New constraints on the current stress field and seismic velocity structure of the eastern Yilgarn Craton from mechanisms of local earthquakes

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The Yilgarn Craton has hosted some of the largest earthquakes within the Australian continent in the last 100 years. Earthquakes have mainly been studied in the western part of the craton, and are thought to result from the reactivation of Precambrian structures in an E–W compressive regional stress field imposed by plate-scale processes. Here we present moment tensor solutions for three recent moderate-sized earthquakes around the town of Kalgoorlie that are inconsistent with E–W compression, but instead suggest E–W extension in the eastern Yilgarn Craton. Waveforms of earthquakes at Boulder (MW = 4.0, 20 April 2010), Kalgoorlie (MW = 4.3, 26 February 2014) and Coolgardie (MW = 3.9, 31 October 2014) were inverted for moment tensors. All three earthquakes were shallow (centroid depth <4 km) normal-faulting events that occurred along roughly N–S-striking planes, either with a steep westward or a relatively shallow eastward dip. The robustness of the retrieved mechanisms has been thoroughly tested, employing different earth models, assuming different locations for the earthquakes and using different period bands for the inversion. The fit of synthetic long-period waveforms to the observations was in all cases substantially improved by assuming a two-layered crust with high S wavespeeds (about 3.9–4 km/s) overlying substantially slower material. Since there is independent evidence from active source profiles for a P velocity increase between the upper and lower crust, a large difference in \(v_p/v_s\) ratio between upper and lower crust is the only way to explain both lines of evidence. This vertical contrast could represent a dominance of felsic material in the upper crust, and substantially more mafic material in the lower crust. Taken together, our results also appear to imply that the regional stress field is E–W extensive in the Kalgoorlie area, and possibly for the entire Kalgoorlie Terrane. This is contrary to current assumptions from continent-scale stress modelling. That the orientations of rupture planes roughly align with the regional structural grain could indicate that Archean structures are reactivated in response to the current stress field.

KEY WORDS: Western Australia, earthquake focal mechanism, crustal structure, stress field, Yilgarn Craton, local seismicity.

INTRODUCTION

The current movement of the Australian Plate can be described, to first order, as that of a rigid block, with little or no internal deformation (<2 mm/yr; Tregoning 2003). However, the occurrence of earthquakes up to magnitudes \(M > 6\) (McCue 1990) and moderately vigorous microseismicity (e.g. Leonard 2008) testifies to the presence of internal deformation in Australia over long timescales. Larger intraplate earthquakes are preceded by a long period of stress accumulation (Leonard 2008). Stresses within the Australian plate are thought to be primarily imposed by processes occurring at its margins (e.g. Reynolds et al. 2003). Local stress indicators, where available, largely confirm these observations (Hillis & Reynolds 2003), but their uneven distribution does not rule out significant local or even regional deviations from this large-scale stress field.

In Western Australia, the western margin of the Yilgarn Craton is seismically active and has hosted some of the largest earthquakes that have occurred within Australia in the last 100 years. Earthquakes in this western region are thought to occur on reactivated Precambrian structures owing to the E–W compressive regional stress field imposed by plate-scale processes (Dentith & Featherstone 2003). Although the regional stress field at the western margin of the Yilgarn Craton is well constrained (Hillis & Reynolds 2003), the stresses acting in its eastern part are currently largely unknown. Australia-wide seismicity catalogues show a band of height-en ed seismicity levels along the southeastern edge of the

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Yilgarn Craton, i.e. in the Kalgoorlie Terrane and the adjacent Albany-Fraser Orogen (Leonard 2008).

However, owing to the scarcity of seismic stations in the region, these earthquakes have not been closely investigated, and actual activity levels may be significantly underestimated.

In the present study, we retrieve hypocentral locations and moment tensors for two moderate-sized ($M_L > 4.5$) earthquakes that occurred in the vicinity of the town of Kalgoorlie, in the Kalgoorlie Terrane of the Eastern Goldfields Superterrane, in 2014. Since the 40-station ALFREX (ALbany FRaser EXperiment) seismic array (see Figure 1) was deployed not far to the east of that region at the time, both earthquakes were exceptionally well recorded by a large number of relatively close stations. By additionally analysing the Boulder earthquake of 2010 as well as local background seismicity in 2013 and 2014, we are able to draw some new constraints on both the regional crustal structure and the stress field within this part of the Yilgarn Craton.

THE 26 FEBRUARY 2014 KALGOORLIE EARTHQUAKE

Hypocentral location

We located the Kalgoorlie earthquake using manual travel-time picks for 46 P and 25 S arrivals at the stations shown in Figure 1. Picking uncertainties were classified into four quality categories, corresponding

![Figure 1](https://example.com/figure1.png)

**Figure 1** (a) Topographic map of southwestern Australia, showing the locations of the seismic stations used in this study. Permanent stations operated by GA are shown in green, permanent stations of the Seismometers in Schools project (Balfour et al. 2014) are shown in cyan, and the temporary ALFREX deployment is marked with blue (first phase) and red (second phase) symbols. Circles represent broadband stations, and triangles denote short-period seismometers. Station symbols with a solid outline denote the stations that were used in the seismic moment tensor inversion (Figure 3); their names are given in the figure. The remainder of the stations were only used for locating the earthquakes. The blue box marks the extent of the map in subfigure b. (b) Local map of the Kalgoorlie area (Neorarchean fault zones modified from Swager 1997), showing small tectonic earthquakes (blue circles) and mine blasts (hollow red circles) recorded between November 2013 and October 2014. The epicentres of the 2014 Kalgoorlie and Coolgardie earthquakes and the 2010 Boulder earthquake are marked with a yellow, purple and green star, respectively, and the double-couple part of their moment tensors is displayed in a lower-hemisphere projection. BSZ, Bardoc Shear Zone; B.F., Boulder Fault.
to uncertainties of 0.05, 0.1, 0.2, and 0.4 s for P and 0.1, 0.2, 0.4 and 0.8 s for S onsets. Picks with uncertainties higher than 0.4 (P) or 0.8 (S) s were not considered. A one-dimensional velocity profile was picked from the three-dimensional AuSREM model (Salmon et al. 2013) at the grid node closest to the earthquake’s epicentre as given by Geoscience Australia (GA). Using the program NonLinLoc (Lomax et al. 2000), we computed a probability density function for the earthquake’s location, 5000 samples from which are shown in Figure 2. The location uncertainty ellipsoid was constructed to contain 67% of this distribution, a procedure that usually yields larger, but also more realistic, error margins compared with those from standard linear location methods. The

Figure 2 Five thousand samples from the probability density function (PDF) for the earthquake location, as determined with NonLinLoc, shown in map view and as projections onto N–S- and E–W-oriented vertical planes. The red circle marks the optimum location, the red ellipse the error estimate, which is defined as containing 67% of the PDF. The green cross in map view denotes the location derived by GA (http://www.ga.gov.au/earthquakes/), which was fixed at a hypocentral depth of 0 km.
previously mentioned picking uncertainties and the event-station geometry for the earthquake are the key parameters that influence the width of this error ellipsoid. For the Kalgoorlie earthquake, we retrieved a maximum likelihood location at 30.70531° S, 121.19209° E, about 25 km WNW of the town of Kalgoorlie (see Figure 1b). The best-fit hypocentral depth places the earthquake very close to the surface (see Figure 2). We consider this rather unrealistic, as it may possibly reflect a locally inaccurate velocity model. Although the event is undoubtedly located in the shallow crust, we think that a hypocentral depth of at least one kilometre, which is within the location error, is much more likely. Our epicentre is very close to the location derived by GA, shown as a green cross in Figure 2, which lies only 2.97 km NNW of our optimum location, well within error. The GA solution was fixed to a hypocentral depth of 0 km, which may indicate a similar problem of converging to too shallow depths.

With a half-axis length of 5.1 km, our retrieved error ellipsoid is largest in the N–S direction, which is due to a lack of observations from due north and south of the epicentre (see Figure 1), and smallest in depth, where the uncertainty is 1.83 km.

**Moment tensor inversion**

**INVERSION DETAILS AND CHOICE OF EARTH MODEL**

We inverted three-component displacement seismograms, bandpass filtered to periods between 15 and 35 s, for the earthquake’s deviatoric moment tensor using the method of Nabelek & Xia (1995). The calculation of structural Green’s Functions was performed with the discrete wavenumber method (Bouchon 1982). All traces were visually checked before inversion, and those featuring low signal-to-noise ratios (SNRs) were excluded (Figure 3). Whereas all three components of the permanent GA stations usually featured reasonable SNRs, most temporary stations were observed to be rather noisy on the horizontal channels. The source time function for the event was parameterised with triangle functions with 1 second half-length, the maximum allowed number of triangles was 5.

The retrieved mechanism is a normal fault striking N–S to NNE–SSW, with one plane dipping very steeply westwards, the other shallowly ESE-dipping (see Figure 3). We obtain a moment magnitude $M_W$ of 4.3, somewhat lower than the local magnitude $M_L$ of 4.6.
boundaries every 5 km in depth, we considered AuSREM and only moderate variance reduction. With layer
structures a relatively large non-double-couple component
accurate arrival times, but the retrieved mechanism fea-
tures a surge in the Green’s Function calculation for such
shallow depths, hence the true centroid depth may be
even smaller than this value.

We carried out moment tensor inversions with differ-
ent earth models, both to assess the robustness of our
results and for structural inference (Figure 4). The
global model ak135 (Kennett et al. 1995) features a two-
layered crust of 35 km thickness, which is close to what
is known about the crustal thickness of the eastern part
of the Yilgarn Craton (e.g. Kennett et al. 2011), and pro-
vided a fair waveform fit. However, the theoretical
arrival times of the surface wave-trains calculated with
this earth model were substantially delayed compared
with the observations, which necessitated large time cor-
rections, especially for the more distant stations. These
corrections imply that the model is generally too slow
for the region. This is hardly a surprise considering that
cratonic crust is usually distinctly faster than the global
average (Rudnick & Fountain 1995).

The AuSREM model (Salmon et al. 2013), which was
also used for the hypocentral location, provides more
accurate arrival times, but the retrieved mechanism fea-
tures a relatively large non-double-couple component
and only moderate variance reduction. With layer
boundaries every 5 km in depth, we considered AuSREM
to be an unnecessarily complicated model for Green’s
Function calculations at the periods used here. Hence,
we simplified AuSREM to a two-layered model by putting
an intracrustal layer boundary at 20 km depth and aver-
aging the crustal AuSREM velocities above and below
this boundary. This yields the model MOD (see
Figure 4b), which achieves a substantially higher var-
iance reduction and a lower proportion of compensated
linear vector dipole (CLVD) compared with both ak135
and AuSREM (Figure 4a). However, the fit for traces
from several stations to the E and SE of the earthquake
was still poor, and in particular the initial wiggle on
the vertical traces was grossly underestimated (see
Figure 4c, left column). Hence, different two-layer mod-
elns for the crust were tested, starting from MOD. The
optimum fit thus obtained was for a model that features
an upper crust with anomalously fast S wavespeeds ($v_s$
= 3.99 km/s), underlain by significantly slower material
(green curves in Figure 4b). We tested two varieties of
this model, one in which $v_p/v_s$ was fixed to a standard
value of 1.73 and one in which $v_p$ was kept at the values
from MOD. The inversion results obtained with these
two models were nearly identical, which implies that the
wavefield in the period band used is dominated by sur-
face waves and hence not sensitive to changes in P wave-
speed. The resulting model with its $v_p$ values fixed to
MOD values, named MOD-SLC, was used in the final
moment tensor inversion shown in Figure 3.

**Figure 4** Test of different earth models for moment tensor inversion of the 2014 Kalgoorlie earthquake. (a) Achieved final var-
iances and double-couple (DC) proportion for the different models, indicated
by the colour their name is written in subfigure a. Note that models MOD and MOD-SLC are identical in the mantle, i.e. below
35 km depth. (b) P and S wavespeeds for the different models, indicated
with model MOD (red synthetics; left column) compared
with model MOD (green synthetics; right column) com-
pared with model MOD (red synthetics; left column) for stations of the ALFREX array.

Robustness of the Retrieved Mechanism

We carried out a number of tests to assess the robustness
of the obtained fault plane solution. First, even though
the inversions with the different earth models (Figure 4)
yield different variances and double-couple propor-
tions, the resulting fault plane solutions are highly similar,
which indicates that our retrieved mechanism is not
critically dependent on the choice of velocity model.

Further tests, all carried out with velocity model
MOD-SLC, are summarised in Figure 5. To check
whether a change in the epicentral location affects the
obtained solutions, inversions with epicentres shifted
towards the NE, NW, SE and SW, by 10 km in each dimen-
sion (which yields a total distance of 14.14 km from
the best-fit epicentre of Figure 2), were conducted. Consider-
ing that these shifts are substantially larger than the
location error calculated above, and since their effects in
the obtained solution were minimal (Figure 5), we con-
clude that our result is robust with respect to errors in
the epicentre location.
beachball (Figure 5) is slightly rotated from our pre-
carried out with fewer stations. Again, the resulting
noisy to be used, so that this inversion had to be
passband for the inversion. Using longer periods
strike, but is otherwise very similar.

Figure 5 Further tests to ascertain the robustness of the
obtained moment tensor. As in Figure 4, the final variance
doUBLE-couple proportion are shown, as well as the focal
mechanism for each inversion run. From the left: location
shifts by 14.14 km in NW, SE, NE and SW direction, respec-
tively, inversion run with reduced amount of stations to the
southeast of the earthquake (‘spatial dist.’), and inversion run with a passband of 20–50 s.

The use of a large number of stations from the
ALFREX array, which all have comparable azimuth angles (see Figure 1), may have put a disproportionately large relative weight to these observations in the moment tensor solution. We hence carried out an additional inversion for which only five (FA10, FA27, FB02, FB09, FB08) instead of 13 ALFREX stations were used, which provides a more even azimuthal distribution of observations. The variance reduction obtained with this configuration is worse than when all stations are used (although still better than for the different earth models), which implies that the MOD-SLC earth model is more appropriate for the southeastern stations than for stations with other azimuths. This is not surprising, since most other stations are located at considerably greater epicentral distances. The obtained mechanism is slightly rotated compared with the result shown in Figure 3, so that both planes acquire a more NNE–SSW strike, but is otherwise very similar.

The final test involves the use of a different period passband for the inversion. Using longer periods (20–50 s), several of the ALFREX stations become too noisy to be used, so that this inversion had to be carried out with fewer stations. Again, the resulting beachball (Figure 5) is slightly rotated from our preferred solution, and a higher final variance and significantly lower double-couple proportion is obtained.

In summary, we can state that although the details of the focal mechanisms obtained in the different tests vary slightly, the main result of a normal faulting event along a roughly N–S striking plane is retrieved with all of the different inversions, and can thus be considered robust.

THE 31 OCTOBER 2014 COOLGARDIE EARTHQUAKE

A second moderately sized earthquake occurred in the same region on 31 October, during phase 2 of the ALFREX deployment (see Figure 1a). We relocated the earthquake with the same method as described above and retrieved an optimum epicentral location at 30.9514° S, 121.1465° E, close to the town of Coolgardie, at a very shallow depth of around 1 km. Our location is 17.24 km SSW of the GA location (http://www.ga.gov.
au/earthquakes/getQuakeDetails.do?quakedId=3594395). Owing to a comparable number of utilised stations and phases, the uncertainties of our hypocenter are com-
parable with those of the 2014 Kalgoorlie event.

The earthquake’s retrieved mechanism (Figure 6) shows a shallow E–W normal faulting earthquake, with a slight rotation of the rupture plane’s strike compared with the Kalgoorlie earthquake, from N–S to NNW–SSE. The best variance reduction is again reached for the shal-
lowest assumed centroid depth. The moment magnitude
Mw of this event was determined as 3.87, substantially smaller than the local magnitude of 4.6 given by GA.

Just as for the Kalgoorlie earthquake, we performed the moment tensor inversion using different earth models, and as in the former case the use of model MOD-
SLC substantially improved the retrieved moment ten-
sor solution compared with model MOD, which resulted in a lower final variance (0.368 compared with 0.493) and higher double-couple proportion (94% compared with 72%).

THE 20 APRIL 2010 BOULDER EARTHQUAKE

In April 2010, a Ml 5.0 earthquake occurred within the centre of the town of Boulder (just southeast of Kalgoor-
lie), causing substantial structural damage (McCue 2010). We used available waveform data from those per-
manent GA stations (Figure 1) that were already operat-
ing at that time to invert for a moment tensor in the same way as described above, using the same earth model (MOD-SLC). Since we have no additional local data for this event, we fixed the epicentre to the location provided by McCue (2010), who modified the original GA location based on records from a local array of acceler-
ometers (location: see Figure 1b). Although only five sta-
tions could be used for the moment tensor inversion, their rather favourable azimuthal distribution should still allow the retrieval of a moderately robust mecha-
nism. As shown in Figure 7, the mechanism of the 2010 Boulder earthquake resembles that of the two 2014 earth-
quakes; all three were shallow normal faulting events along roughly N–S striking planes. The moment magni-
tude Mw of 4.0 we obtain is, again, surprisingly small compared with the Ml estimate of 5.0 by GA (e.g. http://
www.ga.gov.au/ausgeonews/ausgeonews201012/kalgoor-
lie.jsp). The relatively low proportion of double-couple we retrieve here is most likely due to the low number of stations and the relatively large azimuthal gaps between them. Given the station coverage, this mechanism should be considered significantly less robust than those presented above. However, taken together, they imply that the 2014 events were not isolated cases of normal faulting in this region, but may be representative of the general local or even regional stress field.

LOCAL BACKGROUND SEISMICITY

Local seismicity in the Kalgoorlie area was investigated for the deployment time of the first phase of the ALFREX
array, November 2013 to October 2014. P onsets of local
earthquakes were detected with an STA/LTA trigger
algorithm (Withers et al. 1998) and an event association
routine, after which P and S phases of local events were
picked manually, using the quality-weighting scheme
mentioned above. Based mainly on the characteristics of
the S onset, we could discriminate between blasts
from the local mining sites and tectonic earthquakes.
Even though the signals created by these two different
event types look highly similar at distant stations,
nearby stations show no clear S arrival in the case of a
mine blast (see Figure 8a). Hence, we defined events for
which we were able to detect a clear S onset on at least
one of the stations AUKAL and KMBL as tectonic. This
distinction based on S onset characteristics could be ver-
ified by plotting the distribution of origin times for all
events (Figure 8b), which is rather uniform for the tec-
tonic earthquakes but shows a clustering of blasts in
local daytime. All 285 local events were initially located
with HYPO71 (Lee & Lahr 1975) and then relocated using
NonLinLoc (Lomax et al. 2000) and the AuSREM velocity
model.

The distribution of local seismicity we have obtained
is shown in Figure 1b. In this plot, we only show events
that had at least six P and two S picks. It is obvious that
most events identified as mine blasts are located in the
vicinity of the Kalgoorlie Superpit open pit gold mine,
whereas most tectonic events are situated elsewhere.
Although the 26 February 2014 Kalgoorlie earthquake
was followed by a period of heightened local seismicity,
most of the detected small earthquakes did not occur
close to that earthquake’s epicentre and hence can not
be counted as aftershocks in the classical sense. It
appears that most background events occur in small
clusters, the two most prominent of which are located in
the vicinity of mapped fault traces (Zuleika and
Kanowna faults; Figure 1b). As for the three larger earth-
quakes, the hypocenters for all small events are very
shallow (less than 5 km depth, most in the uppermost kil-
ometre). However, given that the area we are investigat-
ing here is outside the ALFREX array, our depth
resolution will be limited, and the choice of velocity
model has a huge impact on hypocentral depths.
The mine blasts offer a good ground truth check of
location accuracy. As shown in Figure 1b, most mine
blasts cluster around the location of the Kalgoorlie
Superpit mine when the AuSREM velocity model is
used. If the P velocities are kept at their AuSREM values,
but S velocities are shifted to MOD-SLC, this has no large
effect on the location of these events, since they do not
have any S picks on nearby stations. However, if the S
velocities of MOD-SLC are used, and a homogeneous
$v_p/v_s$ ratio of 1.73 is assumed, the location of the mine blasts
is shifted westwards by more than 10 km, to the western
side of the town of Kalgoorlie. Using the same two velocity
models for the 26 February 2014 Kalgoorlie earth-
quake has only a minor effect on its epicentre, but the
hypocentral depth changes to 6.9 km if a fixed $v_p/v_s$ ratio
of 1.73 is used, whereas it stays in the uppermost kilo-
metre if only S velocities are changed.
DISCUSSION

New constraints on the regional velocity model

Our moment tensor inversion results imply that current crustal models for the Kalgoorlie region underestimate upper crustal wavespeeds in this area. However, since seismic signals in the passband we utilised are dominated by surface waves, we can make this statement only for S wave velocity, because the surface waves are relatively insensitive to changes in P wavespeeds. In a seismic reflection study by Drummond et al. (1993), an E–W profile passing close to Kalgoorlie was analysed. These authors found a generally two-layered crust, with a 16–21 km-thick, felsic upper crust and a more mafic lower crust reaching to the Moho at 35–36 km depth. The general subdivision of the crust in this region corresponds closely to what we find here. The P wave velocities obtained by Drummond et al. (1993) are 6.0–6.2 km/s in the upper crustal layer, and around 6.8 km/s in the lower crust. This is close to the values in the AuSREM model (Salmon et al. 2013), which also made use of these constraints. Our observation that mine blasts from the Superpit mine are only correctly located if the AuSREM P velocity model is used confirms these assertions.

One-dimensional S velocity profiles from inverted P receiver functions for the Eastern Goldfields region (Reading et al. 2007) show fairly high S wavespeeds in the upper crust (up to 3.9 km/s), and generally lower $v_s$ values in the lower crust, which corresponds well to what we retrieve in this study. Taken together, these pieces of evidence imply that the contrast between upper and
Figure 8 (a) Unfiltered seismograms for an event classified as tectonic (left column) and one classified as mine blast (right column), recorded at the two closest stations AUKAL and KMBL. Whereas the tectonic event shows clear onsets of P and S phases (the latter mainly on the horizontal channels), especially S is considerably more emergent and thus harder to pinpoint for the mine blast event. (b) Distribution of origin times among mine blast and tectonic events, shown in local time for Western Australia. It is clearly apparent that events we picked as mine blasts almost exclusively occur during daytime, with some distinct peaks around noon and 5 pm, which probably correspond to the standard blasting times in the surrounding mines.
lower crust is mainly expressed by significantly different \( \frac{v_p}{v_s} \) ratios. Assuming a relatively low ratio of 1.6 for the upper crust that has a P wavespeed of 6.2 km/s yields an S velocity of nearly 3.9 km/s, close to what we prescribed in the model MOD-SLC that provides the optimum fit for the moment tensor inversion. In contrast, a \( \frac{v_p}{v_s} \) ratio of 1.85 in a lower crust with \( v_p = 6.8 \) km/s gives a \( v_s \) of 3.68 km/s, not much faster than what we assumed in our model. This marked contrast in \( \frac{v_p}{v_s} \) between upper and lower crust must thus stem from a lithological division between a highly felsic upper crust and a considerably more mafic lower crust, as already indicated by Drummond et al. (1993).

### Stress field of the eastern Yilgarn Craton

The observation of active E–W extension in the Kalgoorlie Terrane of the eastern Yilgarn Craton comes as a surprise, since current stress field models for Australia describe southwestern Australia as in an E–W compressive regime (Hillis & Reynolds 2003). However, these models are based on a limited number of \textit{in situ} stress indicators with a highly heterogeneous distribution. In the case of the Yilgarn Craton, only its western part is well constrained to be under E–W compression. For the eastern part of the Yilgarn Craton, there are only three stress measurements in the Australia-wide database. All are judged to be of rather low fidelity: one thrust, one strike-slip and one normal faulting event (Hillis & Reynolds 2003). This means that the regional stress field is practically unconstrained \textit{in situ}, and so previously inferences have been drawn from plate-scale considerations alone. Since Australia is situated in the centre of the plate, its internal stress field is thought to originate, to a first order, from the stresses imposed at the boundaries of the India–Australian plate (Hillis et al. 2008).

Numerical models of the stress distribution in Australia in response to the plate boundary processes (e.g. Reynolds et al. 2003) are largely consistent with the stress map compiled from \textit{in situ} measurements. However, local or regional effects might exist that are currently not captured by either observations or models.

There are some \textit{in situ} stress measurements in the mines around Kalgoorlie that have been independently published and are not listed in the Australian Stress Map (e.g. Villaescusa et al. 2002). Although these \textit{in situ} results show considerable variety, they are more consistent with E–W compression than with E–W extension. However, the precision of these measurements and the effect of the local mining environment on them is rather uncertain. Since these measurements were made at very shallow depths of a few hundred metres, whereas the earthquakes are most probably located at a significantly greater depth, the stress field may also change with depth. However, such vertical changes in stress orientation have to date mostly been observed in sedimentary basins (e.g. Gruenthal & Stromeyer 1992), not in areas where cratonic basement is exposed.

It is interesting to note that the fault plane orientation for all three investigated earthquakes corresponds rather well to the regional structural grain, which is oriented NNW–SSE (Figure 1b; e.g. Blewett et al. 2010). These faults experienced several periods of extension and compression at about 2.7–2.6 Ga, and no period of younger major activity is known. The Kalgoorlie and Boulder earthquakes as well as a large proportion of the background seismicity are situated close to fault traces. Intraplate deformation is usually concentrated in zones of relative weakness that can have a thermal or mechanical origin. With heat flow values in the Kalgoorlie Terrane being among the lowest in Australia (\( \leq 40 \) mW/m\(^2\); Raimondo et al. 2014), mechanical weakness is the far more likely candidate here.

Although our location precision is insufficient to discriminate whether the observed earthquakes actually occurred on the existing faults or not, we can speculate that these Archean structures, which most likely still represent local areas of reduced rock strength, could have been reactivated in the current stress field, in a similar way to the proposal of Dentith & Featherstone (2003) for the western Yilgarn Craton.

The potential for reactivation of Neoarchean structures, however, does not answer the question as to what causes the E–W extensional stress regime. There is significant mining activity in the area around Kalgoorlie, and although large-scale mining has a modest potential to affect the regional stress field, we do not think mining can cause the extension. The removal of rock masses, through open-pit or underground mining, can reduce the normal stress on a fault under horizontal compression, and hence lower the critical stress necessary for a rupture to occur (Simpson 1986). For a horizontally extensive setting as we find here, the removal of overburden would have the opposite effect of decreasing the differential stress. In any case, the mechanical loading still has to occur within the regional stress field, i.e. the earthquake can only be shifted to an earlier or later point in time. Hence, mining activity cannot explain the unexpected stress regime in this region. One possible tectonic cause is the accommodation of the ongoing large-scale tilting of Australia (Sandiford 2007), during which the southwestern part of the continent has been uplifted by 200–300 m since the Miocene. Although this is a very slow process, it is feasible that sufficient stresses for seismic activity have accumulated over long time-scales. We emphasise that this scenario is highly speculative, and the proposed hypothesis needs further testing, which is beyond the scope of the present article, but may prove a worthwhile direction for future research.

### CONCLUSIONS

We have determined locations and moment tensors for the 2014 Kalgoorlie and Coolgardie earthquakes in the eastern Yilgarn Craton. Both events were shallow normal-faulting earthquakes, with moment magnitudes of 4.3 and 3.9, which occurred along roughly N–S-trending fault planes. Multiple tests indicate that these results are robust, and not the result of an erroneous earth model, a misplaced location or some other artefact. The Boulder earthquake of 2010 was likewise investigated, and the fault plane solution obtained is similarly pointing towards normal faulting along N–S striking planes.

This orientation is compatible with the strike of Archean structures in the region, which suggests a
recent reactivation of these faults, comparable with what might be occurring in the western Yilgarn Craton. However, the regional stress field of the region has thus been inferred as in E–W compression, which is contradicted by our observations that are consistent with a stress regime that locally or regionally deviates from the behaviour expected from plate-scale processes.

From experiments with the earth models used for both the moment tensor inversion and the location of local seismicity, we find that the crust of the Kalgoorlie Terrane can be adequately described with a two-layer model, in which the upper crust must have a rather low $v_p/v_s$ ratio, so that upper crustal S velocities are high (3.9 km/s). In contrast, the lower crust has faster $c_p$ and slower $v_s$ values, which implies a substantially higher $v_p/v_s$. These significant differences most likely derive from a contrast in lithology, with felsic rocks in the upper crust and considerably more mafic material in the lower crust, as previously described in other studies.

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**REFERENCES**


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