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# The role of crustal fluids in the tectonic evolution of the Eastern Goldfields Province of the Archaean Yilgarn Craton, Western Australia

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Gold deposits in the Archaean Eastern Goldfields Province in Western Australia were deposited in greenstone supracrustal rocks by fluids migrating up crustal scale fault zones. Regional ENE-WSW D2 shortening of the supracrustal rocks was detached from lower crustal shortening at a regional sub-horizontal detachment surface which transects stratigraphy below the base of the greenstones. Major gold deposits lie close to D3 strike slip faults that extend through the detachment surface and into the middle to lower crust. The detachment originally formed at a depth near the plastic-viscous transition. In orogenic systems the plastic-viscous transition correlates with a low permeability pressure seal separating essentially lithostatic fluid pressures in the upper crust from supralithostatic fluid pressures in the lower crust. This situation arises from collapse in permeability below the plastic-viscous transition because fluid pressures cannot match the mean stress in the rock. If the low permeability pressure seal is subsequently broken by a through-going fault, fluids below the seal would flow into the upper crust. Large, deeply penetrating faults are therefore ideal for focussing fluid flow into the upper crust. Dilatant deformation associated with sliding on faults or the development of shear zones above the seal will lead to tensile failure and fluid-filled extension fractures. In compressional orogens, the extensional fractures would be sub-horizontal, have poor vertical connectivity for fluid movement and could behave as fluids reservoirs. Seismic bright spots at 15–25 km depth in Tibet, Japan and the western United States have been described as examples of present day water or magma concentrations within orogens. The likely drop in rock strength associated with overpressured fluid-rich zones would make this region just above the plastic-viscous transition an ideal depth range to nucleate a regional detachment surface in a deforming crust.

**Key words:** Fluids, faults, shear zones, seismic, Yilgarn Craton.

## 1. Introduction

The Archaean Yilgarn Craton in Western Australia has a rich endowment of minerals, with gold the traditional mainstay of the mining industry in the region. The richest gold camps are in greenstone supracrustal rocks that lie on a granitic and felsic gneissic basement in the region around Kalgoorlie. The gold was deposited from aqueous fluids, usually in second or higher order splays off major faults and shear zones whose lengths imply a crustal depth-scale. The relationship of gold deposits to crustal-scale fault systems implies fluids circulate throughout the crust. In this paper we describe the geometry of the crust at depth based on seismic imaging, and then discuss whether crustal architecture controlled the fluid circulation, or whether high fluid pressures locally reduced rock strength and therefore indirectly influenced the tectonic processes and crustal architecture in this part of the Yilgarn Craton.

## 2. Crustal Structure of the Yilgarn Craton

The Yilgarn Craton has been divided into a number of geological provinces based on the ages of the rocks, particularly granitic rocks, and the shapes and trends of the greenstone supracrustal rocks (Myers, 1995). In the eastern part of the craton, the Eastern Goldfields Province is further subdivided into a number of fault bounded terranes (Kalgoorlie, Gindalbie, Jubilee Terranes) (Swager, 1997). The Eastern Goldfields Province abuts the Southern Cross Province (Barlee Terrane) along the Ida Fault (Figs. 1, 2). Over a period of approximately 100 million years ending at 2600 Ma, regional stress patterns in the Eastern Goldfields Province resulted from an early extension episode (DE), followed by N-S compression (D1), compression along ENE-WSW axes which imposed the current broadly elongate NNW-SSE fabric to the granites and greenstones (D2), strike-slip faulting along regional NNW-SSE trending faults (D3), and local oblique-slip (D4) (Hammond and Nisbe, 1992; Swager, 1997). However, stress patterns deviated locally from the regional patterns. For example, local extension may have occurred during regional D2 compression (Blewett *et al.*, 2004). DE structures are not widely observed, and none are shown in Fig. 1. D1 faults are identified in the greenstone supracrustal sequences, for example immediately north of the Talcum Fault (Fig. 1) (Swager, 1996), and around the ends of a number of the granitoid domes within the greenstone belts. Several linked D1 faults crop out in the greenstone rocks. D2 thrust faults and back thrusts, many of which reactivated as D3 strike slip faults, dominate the geological map at the scale of Fig. 1. More deeply penetrating

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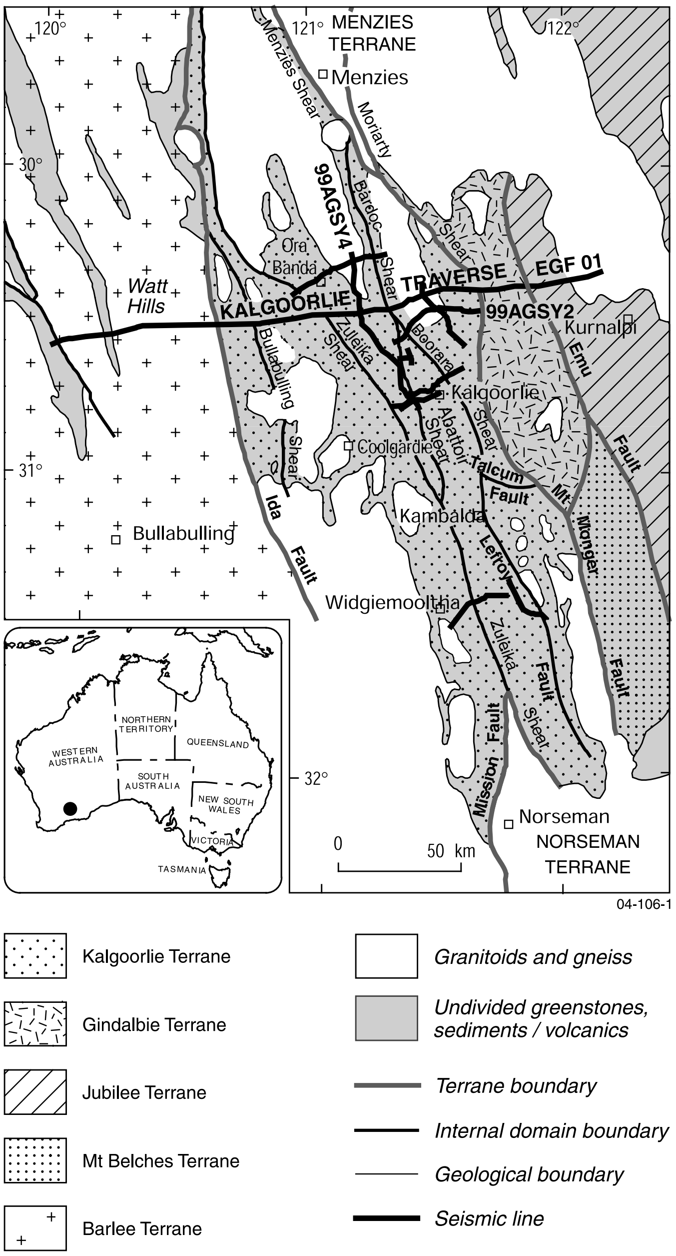

Fig. 1. Solid geology map showing the position of the seismic line EGF 01 used to construct the crustal cross section in Fig. 2.

examples would be the Ida Fault (thrust) and Bardoc Shear Zone (backthrust) (Drummond *et al.*, 2000a). Note that subsequently the Ida Fault has had undated normal, down-to-the-east movement; its sense of initial movement as a thrust is interpreted from the deep crustal seismic image (Fig. 2, and see below). D4 deformation is very localised, and not readily shown at the scale of Fig. 1.

The upper crust, excluding the greenstone supracrustal rocks, is likely to be quartzofeldspathic of acidic composition (Drummond, 1988; Drummond *et al.*, 1993). Seismic imaging of the Southern Cross and Eastern Goldfields Provinces (Swager *et al.*, 1997; Drummond *et al.*, 2000a) shows west-directed thrusting of duplexes in the middle crust, linked to west-dipping faults in the upper crust, probably resulting from D2 compression. The duplexes sole into an apparently (at the time of deformation) ductile lower crust. The middle and lower crust are likely to be of intermediate composition, and have a reflection character that indicates a rock fabric variably parallel and at high angle to the subsidiary faults bounding the duplexes. The duplexes contain internal reflectors that may represent earlier events (DE, D1). Immediately to the east of the Ida Fault, a zone of poorly reflective middle crust shows no evidence of duplexes, and may represent protocrust of a different composition, and perhaps rheology, to the middle crust to the east and west. The more deeply penetrating D3 strike slip faults (e.g., Bardoc Shear, Avoca Fault) appear to have been focussed mainly by D2 backthrusts in the upper crust (Fig. 2). In the middle to lower crust, a number of mechanisms accommodated D3 movements. The Ida Fault followed a subsidiary fault between a D2 duplex and the zone of poorly reflective middle crust. The west-dipping Avoca Fault appears to have cut through the middle crustal duplexes to the ductile lower crust in a broad semi-vertical zone, possibly

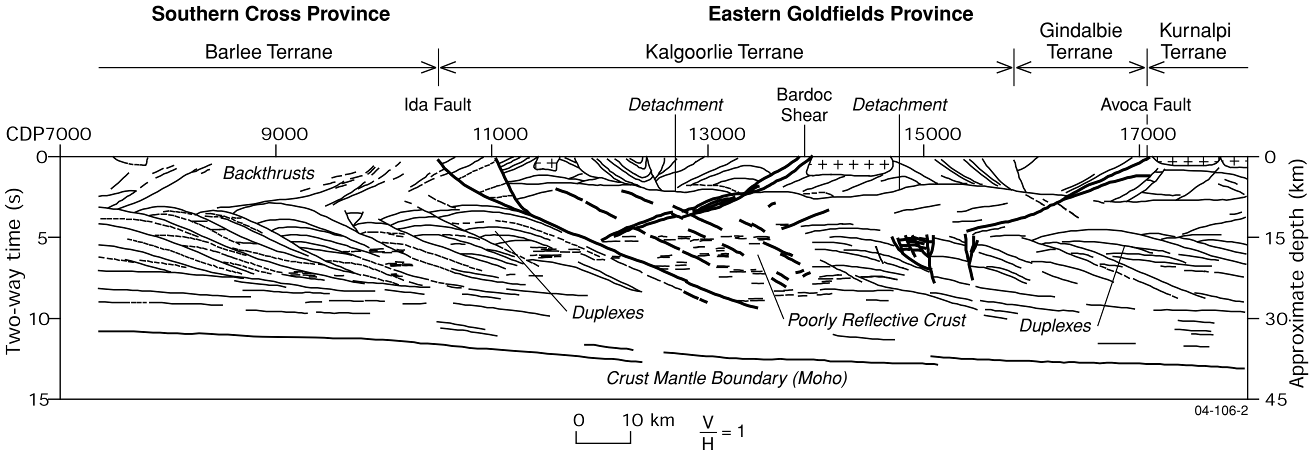

Fig. 2. Cross section based on the seismic reflection section along the seismic line EGF 01 whose position is shown in Fig. 1.

generating a flower structure (Drummond *et al.*, 2000a).

In the Eastern Goldfields Province, the upper 3–7 km was decoupled from the deeper crust along a regional detachment that can be traced for over 100 km from east to west, and a similar distance from north to south. The reflections from the detachment often have very high amplitudes. In places, but not everywhere, the detachment forms the base of the greenstone sequences; there the greenstones are structurally truncated (e.g., Fig. 3). Note that the geometry of the greenstone rocks above the detachment in Fig. 3 could be evidence of extension during the regional D2 compression, as reported by Blewett *et al.* (2004). Elsewhere, quartzofeldspathic basement rocks are interpreted both above and below the detachment (Swager *et al.*, 1997; Bell *et al.*, 2000), implying that the depth of the detachment was not determined by a rheological contrast caused by lithological differences.

## 3. The Behaviour of Fluids

The geology (e.g., Myers, 1995) and crustal structure suggest that the region formed in an accretionary orogen. Present day crust in the region is 33–39 km thick, and because the rocks at the surface are at least greenschist grade an additional 5–10 km are likely to have been eroded. The greenstone supracrustal rocks are interpreted to have been shortened by a factor of two; the structures in the seismic sections would be consistent with a similar amount of shortening in the middle crust. Therefore the pre-shortened crust must have had a maximum thickness of about 25 km. Isostatic considerations would suggest that the surface of such thin, juvenile crust must have been close to or below sea level and therefore hydrated. The estimated crustal composition, the style of crustal deformation, and the crustal mixing implied by the seismic data imply that the crust would have contained fluids that would have been released during orogenesis and subsequent metamorphism.

Early attempts to model the dehydration of, and subsequent fluid flow through the crust were summarised by Goleby *et al.* (1997) and Drummond *et al.* (2000b). The modelling assumed a layered crust, as defined by the seismic imaging, with much lower permeability in the crustal layers than in the main fault zones, the Bardoc Shear and Ida Fault. The crust was deformed under horizontal compression. The modelling predicted that the middle to lower crust would have been dehydrated by dominantly upward fluid flow, consistent with slow flow along grain boundaries and through annealing microfractures (Etheridge *et al.*, 1983). When the fluids reached the fault zones, they moved into and upwards along the fault zones. Because the fault zones are inclined, the fluids then broke out of the fault zones into the hanging wall blocks. Eventually the fluids concentrated in inclined zones within the quartzofeldspathic upper crust and greenstone rocks, with greater flow above and in places parallel to the contact in the model representing the regional detachment surface.

In this modelling, the permeability was imposed upon a pre-existing crustal structure that was based on present-day crustal thickness. Consideration should be given to the effects of high metamorphic fluid pressures on the rheology of a thin, deforming crust as it doubles in thickness. Cox *et al.* (1990) described the fluid pressure regimes that form during the deformation of low-grade metamorphic terrains. In the uppermost crust, fracture porosity is such that fluid pressures will stay close to hydrostatic. They defined two types of regime at deeper levels: a supralithostatic fluid pressure regime in the lower crust, and a litho-

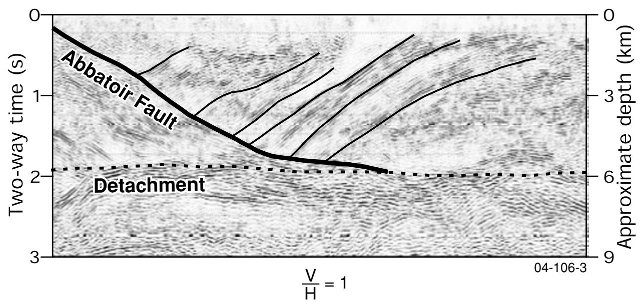

Fig. 3. Post-stack migrated image of part of the regional detachment surface, in this case showing dipping mafic and ultramafic supracrustal greenstone sequences and the Abbatoir Fault truncated against the detachment. North is to the right of the figure. This is the central part of Line 99AGSY4, extending south from its crossing with Line EGF 01 (Fig. 1).

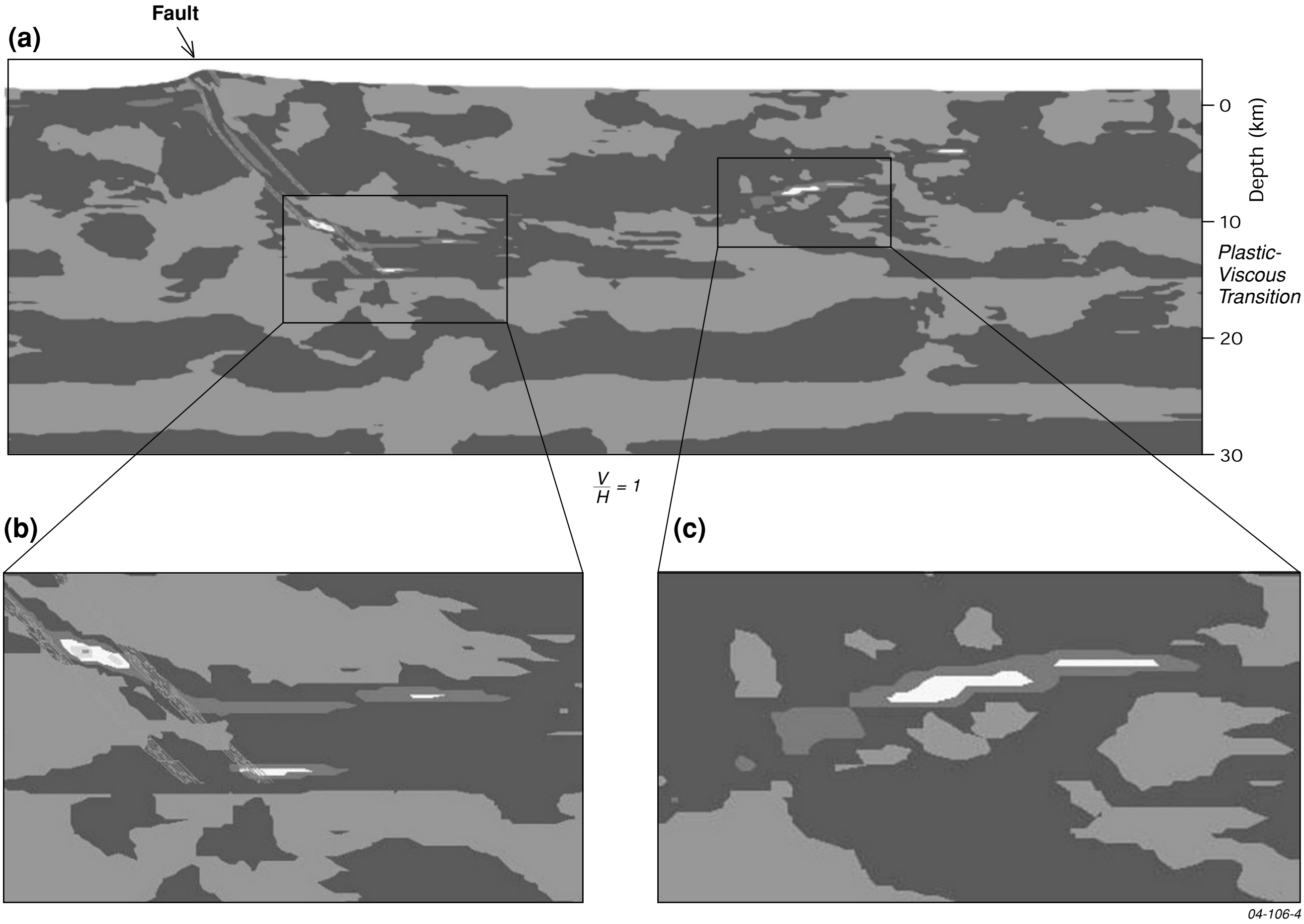

Fig. 4. Volumetric strain rate following shortening. Arrow at the top of (a) marks the position and attitude of the pre-imposed fault. Position of plastic-viscous transition labelled at right. Dark areas are relatively unstrained. Increasingly lighter shades indicate increasing volumetric strain rate.

static fluid pressure regime at depths below "a few kilometres" in the upper crust. The boundary between the two regimes corresponds to the boundary between different deformation styles in the crust (Sibson, 1977), represented by the commonly named ductile lower and brittle upper crust, respectively. The boundary between the regimes occurs around the depth of greenschist metamorphism (300–350°C, depending on the abundance of water; Sibson, 1977). In most of the crust, metamorphic fluid pressures can be high (Etheridge *et al.*, 1983) and fluid flow is determined by "deformation-induced porosity-creation and porosity-destruction processes" (Cox *et al.*, 1990). However, low permeability pressure seals can develop (Cox *et al.*, 1990; Connolly and Podladchikov, 2004). Where fluid pressures build up below the seals and exceed (lithostatic pressure+tensile strength), the fluids will hydrofracture the rock. In orogens, where the maximum principal stress is horizontal and the minimum principal stress is vertical, the hydrofractures will form horizontally, resulting in maximum fluid connectivity between fractures horizontally and minimum connectivity vertically through the overlying low permeability pressure seal.

Sibson (1977, 1990) suggested that the low permeability pressure seal would form at 10–15 km depth. This is the depth range at which the Yilgarn Craton detachment would have formed, when the effects of subsequent erosion have been taken into account. Modern fluid filled fracture systems have been imaged near the base of the seismogenic zone around 15–25 km km depth in Japan (Matsumoto and Hasegawa, 1996), Tibet (Brown *et al.*, 1996), and the western United States (Ryberg and Fuis, 1988). In these studies, high amplitude reflections ("bright spots") with negative impedance contrasts have been interpreted to be from fluid filled cracks. In Japan, some bright spots have been attributed to magma (Matsumoto and Hasegawa, 1996) and others to water (Umino *et al.*, 2002). The Tibetan reflectors have been attributed to both magma (Brown *et al.*, 1996) and water (Makovsky and Klemperer, 1999).

## 4. Modelling the Formation of Bright Spots

The results of numeric modelling of crustal fluid flow in which very little pre-existing crustal structure is assumed are shown in Fig. 4. Drummond *et al.* (2000a) interpreted the seismic data along line EGF 01 to show that the Bardoc Shear (D2 backthrust re-activated as a D3 strike-slip fault) and the regional detachment (D2) to both be active at late D2 and early D3 time. This model seeks to represent deformation within the crust at that time; i.e., at the last stages of crustal D2 shortening, by which time the main fault systems would have been in place. It allows us to consider the effects of crustal shortening on the distribution of strain in the crust, particularly in the region of the plastic-viscous transition at the time leading up to the formation of gold deposits, which we interpret as an indication of the later stages of crustal dewatering. The modelling method is described in more detail by Hobbs *et al.* (2004).

The model in Fig. 4 assumed a crust 30 km thick. A granitic composition was assumed throughout the crust. This is broadly consistent with estimates of crustal composition based seismic observations of crustal velocity, as discussed above (Drummond, 1988; Reading *et al.*, 2003). A fault dipping at 45° was embedded in the top half of the crust. Its inclusion allowed localisation of deformation to be an emergent phenomenon of crustal shortening. Faults commonly penetrate to the detachment surface in the Yilgarn Block (Fig. 1). Shortening was imposed at a strain rate of $10^{-13}$ $s^{-1}$ normal to the strike of the fault. A temperature gradient of 20°C $km^{-1}$ was assumed. Full coupling between mechanical behaviour and fluid flow included deformation-induced permeability in both the plastic and viscous regimes. Although some authors (Stuwe and Sandiford, 1994; Petrini and Podladchikov, 2000) have postulated that the fluid pressure in a deforming crust should be equal to the mean normal stress, arguments presented in Hobbs *et al.* (2004) indicate that throughout the crust, below some relatively shallow seal, both the fluid pressures and the fluid pressure gradients are close to lithostatic. This has a basis in observation in that it is consistent with observations from the Kola superdeep drill hole where high fluid pressures leading to hydrofracturing were observed in the upper crust below 4 km depth (Kozlovsky, 1984).

Figure 4 shows volumetric strain rate, which we use as a proxy for porosity. During shortening of the crust, deformation concentrated in the region of the fault, with surface uplift most pronounced in the hanging wall block above the fault (Fig. 4(a)). Porous zones formed above the plastic-viscous transition in the hanging wall side of the fault (Fig. 4(b)), and have a greater longevity than other similar zones that formed at shallower depths (Fig. 4(c)). The modelling therefore demonstrates that porous zones form and can be stable for relatively long time intervals near the brittle-ductile transition. The modelling implies considerable fluid flux through these zones. Hobbs *et al.* (2004) show the results for a range of similar geological models, including, in their figure 4(d) fluid flow vectors that demonstrate to a first order approximation the fluid flux. When filled with fluid, these zones would be strong reflectors of seismic energy. The fluid flux would also cause alteration of the rocks within the zones, so that in old environments such as the Yilgarn Block, which is probably now dry, the reflection signature would come from the impedance contrasts caused by alteration.

## 5. The Role of Fluids in Focussing Deformation

Irrespective of whether the fluids are aqueous or magmatic, their accumulation at a common depth across large areas must create zones of weakness at that depth because the crust is hydrofractured and the local strength is controlled by the strength of the fluid-rich region. When the zones of weakness correspond to changes in crustal rheology, as at the plastic-viscous transition, they are likely to focus the development of sub-horizontal detachments in a shortening crust. We note in the modelling in Fig. 4 that high shear strain occurs at the plastic-viscous transition and in the porous zones that are generated near the plastic-viscous transition. The detachment in the Yilgarn Craton may have formed in such an environment, separating different deformation styles in the upper and lower crust. For example, Drummond *et al.* (2000a) noted the different length scales of deformation above and below the detachment. Constraining the depth of the detachment to a fluid-rich zone rather than a boundary between different rock types would also be consistent with the observation (above) that the detachment is not consistently along a lithological boundary, but rather was controlled by some other rheology contrast.

Further evidence comes from the nature of the reflections from the detachment in the Yilgarn Craton. Synthetic seismogram modelling of the way three-dimensional structures will appear in two-dimensional seismic sections allows the detachment to be characterised into regions of thick shear zones (in the plane of the seismic sections), consisting of multiple layers, that are linked by faults (Drummond *et al.*, 2004). The largest amplitude reflections would be caused by the combined effects of chemical alteration within the detachment and immediate country rocks, vertical tuning of the signal in places where the detachment consists of many layers of altered rock interlayered with country rock, and the effects of out-of-plane energy due to small-scale three-dimensional structure superimposed on the otherwise sub-horizontal detachment surface. Both the shear zones and the linking faults have lateral extents of 10–20 km. Examples of a shear zone and a fault are shown in Fig. 5. We propose the hypothesis that the detachment formed as hydrofracture-driven faults connecting deformation-induced high porosity zones that behaved as shear zones during subsequent deformation.

Thus fluid behaviour would not be imprinted on a pre-existing permeability model, but rather fluid pressures coupled with deformation-driven permeability creation and destruction would determine the permeability and therefore locally the weakest parts of the deforming crust.

## 6. Lessons from a Modern Orogen—Northeast Japan

The influence of fluids on the rheology of a shortening crust in the Archaean must be studied indirectly using images of structure, alteration and anisotropy. The Japanese orogen provides an opportunity to consider fluid behaviour directly in a modern setting. Nakajima *et al.* (2001) proposed that the lithosphere of northeast Japan contains considerable fluid, in the form of ubiquitous melt in the uppermost mantle, melt in the lower crust concentrated under present-day volcanic centres, and water in the upper crust. The water would have formed through dehydration of cooling magmas deeper in the crust and mantle. They based their conclusions on the distribution of melt and water on Vp, Vs and Vp/Vs in seismic tomograms generated from the arrival times of earthquakes at seismic monitoring stations. They did not discuss fluids released by the metamorphism of the deep crust.

In NE Japan, the Nagamuchi-Rifu fault dips to the NW,

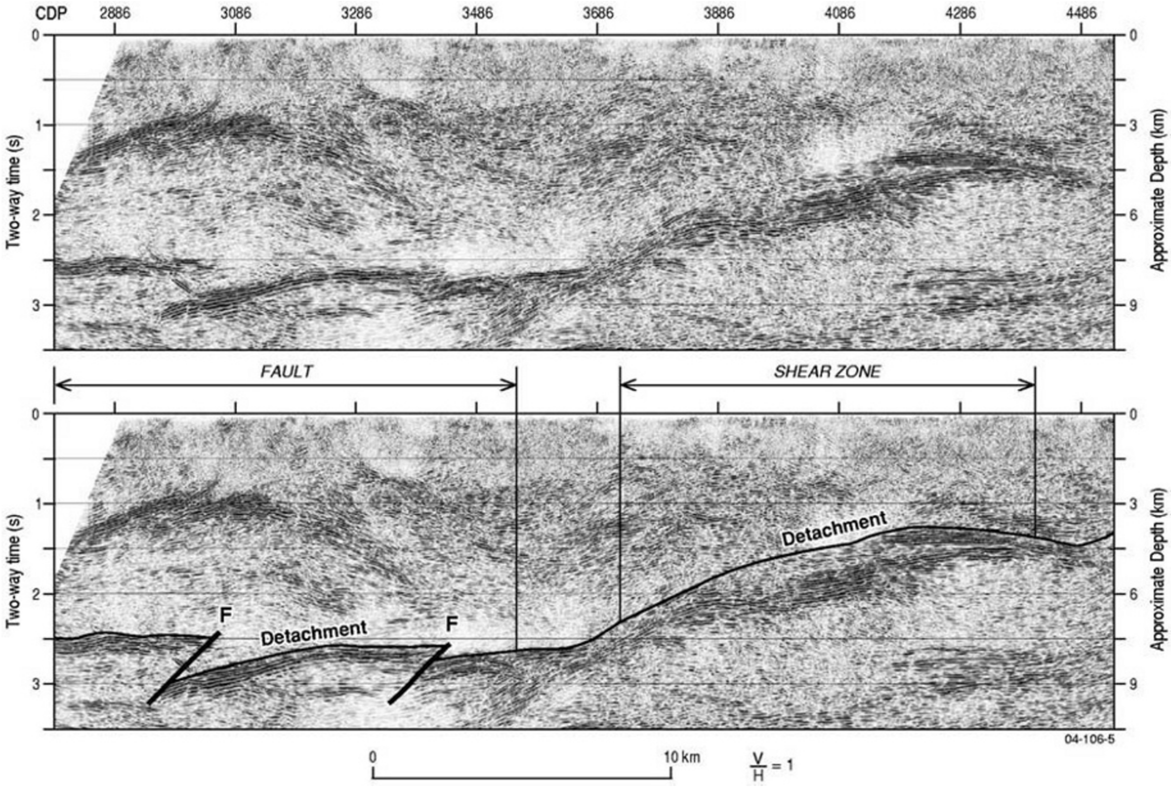

Fig. 5. Uninterpreted (top) and interpreted (bottom) post-stack migrated seismic section showing a portion of the regional detachment surface. The surface can be categorised into a thick, multilayer shear zone on the right, and a thinner zone or fault on the right. It is broken by younger brittle faults in two places marked “F”. This is line 99AGSY2 (Fig. 1).

is listric and links into an apparent detachment near 12–14 km depth. It occurs in a region that underwent initial extension in the Miocene, and has subsequently been inverted. The locus of the 1998 M5.0 Sendai earthquake lies on the fault at depth. The fault is reflective in normal incident multifold reflection data (Sato *et al.*, 2002). A number of strongly S-wave reflecting structures lie 5–10 km beneath the fault. Umino *et al.* (2002) estimate that one of them is NW dipping, partially fluid-filled, and about 50 m thick. This reflector correlates spatially with the top of a broad zone (in width and depth) of low Vp, relatively lower Vs and high Vp/Vs. It links two zones of high electrical conductivity, one of which correlates spatially with the velocity anomalies below the reflector, and one that is higher in the crust and to the southeast (Ogawa *et al.*, 2004). The coincidence of broad seismic and electrical anomalies underneath the reflector would indicate the presence of fluids disseminated through the crust in this region. The presence of fluid-related reflectors at the top of and linking two anomalous zones would suggest that the fluids are nucleating into a series of vertically stacked cracks near the plastic-viscous transition in the region. This could be interpreted as the first phases in the formation of fluid-rich shear zones similar to those interpreted in the Yilgarn Craton.

## 7. Impact of Fluid Focussing

Resolving whether lower crustal fluids controlled the formation of the detachment in the Yilgarn Craton has important implications for understanding fluid focussing in the crust. Fluids trapped near the plastic-viscous transition would constitute a reservoir from which fluids could be focussed into the upper crust by through-going, deeply penetrating faults. Fluid movement on the through-going faults may be episodic due to fault valve behaviour as fluid pressures below the low permeability seal systematically grow to greater than (lithostatic pressure+tensile strength), force open the fault, and then drop as the fluids are drained from the reservoirs (Sibson, 1990). The regions near and immediately above the areas where the through going faults breach the detachments would be subject to higher fluid fluxes than elsewhere above the detachment, where fluid flux would be controlled by fluids leaking from the detachment, which have relatively poorer vertical connectivity.

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## References

Bell, B., B. R. Goleby, T. Fomin, M. G. Nicoll, and A. J. Owen, Detailed gravity and magnetic modelling to contain crustal structures within the Eastern Goldfields, Western Australia, in *Crustal Structure and Fluid Flow in the Eastern Goldfields, Western Australia*, edited by K. F. Cassidy, Aust. Geol. Surv. Org., Rec., 2000/34, 75–82, 2000.

Blewett, R. B., K. F. Cassidy, D. C. Champion, and A. J. Whittaker, The characterisation of granite deformation events in time across the Eastern Goldfields Province, Western Australia, *Geosci. Aust., Rec.*, 2004/10 [on CD ROM], 2004.

Brown, L. D., W. Zhao, K. D. Nelson, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, M. Clark, X. Liu, and J. Che, Bright spots, structure, and magmatism in southern Tibet from INDEPTH seismic reflection profiling, *Science*, **274**, 1688–1690, 1996.

Connolly, J. A. D. and Y. Y. Podladchikov, Fluid flow in compressive tectonic settings: Implications for midcrustal seismic reflectors and downward fluid migration, *J. Geophys Res.*, **109**, B04201, doi:10.1029/2003JB002822, 2004.

Cox, S. F, M. A. Etheridge, and V. J. Wall, Fluid pressure regimes and fluid dynamics during deformation of low-grade metamorphic terranes Implicatons for the genesis of mesothermal gold deposits, in *Greenstone Gold and Crustal Evolution. Nuna Conference Volume*, edited by F. Robert, P. A. Sheahan, and S. B. Green, Geol. Assoc. Can., pp. 46–53, 1990.

Drummond, B. J., A review of crust/upper mantle structure in the Precambrian areas of Australia and implications for Precambrian crustal evolution, *Precamb. Res.*, **40/41**, 101–116, 1988.

Drummond, B. J., B. R. Goleby, C. P. Swager, and P. R. Williams, Constraints on Archaean crustal composition and structure provided by deep seismic sounding in the Yilgarn Craton, *Ore Geol. Rev.*, **8**, 117–124, 1993.

Drummond, B. J., B. R. Goleby, and C. P. Swager, Crustal signature of Late Archaean tectonic episodes in the Yilgarn craton, Western Australia: Evidence from deep seismic sounding, *Tectonophys*, **329**, 193–221, 2000a.

Drummond, B. J., B. R. Goleby, A. O. Owen, A. N. Yeates, C. Swager, Y. Zhang, and J. K. Jackson, Seismic reflection imaging of mineral systems: three case histories, *Geophys*, **65**, 1852–1861, 2000b.

Drummond, B. J., R. W. Hobbs, and B. R. Goleby, The effects of out-of-plane seismic energy on reflections in crustal-scale 2D seismic sections, *Tectonophys*, **388**, 213–224, 2004.

Etheridge, M. A., V. J. Wall, and R. H. Vernon, The role of fluid phase during regional metamorphism and deformation, *J. Met. Geol.*, **1**, 205–226, 1983.

Goleby, B. R., B. J. Drummond, A. Owen, T. Yeates, C. Swager, P. Upton, and J. Jackson, Recent Case histories: Seismic profiling and structurally controlled mineralisation in Australia. How regional seismic helps find minerals, Proceedings of Exploration '97: 4th Decennial International Conference on Mineral Exploration, Toronto, Canada, edited by A. G. Gubins, 409–420, 1997.

Hammond, R. L. and B. W. Nisbet, Towards a structural and tectonic framework for the central Norseman-Wiluna greenstone belt, Western Australia, in *The Archaean: Terrains, Processes and Metallogeny*, edited by J. E. Glover and S. E. Ho, Geol. Dept (Key Centre) and Univ. Ext., *Univ. West. Aust., Pub.*, **22**, 39–49, 1992.

Hobbs, B. E., A. Ord, and K. Regenauer-Leib, Fluid reservoirs in the crust and mechanical coupling between the upper and lower crust, *Earth Planets Space*, **56**, this issue, 1151–1161, 2004.

Kozlovsky, Ye. A., The World's deepest well, *Scientific American*, **251**(6), 106–112, 1984.

Makovsky, Y. and S. L. Klemperer, Measuring the seismic properties of Tibetan bright spots: Evidence for free aqueous fluids in the Tibetan middle crust, *J. Geophys. Res.*, **104**, 10795–10825, 1999.

Matsumoto, S. and A. Hasegawa, Distinct S wave reflector in the midcrust beneath Nikko-Shirane volcano in the northeastern Japan arc, *J. Geophys Res.*, **101**, 3067–3083, 1996.

Myers, J. S., The generation and assembly of an Archaean supercontinent: Evidence from the Yilgarn craton, Western Australia, in *Early Precambrian Processes*, edited by M. P. Coward and A. C. Ries, Geol. Soc. Lond., pp. 143–154, 1995.

Nakajima, J., T. Matsuzawa, and A. Hasegawa, Three-dimensional structure of Vp, Vs and Vp/Vs beneath northeastern Japan: Implications for arc magmatism and fluids, *J. Geophys. Res.*, **106**, 21,843–21,857, 2001.

Ogawa, Y., M. Mishina, Y. Honkura, K. Takahashi, and S. B. Tank, Electromagnetic imaging of the Nagamuchi-Rifu fault and its deep extension. 2nd Int. Symp. Slip and Flow processes in and below the seismogenic region, Tokyo, Abstracts, (no page numbers), 2004.

Petrini, K. and Y. L. Podladchikov,ithospheric pressure-depth relationship in compressive regions of thickened crust, *J. Met. Geol.*, **18**, 76–77, 2000.

Reading, A. M., B. L. N. Kennett, and M. C. Dentith, Seismic structure of the Yilgarn Craton, Western Australia. *Aust. J. Earth Sci.*, **50**, 427–438, 2003.

Ryberg, T. and G. S. Fuis, The San Gabriel Mountains bright reflective zone: Possible evidence of young mid-crustal thrust faulting in southern California, *Tectonophys*, **286**, 31–46, 1988.

Sato, H., T. Imaizumi, T. Yoshida, H. Ito, and A. Hasegawa, Tectonic evolution and deep to shallow geometry of Nagamuchi-Rifu active fault system, NE Japan, *Earth Planets Space*, **54**, 1039–1043, 2002.

Sibson, R. H., Fault rocks and fault mechanisms, *Geol. Soc. Lond.*, **133**, 191–213, 1977.

Sibson, R. H., Fault structure and mechanics in relation to greenstone gold deposits, in *Greenstone Gold and Crustal Evolution*, Nuna Conference Volume, edited by F. Robert, P. A. Sheahan, and S. B. Green, Geol. Assoc. Can., 54–60, 1990.

Stuwe, K. and M. Sandiford, Contribution of deviatoric stresses to metamorphic P-T paths: An example appropriate to low-P, high-T metamorphism, *J. Met. Geol.*, **12**, 445–454, 1994.

Swager, C. P., Geology of the greenstone terranes in the Kurnalpi-Edjudina region, Yilgarn Craton, *West. Aust. Geol. Surv., Rept*, **47**, Plate 1, 1996.

Swager, C. P., Tectono-stratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia, *Precamb. Res.*, **83**, 11–42, 1997.

Swager, C. P., B. R. Goleby, B. J. Drummond, M. S. Rattenbury, and P. R. Williams, Crustal structure of granite-greenstone terranes in the Eastern Goldfields, Yilgarn Craton, as revealed by seismic reflection profiling, *Precamb. Res.*, **83**, 43–56, 1997.

Umino, N., H. Ujikawa, S. Hori, and, A. Hasegawa, Distinct S-wave reflectors (bright spots) detected beneath Nagamachi-Rifu fault, NE Japan, *Earth Planets Space*, **54**, 1021–1026, 2002.

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