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Circum-Antarctic palaeobathymetry: Illustrated examples from Cenozoic to recent times

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Abstract

We use a revised set of seafloor spreading isochrons and updated plate tectonic reconstructions to produce palaeo-age and basement depth grids for the Southern Ocean. The palaeo-depth maps illustrate the evolution of the ocean basins (widening and deepening) and oceanic gateway development surrounding Antarctica. We provide examples of palaeo-basement depth profiles at selected times between 45 Ma and the present across the Tasman Gateway and Drake Passage. The digital grids provide improved boundary conditions for palaeoceanographic circulation models as well as for backtracking sediments from ODP drilling.

Keywords: Antarctica; Plate reconstructions; Gateways; Seafloor age; Palaeo-depth

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1. Introduction

The breakup of Gondwana and subsequent opening of Southern Ocean gateways and isolation of Antarctica coincided with changes to ocean circulation and climatic conditions, in particular the cooling of the Southern Ocean region and growth of the Antarctic ice-sheet. On a geological timescale such changes in the geometry and geography of land masses and ocean basins lead also to first-order ocean current distribution and marine sedimentation patterns. Changes in the width and depth of oceanic gateways, and changes in seafloor bathymetry influence ocean current transport and overturning (Bice et al., 1998, 2000). The Antarctic Circumpolar Current (ACC) is recognized as being strongly dependent on seafloor bathymetry, particularly the mid-ocean ridge system (Huber and Sloan, 2001; Lazarus and Caulet, 1993; Rack, 1993).

Many uncertainties exist regarding the factors that impact Cenozoic climate, such as the relative contributions of deepwater formation and the development of the ACC (Kennett, 1977), the effects of the atmospheric carbon dioxide balance (DeConto and Pollard, 2003), and impacts of distant orogenic events and topographic/bathymetric changes (e.g., activity of Large Igneous Provinces, erosion and uplift of the Himalaya and Gamburtsev Mountains). The increasing use of multidisciplinary computer models (e.g., Hill et al., 2004) is helping us to understand the complex interactions within the palaeo-climate system, particularly those with dynamic equilibrium conditions. Present-day ocean circulation and coupled climatic models use degraded or very low resolution bathymetry (e.g. Huber and Sloan, 2001; Otto-Bliesner et al., 2002; Saenko and England, 2003), and generalized plate reconstruction models. Increasing computer power and model sophistication, is leading to a requirement for detailed information on

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ocean basin configuration (palaeo-geographic model) and bathymetry.

Recent work by Marwick and Valdes (2004) provides a detailed description and analysis for the construction and use of global, digital palaeo-elevation models on land and at sea. They show an example of a Late Cretaceous GIS-based digital elevation model (DEM) from the databases of the Palaeogeographic Atlas Project (e.g. Ziegler et al., 1997). The concepts they discuss give a useful background for the types of data used to construct global palaeo-geographic base-maps (lithological, palaentological and environmental data). They use the Müller et al. (1997) digital gridded ocean-age dataset to construct synthetic isochrons in 5 Ma increments as a base for estimated palaeo-bathymetry for the world's oceans. Recent plate reconstructions in the circum-Antarctic region by Lawver and Gahagan (2003) provide a series of maps based on a large database of seafloor spreading magnetic lineations, fracture zones, boundaries between oceanic and continental crust and plate rotations. Their paper provides an extensive overview of the tectonic evolution of the Cenozoic seaways and analysis of changes in Cenozoic climate; therefore we do not repeat such an analysis here in this study; instead our paper focuses on developing circum-Antarctic digital gridded palaeo-age and palaeo-depth models based on an updated plate reconstruction model for the Southern Ocean. We use the palaeo-depth maps to illustrate the widening and deepening of ocean basins around Antarctica and the evolving depth of the major Antarctic oceanic gateways (i.e. the Tasman Gateway and the Drake Passage) through time. We hope that the palaeoceanography community will use the new digital grids to improve existing palaeoclimate models for circum-Antarctic seaway development and deep-water circulation in the Southern Ocean.

2. The evolution of oceanic crust around Antarctica

New geological and geophysical datasets and refined tectonic models have offered the opportunity to re-examine the evolution of oceanic crust in the circum-Antarctic realm since the Cretaceous. Our circum-Antarctic model incorporates plate reconstructions based on the Müller et al. (1997) digital seafloor-age (isochron) dataset and recently updated tectonic models in: the Enderby Basin (south of Kerguelen Plateau) (Brown, 2004; Gaina et al., 2003), the area southeast of Australia and the northern Ross Sea region (Cande and Stock, 2004; Cande et al., 2000b), and the South Pacific (modified after (Eagles et al., 2004)). In addition to preserved oceanic crust, subducted oceanic crust in the south and southeast Pacific has been reconstructed by creating "synthetic plates" whose locations and geometries are established on the basis of preserved magnetic lineations, palaeogeography, regional geological data and the rules of plate tectonics. In the case of preserved magnetic (and/or fracture zone) data on one oceanic flank only, the conjugate flank is reconstructed by computing stage pole parameters based on existing isochrons and, supposing a symmetric spreading process, calculating the width of oceanic crust created during each stage. If the oceanic crust has been fully subducted or there are no geophysical data to confirm the age of oceanic crust, then we reconstruct the ocean crust using geological information from adjacent onshore regions (age of ophiolites, evidence of collisions, terrane docking etc.) and an assumption of symmetric seafloor spreading. Reconstructed oceanic seafloor ages and plate boundary configurations around Antarctica are produced using a revised absolute plate motion model based on an Atlantic/Indian ocean moving hotspot reference frame (O'Neil et al., 2005).

Breakup around Antarctica started at around 155 Ma in the Riiser–Larsen Sea (south of Africa), then west of it in the Weddell Sea (south of South America) at 145 Ma (Jokat et al., 2003). The new model for the early Indian–Antarctic spreading system (Brown, 2004; Gaina et al., 2003) places the onset of seafloor spreading at around 130 Ma (M9), the timing and direction of opening being consistent with that observed between India and Australia in the Perth Abyssal Plain (~130 Ma) (Powell et al., 1988). Early Australian–Antarctic spreading to the east of the Vincennes Fracture Zone (~105°E) has been identified with a Late Cretaceous spreading system between Chron 34 (~83.5 Ma) and 31 (~71 Ma) (Tikku and Cande, 1999). Seafloor spreading in the south Tasman Sea, between eastern Australia and the Lord Howe Rise and New Zealand, began in the Late Cretaceous (~83 Ma) propagating northwards to the Coral Sea in the Tertiary, where spreading stopped at about 52 Ma (Gaina et al., 1998). The Gaina et al. (1998) model of the opening of the Tasman Sea, east of Australia, has now been combined with new models that document incipient motion between East and West Antarctica (Cande and Stock, 2004; Cande et al., 2000a), indicating the formation of a triple junction off Victoria Land in the Paleocene.

The tectonic models and rotations used in the eastern Indian Ocean area have traditionally presented high degrees of overlap or underlap. Overall, the plate reconstructions used here (modified after Müller et al., 1997) leads to a relatively tight pre-rift reconstruction between India, Australia, and Antarctica. In Mesozoic plate reconstructions for the Indian and Southern Ocean the revised fit of Madagascar to the east of Gunnerus Ridge (Marks and Tikku, 2001) requires a new pre-rift fit of Australia and India relative to Antarctica further to the east. This shift subsequently leads to less overlap between Australia, Tasmania, the South Tasman Rise (STR) and Antarctica. The reconstruction model also implies left-lateral strike-slip motion through the Otway Basin and South Tasman Rise.

The development of the West Antarctic continental margin has involved a complex seafloor spreading history off the Pacific–Antarctic margin and the Atlantic–Antarctic Margin. We have used a modified version of the most recently revised tectonic model for the South Pacific by Eagles et al. (2004). The main area of uncertainty involves establishing the timing of the Drake Passage opening because several different tectonic scenarios have been published, with ocean floor ages ranging between 34–20 Ma. Seafloor spreading in the Drake Passage/Scotia Sea region is most commonly thought to have begun at a time prior to 26 Ma (Chron 8) (Barker et al., 1991). Lawver and Gahagan (2003) suggest a precursor to Drake Passage opening through the Powell Basin, prior to 30 Ma (31 ± 2 Ma); however Eagles and Livermore (2002) model shows that this basin did not open before 29.7 Ma. The Scotia Sea region is a complex spreading system due to the kinematics of several smaller microplates adjacent to the Antarctic Plate, as well as the inclusion of continental rift fragments and an extinct spreading ridge. Although several microcontinents and elevated ridges were involved in the opening of the Drake Passage (Lawver and Gahagan, 2003; Maldonado et al., 1998), we use a simplified model that accounts only for the South Orkney and South Georgia microcontinents because their history and size are better constrained. The tectonic history of the Drake Passage region needs further revision (and there are new studies and corresponding kinematic models about to be published, i.e. Livermore et al., 2005); for this study we use the commonly cited model of Barker (2001) to construct seafloor spreading isochrons for the palaeo-age grids.

3. Palaeo-age and palaeo-depth models

We have used the revised plate tectonic model to construct digital grids for ocean floor age for the circum-Antarctic region from the Late Cretaceous to the present. The new set of isochrons and restored plate boundaries have been linearly interpolated using Müller et al. (1997) method in order to create oceanic "palaeo-age" digital grids. The reconstructed grids were computed at selected timesteps: 61, 52, 43, 32, 25, 10, 5 and 0 Ma.

The palaeo-age grids were used to create a series of palaeoceanic basement-depth grids (Fig. 1). The thermal boundary layer model is used to calculate the approximate depth to oceanic basement for crust younger than 80 Ma (Parsons and Sclater, 1977). The plate model is used to calculate the approximate palaeo-depth to oceanic basement for crust older than 80 Ma (McKenzie, 1967, Parsons and Sclater, 1977). Areas that have experienced hot-spot activity (e.g. Kerguelen Plume, Ross Plume) and anomalous mantle topography, such as the Australian–Antarctic Discordance (Marks et al., 1999), will deviate from the normal age–depth relationship for oceanic basement subsidence (Kearey and Vine, 1996; Parsons and McKenzie, 1978), but we do not incorporate these deviations in our preliminary palaeo-depth grids.

A realistic bathymetry should take into account increased oceanic crust subsidence due to sediment loading and decreasing water depth due to sediment thickness. In order to investigate whether we can derive a correlation between the age of oceanic crust and sediment thickness, we analysed the global present day oceanic crust age south of 30° south (Gaina and Müller, 2004) and the National Geophysical Data Center sediment thickness digital dataset for the same region (www.ngdc.noaa.gov/mgg/sedthick). The two datasets do not show a striking correlation, but we tentatively derived a polynomial that best expresses a function of sediment thickness vs. age. Using this relationship and a sediment load correction derived by Schroeder (1984), we calculated that due to sediment accumulation and isostacy, the decrease in water depth would be less than 100 m for oceanic crust younger than 40 million years, between 100 and 200 m for oceanic crust between 40 and 90 million years, and more than 1000 m for oceanic crust older than 100 million years. Thus our correlations between age and sediment thickness predict a relatively thin layer of sediments for oceanic crust less than 30 million years, which is the oldest age for southern hemisphere gateways. A more detailed analysis, based on latitudinal variation in sedimentation and possibly integrating ODP data would be more appropriate for attempting to "predict" a sediment–age relationship that could be extrapolated in time.

Due to limitations noted in the above discussion, our palaeo-bathymetric grids are based only on palaeo-

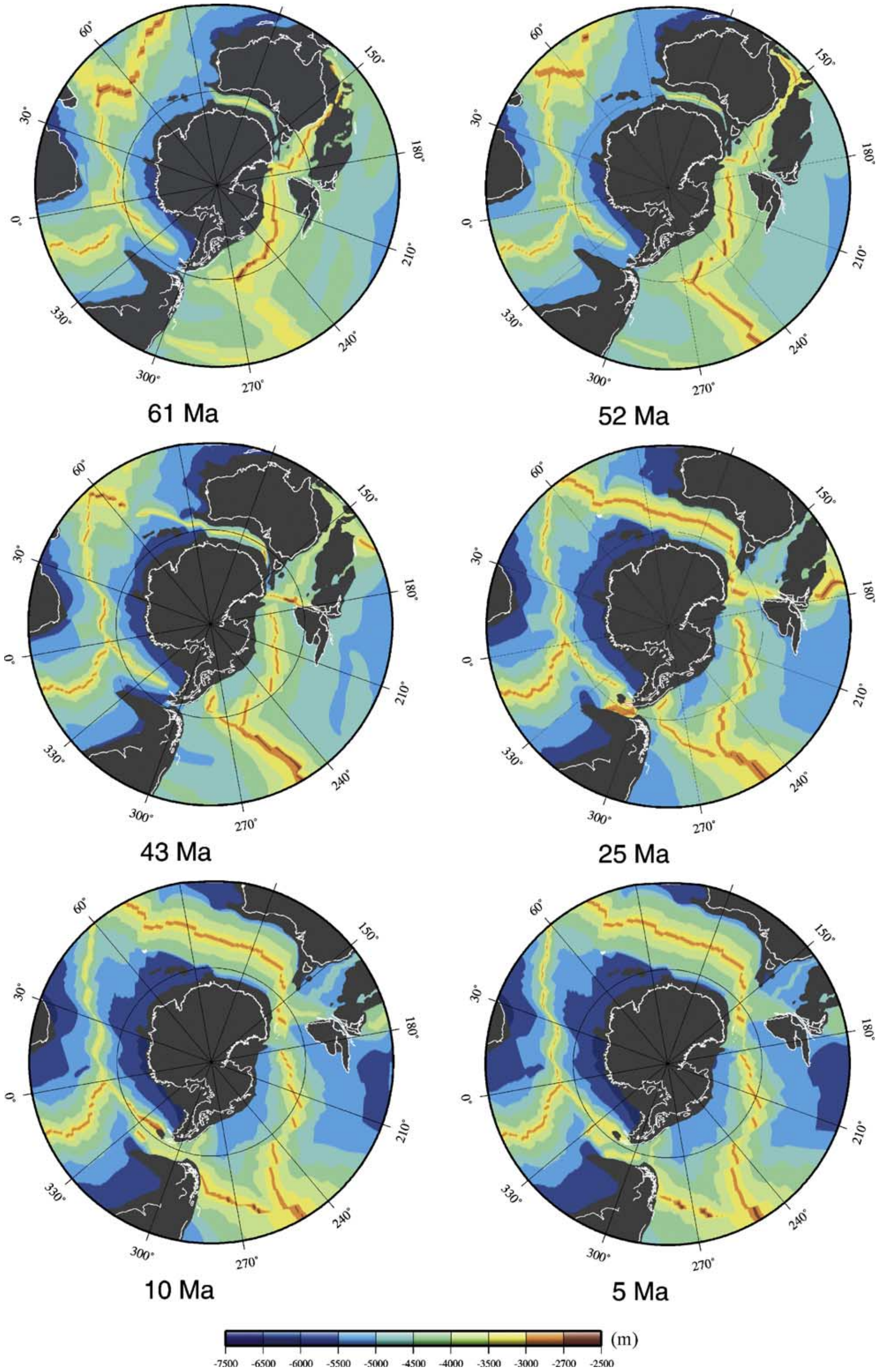

Fig. 1. Illustrated examples of circum-Antarctic palaeo-depth models for the seafloor at 5, 10, 25, 43, 52 and 61 Ma.

basement depths and ignore sediment loading and deposition. Also, we have not computed the amount of stretching and subsidence of the continental crust adjacent to the oceans, therefore our grids can be used only as a rough estimate for depths and geometries of shallow and deep water paths.

Basement ridges along fracture and transform zones, i.e. ridges not related to depth-age steps of the topography across fracture zones, which run parallel to opening flowlines also may be major obstacles to ocean circulation through gateways, especially if the ridge/transform morphology changed from a simple ridge-transform configuration (i.e. Livermore et al., 2004). Our palaeo-bathymetry grids show differences in water depth due to offset in oceanic crust age and therefore thermal subsidence, but do not include information about the subsequent deformation of ridges or transform zones.

The color palaeo-depth grids (Fig. 1) show the deepening of oceanic crust around the Antarctic continental margin through time and the changing configuration of the mid-ocean ridge system. These grids provide an opportunity to visualize and assess the widening and deepening of the surrounding ocean basins off Antarctica (Fig. 1), and subsequently the formation of a continuous deep water path.

4. Depth profiles for the Tasman and Drake Passage gateways

A relatively narrow zone of slow-spreading seafloor crust was produced over the 40 million year interval (from approximately 83–43 Ma) between Australia and Antarctica. It was not until around 43 Ma when rapid seafloor spreading commenced that the Australian–Antarctic Basin (AAB) became significantly larger, and Australia advanced much further northwards in latitude (Cande and Mutter, 1982). In the middle to late Eocene, relative motion between eastern and western parts of the South Tasman Rise (Royer and Rollet, 1997) and the final detachment of the western South Tasman Rise from Antarctica led to the opening of the first gateway that enabled changes in the oceanic circulation patterns. This was followed by the final clearance of the Australian and Antarctic plates near the South Tasman Rise by the start of the Oligocene. Thermal cooling of stretched continental lithosphere resulted in subsidence of the Tasman Rise, allowing deep circulation (Exon, 2000), and the onset of full marine conditions. However, a recent study (Stickley et al., 2004) showed that deep marine conditions (more than 3000 m) occurred at 35.5 Ma, 1.8 Ma before the Eocene–Oligocene boundary.

The opening of the Drake Passage (Barker, 2001) between the Late Oligocene and early Miocene (~30–21 Ma), fragmentation of Broken Ridge–Kerguelen Plateau in the late Eocene and the separation of Australia from Antarctica allowed the full development of the Antarctic Circumpolar Current (ACC) (Barker and Thomas, 2004; Beu et al., 1997; Lazarus and Caulet, 1993, Wei et al., 1992) and an open connection between the Indian and Pacific oceans. Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water (AABW) was formed along the Antarctic slope to initiate a new regime of intermediate and deep water circulation between the global oceans (Lawver et al., 1992; You, 2002). It is likely that the eastern Australia current existed at this time (Seidov, 1984), bringing northern warm water poleward and affecting the environment of eastern Australia. DSDP/ODP results suggest that during this time faunal turnover was extensive, with cool water cosmopolitan and true Antarctic endemic forms becoming increasingly common (Lazarus and Caulet, 1993).

Here we look at the development of deep-water pathways for the Tasman Gateway and the Drake Passage. A series of 2500 km long profiles were calculated perpendicular (roughly north–south) to the present day Tasman Gateway (South Tasman Rise) and the Drake Passage (Fig. 2). For given timesteps we calculated the estimated depth from the palaeo-depth grids along the profiles to illustrate the evolving depth through time for the developing oceanic gateways. As the Tasman Gateway widens over time (Fig. 2a–e) it maintains a ridge-flank morphology; subsidence is rapid from the mid-ocean ridge and the area off the Antarctic continental margin deepens between the 4000 and 5000 m range between 25 and 5 Ma. In contrast, the Drake Passage (Fig. 2g–j) is primarily floored by back-arc basin crust, which was formed by several different, eastward migrating spreading centres through time. Therefore its basement topography is not dominated by a simple ridge-crest and flank morphology, as the Tasman Gateway. The Drake Passage today is much deeper over a narrower area between the conjugate continental margins.

Our palaeo-bathymetric grids are based strictly on geological and geophysical data that constrain the age of oceanic crust. In some cases, due to the lack of data, the age for rifting and oldest oceanic crust is the result of a model based on various assumptions (see competing tectonic models for the opening of Drake Passage e.g. Livermore et al., 2005; Barker, 2001). Because of controversial interpretations of marine geophysical data and new studies based on microfossils data that are able to time the deepening of gateways in detail (Stickley et al., 2004), the importance of opening of southern gateways in the Antarctic glaciation is being questioned, and other global phenomena (like the decrease in the global carbon dioxide budget) has been proposed (DeConto and Pollard, 2003; Huber et al., 2004). Fur-

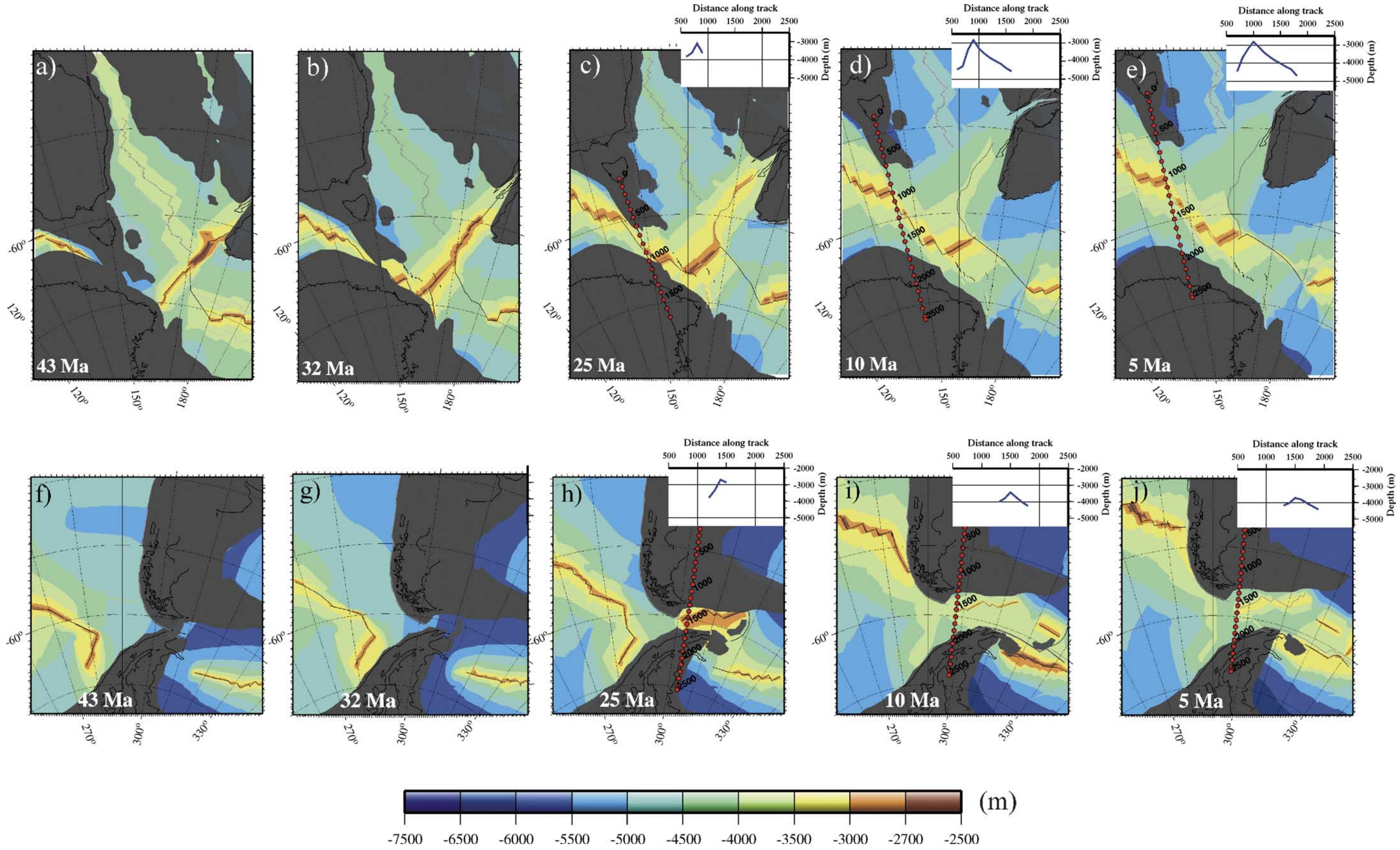

Fig. 2. Illustrated examples of the Tasman Gateway evolution between 45 and 0 Ma (a–e) and of the Drake Passage Gateway evolution between 45 and 0 Ma (f–j). Palaeo-bathymetry profiles (top, right-hand corner) were extracted from the new palaeo-depth grids to show depth to crustal basement over time at the developing oceanic gateway.

ther integration of DSDP/ODP data with palaeo-depth grids will help constrain some unresolved questions about palaeo-environment/ocean circulation conditions. In addition, the relationship between tectonic processes and sedimentation and global geochemical cycles (e.g. Heinze and Crowley, 1997) must also be taken into account when assessing the importance of opening of gateways, seafloor spreading and changes in the global climate.

5. Conclusions

We use updated circum-Antarctic plate tectonic reconstructions to develop a series of palaeo-age and palaeo-depth grids. These digital grids combine frameworks for ocean basin configuration (palaeo-geographic model) and bathymetry (palaeo-basement depth model). The reconstructions and geophysical models are useful for providing realistic boundary conditions for palaeo-environmental studies.

The palaeo-age and basement-depth digital grids as well as a color figure of circum-Antarctic palaeo-age grids supplement this paper and can be retrieved from ftp.ngu.no/pub/Carmen/Antarctic-pbath.

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