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Short communication

Future intraplate stress and the longevity of carbon storage

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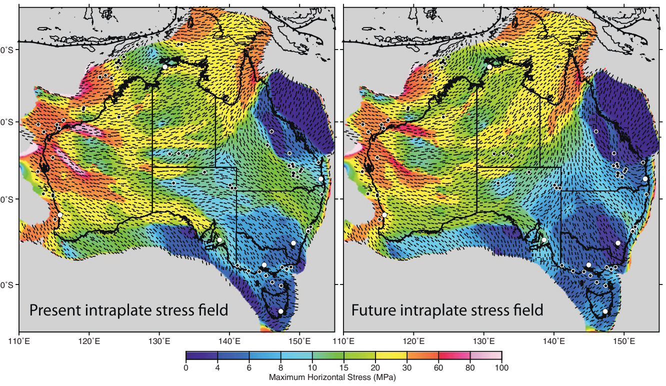
HIGHLIGHTS

- We model the present and future intraplate stress field of Australia.
- We consider stress field changes due to the evolving plate collision in Timor.
- 10 suggested carbon sequestration sites may experience major changes of *in situ* stress regimes.
- Areas at risk include the Timor Sea, the Eromanga Basin, the Bass Strait and the Ipswich Basin.

GRAPHICAL ABSTRACT



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ABSTRACT

Carbon capture and storage (CCS) is regarded as a promising strategy for mitigating global warming. A 19% CCS contribution to CO_2 reduction by 2050, as envisaged by the International Energy Agency, would require the construction of thousands of CCS sites by the 2030s and beyond. CO_2 storage may need to last for tens of thousands of years to avoid potential global warming and major Earth system changes, and a critical site selection criterion will be the likelihood of future escape of stored CO_2 due to fault reactivation. However, future long-term intraplate stress field changes have not been considered in this context. Here we focus on Australia, where 61 potential CCS sites have been proposed, and model the evolving intraplate stress field due to the future growth of tectonic collisional forces north of Australia. Counter intuitively, the largest changes are predicted for some parts of western, central and southeast Australia, all regions far away from plate boundaries, reflecting the non-linear interaction of plate boundary forces with a geologically heterogeneous continent. We suggest that at least ten suggested CCS sites are located in regions where major changes of *in situ* stress regimes can be expected in the next 100,000 years, requiring a careful evaluation of potential future fault reactivation and a breach of reservoir seals. Our results highlight the importance of considering future intraplate stress field changes for selecting CCS sites, particularly within continental regions affected by ongoing mountain building processes including Australia, India, South America, Asia and southern Europe.

1. Introduction

Geological sequestration (geosequestration) of CO_2 is an attractive and widely-discussed mechanism for alleviating the anthropogenic impact on global climate [1]. Carbon capture and storage

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(CCS) remain a core component of national and global emissions-reduction scenarios [2] and substantial funding is being committed to research into carbon capture and sequestration technologies [3]. The International Energy Agency Blue Map scenario envisages a 19% CO_2 reductions contribution from CCS by 2050, implying a need for the evaluation and construction of thousands of CCS sites in the 2030 s and beyond, to store over 8 Gt of CO_2 per year by 2050 — double the mass of current global annual oil consumption [2]. A key selection criterion for CCS sites is the presence of low-permeability formations above the storage zone, alternatively known as seals or caprocks, and usually composed of shales or evaporites – they are expected to prevent escape of CO_2 to the near-surface region [4]. A second key criterion is the potential for leakage via non-sealing faults, but the great heterogeneity in storage sites and conditions, makes direct modeling of the predicted leakage of geologically stored CO_2 very difficult [5,6]. Environmental risks of CO_2 injection sites include leakage of CO_2 into the atmosphere, accumulation of elevated CO_2 concentrations in ecosystems, accumulation of elevated CO_2 concentrations where humans can be exposed, leakage of CO_2 to groundwater, leakage of hydrocarbons to groundwater, displacement of saline brine into drinking water aquifers or surface water and induced seismicity [7,8]. De Connick and Benson (2014) [3] have argued that CO_2 storage would have to last for tens of thousands of years, perhaps up to 100,000 years, to avoid strong, delayed global warming and marked Earth system changes such as vast expansion of ocean 'dead zones'.

Recently, the integrity of seals in terms of their response to fluid-rock interactions has been evaluated [9,10], but the future evolution of *in situ* intraplate stress regimes has not been considered in this context. Here we put forward the argument that if the integrity of CCS sites over a period of 100,000 years into the future is a site selection criterion, then potential changes in the intraplate stress field need to be considered, particularly in onshore or offshore regions affected by evolving plate collisions and orogenic processes. Presently, related investigations are concerned mainly with impacts that the present day *in situ* stress field may have [11,12], with little consideration for changes in stress regimes anticipated in the future. Focusing on Australia, we demonstrate that future changes in plate boundary forces will have a significant impact on intraplate stress regimes over a time period of 100,000 years, with changes in maximum horizontal compressive stress orientations of up to 90° modeled over the next million years associated with changes in stress magnitude in excess of 15 MPa.

2. Plate convergence and collision along the Timor Trench

Previous studies of the contemporaneous plate boundary forces acting on the Indo-Australian plate [13–16] have demonstrated that most margins of the Indo-Australian plate impart a compressional force on the interior of the plate, with only subduction along the Java and Timor trenches transmitting an extensional horizontal force of about $-0.6\ 10^{12}\ \mathrm{Nm}^{-1}$ [see 14, for details]. With an Australia-Indonesia convergence velocity of about ~70 km/Myrs in the Timor Sea area based on the present-day plate rotations from Kreemer et al. [17], collision between the Banda Arc and Australian continental crust north of the Timor Trench is currently most intense along the inner slope of the Timor Trough, but is advancing southward as new thrust slices develop within the subducting Australian margin strata [18,19]. Where the Australian continental margin meets the Timor Trench north of the Ashmore Platform (Fig. 1a), the Australian margin is estimated to have been shortened by about 40 km over the last 2 million years, accompanied by nearly 3 km of uplift on Timor [20]. The Australian subducted oceanic slab has been interpreted as having broken off relatively recently based on a combination of surface observations and geodynamic modeling [21,22]. As the detached slab sinks further into the mantle, part of the Ashmore Platform with a width of about 70 km and a crustal thickness of about 25 km [23], will progressively enter the collision zone over the next million years. This will lead to further shortening and uplift and the establishment of increased compressive forces acting on the Australian margin. Continental collision, already occurring along most of the northern margin, will gradually propagate into the Timor Trench region (Fig. 1). The distance separating the northernmost edge of the Australian continental crust (Ashmore Platform) and Indonesian continental crust is roughly 90 km [24]. With an Australian plate velocity of about 80 mm/yr (8 km/Ma), a stepwise collision of the Ashmore Platform along the Timor Trench gradually change from continent-island arc to continent-continent collision, culminating in full collision about one million years into the future, corresponding to a force of $1.4\ 10^{12}\ \mathrm{Nm}^{-1}$ as previously modeled for the Solomon Trench [14]. Even though the details of such a scenario are difficult to quantify, we use it as an end-member scenario to estimate which parts of the Australian continent will be most severely affected by a gradual switch from dominating slab pull to dominating collisional forces along the Timor Trench.

3. Methodology

We adopt a well-established method for modeling the Indo-Australian current and past stress fields [14,15,25,26] to estimate the future stress regime of the Australian continent. We use an elastic two-dimensional ABAQUS finite-element model with around 33,000 elements and a lateral resolution of roughly 30 km. We distinguish the regional geological elements of the Australian continent (cratons, fold belts, basins and continental margins) by including high resolution geological province outlines mapped into rheological provinces via estimates of an equivalent Young's modulus [25]. The time-dependent ridge-push force is determined from the age-area distribution of ocean floor and slab pull and collisional forces are modeled as described in Dyksterhuis, Albert and Müller [25]. Here we adopt the present-day intraplate stress model for Australia from Müller, Dyksterhuis and Rey [15] and focus on estimating the future evolution of the intraplate stress field. We implement a change from subduction dominated by slab pull along the Timor Trench to a compressional force about one million years into the future similar to that presently modeled along the Solomon Trench northeast of Australia [14], where collisional forces today are roughly equivalent to the future mature collision state along the Timor Trench. We investigate how such an increase in collisional force along the Timor Sea would affect the Australian intraplate stress field.

4. Results

4.1. Contemporary stress field

The maximum horizontal stress field from Müller, Dyksterhuis and Rey [15] displays a characteristic counter-clockwise horizontal stress field rotation from western to central Australia, caused by focusing of the stress field originating from the collision at the Himalayas and Papua New Guinea as well as the extensional force caused by dominating slab pull along the Java and Timor trenches. The interplay between forces acting at the plate boundaries and stress focusing towards relatively strong regions (cratons) and around relatively weak regions (fold belts and basins) results in distinct rotations of maximum horizontal stress directions as well