and breccias (Fig. 3c). Widespread development of shear zone foliation records a component of non-brittle deformation in the area [18]. Northwest from the contractional step, gold deposits occur in a narrow corridor between the northern Playa fault segment and a thrust (the Delta fault). An imbricate array of east- or west-dipping, connecting faults link the Playa and Delta faults and host mineralization. These are predominantly small-displacement thrusts and sinistral-reverse faults, associated with zones of foliation (one to hundreds of metres thick), plus brecciation and veining. Low-grade gold mineralization is also present on some E–W very low-displacement normal faults and shear zones within the mineralized corridor [4]. At the northernmost part of the goldfield, a small number of gold deposits are hosted on small-displacement sinistral faults and shear zones.

Mineralization in both goldfields was coeval with deformation and involved the migration of substantial volumes of hydrothermal fluids that were out of chemical equilibrium with the local host rocks. The field examples are associated with hard-linked, understepping, step-over zones between large-displacement segments of the fault systems. We infer that such large step-overs were long-lived rupture arrest features [4,5], which probably evolved from soft-linked to hard-linked in the latter stages of fault system development. The observed mutually overprinting fault-fill and extension vein geometries are indicative of a fault-valve failure mechanism for many of the mineralized faults. For this mechanism to operate, the transient and repeated attainment of suprahydrostatic fluid pressures is required [1,18,22]. Herein, fluid pressure is described in terms of the pore fluid factor (λ), which is the ratio of fluid pressure relative to the lithostatic overburden pressure (σn, equivalent to σ2 in these studies).

This study examines ancient fault systems in which slip events are inferred rather than observed. Therefore it is necessary to establish the nature of the fault-slip events before we proceed. Faults can fail in stable slip events (frictional creep) as well as unstable seismic slip events. Both modes of failure generate static stress changes that can trigger subsequent failure [12]. Abundant breccias observed in both case study sites are cemented by silica and contain clasts of pre-existing breccia and vein material (Fig. 3). These observations require multiple episodes of fault slip and brecciation, with intervening periods of fluid flow, cementation and sealing, in which faults become healed. Thus, although fault creep may have been a component of deformation, it is apparent that the small-displacement faults were repeatedly triggered as aftershocks, following slip events on adjacent large-displacement fault segments.

### 3. Coulomb stress change and the apparent friction approximation

Changes in static stress, resulting from earthquakes, have been used extensively to explain the distribution of aftershocks and the triggering of subsequent earthquakes [6–8]. We can also relate stress changes to the fossil fault systems described [4,5]. The arrest of fault slip can be strongly influenced by features such as fault tips or step-overs between segments [23–25]. We infer that over the lifetime of a fault system, features like fault tips and fault step-overs act as the starting and stopping points for many ruptures, even though some ruptures can jump across step-overs (e.g. Landers earthquake). This inference allows us to calculate static stress changes from ancient fault-slip events.

In stress transfer modelling, fault slip is simulated as a dislocation in an elastic half-space [9]. A modified Coulomb failure criterion is used to quantify static stress changes on fault planes adjacent to a fault rupture surface [6,26],

\[
\Delta \sigma_F = \Delta \tau + \mu' \Delta \sigma_n
\]

where \(\Delta \sigma_F\) is the change in Coulomb failure stress, \(\Delta \tau\) the change in shear stress and \(\Delta \sigma_n\) the change in normal stress (negative in compression). The apparent coefficient of friction (\(\mu'\)) uses a simple poroelastic assumption to incorporate the effect of changing normal stress on fluid pressure, where during and immediately after slip, stress changes are too rapid for pore fluid migration to occur. Thus strictly, Coulomb stress transfer modelling examines the influence of instantaneous static failure stress changes on the triggering of fault–fracture networks or subsequent ruptures. After rupture events, any changes in fluid pressures, ductile flow of lower crust, or frictional fault creep will alter the initial static stress changes [10–14]. Various stress transfer studies have found that low values for the
The apparent friction coefficient of \( \mu' = 0.2 \) are most consistent with aftershock distributions \([13,27–29]\). The parameter \( \mu' \) relates confining stress to pore fluid pressure by Skempton's coefficient, \( B \), such that,

\[
\mu' = \mu[1-B]
\]  

\( B \) is the ratio of the change in fluid pressure to the change in normal stress due to fault slip \([30]\), with experimental values ranging from 0.5 to 0.9 \([31]\). The friction coefficient \( \mu \) typically has values \( 0.55 \leq \mu \leq 0.90 \) \([32]\). It follows that values of \( \mu' = 0.2 \) are to be expected (Fig. 4) and do not imply a fault is weak, whilst values of \( \mu' = 0.4 \) are at the upper end of the experimentally determined range (Fig. 4). Nonetheless, even higher values of apparent friction, up to \( \mu' = 0.8 \), have been found for continental thrusts \([e.g. 33]\). Such elevated values of \( \mu' \) may not be unusual in fractured

Fig. 4. Relationship between Skempton’s coefficient (B) and apparent friction (\( \mu' \)) for differing values of static friction (\( \mu \)) measured in laboratory experiments. Shaded region represents the domain in which reported experimental values of panel B lie.

Fig. 5. Calculations of Coulomb failure stress change for optimally oriented faults (dextral strike-slip faults). Results are compared from fault slip on the two major segments of the Black Flag fault (white lines) with the distribution of fault-hosted gold deposits (grey polygons) in the Mt Pleasant goldfield. (A) Model setup. (B) Static stress change from slip on northern segment. (C) Static stress change from slip on southern segment. (D) Combined-slip stress change (resulting from slip on both fault segments). An excellent correlation exists between the combined-slip static stress change and the distribution of mineralization. (E) Model with lower value of apparent friction. The distribution of positive static stress change is not significantly affected by variations in this parameter. (F) Model with low Poisson’s ratio appropriate to dry mafic rocks. The distribution of positive static stress change is not significantly affected by variations in this parameter.
rock masses because fracture geometry should have a control on $B$. $B$ is expected to tend towards zero in rock containing fractures parallel to the maximum principal stress \[34\], in which case Eq. (2) indicates that $\mu'$ becomes equivalent to $\mu$. Thus, as stress increases prior to rupture, microcracks and fractures opening parallel to the maximum principal stress drive $B$ towards zero. This scenario may be particularly true for fluid-saturated rocks in high $\lambda$ regions, and for this reason we prefer to use a slightly elevated value of $\mu'=0.4$. A more thorough treatment of apparent friction is given by Beeler et al. \[31\].

4. Coulomb stress changes around the Mt Pleasant and St Ives fault systems

For both case studies we have calculated $\Delta \sigma_F$ generated by mainshock events, then we have examined the static stress changes from large aftershocks or triggered earthquakes (fault lengths $\geq 5$ km) and how

![Fig. 6. Calculations of Coulomb failure stress change ($\Delta \sigma_F$) comparing stress change from fault slip on major segments of the Playa–Lefroy fault system with the distribution of the St Ives goldfield deposits (grey polygons). (A) Model setup. (B) $\Delta \sigma_F$ generated by slip on the 30 km-long Playa–Lefroy fault segment (white line). $\Delta \sigma_F$ is resolved on strike-slip faults parallel to the northern Playa fault segment (close to the optimal fault orientation). Dashed line shows positive stress change at the 1 bar contour, resolved for faults parallel to the Delta fault. Results show that the Delta and northern Playa fault segments are both brought closer to failure. (C) $\Delta \sigma_F$ resolved for strike-slip faults, resulting from mainshock slip on the southern segment of the Playa fault, plus triggered large aftershocks on the northern Playa fault segment and the Delta fault. (D) $\Delta \sigma_F$ resolved on thrust faults. The $\Delta \sigma_F$ pattern is the result of mainshock slip on the southern segment of the Playa fault, plus triggered large aftershocks on the northern Playa fault segment and the Delta fault. An excellent correlation exists between the cumulative static stress change due to slip on all these fault segments and the distribution of mineralization.](image-url)
they modify the mainshock stress change distribution (Figs. 5 and 6). Thus, in the Black Flag fault case study we account for stress triggering of one large Black Flag fault segment by slip on the other. In the Playa–Lefroy fault case study we account for triggering of the Delta fault and northern Playa fault segment by large slip events on the southern Playa fault segment. Herein we refer to these as “combined-slip” calculations. A similar approach was employed by Stein et al. [8], where static stress changes were correlated with the historic triggering of progressive ruptures along the North Anatolian fault, Turkey, since 1939. Although model calculations were carried out in 3D, results are presented in 2D map view for ease of comparison with the mapped fault configuration. $\Delta \sigma_F$ was calculated on a 100 m grid spacing. For each goldfield the results from the combined-slip calculations are compared with $\Delta \sigma_F$ patterns due solely to single mainshock ruptures (e.g. Fig. 6b and c). Previous stress transfer studies of the Mt Pleasant and St Ives goldfields considered single mainshock slip events only [4,5]. However, although there was a correlation between the distribution of mineralization and positive $\Delta \sigma_F$ it was found that significant areas did not contain mineralization where it may be expected. In addition, understanding of the geometry and kinematics of the fault systems in the two case study areas has improved since the earlier studies [4,5].

We model the structures shown in Fig. 2 as vertical and dipping faults, using COULOMB 2.5 [9]. Estimates of the orientations for regional stress during mineralization were gained from consistent vein orientations and fault kinematics measured at both case study sites. The inferred stress fields are in broad agreement with the structural evolution of the entire terrane as identified from pervasive fabrics, fold geometries and fault-shear zone orientations elsewhere [35]. Both sets of far-field stress are appropriate to Andersonian-type wrench fault systems, and the magnitudes of vertical stress gradients were estimated on this basis (Table 1). The imposed maximum principal stress ($\sigma_1$) is horizontal and strikes 060° at Mt Pleasant and 100° at St Ives. Co-seismic slip distributions for the faults at both case study sites cannot be known. The normalised slip profile, shown in Fig. 2 for the Black Flag fault system, is the cumulative result of multiple slip events and for that reason the direct application of this slip distribution is avoided in our calculations. Instead, for ease of comparison between both sites we simplify slip distributions to first-order uniform slip models (Table 1). This has the effect of amplifying static stress changes at the rupture surface tips. However, the location and distribution of the static stress changes are not significantly altered, as these factors are more dependent on the geometry and slip direction of the faults, which are known. In addition, tests were carried out on the Mt Pleasant goldfield, using tapered slip distributions and it was found that results were not significantly affected.

Hydrothermal alteration assemblages in our case study areas indicate faulting took place at mid-crustal depths; accordingly we sample stresses in the models at 10 km depth. In any case, because the Black Flag fault is a vertical strike-slip fault system, with no oblique-slip component, the model results are similar for the entire depth-extent of the modelled dislocations (2–15 km). This is not true of the St Ives case study (Fig. 2) where both the northern Playa fault segment and the Delta fault are moderately to steeply dipping, oblique-slip structures—the latter dominantly dip-slip (Table 1).

### 4.1. Results

Results for the Mt Pleasant goldfield show that combined-slip events on the large-displacement northern and southern segments of the Black Flag fault, induce cumulative positive static stress changes with an excellent correlation with the distribution of mineralized small-displacement faults (Fig. 5d). Those few areas where there is no apparent correlation, such as fault bends (Fig. 5d), have not yet been well-explored.

Field evidence, such as multiple vein types and hydrothermal alteration, indicates that the Mt Pleasant and St Ives fault networks were fluid-saturated. For this reason both goldfields were modelled using a high Poisson’s ratio ($\nu=0.4$), representative of fluid-saturated upper crustal rocks. However, we used the Mt Pleasant case study to explore in a simple way the effect of

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF slip</td>
<td>1.0 m right-lateral</td>
</tr>
<tr>
<td>PL slip</td>
<td>1.0 m left-lateral (0.5 m on northern-most plane)</td>
</tr>
<tr>
<td>P slip</td>
<td>0.2 m left-lateral, 0.1 m reverse</td>
</tr>
<tr>
<td>D slip</td>
<td>0.2 m left-lateral, 0.05 m reverse</td>
</tr>
<tr>
<td>Apparent friction</td>
<td>0.4</td>
</tr>
<tr>
<td>$E$</td>
<td>7.0 × 10^6 MPa</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.4</td>
</tr>
<tr>
<td>$d\sigma_{1}/dz$</td>
<td>36.5 MPa/km</td>
</tr>
<tr>
<td>$d\sigma_{2}/dz$</td>
<td>29.0 MPa/km</td>
</tr>
<tr>
<td>$d\sigma_{3}/dz$</td>
<td>21.5 MPa/km</td>
</tr>
</tbody>
</table>

BF—Black Flag fault (north and south segments), PL—Playa–Lefroy fault, P—northern Playa fault segment, D—Delta fault. Parameters $\mu'$ and $\nu$ were modified in tests to examine their influence on results.
varying \( \mu' \) and \( v \). Fig. 5e–f shows that there is very little sensitivity to variations in these parameters in terms of the resulting distribution of positive static stress changes.

At St Ives, the northern Playa and Delta fault segments can be regarded as relatively large faults (\( \geq 5 \) km in length) within the Playa–Lefroy fault system. The largest structure in the system is the southern Playa–Lefroy fault segment (\( \sim 30 \) km-long). The combined-slip static stress changes, from slip on all three faults, match well the distribution of mineralized faults and also the orientation of faults that are mineralized (Fig. 6c–d). Where mineralized thrust faults dominate in the central corridor at St Ives (between the Delta fault and northern Playa fault) positive stress changes occur on optimally oriented thrusts (Fig. 6c), but \( \Delta \sigma_F \) is also positive for strike-slip faults. Where there is a dominant lobe of positive \( \Delta \sigma_F \) resolved on strike-slip structures in the north of the goldfield (Fig. 6d), some mineralization is indeed hosted on strike-slip faults in the field.

Two final observations are relevant. Firstly, Figs. 5 and 6 show that, in both case studies, the domains of positive \( \Delta \sigma_F \) obtained from combined-slip calculations fit the distribution of mineralization far better than those that consider just a single major slip event on the large-displacement fault segments [e.g. Figs. 5b–c and 6b; see also Figs. 4 and 5]. Secondly, in the Mt Pleasant case study, stress changes from a single fault-slip event on the northern fault segment increase the proximity to failure on the southern segment, and vice versa (Fig. 5b–c), indicating such events would have had the potential to trigger one another. Similarly, in the St Ives case study, modelling indicates the northern Playa fault and Delta fault segments would have been brought closer to failure, and therefore prone to triggering, following fault-slip events on the large-displacement, southern Playa fault segment (Fig. 6b).

5. Discussion

Field observations have been combined with static stress change calculations, in two examples of fossil fault systems. Both fault systems feature strongly mineralized small-displacement faults developed around understepping fault step-overs, between large-displacement fault segments. The patterns of static stress changes associated with large fault-slip events mimic the distribution of those small-displacement faults that host gold mineralization. In particular, we have found that combined-slip calculations accounting for slip from all the moderate-to large-displacement faults in a goldfield, have an excellent correlation with the distribution of mineralized small-displacement networks (Figs. 5d and 6c–d). The correlation exists over distances in excess of 10 km away from the large-displacement fault step-overs. In this section we discuss how the distribution of gold deposits around crustal-scale fault systems reflects not just static stress changes driven by mainshocks, but is also critically dependent on how static stress changes evolve during triggered rupture sequences. We explore the implications for the migration of fluids through fault systems and the concomitant impact of changes in fluid pressure.

5.1. Effects of rupture sequences on evolution of static stress changes and fluid flow

A number of features make the case studies detailed here particularly interesting: (1) Our observations on fossil fault systems affirm the concept that static stress changes exert a first-order control on subsequent near-field faulting and fracturing. (2) Static stress changes from single slip events on large-displacement fault segments would have brought other large-displacement and moderate-displacement faults closer to failure, potentially triggering them. (3) Static stress changes from the resulting combined-slip calculations have the best correlation with the distribution of small-displacement faults that are mineralized. (4) Gold mineralization preferentially hosted in small-displacement faults implies that those faults experience high fluid fluxes relative to adjacent, poorly mineralized large-displacement faults [3]. (5) Where stress shadows are predicted, mineralization is absent.

Overall, our results are consistent with crustal-scale fault systems in the late Archaean operating in much the same way as modern day fault systems. The Black Flag and Playa fault systems record behaviour such as earthquakes triggering subsequent earthquakes [6–8] and secondary aftershock behaviour (the triggering of small aftershocks by large aftershocks [36,37]). At Mt Pleasant, it could also be argued that similar \( \Delta \sigma_F \) patterns could result from ruptures propagating along one segment of the Black Flag fault and jumping the step-over. However, at St Ives the best fit between mineralization and cumulative static stress change required triggering of the Delta fault in addition to the Playa fault segments. The important point to emerge is that there is potential for radical reorganisation of aftershock distributions when large aftershocks or ruptures on adjacent faults are triggered by initial large-displacement ruptures. As a consequence there is also radical reorganisation of fluid flow pathways within an aftershock sequence when this happens.
Fig. 7 illustrates the above point for the St Ives case study. In the first stage of the rupture sequence, a large rupture propagating along the southern Playa–Lefroy fault segment is arrested at the contractional step, promoting aftershocks, permeability enhancement and fluid migration over a broad lobate area. However, the resulting changes in static stress promote failure on both the northern Playa fault segment and the Delta thrust fault. The triggering of slip on these structures has a significant impact on the distribution of $\Delta \sigma_F$, modifying the domain of positive $\Delta \sigma_F$ so that it becomes restricted to a central corridor between the northern Playa fault and the Delta fault. Accordingly, the distribution of aftershock activity is expected to be correspondingly restricted. Outside of the central corridor, initial aftershock porosity, triggered by the mainshock, is rapidly sealed by migrating hydrothermal fluids because those structures do not continue to fail repeatedly. Therefore the permeability enhancement due to initial aftershock activity is lost. Fluid migration and ultimately gold mineralization becomes confined to the modified aftershock distribution, where repeated failure maintains active percolation networks over the life span of the aftershock sequence (months to decades in contemporary active fault systems).

It is worth noting in both examples that a consistent correlation exists between the distribution of mineralization and positive $\Delta \sigma_F$ resulting from rupture sequences, in excess of 10 km from the large fault step-overs (Figs. 5 and 6). Thus aftershock-related fault networks can control fluid flow at large distances away from fault step-overs, or other rupture arrest locations. A close spatial association between fluid flow, mineralization and fault step-overs is well known [e.g. 38], although there has been a tendency in the literature to emphasise the importance of dilational fault steps over contractional fault steps [e.g. 39]. The studies described here show that fluid flow need not be associated just with permeability enhancement in fault step-overs. This study and previous work [4,5] indicate that an association exists because repeated triggering of aftershocks around such features can generate large domains of permeability enhancement. Contractional and extensional fault steps are both important. Mineralization at Mt Pleasant and St Ives must have occurred in the potentially short period that their extensional and contractional fault steps acted as effective geometric barriers to repeated ruptures.

5.2. Fluid flow in aftershock networks

A number of hydromechanical models have considered the interaction between fluid migration, fluid pressure evolution and static stress changes resulting from an earthquake [see 40]. In one class of model, wall rock porosity and fractures local to the triggering faults are considered to be fluid-saturated, with a drained response to co-seismic stress changes [13,15,41]. Fluids migrate, pore pressures evolve and seismicity is promoted, in an essentially diffusive process, controlled by...
poroelastic responses to a fault-slip event. A second class of model recognises that aftershock failure can be driven by migration of fluid pressure pulses from breached overpressured reservoirs [e.g. 14]. Failure of faults in response to increases in fluid pressure may take precedence over co-seismic static stress changes, once high pore fluid factor fluids migrate in to an aftershock fault network [14,16].

Our observations show static stress changes, most likely from repeated compound rupture sequences, control the distribution of structures that experienced enhanced fluid flow. However, fluids evidently attained high pore fluid factors in the mineralized fault networks (e.g. the occurrence of extension veins), whilst hydrothermal alteration in and around the mineralized faults demonstrates that the fluids were out of chemical equilibrium with the wall rocks. Likewise, gold and silica solubilities are such that very large finite volumes of fluid are required to explain the gold deposits and their related fault-vein networks [3]. For example, the observed gold resource of >100 tonnes at Mt Pleasant requires a minimum fluid volume of $10^6$ to $10^{12}$ m$^3$, on the basis of the solubility of Au in mid-crustal fluids [42]. This value is several times larger for the St Ives goldfield. We propose that fluid-pressure driven failure of faults in the aftershock zone exploited those faults already brought closer to failure by static stress changes associated with large rupture events (Fig. 8). The mineralizing fluids were not stored in local wall rock or fracture porosity but instead infiltrated the fault networks from overpressured fluid reservoirs, which were breached initially by the rupture sequence. As such, fault-valve failure mechanisms, triggered by migrating high fluid pressure pulses, may be characteristic of fluid-rich aftershock sequences. Similar fluid-rich aftershock sequences associated with active fault systems may display both double-couple and non double-couple seismic signals, and anomalous seismic velocity ratios.

At the St Ives and Mt Pleasant goldfields gold deposition was localised in repeatedly reactivated aftershock networks, rather than in the nearby large-displacement faults. This implies that transient increases in permeability and fluid redistribution between crustal reservoirs are preferentially enhanced in aftershock networks relative to mainshock rupture surfaces (Fig. 8). Fluid reservoirs are expected to be common in the crust and could include magmatic or metamorphic volatiles trapped beneath a low-permeability carapace, beneath fold closures, beneath low permeability seals within crustal stratigraphy, or even trapped in sealed compartments within the fault system. A conceptual model presented in Fig. 8 shows a mainshock rupture breaching the upper part of a fluid reservoir, with a fluid pressure wave migrating upwards along the mainshock rupture, as well as exploiting the triggered aftershock domain. Hydrothermal sealing rapidly destroys permeability and inhibits fluid flow along the mainshock rupture, whereas aftershock networks are active for substantial periods

Fig. 8. (A) Schematic map and longitudinal-section of a strike-slip fault system, with a sealed, overpressured fluid reservoir at depth. Aftershocks (small circles) depicted to illustrate the concept only. A migrating pulse of high-pressured fluid (grey) penetrates the aftershock fault network adjacent to a recently ruptured large-displacement fault segment. If fluid migrates vertically from depth, there will be no marked evolution in the map distribution of aftershocks with time. Grey arrow—movement vector of the fluid pulse. (B) The cementation potential of fluids migrating up faults and down temperature gradients leads to rapid sealing of the mainshock fault. Aftershock fault networks, with their extended period of activity, can maintain connectivity and permeability for longer. Over repeated mainshock events, much larger time-integrated fluid fluxes are attained in aftershock zones relative to the mainshock rupture [5]. Note, in some cases, even if a mainshock rupture does not breach the fluid reservoir, the more volumetrically extensive and deeply penetrating aftershock network may do so.
following mainshock rupture and are likely to sustain longer-lived, fracture-enhanced permeability than mainshock fault planes [5]. Additionally, aftershock fault networks develop over substantial crustal volumes, in donut-like domains around the tip of the mainshock slip patch. Accordingly, the network drains a larger, hydraulically accessible portion of the fluid reservoir than a single mainshock rupture surface (Fig. 8). The after-shock network may also penetrate to a deeper level in the fluid reservoir. As the fluid pressure pulse migrates upward through the aftershock network, elevated pore fluid factors promote fluid-driven aftershock nucleation (Fig. 8). Furthermore, the greater fault-related surface area affords much greater potential for fluid–rock interaction and gold deposition relative to a single mainshock surface.

6. Conclusions

It has been shown that the geometry and distribution of domains of positive Coulomb failure stress change ($\Delta \sigma_F$) from large fault-slip events can be substantially modified by the subsequent triggering of other medium- and large-displacement faults within the initial zone of positive static stress change. This process happens often enough that a record of the process is preserved in Archaean fault systems that localised high fluid flux during gold mineralization.

In two case studies of Archean fault systems, we found that the modification to patterns of mainshock-induced positive $\Delta \sigma_F$, due to the triggering of large aftershocks, very closely matches the distribution of small-displacement faults hosting gold mineralization. Thus, large aftershocks or subsequent triggered earthquakes can exert a strong control on where the highest fluid fluxes occur through small-event aftershock fault networks. We infer that the repeated triggering of aftershock networks plays a critical role in inducing permeability enhancement and controlling fluid redistribution between crustal reservoirs.

The case studies provide evidence that fluids in the aftershock networks were at high pressure and came from deep-level, overpressured fluid reservoirs. Fluids were out of equilibrium with the host rocks and were not sourced from local wall rock or fracture porosity.

The field evidence indicates that higher fluid fluxes are preferentially localised in aftershock networks relative to adjacent, mainshock, large-displacement faults. We interpret this to be due to the extended period of activity of aftershocks following mainshock rupture, which sustains longer-lived, fracture-enhanced permeability. The permeability of the mainshock fault is rapidly lost due to hydrothermal sealing. Additionally, aftershock networks can tap deeper in to fluid reservoirs than mainshock faults and generate enhanced transient permeability over larger volumes of the crust.

Applying stress transfer modelling to the rock record provides a novel opportunity to study how the dynamics of seismogenic fault systems may influence fluid redistribution in the continental crust. In a similar manner, stress transfer modelling is a powerful tool for gold exploration and may also afford insights in to petroleum reservoir leakage during active faulting.

Acknowledgements

This research was supported by an AMIRA International Ltd. and Australian Research Council Linkage grant. Placer Dome Ltd. and Gold Fields Ltd. are thanked for geological, financial and logistical support, including open access to mine sites and company data. In particular, Alan Goode, Bob Morrison, Karen Connors, Gerard Tripp and Brett Davis provided excellent logistical support, geological input and numerous discussions. We are also indebted to Ross Stein and an anonymous reviewers whose comments greatly improved the manuscript. The U.S. Geological Survey and S. Toda are thanked for making the Coulomb modelling package freely available.

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