An integrated multi-scale 3D seismic model of the Archaean Yilgarn Craton, Australia

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Abstract

The collection of a range of different seismic data types has greatly improved our understanding of the crustal architecture of Australia’s Archaean Yilgarn Craton over the last few years. These seismic data include broadband seismic studies, seismic receiver functions, wide-angle recordings and mine-scale to deep seismic reflection transects. Each data set provides information on the three-dimensional (3D) tectonic model of the Yilgarn Craton from the craton scale through to the mine scale. This paper demonstrates that the integration and rationalisation of these different seismic data sets into a multi-scale 3D geological/seismic model, that can be visualised at once in a single software package, and incorporating all available data sets, significantly enhances this understanding. This enhanced understanding occurred because the integrated 3D model allowed easy and accurate comparison of one result against another, and facilitated the integrated questioning and interrogation across scales and seismic method. As a result, there are feedback questions regarding understanding of the individual seismic data sets themselves, as well as the Yilgarn Craton as a whole.

The methodology used, including all the data sets in the model range, had to allow for the wide range of data sets, frequencies and seismic modes. At the craton scale, P-wave, S-wave and surface wave variations constrained the 3D lithospheric velocity model, revealing noticeable large-scale velocity variations within and across the craton. An interesting feature of the data, easily identified in 3D, is the presence of a fast S-wave velocity anomaly (>4.8 km s⁻¹) within the upper mantle. This velocity anomaly dips east and has a series of step-down offsets that coincide approximately with province and terrane boundaries of the Yilgarn Craton.

One-dimensional receiver function profiles show variations in their crustal velocity across the craton. These crustal velocity variations are consistent with the larger-scale geological subdivision of the craton, and provide characteristic profiles for provinces and terranes. The receiver function results and the deep seismic reflection data both agree on the depth to the Moho, and both indicate an increase in Moho depth to the east. The 2D seismic refraction results in the south-west of the craton provide crustal thickness information, an indication of middle and lower crustal compositions, and information regarding the broad-scale architectural framework.

At the province- and terrane-scale, the deep seismic reflection data and the mine-scale seismic data provide geometric constraints on crustal architecture, in particular the orientation of the region’s fault systems as well as variations in the thickness of...
the granite–greenstone succession. Integration of the results from wide-angle seismic refraction data coincident with the deep seismic reflection data provided additional constraints on likely upper crustal lithologies.

The integrated 3D seismic model implies the dominant geodynamic process involved the development of an orogenic belt that developed with a series of contractional (folding and thrusting) events, separated by equally important extensional events. The seismic reflection data in particular suggests that extensional movement on many shear zones was more common than previously thought.

The seismic reflection data suggest that the dominant mineral systems involved deeply sourced fluid flowing up crustal-penetrating shear zones. These deeply sourced fluids were further focussed into sites located above fault-breached domal regions in the upper crust.

Keywords: 3D seismic model; Seismic reflection studies; Tomography data; Receiver function data; Yilgarn Craton; Crustal architecture; Archaean

1. Introduction

The integration (merging) and simultaneous visualisation of different seismic data sets, each with its own scale, different frequencies, different wave-modes and different dimensions is the easy part of constructing a 3D seismic model of an area. The interpretation of this multi-seismic data volume is complex. The process of integration of crustal-scale and high-resolution 2D seismic reflection profiling with 2D crustal scale P- and S-wave velocity models with 1D receiver function velocity models and with low-resolution 3D tomographically inverted velocity models becomes a function of the resampled resolution of each data set and the constraints chosen. If these constraints are chosen correctly then a self-consistent 3D velocity model will be constructed. When integrated with other geological understanding (e.g., geological mapping, geochemistry, structural geology, numerical modelling, etc.), the result is an improved 3D geological/tectonic model of the region.

The seismic studies available and used for this model of the Yilgarn Craton include seismic reflection data (Goleby et al., 1993, 2000, 2003), seismic refraction data (Dentith et al., 2000), portable short-period wide-angle data (Fomin et al., 2003), receiver function analysis (Reading et al., 2003, in press) and broadband seismic experiments (Kennett, 2003; Fishwick et al., 2005). In addition to the regional coverage, this study focused on data sets from within the Eastern Goldfields Province, the more mineralised eastern third of the Yilgarn Craton (Fig. 1).

Individually, each seismic data set has provided new insights into the crustal architecture or the velocity structure of the region, however, when all the seismic data sets are integrated, the results provide an even larger increase in understanding of the structure and likely geodynamics of the crust and lithosphere of the Yilgarn Craton. Taken together, these data enhance the knowledge required for area-selection by the exploration industry and the prediction of new mineral occurrences.

By combining both architectural information from the 2D seismic reflection data sets with the 2D and 3D velocity information from the 2D and 3D refraction and tomographic data sets, then extending all to 3D, more can be inferred about the crustal geological variations and hence tectonic processes that have operated within the craton. The three areas where the biggest impact has occurred is in improving our understanding and assessment of the crustal architecture, understanding structural controls on crustal history and understanding relationships between deformation processes, timing and mineral systems, which all impact on reducing risk in exploration.

In particular, the regional deep seismic reflection traverses within the Eastern Goldfields Province have successfully imaged the prominent crustal-scale geometric features (Fig. 2; Goleby et al., 2003) and have shown the potential of the method to assist in the development of a mineral systems model for the region. Coincident with the seismic reflection traverses, a wide-angle reflection profile, using the same energy source (Fomin et al., 2003), provided additional information on upper crustal velocity variations.

P- and S-wave data have provided information on the 3D velocity structure within the lithosphere of the Yilgarn Craton. These data, when integrated with both near-surface geological and geophysical data, allowed investigation of the tomographically determined velocity structure of the granite–greenstone succession within the Yilgarn Craton. A craton-wide receiver function analysis, using the same S-wave data set, was used to investigate the crustal–uppermost mantle Vs velocity
Fig. 1. (a) Map of Australia showing location of the Yilgarn Craton. (b) Map of the Yilgarn Craton showing subdivision into different provinces, terranes and domains, with location of the deep seismic reflection traverses. (c) Map of the Yilgarn Craton showing location of different seismic experiments undertaken during the last few years. Dots are legacy broadband recording sites (BRS) recorded by the Research School of Earth Sciences (Australian National University). Small and large stars refer to the recent BRS sites. Thick dashed line is the location of the wide-angle seismic survey. Seismic reflection traverses (regional- and mine-scale) are shown as thin lines. Grey dots are refraction stations.
structure of the region. This data set showed significant variation within the different crustal blocks of the Eastern Goldfields Province.

When integrated and visualised together, these various seismic data sets allowed the construction of a well-constrained 3D velocity/geo logical model of the region. The seismic reflection data provided the 2D crustal architectural constraints along several key regional seismic transects. The seismic tomography data sets, at a range of scales, were used to infill the model at both crustal and lithospheric scales. This infill process was important in understanding the region’s distribution of mineral deposits within a 3D crustal architecture framework.

The basic philosophy employed in this 3D model construction fell into two methods, dependent on the available data. The first and most reliable was at the crustal scale where there were more depth constraints, the second was at the lithospheric scale where only teleseismic data sets were available. At the crustal scale, the architectural constraints, primarily obtained from the seismic reflection sections, were extrapolated outward and linked with distant reflection sections to construct the key structural elements of the model space. The surface location of these major structural elements, primarily crustal shears, and the orientation of the deeper-seated geophysical anomalies was fundamental in this extrapolation process. In general, we chose smoothly varying and continuous model parameters within similar geological terranes, but allowed sudden model parameter changes across crustal shears.

The principal software package used in the visualisation and construction of the Yilgarn Craton is the commercially available software GOCAD (http://www.earthdecisionsciences.com/). In addition, several surface building and gridding routines were used to manipulate and reformat the incoming data sets. The software was not limited by large object sizes, so resolution (cell size) of the various data sets was kept as detailed as possible, given the limitations and resolution of that particular seismic method. This allowed zooming into the model to check and inspect the finer details in a given area. In the process, we did not assign any weights to one data set over another, rather we visualised all the data we had. During interpretation, however, the accuracy and precision of one data set over another was taken into account. This allowed the comparison of 1D velocity functions or borehole logs, detailed 2D sections from reflection profiling, and sparse but even 3D velocity models, both in making the generalised velocity model and in its geological interpretation.

2. Geology

In developing the 3D geological model of the Yilgarn Craton, an understanding of the surface geology, in particular key structural elements, including shear zones, terrane boundaries, large granitic areas, basement gneissic areas etc, was fundamental. Without this knowledge, extrapolation of features from one area to another and across one boundary to another could not be constrained. The 3D model of the Yilgarn Craton was constructed from a scale of 1:250,000. This chosen scale allows the essential geological packages and key structures to be defined, and importantly displayed and interrogated without confusing the model with larger scale (detailed and less relevant) complications. The scale needs to be set so all the key features involved in the main tectonic processes are included while the ‘noise’ is filtered.

At the scale of the model, the geology of the Yilgarn Craton is simplified into a region that is dominated by large volumes of Archaean granites and greenstones (Fig. 1). These granites and greenstones define a north–south tectonic grain to the craton, made up a regional north–south fault pattern and the location of north–south elongated granite batholiths into regional north–south antiforms. The north–south faults define tectonostratigraphic belts, and subdivide the craton into fault-bounded provinces, terranes and domains based on similar and differing geological characteristics (Fig. 1). The province-scale subdivisions include an easternmost Eastern Goldfields Province, a central Southern Cross Province and a western Murchison Province (Myers, 1995; Barley et al., 2003).

The Eastern Goldfields Province, the craton’s most mineralised province, has a broad lithostratigraphy (Swager et al., 1997; Barley et al., 2003) that has been
used to further subdivide the province into a number of terranes (e.g., Kalgoorlie, Kurnalpi, Laverton, Duketon; Fig. 1) and in several cases, further into discrete domains (Swager and Griffin, 1990; Swager et al., 1992; Swager, 1997). This broad greenstone succession lithostratigraphy consists of komatiites, basaltic rocks, felsic volcanic rocks and sedimentary rocks; however, this lithostratigraphy cannot be correlated between terranes (Swager et al., 1997).

The craton’s granites have been subdivided by Champion and Sheraton (1997) into five principal granite types; namely: high-Ca, low-Ca, mafic, high high-field strength elements (Hi-HFSE) and syenitic granites. The high-Ca and low-Ca granites dominate the craton by area, with 60% high-Ca granites and 20% low-Ca granites. The high-Ca granites were intruded over a prolonged period terminating at ∼2660 Ma. Champion (1997) interpreted these high-Ca granites as lower-crustal to upper-mantle melts developed during subduction. In contrast, the low-Ca granites were emplaced towards the end of orogenesis (2655 Ma to 2630 Ma) across the entire craton (Cassidy et al., 2002). The low-Ca granites are high-temperature crustal melts, interpreted to have developed during delamination of the lower crust (Smithies and Champion, 1999).

Structurally, the deformation history for the Yilgarn Craton is complex and long-lived (e.g. Cassidy and Champion, 2004). Deformation of the Eastern Goldfields Province has been generalised from that determined for the well-studied, gold-rich, Kalgoorlie terrane (Swager, 1997; Blewett et al., 2004a,b). The north–south, structurally bounded, regional-scale belts, form distinct structural terranes (Swager, 1997) that are considered to reflect a sequence of extensional and contractional deformational events. This deformation history, as summarised by Blewett et al. (2004a), commenced with an early extensional event that was followed by a series of episodic contractional and extensional episodes. The first of these contractional events was north–south orientated recumbent folding and thrusting during a D1 shortening event. This was followed by a period of large scale upright folding during the east northeast–west southwest widespread contractional and extensional events that evolved episodically and rapidly, with a diachronous series of approximately coaxial switches in tectonic mode during a series of D2 folding and thrusting events (Blewett et al., 2004a). D3 deformation was minor and occurred as north–south orientated strike–slip faulting and associated faulting. The deformation history ended with localised transpressive oblique and reverse faulting during D4 deformation (Swager, 1997; Blewett et al., 2004a).

The boundaries to each province, terrane and domain are mapped as regional scale shear zones. The deep seismic reflection images cross most of these boundaries and in most cases has successfully imaged the dip, depth penetration and relationship to nearby faults and shear zones. The seismic does indicate which faults or shear zones cut which others, however, it does not indicate any timing information about when the fault moved through time. This information is provided through the transferring of the deformation history understanding to each fault or shear zone during the construction and interpretation of the 3D model.

The cumulative effect of this deformation history has resulted in the Eastern Goldfields Province having a pronounced north–northwest–south–southeast fabric or regional strike that is seen in both the orientation of the granite and greenstone units as well as the orientation of the major shear zones (Fig. 1). This has led workers (e.g., Blewett et al., 2004a) to conclude that, in the eastern Yilgarn Craton, and perhaps for the whole craton, the preferred tectonic environment is a subduction setting, possibly a long-lived accretionary margin (Barley et al., 2003).

3. Seismic data sets input into the 3D model

3.1. 2D seismic reflection traverses

The network of regional deep seismic reflection traverses recorded within the Eastern Goldfields Province crossed a number of regionally significant terrane boundaries and internal shear zones (Figs. 1 and 2). These include the regional crustal-penetrating shear zones such as the Ida, Ockerburry, Hootanui and Yamarna Shear Zones (Fig. 1) as well as shear zones limited to shallow depths such as the Bardoc, Keith-Kilkenny and Celia Shear Zones. In addition, the seismic imaged a series of crustal-scale features including a change in the thickness of the crust across the Eastern Goldfields Province, a subdivision of the crust into three broad layers, an east dip to the majority of the reflections, and the presence of a series of east-dipping crustal-penetrating shear zones. Each of these features was interpreted and input into the 3D model.

The deep seismic reflection data reveal an Eastern Goldfields Province crust with a fabric that has a pronounced 30° easterly dip. Within this east-dipping fabric, there are a series of east-dipping reflective bands that can be traced from the surface to the lower crust and in several cases to the Moho. These represent the province’s terrane boundaries (Ida, Ockerburry, Hootanui and Yamarna) as well as numerous internal shear
zones which all divide the province into a series of distinct domains. The Ida, Hootanui and Yamarna Shear Zones are clearly imaged, whereas about 9 km of the Ockerburry Shear Zone, from 3 km to 12 km depth, appears to have been intruded by later granite emplacement and/or affected by subsequent deformation. All shear zones have complex internal geometry that suggests that these shear zones have been deformed several times.

There are several locations where west-dipping reflections have been imaged, some show linkage with a crustal penetrating shear zone. The most important of these is the Bardoc Shear Zone, a highly mineralised zone containing numerous operating mines. The Bardoc Shear Zone and the crustal-penetrating Ida Fault form a zone containing numerous operating mines. The Bardoc Shear Zone and the crustal-penetrating Ida Fault form a suitable fluid-focusing mechanism that directed fluids into the Bardoc Shear Zone (Goleby and Drummond, 2000). Fluid flow modelling (Hobbs et al., 1997) supports this hypothesis.

The three distinctly different sub-horizontal layers (Fig. 2) have different seismic characteristics and provide constraints on the evolution of the craton. There is a broad correspondence between these layers and the receiver function data. The lowest layer, the lower crust, is essentially devoid of reflections other than several bands of east-dipping reflections that extend through to the base of the crust. These east-dipping reflections have been interpreted as representing the location of deep penetrating shear zones. The upper surface to this lowest crustal layer is marked by a sudden change in reflection character to a zone where overlying large packages of dipping reflections are typical (Fig. 2). Seismic reflectivity in the middle crust is characterised by numerous prominent east-dipping reflections that define the boundaries to large-scale, lozenge-like, mid-crustal bodies. Drummond et al. (2000) described duplex structures in the mid crust of the 91EGF01 seismic traverse related to D2 thrusting and imbrication. Similar features are evident in segments of the 01AGSNY1 seismic traverse (Fig. 2). One exception to this pattern is within the middle crust of the Kalgoorlie region, where an anomalous region of low reflectivity has been interpreted to represent either extensive deformation or large scale alteration within the area (Drummond et al., 2000). The boundary between this middle layer and the upper layer is diffuse and irregular. The upper layer is complex and variable in its seismic character, reflecting complexities within the granite–greenstone succession.

Mine-scale seismic traverses, recorded within the Kalgoorlie, Leonora and Laverton mineralised regions, were undertaken to define mine scale architecture and developing three-dimensional structural models of the top 5–10 km of the mineralised sequences within the granite–greenstone succession (Cassidy et al., 2003; Stolz, 2003; Beeson et al., 2004). Integration of the resultant seismic reflection sections with the mine scale geological and drilling data has produced 2D cross sections and 3D models through the ore rich mineralised zones, which the exploration company has used to identify drilling targets.

These seismic data and its interpretation was input into the 3D model in two forms, images of the seismic sections and lines representing the various structures, including lines representing the shear zones, the boundaries to the various layers, lithological marker horizons and outlines to the upper crustal granite bodies. These lines were then extrapolated outwards from the traverse, using the surface geology to link with the same/similar features identified on the other seismic traverses. This process formed surfaces that defined the various provinces, terranes and domains, as well as the internal structure within each of these. There was no attempt made to parameterise these surfaces other than some identifying colour scheme. As discussed above, in 3D there has to be a stage during construction of each surface regarding which fault cuts what surface. Once this has been determined, the implications of this decision on the whole model need to be determined and resolved.

3.2. 2D wide angle seismic profile

Wide-angle data, recorded in conjunction with the acquisition of the 2001 deep seismic reflection survey within the Eastern Goldfields Province provided additional velocity information on the top 10 km of the granite–greenstone succession (Fig. 3). These data reveal the presence of a higher-velocity region beneath one of the regions geological domes (Fomin et al., 2003, 2004; Fomin and Goleby, 2005). The higher velocities (6.5–6.7 km s\(^{-1}\), top at 3 km depth) are restricted to a ∼2 km thick body located to the western part of the wide-angle experiment (Fig. 3). This higher-velocity body is interpreted to represent mafic rocks, occurring as sills or flows, in a poorly mineralised area within the greenstone succession to the west of Laverton Mineral Field, (Fomin et al., 2004). This body is underlain by lower velocity rocks (6.0–6.1 km s\(^{-1}\)), most likely granite–gneissic in composition (Fomin et al., 2004).

The higher-velocity body appears to be relatively transparent on the deep seismic reflection image, as there are far fewer reflective horizons interpreted in this area compared with the eastern and western flanks of the
line (Goleby et al., 2004; Fomin et al., 2004). Such a correlation is suggestive of a relatively smooth, long wavelength velocity effect, probably related to metamorphism associated with the formation of the greenstone belt that significantly altered the velocity distributions within the internal structure of the area (Fomin et al., 2004). This can also explain why steeply dipping reflectors, well imaged to the east and west of the line, are not imaged in this region.

The boundary separating this high-velocity layer from the low-velocity layer below it is possibly a compositional boundary between greenstones and underlying felsic gneisses. There is no evidence for high-velocity material below this boundary. Assuming the Moho is associated with the deepest reflections modelled, total crustal thickness in the region can be speculatively estimated to be in the range of 32–37 km, consistent with both the deep seismic reflection data and the receiver function analysis.

3.3. 1D receiver function studies

Receiver functions results, calculated from the teleseismic arrivals, not only cover the entire craton but are also concentrated within the Eastern Goldfields Province. This focus on the Eastern Goldfields Province was part of an ongoing experiment to investigate gross velocity differences between mineralised and non-mineralised terranes that would be attributed to the crustal scale changes associated with the presence of the gold mineralising system (Figs. 1 and 4). Reading et al. (2003, in press) and Reading and Kennett (2003) present much of the recent receiver function data available on the Yilgarn Craton. Their results indicate a pronounced variation in crustal and upper mantle velocity structure across the craton (Fig. 4), with each province showing characteristic velocity structures that are internally consistent within each province (Reading et al., 2003, in press). This variation correlates with the mapped geological provinces.

The receiver function results show the Moho deepening eastward across the craton (Reading et al., 2003). Reading et al. (in press) proposed extensive reworking of crustal rocks, resulting in the lower crust becoming more felsic and therefore lower in seismic velocity, as the mechanism for the formation of the observed sharp Moho discontinuity observed beneath parts of the craton. Given this, there would be a corresponding increase in the $V_p/V_s$ ratio in the region of the lower crust. It is therefore likely that the crustal architecture seen across the province was ‘frozen in’ for each province prior to the assembly of the craton.

The receiver function data was input into the 3D model as single 1D velocity laths, with their thickness and colour representing the changes in Vs velocity with depth. Given that this data set is 1D and the results are very dependent on the data used in the received function.
inversion, this type of visualisation is an appropriate means of representing the data. It allows a rapid examination of the results themselves and variations across the model without being too detailed or descriptive. In the current 3D model, no attempt has been made to contour these data; rather the model is used to identify craton scaled variations. The one surface constructed from the receiver functions data is the depth to the Moho as this is the most precise part of the data set. There was no attempt adding parameters to either the laths or the Moho. In the model, the receiver functions successfully locate the subsurface extent of several of the crustal-penetrating shear zones. The western boundary to the Eastern Goldfields Province, the Ida Fault (Fig. 1), is defined by the presence of a region of higher-velocity lower crustal material within the footwall of this crustal penetrating fault.

3.4. 3D seismic tomography

Teleseismic S-wave data from distant earthquakes show that the lithosphere beneath the Yilgarn Craton has a low velocity crust underlain by mantle with a S-wave velocity faster than the world average (Kennett, 2003; Fishwick et al. (2005) confirms the existence of a region of fast S-wave material beneath the Yilgarn Craton to at least 250 km depth. They also show that this feature, although not continuous, has slower velocities in the central Yilgarn and faster zones at the western and eastern edges of the craton.

The sparse low-resolution 3D tomographically inverted S-wave velocity data were input into the 3D model as a 3D grid, represented by an array of velocity values within a regular 3D grid. This data set was then capable of being sliced through each axis as well as being 3D contoured to produce a series of iso-surfaces. Both displays were equally important as both were used during interpretation.

The 3D model of the teleseismic S-wave data shows a higher-velocity, southeast dipping body approximately 70 km beneath the Murchison Province, increasing to approximately 100 km beneath the Ida Fault, then to approximately 120 km (Fig. 5). Although the spacing of the sample points, and hence the gridding of the teleseismic S-wave volume is coarse compared to the other data sets, the \(\sim 50 \times 50 \times 50 \text{ km}^3\) grid size shows that there is an indication that this body is not just a single southeast dipping body but rather it is broken into
a series of segments. The 3D model shows a first order spatial correlation between the subsurface location of these breaks and the location of main province boundaries mapped within the craton.

4. 3D seismic features of the Yilgarn Craton crust

The seismic techniques described above subdivide the Yilgarn crust into a series of similar regions, each characterised according to the following seismic features of the crust (Goleby et al., 2003; Blewett et al., 2004b). These features include:

- the presence of a higher-velocity, southeast dipping body within the mantle lithosphere beneath the Yilgarn Craton,
- this mantle lithospheric body is not a simple dipping body, rather is complexly shaped,
• each province, and in several cases terranes, has its own characteristic crustal seismic velocity structure, that can be used to identify that terrane or province,
• the Moho dips to the east and implies a change in the thickness of the crust across the craton,
• the crust can be subdivided into three distinct broad layers,
• a pronounced east-dip to the fabric within the crust and mantle, best imaged by the majority of the seismic reflections,
• the presence of a series of east-dipping crustal-penetrating shear zones that appear to sole into the base of the crust; and
• the observation that the seismic reflection technique is imaging district scaled structures associated with mineralised structures.

All these features are visible in the 3D model and given most are ‘imaged’ by more than one technique; their reliability and our confidence in the interpretation of the craton are enhanced. Fig. 6 shows two ‘snap shots’ of the 3D model illustrating several of these features. The following observations are taken from interrogation and inspection of the integrated 3D model.

4.1. Yilgarn Craton crustal structure

There is a pronounced easterly dip to the fabric of the Yilgarn crust. The majority of reflectivity observed along the seismic traverse, both within the middle and upper levels of the crust typically dips eastwards at 30° (Figs. 2 and 6a). West-dipping features are imaged but these are far less common. The crust is subdivided into three sub-horizontal layers. Many of the receiver function sites support this simple subdivision of the Eastern Goldfields Province crust into three distinct sub-horizontal seismic layers as well as supporting a division of the craton into at least three different geological provinces; a difference that exists throughout the entire crust.

The upper crustal layer, with its granite–greenstone succession, is complex and variable in its seismic character. The lozenge-like bodies imaged within the middle crust suggest large-scale compressional deformation, that at one time was coupled to upper crustal deformation but later became decoupled, though the evidence suggest that there was not large amounts of relative horizontal movement. The ductile lower crustal is devoid of reflectivity with the exception of three instances where dipping reflections are recorded within this layer and all relate to the location of the interpreted deep-penetrating shears zones.

4.2. Yilgarn Craton Moho depth (implied crustal thickness)

The depth to the Moho has been determined from three different seismic data sets, deep seismic reflection, seismic refraction and receiver function analysis. In the Eastern Goldfields Province, the deep seismic reflection traverses has imaged the Moho and along-traverse variations in this boundary. The deep seismic data shows the Moho as a prominent thin, sub-horizontal band of reflections. The Moho in this area is interpreted to be at about 36 km depth beneath the Ida Fault on the 91EGF01 traverse (Goleby et al., 2000), 40 km beneath the town of Leonora and about 46 km at the eastern end of the 01AGSNY1 traverse (Goleby et al., 2004). This deepening of the Moho is achieved through a series of ramps and flats, with the Moho generally sub-horizontal for long sections, and then ramping down over a short distance. This feature is observed on both the north-eastern Yilgarn traverse 01AGSNY1 and the Eastern Goldfields Traverse 91EGF01.

In the south-western part of the Yilgarn Craton, crustal-scale refraction profiles indicates the crust is ∼35 km thick (Dentith et al., 2000), whereas in the northern Yilgarn Craton, refraction profiles indicate that the crust is ∼38 km thick (Drummond, 1998). In both areas, the respective authors identified significant lateral velocity variation. Receiver function data across the craton support these depths where they coincide with the reflection or refraction interpretations and provide infill point values elsewhere. Reading et al. (2003) reported Moho depths, based on receiver function analysis, of ∼40 km at the western end of traverse 01AGSNY1, deepening to ∼45 km at the eastern end near the craton.

When the various Moho estimates are contoured and displayed in 3D, a craton-wide Moho surface is produced (Fig. 6b). This surface shows a good first-order correspondence to the estimates of the crustal thickness obtained from the teleseismic S-wave volume.

4.3. Lithospheric structure

Teleseismic results (Kennett, 2003; Reading and Kennett, 2003) show the Yilgarn Craton has fast S-wave velocities and contains a southeastwards dipping high-velocity three-dimensional body that is approximately 70 km deep beneath the western Yilgarn Craton, 100 km beneath the Ida Fault, and approximately 120 km near the eastern margin of the Yilgarn Craton (Figs. 5 and 6b). Although not clear, the lithosphere beneath the craton is of the order of 220 km deep.
Unlike the previous data sets, this data set had no other constraints and thus could only be used on its own. The locations of recorded mantle nodules, kimberlites, lamprophyres and carbonitites were displayed in the model; however, the dramatic age differences between the latter’s ages (Phanerozoic, mostly Mesozoic) and the age of the craton (Archaean) raised unanswerable question regarding the possibility of relative movements between the crust, the mantle and the lithosphere. Even so, arguments presented earlier indicate very little movement post the D2 deformation (~2660 Ma) so we have assumed only little relative horizontal movement between the crust and mantle. Thus, the recent mantle nodules have sampled a region of the mantle that was not too different from that of the Archaean. Given this, it is interesting to note that all kimberlite locations lie within 100 km of one of the major breaks (offsets) in the 4.8 km s\(^{-1}\) S-wave iso-surface.

5. 3D integration and interpretation of the 3D model

Each of the seismic data sets presented within, provides valuable information on the crustal architecture of the Yilgarn Craton. The merging and integration of these data sets through the construction of a 3D geological model of the craton (Goleby et al., 2002; Blewett et al., 2003) provides significantly more information on the crustal architecture and possible geodynamic evolution of the Yilgarn Craton. Through the incorporation of seismic and geological data sets, the 3D model presents both detailed velocity distributions at various scales within a defined geological crustal architecture (Fig. 6). This combination of velocity, structural and geological data set displays velocity—geological variations across the Yilgarn Craton, as well as differences between the velocity structure of mineralised and less mineralised terranes of the Eastern Goldfields Province and their underlying relatively low-density and low-velocity middle crust.

The integration process including the different seismic data sets into the 3D model focused on the presentation and visualisation of the various data sets rather than trying to adjust any particular data set to match the scale, frequencies, and wave-modes of different dimensions of any other data set. This methodology allowed the integration of 2D high-resolution reflection data with 2D crustal-scale seismic reflection profiling with 2D crustal scale P- and S-wave velocity models with 1D receiver function velocity models and with low-resolution 3D tomographic velocity models. The most important part of the crustal component of the model was the construction of a regional crustal architecture framework, which then allows for the development of a 3D geological/tectonic model of the area. The above process resulted in the development of a terrane-scaled geologically consistent 3D model, within which, a craton-wide velocity model is superimposed.

At the lithospheric scale, the 3D image of the teleseismic data set indicates the lithosphere beneath the Yilgarn Craton is far more complex than originally suggested. The main observation being the presence of a fast S-wave velocity layer at depths of 100–120 km. From the 3D model’s velocity structure, we can categorise the mantle beneath the Yilgarn Craton as being fast, depleted, refractory, cold, less dense, dry, strong and buoyant; compared with the mantle beneath the eastern part of Australia which is slow, undepleted, fertile, warm, dense, wet, weak and less buoyant. The fast velocities beneath the Yilgarn Craton suggest that the mantle beneath the Yilgarn consists of material similar to harzburgite, with the 100–120 km deep, high S-wave body indicating a possible compositional change from harzburgite to garnet lherzolite or the change from garnet lherzolite to eclogite. We do not see evidence for a seismic low-velocity zone beneath the Yilgarn Craton.

Three possibilities exist as to the nature of this higher-velocity body; these being a fossil southeast-dipping subduction zone, a delaminated lower crustal restite layer or the remains of a mantle plume (Blewett, 2005). The seismic data, nor the 3D model, supports a plume model (Campbell and Hill, 1988; Hill et al., 1992) as modern mantle plumes are characterised by low P- and S-wave velocities (not high velocities), and there is no impact on the stratification of the mantle lithosphere (Blewett, 2005). Although there is some evidence for the high-velocity body being a fossil east-directed subduction zone, primarily the observation that modern subduction zones are characterised by fast S-wave velocities, we support the interpretation that this
layer represents delaminated material from the base of the crust. Delamination is a geodynamic process with a scale large enough to account the temporal link between the late-stage low-Ca granites and the late-stage gold event occurring almost simultaneously across the entire Yilgarn Craton (Cassidy et al., 2002; Blewett, 2005). Delamination is consistent with most of seismic and geological observations, in particular the presence of a Moho with gentle easterly dip, a thin crust, a fast easterly dipping S-wave velocity layer body at 100–120 km and an apparent simple layering within the crust and upper mantle. The delamination argument is further strengthened by Champion and Sheraton (1997) and Smithies and Champion (1999) who suggested that the delamination of a dense garnet-rich lower crust (restite), formed during extraction of earlier voluminous high-Ca granite magma, allowed heat to be introduced into the base of the crust. This heat resulted in widespread melting and emplacement of low-Ca granites during late-orogenic extensional collapse (Blewett, 2005). The presence of the relatively flat Yilgarn Moho (Drummond et al., 2000; Goleby et al., 2004) indicates some form of lower crustal thermal erosion or modification by delamination (Nelson, 1998).

Evidence that the layer could be subduction related comes from several authors (e.g. Cassidy and Champion, 2004; Morris and Witt, 1997) who proposed subduction to account for geological observations; however, both their models have opposing dips to the subduction. The high-velocity layer cannot be the signature of slabs from both southeast- and west-directed subduction events. In addition, van der Velden et al. (2006) interpreted several short but continuous reflections that dip into the upper mantle beneath the northeastern Yilgarn as possible remnants of convergent lithospheric boundaries between plates, and concluded that these reflections represent relict subduction zones.

The low velocity structure of the Yilgarn crust today (Fig. 6b), implies an essentially felsic composition (Drummond et al., 1993; Fomin et al., 2003). This felsic composition questions the inference for a dense garnet-rich lower crust as a residue of high-Ca granite magmatism (Champion and Sheraton, 1997; Smithies and Champion, 1999). However, the integrated 3D model does not preclude either the presence of a small percentage of dense material (up to 20%) within the lower crust, or the possibility that the high-velocity layer (dense) in the upper mantle represents the delaminated layer of previously thicker Archaean crust.

Many of the features seen on the regional seismic reflection data, in particular the more recent fault movements, support late extension (Swager, 1997). These arguments are all consistent with the velocity and geological structures shown within the 3D model.

At the crustal scale, the reflection data and receiver function results show an eastward thickening of the Yilgarn crust and a series of prominent east-dipping crustal-penetrating shear zones, which correlate at the surface with mapped terrane boundaries (Fig. 6b). The 3D geometry of these crustal-penetrating shear zones terrane boundaries within the Eastern Goldfields Province is important, as the major gold deposits are all spatially associated with these structures. The Kalgoorlie region and Laverton Tectonic Zone, two mineral-rich regions within the Eastern Goldfields Province, are controlled by the location of domical low-angle shear zones linked to the major crustal-penetrating structures (Henson et al., 2005). This geometry is critical in focusing upward moving fluids and subsequent distribution of fluids into the overlying complexly deformed greenstones. Elsewhere, faults unrelated or unlinked to the main crustal-penetrating structures appear poorer in economic endowment.

From the 3D model, we can show that the gold deposits in the Yilgarn were the product of the focussing of fluid fluxes from deeper in the crust and uppermost mantle into the upper crust via the deep-crustal penetrating shear zones that acted as pre-defined pathways for fluids to be focussed into appropriate nearby structures or lithologically/rheologically suitable areas. Henson et al. (2005) integrated the seismic reflection data, forward and inverse modelled potential field data, together with structural geology of map patterns to show a strong positive relationship between domes and world-class ore deposits. The surface trace, 3D geometry, and relationship of these faults to other shear are key controls in gold distribution. This fluid migration and trapping process operates at a range of scales from crustal (craton) scale to deposit scale. At the crustal scale, these signatures are mapped by seismic reflection methods and, to a lesser extent, seismic refraction methods. However, at the lithospheric scale, seismic tomography methods were required to image the main ‘cracks’ (pathways).

The 3D crustal architecture suggests a foreland basin model with regional folding and thrusting occurring during the main compressive episode (Goleby et al., 2002; Blewett et al., 2003, 2004a). This episode was separated by equally important extension events, with the seismic reflection data suggesting that extensional movement on shear zones was more common that previously thought and that the major domain-bounding shear zones are best interpreted as having late extension that followed an episode of earlier west-directed
thrusting. The seismic reflection data led to the development of a model involving rapid foreland-directed ‘orogenic surge’ of the granite–greenstone wedge above a gently dipping basal detachment during regional compression (Blewett et al., 2004a) during orogenesis.

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