Geohistory of the North West Shelf: a tool to assess the Palaeozoic and Mesozoic motion of the Australian Plate

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Abstract

The Phanerozoic motion of the Australian plate was compared with the geohistory of the North West Shelf of Australia, combining stratigraphic, sedimentary and palaeontological data from 42 wells drilled offshore and onshore along the North West Shelf. This analysis shows stepwise tectonic subsidence curves reflecting a succession of rifting events and uplifts, and allows tectonic and thermal subsidence events to be distinguished

The latitudinal plate motion was derived from global palaeo-plate reconstructions integrating plate tectonic constraints such as ocean spreading rates, plate buoyancy, and dynamic plate boundaries. Latitudinal motion, velocity and rotation of the Australian plate were calculated using virtual palaeo-poles derived from these reconstructions.

The Late Devonian extensional faulting event can be correlated with a rapid southward drift of the Australian plate. The Late Carboniferous-Early Permian opening of Neo-Tethys corresponds to the shift in drift direction from south to north. The Triassic Fitzroy movement is linked with the closures of Palaeo-Tethys and the evolution of the Bowen Basin. Jurassic rifting of the Argo Abyssal Plain is probably a consequence of a rotation of the plate.

Introduction

Depositional rates in sedimentary basins do not only record the evolution of local tectonics but are also sensitive to major geodynamic events. The purpose of this research was to compare and integrate two independent datasets: firstly, subsidence curves calculated from borehole data, and, secondly, latitudinal motion and velocity of the Australian Plate during the Phanerozoic. The latter is derived from global palaeo-plate reconstructions, integrating plate tectonic constraints such as ocean spreading rates, plate buoyancy, dynamic plate boundaries and basin evolution. The complete description of this plate tectonic model is beyond the scope of the present article (see Stampfli & Borel, 2002).

Of particular interest is the relationship between tectonic events and changing plate motions. The North West Shelf of Australia is the ideal location to test this relationship, for two main reasons. Firstly, there is a very large amount of multidisciplinary data such as reflection seismic, wells, apatite fission track analyses and vitrinite reflectance data. Secondly, the North West Shelf has been a long-term passive margin with an almost complete Phanerozoic sedimentary record (Stagg & Colwell, 1994). Time hiatuses can be reasonably estimated thanks to maximum palaeo-temperature data.

This paper describes the borehole data and the regional structural setting that characterise the region. These data allow us to extrapolate the results derived from subsidence analysis to the plate scale. A palaeo-tectonic model has been developed and predictions of latitudinal motion, velocity and rotation of the Australian plate are made. Finally, the ability to associate the latitude of deposition through time can be a useful tool for prediction of source rocks.

Subsidence analysis

A structural map of the areas along the North West Shelf has been compiled (Fig. 1) based on a variety of data (AGSO North West Shelf Study Group, 1994; AGSO, 1995; King, 1998; Moore, 1995; Struckmeyer et al., 1998; Westphal & Aigner, 1997), in order to assess the hypothesis that the results of basin analysis (rifting/uplift events, tectonic/thermal subsidence) can be extrapolated at a regional scale and then to the Australian plate. The orientation of the main structural features has been obtained from the map and plotted on stereograms (Fig. 2) to test if the tectonic conditions in the vicinity of the wells were applicable or not to the basin scale. These features were active and reactivated during the time frame discussed here (O'Brien et al., 1996; Pryer et al., 2002).

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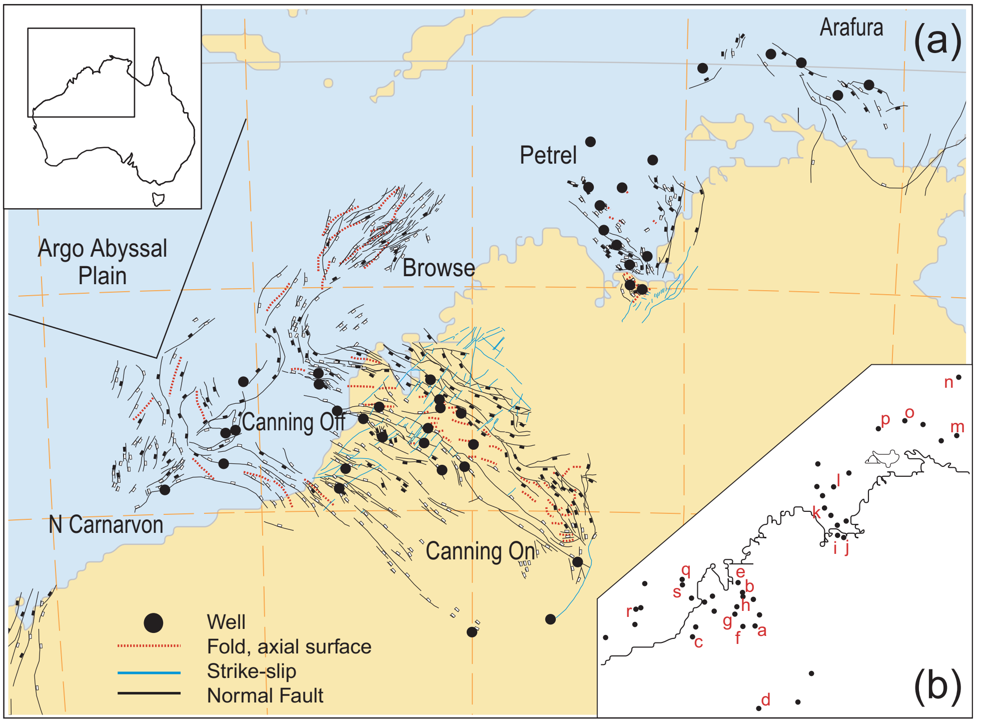

Figure 1: a). Structural map of the North West Shelf of Australia; see text for discussion. Black dots represent well locations listed in Table 1. The tectonic analysis (Fig. 2) is based on this map. b). Black dots represent well locations and red letters denote wells shown on Figure 3 and in Table 1.

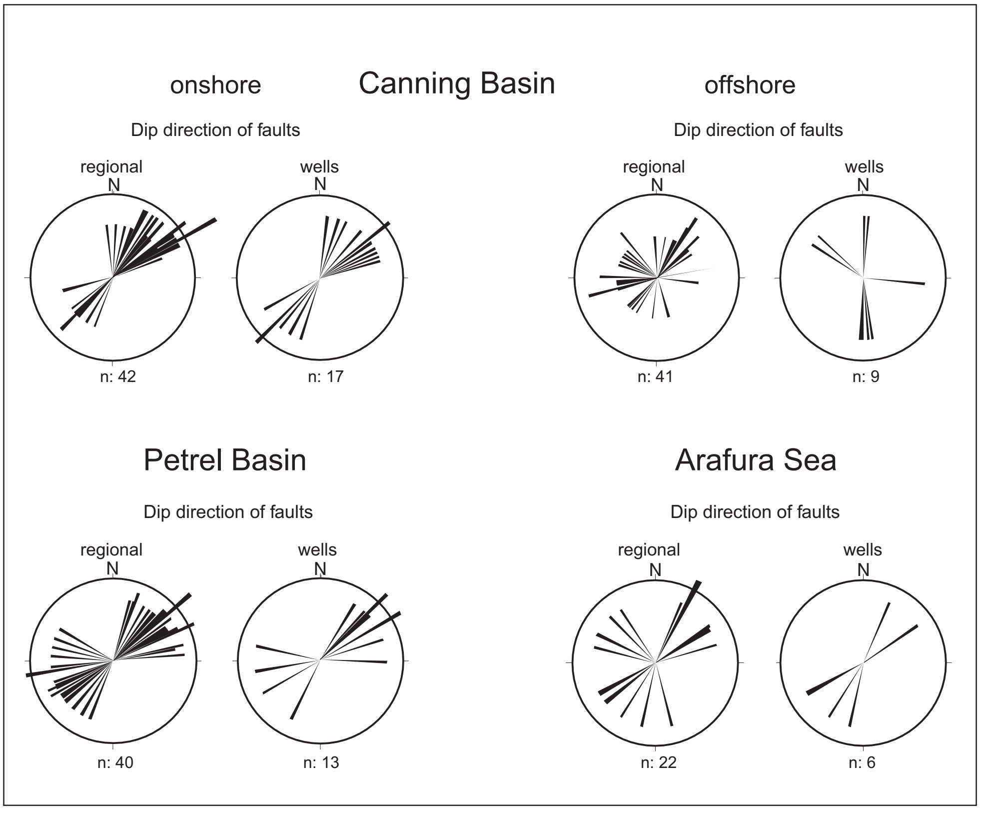

Figure 2: Azimuth diagrams showing the dip direction of the main faults at regional- and well-scale. Note the similarity of orientations between scales, thus the subsidence results could be extrapolated to the whole North West Shelf.

Structural data close to boreholes have been plotted separately in order to compare them with the regional data elsewhere in the basin. The results show that there is no notable difference between the borehole and the regional data (Fig. 2). Consequently, it is reasonable to extrapolate the subsidence analysis at a regional scale.

Passive margins are expected to undergo post-rift thermal subsidence. Moreover, on the North West Shelf of Australia, a remarkably long-term passive margin (Baillie, et al., 1994; Bradshaw, et al., 1998; Jablonski, 1997; Veevers, 2000), extensional and compressive events have occurred since the beginning of the Phanerozoic (Pryer et al., 2002). Using open file well data the subsidence history of the major basins (Canning onshore and offshore, Petrel and Arafura) was investigated. The tectonic subsidence analysis is based on 42 wells (Table 1). Figure 3 shows representative curves of each basin. The subsidence curves integrate age, lithology, thickness

Canning Basin Onshore	Canning Basin Offshore	Petrel Basin	Arafura Sea
a.-Acacia 2	Bedout 1	7-SP1100	m.-Arafura 1
b.-Blackstone 1	Bruce 1	Barnett 2	n.-Koba 1
c.-Calamia	East Mermaid	i.-Bonaparte 1	o.-Kulka 1
East Crab Creek	Keraudren 1	Cambridge	p.-Lynedoch 1
d.-Kidson 1	q.-Lacepede 1A	CB81-11A	Tasman 1
e.-Langoora	r.-La Grange 1	Flattop 1	Tuatara 1
f.-Looma 1	Pearl 1	j.-Keep River	
g.-Matches Spring	Phoenix 2	k.-Lesueur 1	
Mimosa 1	s.-Wamac 1	l.-Petrel 1A	
Mt Hardman 1		Term 1	
h.-Myroodah			
St George Range 1			
Thangoo			
White Hills 1			
Willara			
Wilson Cliffs 1			
Yulleroo 1			

Table 1: Wells used for the subsidence analysis, letters (a - s) denote wells shown on Fig. 3.

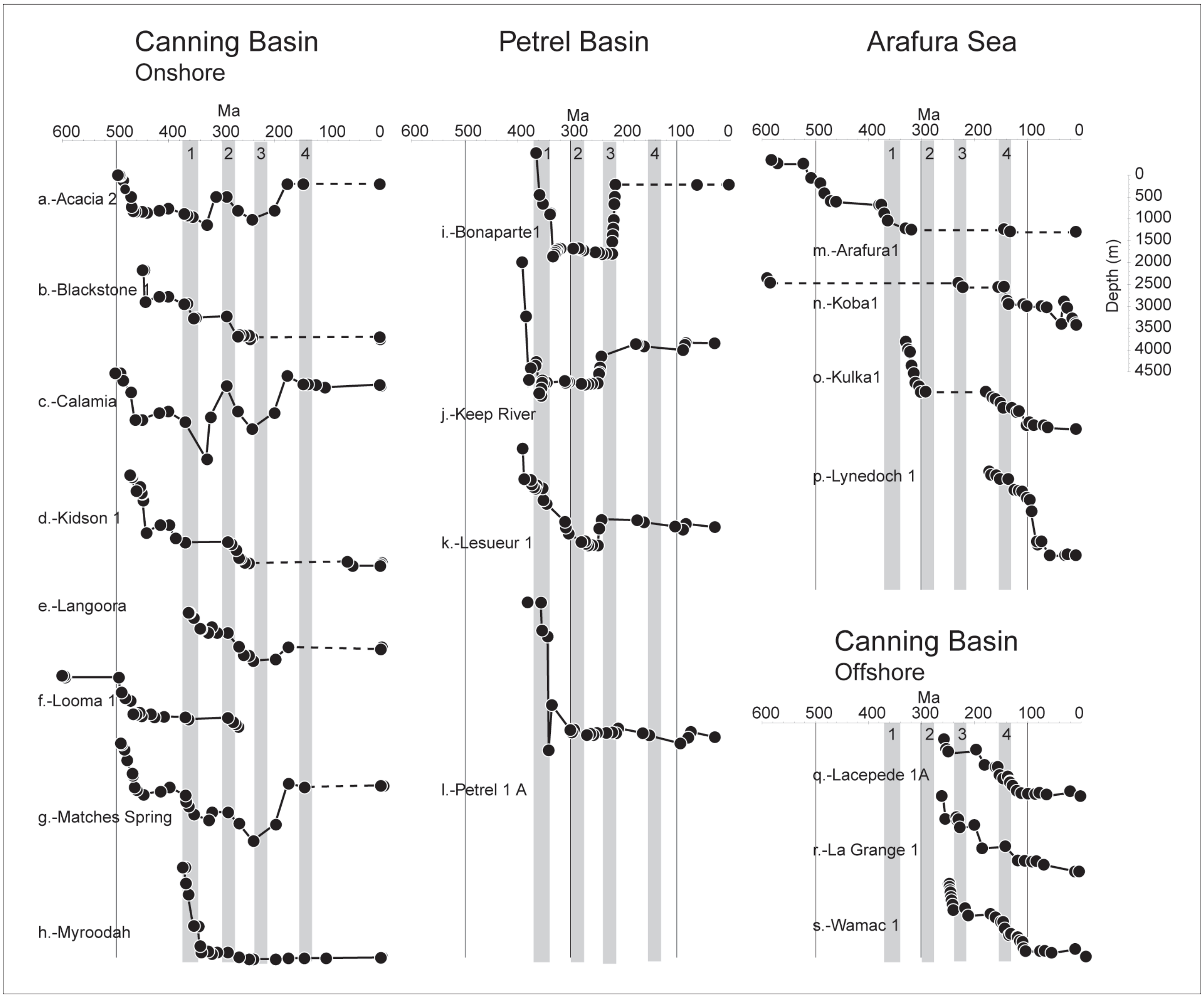

Figure 3: Selected tectonic subsidence curves. These curves show a stepwise geohistory punctuated by major tectonic events. Shaded stripes are labelled: 1=Fitzroy Trough rifting; 2=NeoTethys opening; 3=Fitzroy movement; 4=Argo Abyssal Plain opening. Well locations are shown on Fig. 1. Timescale from Gradstein & Ogg (1996).

and estimated depositional bathymetry of each stratigraphic unit, without eustatic correction (Fig. 3). Lithologies were used to estimate bathymetry. Generally speaking for each time interval, water load factor remained of secondary importance compared to sediment load. In order to isolate the tectonic component of subsidence from the total subsidence the sediment and water load was removed by back-stripping using the method of Bond & Kominz (1984). Apart from evident local differences, all the curves show a stepwise subsidence history, revealing mostly synchronous extensional and compressive phases. Four tectonic events, the Late Devonian Fitzroy rifting, the Late Carboniferous NeoTethys opening, the Late Triasssic Fitzroy movement and the Late Jurassic Argo Abyssal Plain opening, denoted as 1 to 4 on Figure 3, are discussed below.

Palaeo-reconstruction modelling

A plate tectonic model (Fig. 4) was developed for the Palaeozoic and Mesozoic (Ordovician to Cretaceous; see Stampfli & Borel (2002); and Stampfli (2000b) for the nomenclature). It is beyond the scope of the paper to discuss alternative reconstruction models, mainly because most of them do not include plate boundaries and, therefore, cannot be directly compared to the model presented here.

To move plates rather than continents, a dynamic plate boundary concept was applied to reconstructions (e.g. active spreading ridge, subduction zone, and transform fault) by adding to each continent its oceanic surface through time. Palaeo-synthetic oceanic isochrons were constructed through time in order to define the location of the spreading ridges and to restore previous ocean basins (with a symmetrical sea floor spreading for the main oceans). Such a model allows assessment of important geodynamic events such as the onset of subduction (Gurnis, 1992), mid-ocean ridge subduction and presence/absence of slab rollback and related plate motion (e.g. Cloos, 1993; Lithgow-Bertelloni & Richards, 1998). The plate kinematics are essentially driven by slab forces, acting on the oceanic part of the tectonic plates. Generally speaking, the subduction of young buoyant lithosphere generates a cordillera, whereas cordillera collapse and opening of back-arc basins corresponds to the subduction of heavier lithosphere producing slab rollback. These forces can detach two types of terrains. One is detached from an active margin by slab rollback and opening of a back-arc basin, producing both an active margin and a passive margin (e.g. the European Hunic terrains) (Fig. 4a). The other terrain type, separated from a passive margin by slab-pull, has two passive margins (e.g. the Cimmerian blocks) (Fig. 4c). Slab-pull becomes strong enough to detach this second type of terrain only if there is no plate boundary between the subduction slab and the pulled continent, in other words, after the subduction of the mid-ocean spreading ridge. In that case the sedimentary record gives the timing of formation of the oceans located on both side of the terrain (the old one and the new one).

We also used palaeo-magnetic data (e.g. Van der Voo, 1993) and palaeo-bio-geographic data (Stampfli et al., 2002) and references therein), to constrain the pre-Jurassic reconstructions, whilst existing isochrons (Müller et al., 1993) were used to constrain post-Jurassic reconstructions. Geological data, mainly regarding the age of accretion/collision, were compiled for most key areas such as South-East Asia (e.g. Findley, 1998; Hutchinson, 1989), the Tibetan back-arcs (e.g. Yin & Harrison, 2000), and the Australian active margin (the present-day East Coast (e.g. Caprarelli & Leitch, 1998; Dirks et al., 1992). Where possible, this multidisciplinary approach was applied to the entire globe in order to generate self-constrained reconstructions. When geological information is scarce, plate boundaries, which are introduced and modified in time and space, give only little room for alternative plate model solutions. These plate limits are governed by rheological laws, which provide stable constraints for reconstructions.

The use of Euler poles to move plates has a consequence on the geometry of transform boundaries which are by definition small circles of the Euler pole; where they are known the chosen Euler pole has to conform to this geometry. Another consequence is that the maximum spreading of a chosen pole lies along its equator. As a result, an acceptable spreading rate close to the Euler pole maybe unacceptable a few thousands of kilometres away. Sea floor spreading rates at the Euler equator were kept below 20 cm/y.

The model employed here used Europe fixed in its present-day position and Baltica palaeo-poles as a global reference for palaeo-latitudes (Torsvik & Smethurst, 1994). The grid coordinates therefore correspond to Baltica palaeo-poles with respect to Europe fixed. Baltica poles appeared to be the best defined for the Palaeozoic. In a recent publication, (Torsvik et al., 2001) provide a new dataset for the Mesozoic, adjusting the European poles with the North American ones.

Evolution of the Tethyan domain

Our model suggests that Gondwana-directed subduction led to the opening of Palaeo-Tethys (Fig. 4a), associated with the detachment of the ribbon-like Hun superterrain along the northern margin of Gondwana. Subsidence patterns of Tethyan margins since the Early Palaeozoic (Stampfli, 2000b) provide constraints for Palaeo-Tethys opening during the Late Ordovician and the Silurian. Neo-Tethys opened from Late Carboniferous to late Early Permian, commencing east of Australia and progressing to the east-Mediterranean area (Etheridge & O'Brien, 1994; Veevers, 2000) (Fig. 4b) as recorded from subsidence patterns of its southern margin (Stampfli et al., 2001). This opening was associated with the drifting of the Cimmerian superterrain (Figs 4b, c) and the final closure of Palaeo-Tethys in the Middle to Late Triassic. The opening of Neo-Tethys and detachment of the Cimmerian blocks in the Permian was due to increasing slab pull forces in the Palaeo-Tethys domain following the subduction of its mid-oceanic ridge below the Eurasian margin

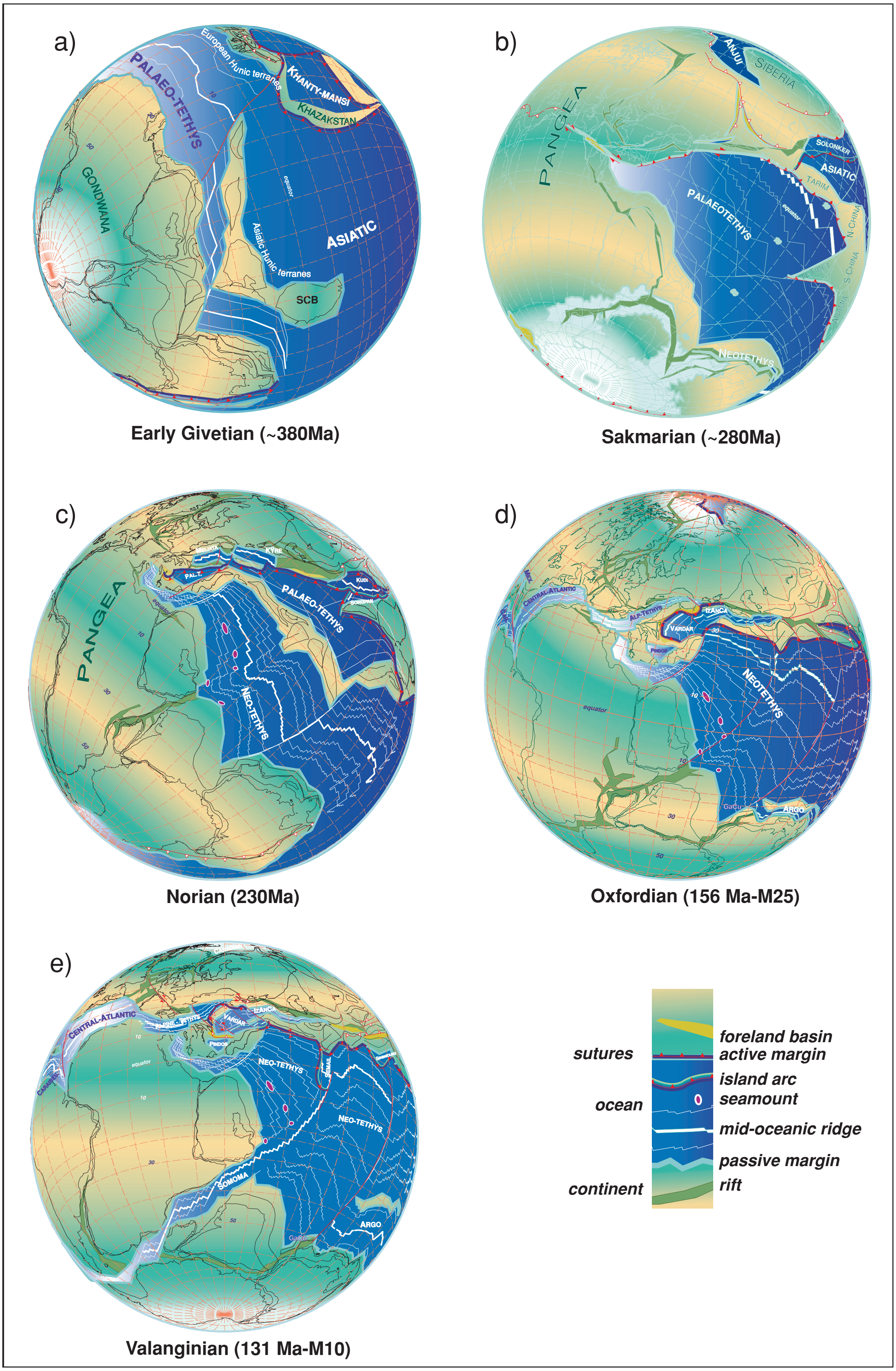

Figure 4: Global palaeo-reconstructions for key-epochs (modified from Stampfli & Borel, 2002). Orthographic projection. See text for discussion.

(e.g. accretion of Permian MORB in Iran, Ruttner, 1993). Neo-Tethys replaced Palaeo-Tethys even when Pangea was stable during Permian and Triassic times, indicating the key role played by slab pull forces on plate tectonics and consequently on plate distribution.

The position of the Indian Plate with respect to Africa is defined by the oceanic isochrons in the Somalia-Mozambique basins from Late Jurassic to Late Cretaceous. The rotation of East Gondwana (comprising the future Indian plate) with respect to Africa is held responsible for intra-oceanic subduction within the Neo-Tethys along a palaeo-transform south of Iran and the onset of spreading of the Semail Marianna-type back-arc (Fig. 4d,e). The age of the oceanic crust on each side of the transform fault controls the direction of the Semail intra-oceanic subduction.

Argo Abyssal Plain

The opening of the Argo Abyssal Plain is usually attributed to the break-up of Greater India from Western Australia and Antarctica (Veevers, 2000) and dated as Late Jurassic. Müller et al. (1998) propose a consistent scenario for the Argo Abyssal Plain opening, which we believe is unrealistic from a geological and plate tectonic point of view. It implies a northwest drifting of Argo Land and North Greater India to open the Argo Abyssal Plain, moving these terrains in-between India and the Eurasian margin. The consequences are firstly the creation of new plate boundaries within Neo-Tethys, excluding slab-pull forces to generate the Indian Plate northward movement during the Cretaceous. Secondly it implies the amalgamation of these terrains to the Indian Plate before its final collision with Eurasia, which is unknown in the geological record. Metcalfe (1996) proposed a Late Triassic separation of the Lhassa terrain from Gondwana and a Late Cretaceous accretion of this terrain to Eurasia. He introduced a fast spreading, highly asymmetric ocean which propagated in Neo-Tethys west of the Lhassa terrain. However, the Dras arc complex and Spongtang ophiolitic melanges are associated to sediments as old as Callovian (Honneger et al., 1982) and Early Cretaceous metamorphic rocks (Yamamoto & Nakamura, 2000) and imply accretion of the Lhassa terrain and subsequent Late Jurassic-Early Cretaceous opening of a back-arc basin south of it (Robertson, 2000). Moreover, the presence of an active ridge would prevent slab forces to pull Greater India northward during the early Late Cretaceous. In our model, the Lhassa terrain is considered as a Cimmerian block (Stampfli et al. 2001).

The major changes in the Late Jurassic to Early Cretaceous plate tectonics can be associated with the diachronous subduction of the Neo-Tethys mid-ocean ridge under the Eurasian northern margin and the final break-up of Gondwana. The slab-pull forces opened the Argo Abyssal Plain and detached the Argo-Burma terrain from Australia, possibly together with the Indian Plate. The lack of evidence of a Jurassic active margin signature along the North West Shelf of Australia also pleads in favour of such mechanism. Some doubts persist about the timing of Argo-Burma separation from Australia. The solution adopted here follows general views on a Late Jurassic drifting of Argo-Burma but remains problematic from a rheological point of view. The problem is the necessity to develop a very long transform fault (over 3,000 km) to link up plate boundaries (Fig. 4e); the new Argo mid-ocean ridge with the still existing Neo-Tethys ridge north of the Indian plate. This solution implies that the opening of the Argo Abyssal Plain was disconnected from the break-up of Greater India from Western Australia. An Early

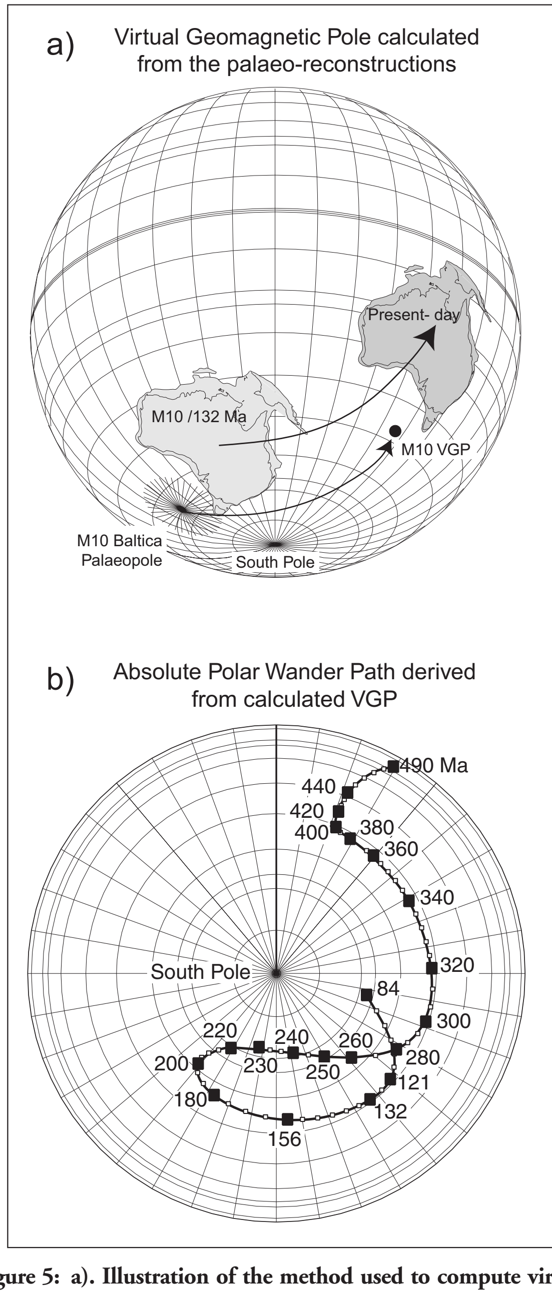

Figure 5: a). Illustration of the method used to compute virtual geomagnetic poles (VGP) for the Australian plate based on the reconstructions. b). Absolute polar wander path of the Australian plate (APWP).

Cretaceous drifting of Argo-Burma together with Greater India and Gascoygne-Cuvier terrain (GaCu) would be preferable, the Neo-Tethyan active ridge being subducted at this time.

Motion and velocity of the Australian plate controlled by well data

The software used (GMAP, Torsvik & Smethurst, 1994) for modelling has been developed to process palaeo-magnetic data (continent fixed in present-day position as reference and the pole describing a path). All the plates are assumed to be mobile on the reconstructions except Baltica. For this reason, to calculate latitudinal motion and velocity a polar wander path was computed from the reconstructions by rotating together the Australian Plate and the Baltica pole, the latter being displaced from its location on the reconstruction to its present-day position (Fig. 5a). Following this method for each reconstruction a set of virtual geomagnetic poles (VGP) for the Australian Plate was obtained and therefore their Phanerozoic absolute polar wander path could be calculated (Fig. 5b). Based on these VGPs, it was possible to compute

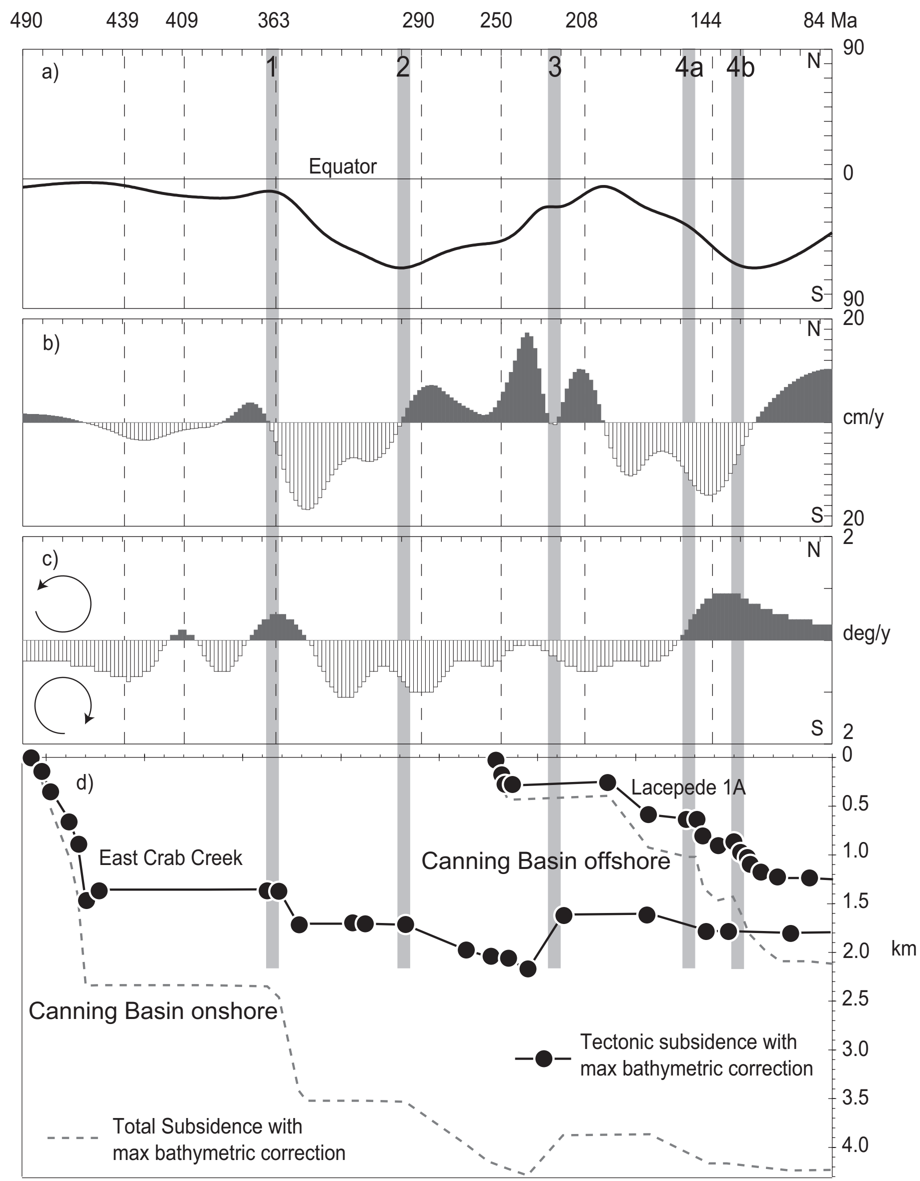

Figure 6: a). Latitudinal motion of the Australian plate during the Palaeozoic and Mesozoic. b). Velocity of the plate in cm/y. c). Rotation of the plate on itself in deg/y. d.) Subsidence curves onshore and offshore Canning basin. The plate tectonic events recorded by the basins can be linked with the movements of the Australian Plate through time. 1-4 denote major tectonic events recorded on the North West Shelf, 1- Fitzroy trough rifting, 2- Neo-Tethys opening, 3- Fitzroy movement, 4- Argo Abyssal Plain opening.

latitudinal motion and velocity of the North West Shelf (present-day coordinates 120°E/20°S, approximately Broome) through time (Fig. 6a,b,c). The VGPs are compared to two subsidence curves (Fig. 6d), which are representative of the major trends. The curves are constructed from Canning basin data, onshore for the Palaeozoic, and offshore for the Mesozoic and Neogene.

Four major tectonic events are recognised:

1) Fitzroy Trough rifting occurred during the latest Devonian (Nicoll & Gorter, 1995), when tectonic subsidence of 2 km in 2 Ma is recorded (Figs 3, 6d) as well as an isostatic rebound of 1 km on the hanging wall of the major faults. At the same time the North West Shelf moved rapidly southward from equatorial locations to reach the latitude of 55°S in the Late Carboniferous.

2) Opening of Neo-Tethys in the Late Carboniferous coincides well with the onset of northward movement of the Australian Plate and probably connects the Neo-Tethys new plate boundary to the back-arc basin along Papua New Guinea and Eastern Australia. The north-dipping subduction of Palaeo-Tethys triggered the break-up of the Cimmerian terrains off Gondwana by slab-pull. During the Permian and Triassic, even when Pangea was stable (thus defining the width of the oceanic Tethyan domain), the Australian plate moved 4,000 km with respect to the geographic poles. This implies a connection, without a plate boundary, between the Tethyan realm and the Palaeo-Pacific north of Australia at that time, enabling the rotation of Pangea around the same Euler pole used to open the Neo-Tethys. Driving forces linked with subduction of the Palaeo-Pacific east of the South China block and along the Antarctic margin activated intra-continental rifts (Somalia, Perth basins which were temporarily aborted).

3) The Late Triassic Fitzroy Movement is a compressive event marked by uplifts (up to 2 km) and flower structures particularly in the Canning Basin (Arne, 1996; Kennard et al., 1994). The Australian Plate motion had temporarily ceased (Fig. 6b) during final closure of Palaeo-Tethys and docking of the Cimmerian blocks along most of the Eurasian margin. This was followed by the onset of subduction of Neo-Tethys, and reactivation of Australian Plate movement. The intra-plate stress at the origin of the faults reactivation and inversion could be related with the Bowen Orogeny on the Australian eastern margin.

4) Subsidence curves show two breaks (Late Jurassic and Early Cretaceous) during the Argo Abyssal Plain break-up . The Late Jurassic rifting event may be associated with plate rotation, with the development of new fault systems and only little reactivation of the pre-existing fault systems (Fig. 6c). The cause of this rotation must be sought along the Antarctic and Australian margins of Palaeo-Pacific. The Early Cretaceous event is more likely directly linked with the increase of slab forces following the subduction of the Neo-Tethys mid-ocean ridge, and detachment of Argo-Burma (and India?) off Australia.

Conclusions

By combining an absolute plate kinematic model with tectonic subsidence analyses of the North West Shelf of Australia major plate tectonic events were identified and evaluated.

The model, which takes in account plate boundary evolution, allows a more comprehensive analysis of the development of the Tethyan realm in space and time. In particular, the relationship between oceanic domains with the geological record on the continental margins is highlighted. Palaeo-latitudes and motion rates of the Australian Plate during the Palaeozoic and Mesozoic derive from the model. Their changes can be related to breaks in subsidence curves. The model also makes possible assumptions about major tectonic events recorded in the North West Shelf basins and their timing. It allows distinguishing between events occurring in the Tethyan realm (e.g. Neo-Tethys opening) and in the Pacific domain (e.g. Fitzroy Movement).

Finally, a Jurassic opening (M25 anomaly) of the Argo Abyssal Plain due to the break-up of Greater India from Western Australia seems to be incompatible with our data.

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