Finite-element modelling of contemporary and palaeo-intraplate stress using ABAQUS™

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Abstract

Knowledge of the contemporaneous and palaeo-orientation of maximum horizontal compressive stress (SHmax) in the Earth’s crust is important for the exploration and recovery of hydrocarbons and also provides insights into the mechanisms driving plate motion and intra-plate seismicity. To date, most approaches for modelling intraplate stress orientations have been based on applying forces to homogeneous elastic plates. However, real tectonic plates consist of oceanic and continental lithosphere, including sedimentary basins, fold belts and cratons with large differences in elastic properties. We have used the finite-element method as implemented in the software package ABAQUS™ along with the optimisation software Nimrod/O to model the orientations and magnitudes of SHmax over the Indo-Australian plate for the present and the Miocene. An elastic 2D plane stress model incorporating realistic mechanical properties for the Australian continent was used consisting of 24,400 elements, providing a resolution of 0.2° in both latitude and longitude. In general, modelled SHmax directions correlate well with observed contemporaneous stress indicator data and reactivation histories over the NW Shelf and Bass Strait regions of the Australian continent, where Tertiary tectonic reactivation through time is best documented. Large perturbations in SHmax orientation over the Australian continent are shown to occur in and around regions of heterogeneous material properties.

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1. Introduction

An understanding of the orientation of contemporaneous maximum horizontal compressive stress (SHmax) is relevant to many areas of earth science, providing fundamental insights into the mechanisms driving plate motion. Knowledge of contemporaneous and palaeo SHmax orientations and magnitudes is also useful for improved exploration and recovery of hydrocarbons, allowing for the creation of a predictive framework for fault reactivation and the planning of deviated drilling.

Since SHmax data can be sparse over large areas of continents and over geologic time, geophysical modelling of SHmax regimes is necessary to provide a satisfactory understanding of the regional stress field. Data compiled as part of the World Stress Map project (Zoback, 1992) provide important constraints on
present orientation and magnitude of $S_{Hmax}$ regimes of continents, and in particular data contained in the Australian Stress Map project (Hillis and Reynolds, 2000) are used here as constraint on modelled contemporary $S_{Hmax}$ orientations for the Indo-Australian plate.

Up to now most approaches for modelling Indo-Australian intraplate stress orientations have been based on applying forces to homogeneous elastic plates (Coblentz et al., 1995, 1998; Hillis et al., 1999; Reynolds et al., 2002). While these studies model the first-order pattern of stress over the Australian continent well, more recently Zhao and Müller (2003) studied the second-order effects of homogeneous material properties on the stress field of Eastern Australia, determining through inverse analysis that inclusion of realistic material properties improves the regional fit between modelled and measured $S_{Hmax}$ orientations.

Modelling of the stress regime of the Indo-Australian plate was carried out here using ABAQUS™, an engineering industry standard finite-element modelling software package, in conjunction with the distributed optimisation software Nimrod/O. ABAQUS™ is a robust, industry accepted finite-element modelling program and allowed for simple creation and alteration of model geometries and parameters using the program ABAQUS™ CAE™ (Complete ABAQUS™ Environment). Implementing ABAQUS™ in conjunction with Nimrod/O allowed for extensive exploration of parameter space through automated execution of thousands of models using intelligent optimisation techniques (Abramson et al., 2000; Lewis et al., 2003).

In order to compare modelled results a residual misfit value was calculated between modelled stress orientations and measured stress orientations contained in the Australian Stress Map database (Hillis and Reynolds, 2000). In order to calculate the residual misfit, modelled $S_{Hmax}$ orientations were averaged over a small window whose centre corresponded to the location of an average $S_{Hmax}$ orientation as determined by Reynolds et al.

2. Modelling method

Finite-element modelling of the Indo-Australian and Australian plate for the present and geologic past was carried out utilising the software packages ABAQUS™ and Nimrod/O. ABAQUS™ is a robust, industry accepted finite-element modelling program and allowed for simple creation and alteration of model geometries and parameters using the program ABAQUS™ CAE™ (Complete ABAQUS™ Environment). Implementing ABAQUS™ in conjunction with Nimrod/O allowed for extensive exploration of parameter space through automated execution of thousands of models using intelligent optimisation techniques (Abramson et al., 2000; Lewis et al., 2003).

In order to compare modelled results a residual misfit value was calculated between modelled stress orientations and measured stress orientations contained in the Australian Stress Map database (Hillis and Reynolds, 2000). In order to calculate the residual misfit, modelled $S_{Hmax}$ orientations were averaged over a small window whose centre corresponded to the location of an average $S_{Hmax}$ orientation as determined by Reynolds et al.

Fig. 1. Mesh of ABAQUS™ contemporary Indo-Australian plate model used in analysis. Model contains 24,400 plane stress elements giving a resolution of roughly 0.2° in both latitude and longitude.
for various regions over the Australian continent and continental shelf. The difference between azimuths of the average modelled and average measured $S_{\text{Hmax}}$ orientations then determined the residual misfit.

Modelling using the ABAQUSTM program is divided into modules, the framework of which will be used to discuss model construction. The ABAQUSTM Part, Assembly, Step, Interaction, Property, Load and Job modules are relevant to model construction while the ABAQUSTM Visualisation module is used for graphical analysis of model output data.

2.1. Parts and partitions

Geometrical models of the plates in the study were constructed as sketches within the ABAQUSTM Part module by projecting the latitudes and longitudes along the model boundaries into Cartesian coordinates using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1991). The projected latitude/longitude data were interpolated along the plate boundary to obtain an even sampling distribution. The data were then filtered to remove high frequencies. ABAQUSTM python sketch files were then created using the projected, smoothed Cartesian coordinate data. The python sketch files can then be easily imported into the ABAQUSTM environment using the ABAQUSTM CAETM Sketch module. Regions representing areas within the model with differing rheological properties were also created within the ABAQUSTM model using the process outlined above. These regions, however, were created as so-called ‘partitions’ within the model. Interaction between ABAQUSTM model parts was set to a tie constraint where a ‘master’ and ‘slave’ surface is defined with all degrees of freedom for the nodes on the ‘slave’ surface being eliminated, allowing for the joining of all parts in the model to form one tectonic plate.

The Australian continent was subdivided into four categories (cratons, fold belts, basins and continental shelf) in the modelling process based on the differing rheologies and strength of the continent as determined by Zuber et al. (1989) and Simons et al. (2000). Regarding terminology, note that use of the words “strength”, “strong”, or “weak”, etc. within this paper refer to relative stiffness or deformability within the elastic regime (as governed by Young’s modulus and Poisson’s ratio), as opposed to some measure of the stresses or stress differences that result in an onset of inelasticity. As we are constrained to (linearly) elastic behaviour, we have no consideration for any departure from that rheology. Fig. 2 shows the Australian continent illustrating these areas. Results from seismic tomography of the Australian continent (Kennett, 1997; Simons et al., 1999) support the findings of Zuber et al. (1989) and further indicate the existence of a seismically slow, probably relatively weak zone located in central eastern Australia (labeled CB in Fig. 2). The existence of a weak zone in this area is also supported by high heat flow data (McLaren et al., 2003). Simons and van der Hilst (2002) pointed out that mechanical strength and seismic thickness of the Australian continent do not always match. Therefore, we only modified our model for mechanical strength in one area in central eastern Australia (CB in Fig. 2) where seismic tomography and heat flow data provide strong evidence for relatively hot and presumably weak lithosphere. The relative strengths of the individual provinces were implemented by altering the Young’s moduli of the materials. Zuber et al. (1989) estimated the northern Australian cratons to have the highest rigidity, with a value of $2.1 \times 10^{25}$ N/m$^2$. Areas with this rigidity were assigned an effective Young’s modulus of $6 \times 10^{10}$ N/m$^2$. All other areas were assigned an effective Young’s modulus scaled according to the ratio between their rigidity and that of the highest rigidity as estimated by Zuber et al. (1989). Table 1 lists the values of rigidity determined by Zuber et al. (1989) and the scaled effective Young’s moduli assigned to each of the provinces implemented in the models.
The mechanical strength of the Australian continental margin remains relatively poorly constrained. However, it cannot exceed that of the continental lithosphere since the continental margins are extended and thinned continental lithosphere, and it cannot exceed that of the adjacent, cool and relatively strong oceanic lithosphere. Modelled $S_{\text{max}}$ directions on the continental shelf and within the continental interior are dependant on the strength of the continental shelf. In order to determine the strength of the continental shelf we have compared two approaches. The first approach was to assume that stretched continental crust thermally reheated in the Late Mesozoic/Cenozoic has remained mechanically weak (effective Young’s Modulus of $1 \times 10^{10}$ N/m²) since breakup, following the suggestion by Fowler and McKenzie (1989) that thinned continental crust does not regain its elastic strength similar to ageing oceanic lithosphere. This produced a model with large residual misfit and poor correlation with observed stress data (Table 2). The second approach was to assume that the elastic strength of the continental shelf has grown equivalent to ageing oceanic lithosphere (Karner et al., 1983) and the continental shelf was divided into three regions corresponding roughly to the last age of thermal reactivation (Fig. 2). Values for the strength of the individual regions were prescribed an effective Young’s modulus range of $1 \times 10^{8}$–$1 \times 10^{10}$ N/m². Final material property values in the model were determined by minimising the residual misfit with measured stress orientations through extensive exploration of parameter space using Nimrod/O. The results (Table 2) indicate that a continental shelf with varying material properties best represents the strength of the Australian continental shelf. This novel approach demonstrates that stress orientation data can be used for constraining the relative strength of continental shelf, therefore helping to resolve the long-standing controversy whether or not stretched continental lithosphere regains its strength like oceanic lithosphere in principle.

2.2. Load definition and boundary conditions

Primary forces applied to models in this study (Table 3) were the topographic forces of ridge push and slab pull and the forces created at collisional boundaries. A basal traction force was not implemented due to the poor understanding and relatively unconstrained nature of this force. In the case of the contemporaneous Indo-Australian Plate the dominant
plate driving forces are the ridge push, slab pull and collisional forces originating at collision zones north of the Indo-Australian plate. The ridge push force \((F_{RP})\) arises due to elevated topography at mid-ocean ridges (MOR), and is a distributed pressure gradient that acts normal to the strike of the mid-ocean ridge (Wilson, 1993). The force contribution from the subsiding oceanic lithosphere created at the MOR is given by the relationship (Turcotte and Schubert, 2002):

\[
F_{RP} = g\rho_m a_c(T_m - T_0) \left[ 1 + \frac{2 \rho_m a_c (T_m - T_0)}{\pi (\rho_m - \rho_w)} \right] kt, 
\]

where gravity \((g)\) is 10 m/s\(^2\), the densities of the mantle \((\rho_m)\) and water \((\rho_w)\) are 3300 and 1000 kg/m\(^3\), respectively, thermal diffusivity \((\kappa)\) is 1 mm\(^2\)/s, the temperature difference between the mantle and the surface \((T_m\) and \(T_0\), respectively) is 1200 K, the thermal expansion coefficient \((a_c)\) is \(3 \times 10^{-5}/K\) and \(t\) is the age of the lithosphere in seconds.

The ridge push force was implemented in the modelling process as a pressure applied along a boundary representing the location where ridge push force would be maximum, for example, if the ridge push force was calculated for a mid-ocean ridge with a spreading age of 45 Ma, the pressure would be applied to the 45 Ma isochron boundary in the model. Figs. 3 and 4 illustrate the locations where forces were applied to the contemporaneous and Miocene models, respectively.

Table 3

<table>
<thead>
<tr>
<th>Location</th>
<th>Contemporary</th>
<th>Miocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Ocean ridge</td>
<td>1.90</td>
<td>1.10</td>
</tr>
<tr>
<td>Australia–Antarctic Discordance</td>
<td>2.1 (3.1)(^a)</td>
<td>1.7 (2.5)(^a)</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>3.80</td>
<td>—</td>
</tr>
<tr>
<td>Banda Arc</td>
<td>–0.50</td>
<td>—</td>
</tr>
<tr>
<td>Java</td>
<td>–0.30</td>
<td>–0.30</td>
</tr>
<tr>
<td>New Hebrides</td>
<td>1.00</td>
<td>—</td>
</tr>
<tr>
<td>Solomon</td>
<td>1.20</td>
<td>—</td>
</tr>
<tr>
<td>Sumatra</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>New Zealand</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>Southern New Zealand Alps</td>
<td>2.80</td>
<td>2.80</td>
</tr>
<tr>
<td>Tasman Sea</td>
<td>1.25</td>
<td>1.20</td>
</tr>
<tr>
<td>Carol</td>
<td>—</td>
<td>–0.60</td>
</tr>
<tr>
<td>Ontong Plateau</td>
<td>—</td>
<td>2.50</td>
</tr>
</tbody>
</table>

Positive forces are directed towards the interior of the plate. Note: Force magnitudes are \(1 \times 10^{12}\) N/m which is equivalent to a stress of 10 MPa across a plate of thickness 100 km. 

\(^{a}\)Force applied where the effects from the Australia–Antarctic Discordance were not included.

Table 2

Residual misfit between average predicted and average measured stress orientations

<table>
<thead>
<tr>
<th>Province(^a)</th>
<th>Homogeneous(^b)</th>
<th>Best Fit(^c)</th>
<th>No Australia Antarctic Discordance(^d)</th>
<th>Uniform Continental Margin(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amadeus</td>
<td>68.1</td>
<td>12.5</td>
<td>106.2</td>
<td>53</td>
</tr>
<tr>
<td>North Bonaparte</td>
<td>14</td>
<td>4.8</td>
<td>24</td>
<td>92.2</td>
</tr>
<tr>
<td>South Bonaparte</td>
<td>0.6</td>
<td>1.1</td>
<td>11</td>
<td>68.9</td>
</tr>
<tr>
<td>Bowen</td>
<td>143.1</td>
<td>92.3</td>
<td>95.4</td>
<td>74.15</td>
</tr>
<tr>
<td>Canning</td>
<td>21.7</td>
<td>11.5</td>
<td>33.8</td>
<td>44.7</td>
</tr>
<tr>
<td>Canarvon</td>
<td>1.8</td>
<td>7.9</td>
<td>16.8</td>
<td>5</td>
</tr>
<tr>
<td>Cooper</td>
<td>46.1</td>
<td>6.7</td>
<td>65.2</td>
<td>3</td>
</tr>
<tr>
<td>Gippsland</td>
<td>6.5</td>
<td>1.0</td>
<td>4.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Otway</td>
<td>3.5</td>
<td>6.5</td>
<td>6.4</td>
<td>102.4</td>
</tr>
<tr>
<td>Perth</td>
<td>37</td>
<td>2.9</td>
<td>28</td>
<td>24.6</td>
</tr>
<tr>
<td>Total Residual Misfit</td>
<td>342.4</td>
<td>147.2</td>
<td>391.3</td>
<td>469.05</td>
</tr>
</tbody>
</table>

\(^a\)As defined by Coblentz et al. (1998) and Reynolds et al. (2002). The Models have the following differences: 

\(^b\)homogeneous material properties (Fig. 5); 

\(^c\)model producing best fit with observed stress data (Fig. 6); 

\(^d\)residual misfit of model where effects of the Australia–Antarctic Discordance were not implemented; 

\(^e\)residual misfit of model with a uniform continental margin with an effective Young's Modulus of \(1 \times 10^{-8}\) N/m.
The slab pull force \( F_{SP} \) originates from the negative buoyancy of the down-going dense oceanic lithosphere at subduction zones and is proportional to the excess mass of the cold slab in relation to the mass of the warmer displaced mantle (Spence, 1987). The force contribution can be given by the relationship (Turcotte and Schubert, 2002):

\[
F_{SP} = 2 \rho_m g b (T_c - T_0) \left( \frac{\kappa \dot{\lambda}}{2\pi u_0} \right)^{\frac{1}{2}} + \frac{2(T_c - T_0)\gamma \Delta \rho_{os}}{\rho_m} \left( \frac{\kappa \dot{\lambda}}{2\pi u_0} \right)^{\frac{1}{2}},
\]

where \( b \) is the slab length, \( \dot{\lambda} \) is 4000 km, \( u_0 \) is 50 mm/yr, \( \gamma \) is 4 MPa/K, \( \Delta \rho_{os} \) is 270 kg/m\(^3\), other parameters are described in Eq. (1).

For fast moving plates (5–10 cm/yr) the subducting slab attains a ‘terminal velocity’ where forces related to the negative buoyancy of the slab are balanced by viscous drag forces acting on the slab as it enters the mantle and the net force experienced by the horizontal plate is quite small (Forsyth and Uyeda, 1975). The amount of net force actually transferred to the horizontal plate, however, is still quite controversial. Schellart (2004) suggests as little as 8–12% of slab pull force is transferred to the horizontal plate while Conrad and Lithgow-Bertelloni (2002) suggest as much as 70–100% may be transmitted. Magnitudes of slab pull forces were varied over a range of \( 1 \times 10^7 \) to \( -1 \times 10^{-7} \) N/m with final force magnitudes constrained by the resulting fit with the measured stress directions contained in the Australian Stress Map database (Hillis and Reynolds, 2000), as were the forces at collisional boundaries. The collisional boundary between the IAP...
and Eurasian plate at the Himalayas was modelled as a fixed boundary in the modelling process in order to maintain mechanical equilibrium.

2.3. Visualisation

The ABAQUS™ CAE™ Visualisation module is used to view the model results, however, it was found to be limited in its capabilities of data representation. In order to have more control over the data visualisation the ’El Print and ’El File options in the analysis input file were used to output variable data from the analyses into the analysis data and results files. The ABAQUS™ fprin subroutine was then used to calculate the elemental stress values and also the direction of the stress vectors. These data were then plotted using the GMT software, allowing for more flexibility in data visualisation.

2.4. Palaeo-modelling method

A palaeo-stress model (Fig. 4) for the Miocene (20 Ma) was created using reconstructed plate boundary configurations (Heine et al., 2004; Hall, 2002) and the age–area distribution of ocean crust around Australia (Müller et al., 2000) to obtain estimates of spatial distribution and magnitude of ridge push and slab pull forces, while estimates of forces acting at other boundaries were extrapolated using results of contemporary stress modelling. Values for material properties were held constant with the values used in and obtained from the contemporary stress analysis.

3. Results

3.1. Contemporary

Our results show that spatially significant rotations of the $S_{H\text{max}}$ direction can be modelled as a consequence of perturbations of $S_{H\text{max}}$ in areas of juxtaposed strong and weak rheologies. The materials with higher values of rigidity deform only slightly under a given loading, and so place relatively small displacements on the boundaries of adjacent, weaker materials. This results in

Fig. 4. Miocene model setup illustrating forces applied. CA = Carol Trench; refer to Fig. 3 for more details on other plate boundary names.
deviation of stress trajectory directions within higher rigidity materials around weaker materials. Large differences in both magnitude and direction of $S_{Hmax}$ can be seen around areas in the Australian continental lithosphere where there are juxtaposed strong and weak rheologies. Fig. 5 shows the predicted $S_{Hmax}$ regime for a model with homogeneous material properties while Fig. 6 shows the “best fit” model obtained out of many thousands of model runs using heterogeneous material properties. It is clear that the stress pattern predicted by a model with heterogeneous material properties shows more variance in $S_{Hmax}$ direction and magnitude than that of a model with homogeneous material properties. This is best illustrated over the western margin of the Yilgarn Craton (marked YL in Fig. 2) where there is up to roughly a 90° rotation of the stress direction over an area roughly 200 km in diameter. The model also emulates the observed 89° rotation in $S_{Hmax}$ orientation between the Amadeus and Cooper basin stress provinces defined by Reynolds et al. (2002) well with reasonably low residual misfits in the Amadeus and Cooper basins of 12.5 and 6.7, respectively. Such spatially rapid variation in $S_{Hmax}$ directions is not present in the homogeneous model. While the value of residual misfit for the heterogeneous model in the Bowen Basin is quite high (Table 2), modelled $S_{Hmax}$ magnitudes are lowest in this region indicating that local sources of stress may play a dominant role in controlling the orientation of $S_{Hmax}$ (Zoback, 1992).

3.2. Miocene

Forces applied to the boundaries of the Miocene (20 Ma) model are illustrated in Fig. 4 and listed in Table 3. Docking of the Australian plate with the Ontong–Java plateau had begun in the early Miocene (Hall, 2002), however, collision with Papua New Guinea had not yet been initiated; instead the Australian plate was subducting beneath the Caroline plate (Hall, 2002). Forces along the plate boundary at New Zealand were similar to those at present with the inception of the Alpine Fault occurring at 23 Ma (Kamp, 1986). The absence of the collisional Papua New Guinean boundary to the north of the Australian continent in the
Miocene produces a dramatically different stress regime (Fig. 7) to that of the present. The stress distribution is more uniform with less spatially rapid variation. A general NW–SE $S_{H_{\text{max}}}$ orientation is evident over the Australian continent during the Miocene, whereas at present there exists a general NE–SW trend over Northern Australia with $S_{H_{\text{max}}}$ orientations over the southern continent displaying more variation. Orientations of $S_{H_{\text{max}}}$ directions over the NW shelf and Bass Straight region in particular show large differences during the Miocene compared to present, with modelled $S_{H_{\text{max}}}$ orientations agreeing well with fault reactivation histories of these areas.

$S_{H_{\text{max}}}$ directions over the NW shelf have changed from a NW–SE orientation in the early Miocene to a general NE–SW at present. Reactivation histories of coast-paralleling extensional basin forming faults on the Canarvon Terrace on the NW shelf occurred during the Miocene (Baillie and Jacobson, 1995; Müller et al., 2002) with migration of hydrocarbons also taking place at this time (Crostella and Boreham, 2000). This is consistent with the results of this study which show rotation of $S_{H_{\text{max}}}$ directions over the Canarvon Terrace from orientations oblique to the coastline during the early Miocene to orientations normal to the coastline at present.

Inversion in the Torquay Embayment and Otway Ranges of the Bass Strait region occurred in the Miocene due to compressional reactivation of numerous NE striking extensional faults (Hill et al., 1995). Modelled $S_{H_{\text{max}}}$ results in this region of the Bass Strait show a rotation from roughly EW in the early Miocene to NNW–SSE at present, indicating a $S_{H_{\text{max}}}$ regime conducive to compressional inversion in the Torquay Embayment and Otway Ranges existed between the early Miocene and present.

4. Summary

Modelling the intraplate stress regime of tectonic plates represents a novel use for the engineering software
package ABAQUSTM that has not previously been explored. We have developed a methodology implemented as programs and shell scripts which allows for straightforward creation of geophysical models within ABAQUSTM CAE TM. All programs and scripts used to create models in ABAQUSTM as part of this work can be accessed at www.geoframework.org and are freely available for use and alteration under the GNU license agreement.

We have modelled the maximum horizontal compressive stress regime for the Indo-Australian plate for the present and Miocene. Methods developed allow for easy creation of models with different geometries. The Generic Mapping Tools software (Wessel and Smith, 1991) has been used to plot the modelled and measured data. Modelling results show significant perturbations of $S_{Hmax}$ orientations and magnitudes in areas of juxtaposed weak and strong materials in the heterogenous model. The results demonstrate that models with heterogeneous material properties fit observed stress directions contained in the Australian Stress Map database better than models with homogeneous material properties. Modelled Palaeo-$S_{Hmax}$ orientations also demonstrate the dramatic changes in $S_{Hmax}$ regime that occurred over the Indo-Australian plate between the Miocene and present day, with modelled $S_{Hmax}$ regimes agreeing well with fault reactivation histories over the NW Australian Shelf and in the Bass Strait region.

References


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