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SCAR-Marine Biodiversity Information Network

BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

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THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

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3.2. Reconstructions of the Southern Ocean and Antarctic regions

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1. Introduction

The plate reconstructions shown in this paper are derived from a global database compiled by the PLATES project at the University of Texas at Austin [see: http://www.ig.utexas.edu/research/projects/plates/]. For Late Cretaceous to Present plate reconstructions, the database includes marine magnetic anomalies collected by ships and airplanes, tied to the Gee & Kent (2007) timescale to constrain seafloor ages; it also includes fracture zone and transform fault lineations (Gahagan *et al.* 1988) picked from ship track and satellite altimetry data (Sandwell & Smith 2009, Smith & Sandwell 1997) to constrain plate motions and seafloor spreading directions. For individual plates where seafloor ages are not known or where fracture zones are not available to constrain plate motions, paleomagnetic poles for the various plates, seafloor age dates based on drilling results, and conjugant margin geology are used to approximate the paleo-locations of these continental pieces.

We use continental block outlines based on our own digitization of the satellite altimetry data from Sandwell and Smith (2009). Off southern Africa, there is a close correlation between the steep gradient in the satellite altimetry data used by Lawver *et al.* (1998) and the ocean-continent boundary deduced from seismic refraction and reflection data, both off Namibia (Gladczenko *et al.* 1997, Bauer *et al.* 2000) and off Mozambique (Lineweber *et al.* 2013). The same steep gradient in the satellite altimetry data was used by Royer & Sandwell (1989) to determine a limit to the continental shelves in the eastern Indian Ocean. They referred to this limit as the continental shelf break (CSB) and found a tight fit at 160 Ma between conjugate CSBs for parts of the southern margin of Australia with East Antarctica. Given the precedence established by Royer & Sandwell (1989), we use their nomenclature and show our CSBs in Map 1, overlain on the satellite bathymetry of Smith & Sandwell (1997, version 15.1). The term CSB should not be conflated with the term ocean-continent boundary or OCB. Along most continental margins, there is stretched continental, under-plated oceanic, or even exhumed mantle material, known collectively as transitional crust that lie ocean-ward of the steep gradient that we use. For our reconstructions, we assume the crust is predominantly continental landward of the CSB and transitional to oceanic, seaward of the CSB. It should be noted that both post-rifting volcanic constructs along the continental margins as well as deposition of glacial or riverine sediments on isostatically uncompensated older oceanic crust will give a false indication of the true continental edge based on our simplistic CSB determination.

For the maps that show the locations of the continents surrounding the southern oceans from the Late Cretaceous to Recent, two major seaways or gateways, Drake Passage and the Tasman or Australian–Antarctic passage are considered of major importance. The opening of these two passages as deepwater gateways are often cited as the initiators of major changes in ocean circulation and Cenozoic climate. As shallow to medium depth seaways, these passages also had significant impacts on the dispersal of land-based mammals and other fauna as well as allowing the interchange of marine fauna that were previously isolated from one another. The oft-discussed, opening of Drake Passage between the southern tip of South America and the Antarctic Peninsula as a deep water gateway has been the subject of many articles including Dalziel & Elliot (1971), Foster (1974), Kennett (1977), Barker & Burrell (1977, 1982), Barker (2001), Lawver & Gahagan (2003), Eagles *et al.* (2005), Livermore *et al.* (2005, 2007), Lagabrielle *et al.* (2009), and numerous other articles. Kennett (1977) surmised that the development of the Antarctic ice sheets in the late Eocene was the direct result of thermal isolation of the Antarctic continent by the initiation of the Antarctic Circumpolar Current [ACC] while Foster (1974) correlated changes in echinoids with timing of opening of the initial Drake Passage. Barker & Burrell (1977) concluded, based on identification of magnetic anomalies in the western Scotia Sea dated as C8 [25.8–27.0 Ma], that "*By comparison with other regions around Antarctica, we have shown that this opening of Drake Passage removed the final barrier in an otherwise complete circum-polar deep-water path, and would therefore have led directly to formation of the ACC.*" They dated the onset of the ACC at 23.5 ± 2.5 Ma. It is not clear that simple opening of Drake Passage led directly to the onset of the ACC. Lawver & Gahagan (2003) suggested that significant development of the ACC did not begin until there were closures of tropical seaways, in particular the collision of Australia with Southeast Asia during the middle Miocene which significantly diminished the east-to-west Equatorial Currents and caused the Pacific South Equatorial Current to strengthen flow along the eastern margin of Australia as the East Australian current. This flow led to enhancement of the ACC with later closure between the Americas producing increased flow of the Gulf Stream, increased warm water entering the North Atlantic, and the development of the "Great Ocean Conveyor Belt" (Broecker 1991) and the inter-ocean thermal haline circulation discussed by Gordon (1986).

The significant increase in $\partial^{18}O$ at the Eocene–Oligocene boundary (Zachos *et al.* 2001) is taken as a proxy to the chilling of the world's oceans. Besides the possible opening of deepwater gateways around Antarctica, they discuss a number of other factors that influenced the Cenozoic climate and state "*However, as the complex nature of the long-term trend comes into focus, it is becoming clear that more than one factor was responsible.*" While atmospheric carbon dioxide (pCO_2) is often cited as major contributor to the sudden drop in marine and atmospheric temperatures, pCO_2 was below the 3 times pre-Industrial atmospheric pCO_2, a threshold cited by DeConto & Pollard (2003), at numerous times in the Late Cretaceous and Paleocene. Those dips (Royer 2010, Beerling & Royer 2011) to levels around 500 ppm pCO_2 during the Maastrichtian (70.6 Ma to 65.5 Ma) and to ~350 ppm during the Paleocene did not seem to trigger significant marine cooling and there are no indications of an Antarctic ice sheet prior to the Late Eocene. De Conto *et al.* (2008) show a significant correlation of the Eocene-Oligocene $\partial^{18}O$ event with a reduction in the amplitude of the obliquity at 34 Ma coupled with a second significant increase in the $\partial^{18}O$ at 33.6 Ma after the ice sheet has developed and the albedo has increased leading to more Antarctic ice. The reduction in the amplitude of the obliquity would lead to cooler summers in the high latitudes.

2. Tasman Passage or Australia-Antarctica Passage

The CSBs determined from the satellite gravity data of Sandwell & Smith (1997) and the fit pole of rotation of Royer & Sandwell (1989) for Australia with East Antarctica were used by Lawver *et al.* (1998) to determine a tight-fit for East Gondwana. Their fit is shown with the BEDMAP data for East Antarctica of Lythe *et al.* (2001) in Lawver *et al.* (2011, Figure 3). Their reconstruction of Australia, Tasmania, and East Antarctica is remarkably similar to the empirical fit of Foster & Gleadow (1992) and is also very close to the fit of the reconstructed aeromagnetic data of Finn *et al.* (1999) who matched the magnetic signature between the Glenelg and Stawell zones of southeastern Australia with the magnetic signature of the Bowers zone of North Victoria Land, East Antarctica. The initial fit between East Antarctica and Australia is crucial to the later opening of the Tasman gateway. There is still debate (Norton & Molnar 1977, Cande & Mutter 1982, Royer & Sandwell 1989, Veevers *et al.* 1991, Williams *et al.* 2011) about the exact fit of East Antarctica and Australia. Even so, by the time of our 70 Ma reconstruction (magnetic anomaly C31r) shown in Map 2, there is general agreement concerning the reconstructed positions of Australia with respect to Antarctica. For the reconstructions shown, magnetic anomaly picks by Royer & Rollet (1997) are used for chrons C34y [83.0 Ma] to C13o [33.5 Ma] and picks by Marks *et al.* (1999) are used for chrons C6y [19.0 Ma] to present. It is important to note that motion between Tasmania and the South Tasman Rise is calculated to have ceased before 65 Ma (Exon *et al.* 1997) and a seaway, the South Tasman Saddle that is presently almost 200 km across and reaches depths in excess of 3000 m must have been in existence by that time. A number of volcanic cones are present along the South Tasman Saddle (Crawford *et al.* 1997) that may be linked to the Balleny Islands hotspot (Lanyon *et al.* 1993, Gaina *et al.* 2000, their figure 10). Lawver *et al.* (2011) suggested the Balleny Islands hotspot may have uplifted the gneissic (Berry *et al.* 1997, Fioretti *et al.* 2005) South Tasman Rise during the Eocene but did not produce a complete barrier to deepwater flow through the South Tasman Saddle during that time. In fact, Huber *et al.* (2004) and Huber & Nof (2006) argue that there is no real evidence that Eocene ocean heat transport was greater than present and that the most important influence on the change from a warm Eocene climate to initiation of Antarctic ice cover was a significant change in atmospheric Greenhouse gas concentrations and that Antarctic snow accumulation correlate to changes in summer temperatures, not precipitation. They conclude that snow did not remain on Antarctica during summer months in Eocene even at low greenhouse gas concentrations. Consequently, opening of the Tasman Gateway cannot be timed by the drop in ∂O^{18} at the Eocene-Oligocene boundary and may have occurred much earlier. Our plate tectonic models suggest that if the CSB anomaly off the coast of the Wilkes Land subglacial basin is an artifact of the deposition of glacial sediments onto as-yet-isostatically adjusted older oceanic seafloor (Lawver *et al.* 2011) then the South Tasman Saddle may have cleared the East Antarctic margin as early as the Early Eocene.

3. Drake Passage

The relative positions of South America and the Antarctic Peninsula are based on major plate motions between South America and Africa and between Africa with respect to East Antarctica with the assumption that there has been no significant motion between East and West Antarctica in the Weddell Sea region of Antarctica since the early Late Cretaceous. There are good magnetic anomaly picks in the west Scotia Sea, with both Barker & Burrell (1977) and later Eagles *et al.* (2005) dating most of the seafloor as chron C8 (~27 Ma) to chron C3A (~6 Ma). Even though Barker & Burrell (1977) used the timescale of Heirtzler *et al.* (1968), their ~6 Ma age is very close to the Gee & Kent (2007) timescale age for chron C3A as identified by Eagles *et al.* (2005). In both cases, there is additional seafloor material beyond chron C8 that others (BAS 1985, Lodolo *et al.* 1997) have identified as extending to at least chron C10 (29.4 Ma) and even Chron C12 (30.9 Ma) according to Maldonado *et al.*

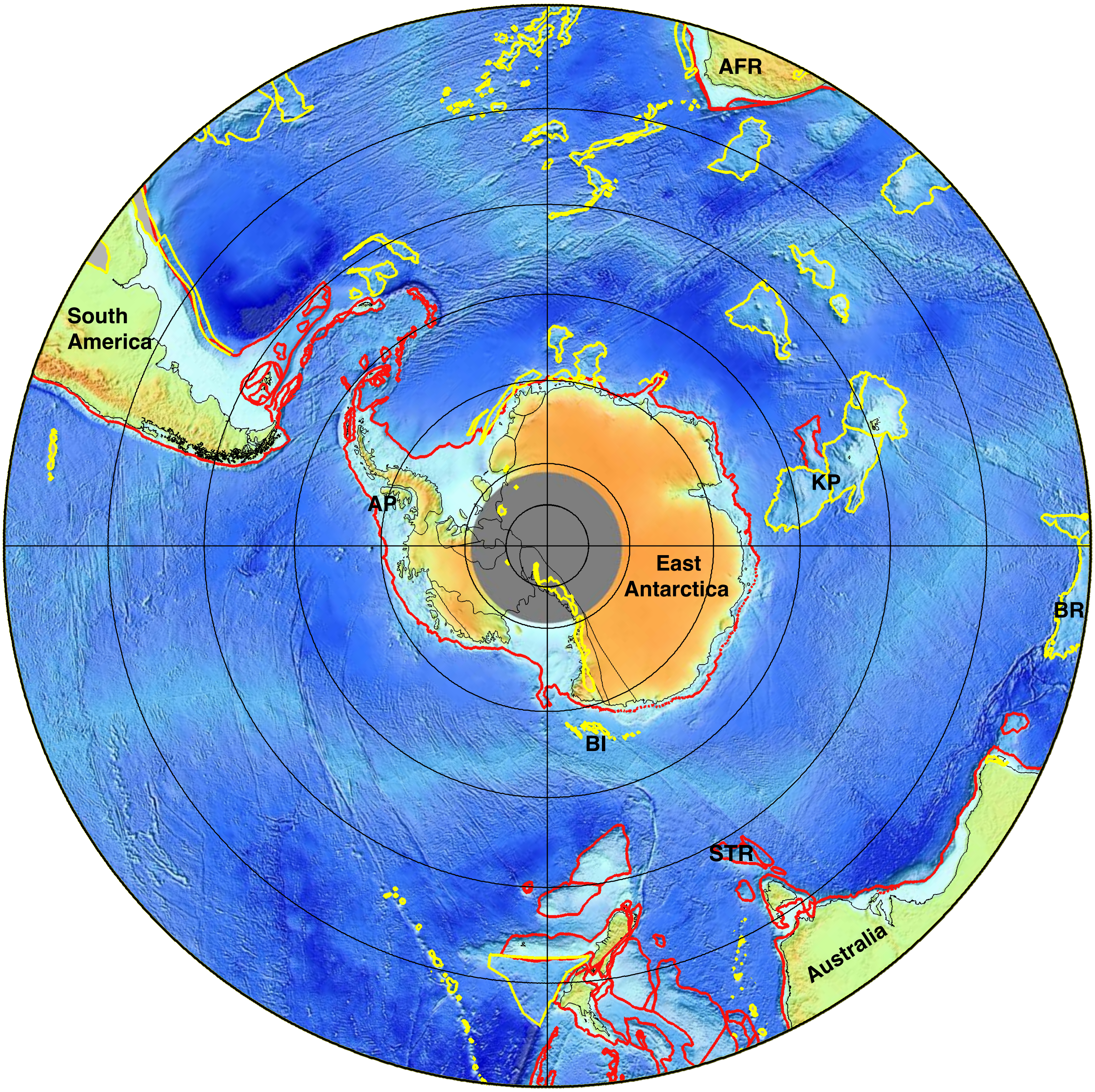
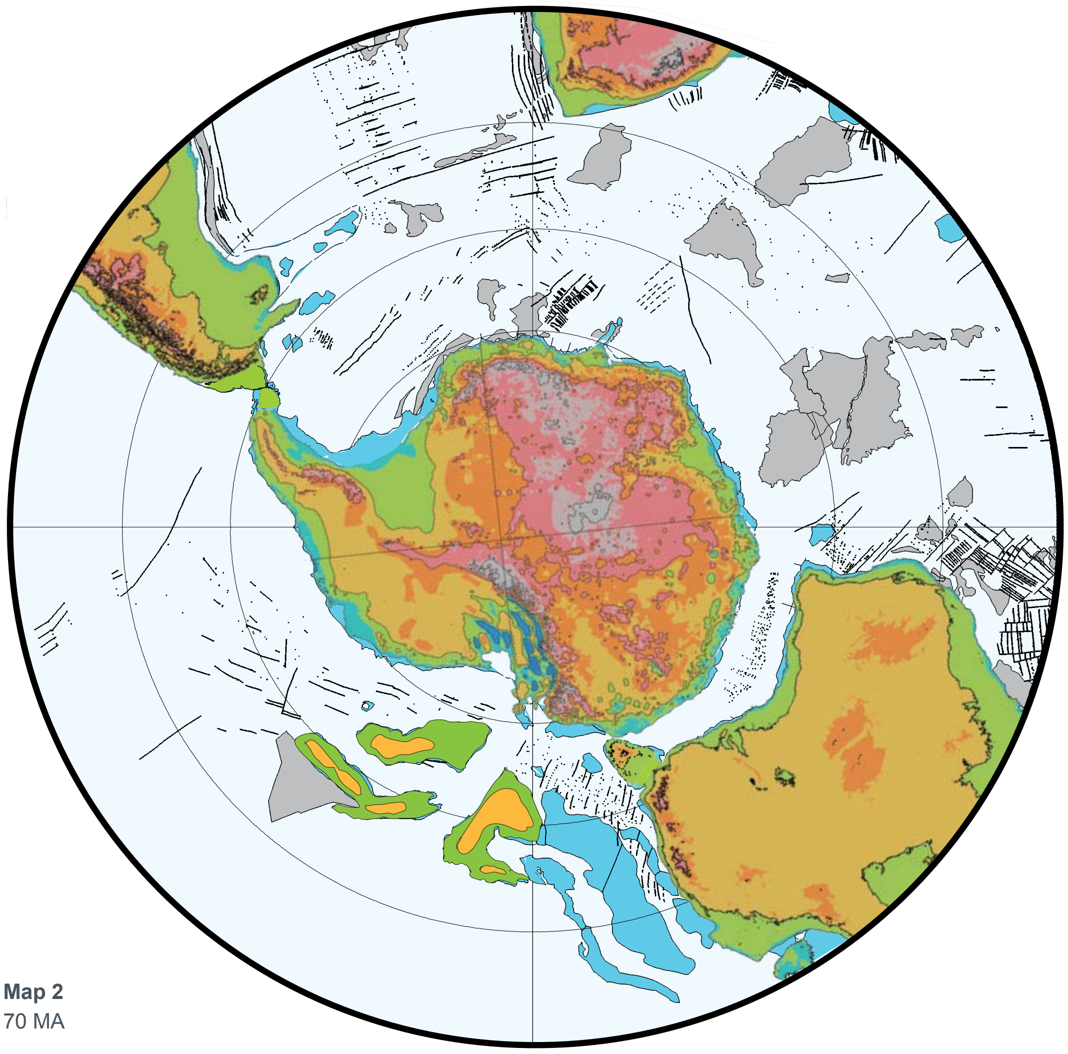
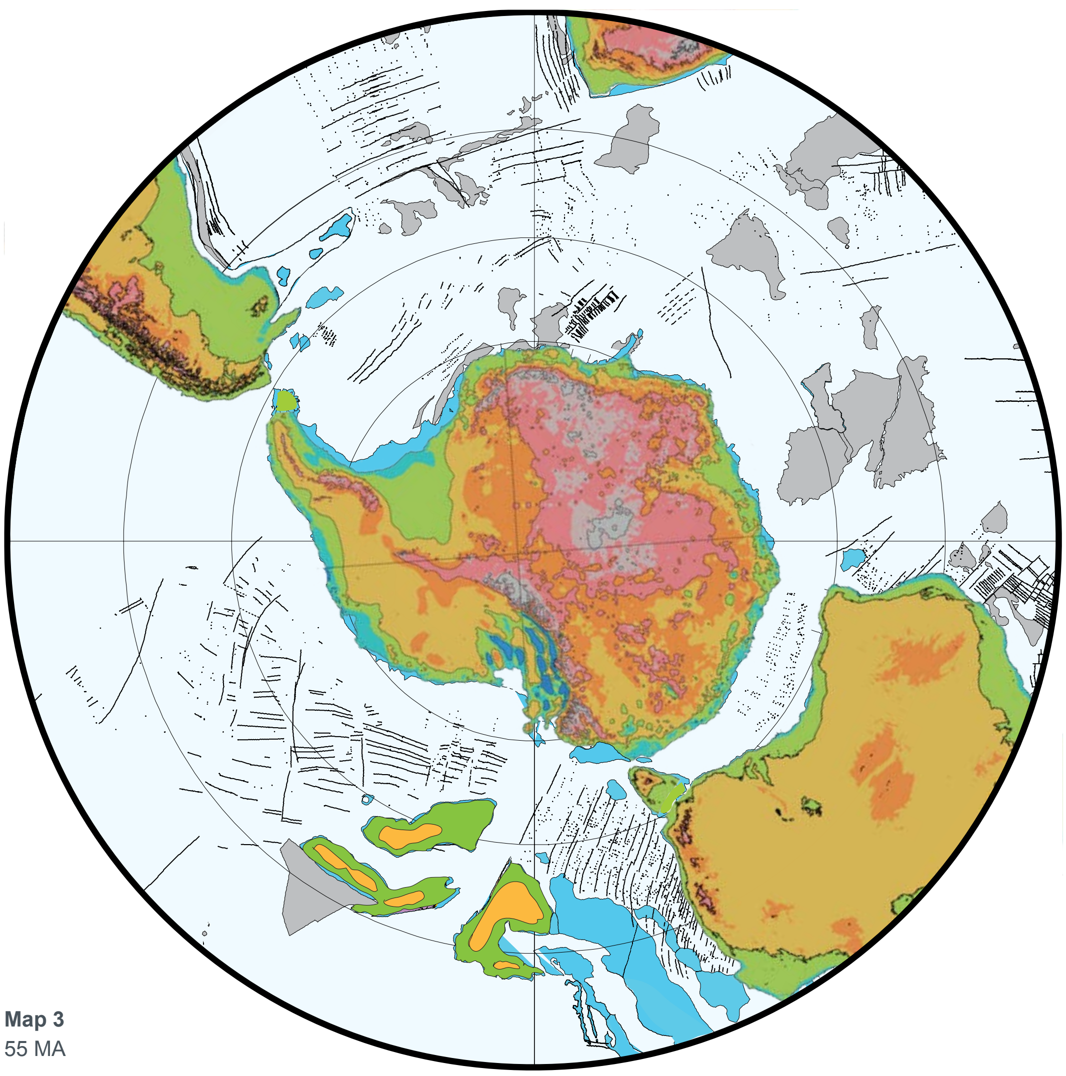


Plate Tectonics Map 1 Present-day map of the Southern Ocean region (polar stereographic projection to 40ºS). Red lineations are the continental shelf break based on the free-air gravity data (Sandwell and Smith, 2009). Yellow lineations outline the large igneous provinces (PLATES data compilation). Topography and bathymetry from Smith and Sandwell's (1997) gridded data set, version 15.1. AFR: Africa; AP: Antarctic Peninsula; BI: Balleny Islands; BR: Broken Ridge; KP: Kerguelen Plateau; STR: South Tasman Rise.

(2007). Livermore *et al.* (2005) found room for what they suggest may be C11 if the initial rates are constant starting at break up or C13 (33.5 Ma) if they are slower. Even so, it has been recognized for some time that major plate motions have the tip of the Antarctic Peninsula moving away from southern South America by the middle to late Eocene (Cunningham *et al.* 1995). Their quantitative determination of the motion between southern South America and the Antarctic Peninsula for the period 50 Ma to 30 Ma predicted as much as 290 km of east-west left-lateral strike-slip motion and 150 km of north-south divergent motion. Livermore *et al.* (2005) calculated 278 km of WNW–ESE extension between 50 and 33 Ma, close to that determined by Cunningham *et al.* (1995) and significantly faster than the 57 km of mostly N-S motion that they found for the period 66 Ma to 50 Ma. Recent heat flow measurements in the small basins along the southern margin of the Scotia Sea support a middle Eocene age for Dove Basin (Barker *et al.* 2013), in good agreement with the age that Eagles *et al.* (2006) suggested for Dove Basin based on magnetic anomaly interpretations as well as depth-to-basement calculations. Perhaps the most important aspect of development of a seaway between South America and the Antarctic Peninsula is the assumption concerning Late Cretaceous to Eocene sea level. Ghiglione *et al.* (2009) proposed latest Paleocene to early Eocene basin formation along Tierra del Fuego in a N-S direction but concede that those basins did not allow interchange of ocean waters between the Pacific and the Atlantic but they suggest the same significant change in separation direction between South America and the Antarctic Peninsula as Livermore *et al.* (2005) suggested but Ghiglione *et al.* (2009) date the change at 49 Ma. Livermore *et al.* (2005) cite the work by Reguero *et al.* (2002) concerning terrestrial fauna and the development of a seaway between South America and the Antarctic Peninsula that left the Seymour Island fauna as a distinct group from their cohorts in Patagonia by the Early Eocene. Reguero & Marenssi (2010) state that the La Meseta formation fauna "*is dissimilar to other early to middle Eocene faunas of Patagonia, where notoungulates constitute a significant proportion of identified specimens*". The 57 km of N-S Paleocene to Early Eocene motion between Patagonia and the Antarctic Peninsula (Livermore *et al.* 2005) was probably sufficient to produce a marine seaway by the 51 Ma time that Reguero & Marenssi (2010) cite for separation of the Seymour Island fauna from the Patagonian fauna.



Map 2
70 MA



Map 3
55 MA

Plate Tectonics Maps 2–3 Map 2. Plate reconstruction of the Southern Ocean region at 70 Ma (Maastrichtian, Late Cretaceous). Topographic data shown on Antarctica are the minimum reconstructed topography at the Eocene–Oligocene boundary from Wilson et al. (2012a). Present-day topographic data on remaining plates are from Smith and Sandwell's (1997) gridded data set, version 15.1. Colour bar is in kilometers (see below Map 7). Gray-filled regions are large igneous provinces. Magnetic anomaly lineations, picks and fracture zones are from the PLATES Project's compilation. Euler poles for the major plates are shown in Table 1. Reconstruction made using the PLATES Project software and plate model. — Map 3. Plate reconstruction of the Southern Ocean region at 55 Ma (Ypresian, Early Eocene).

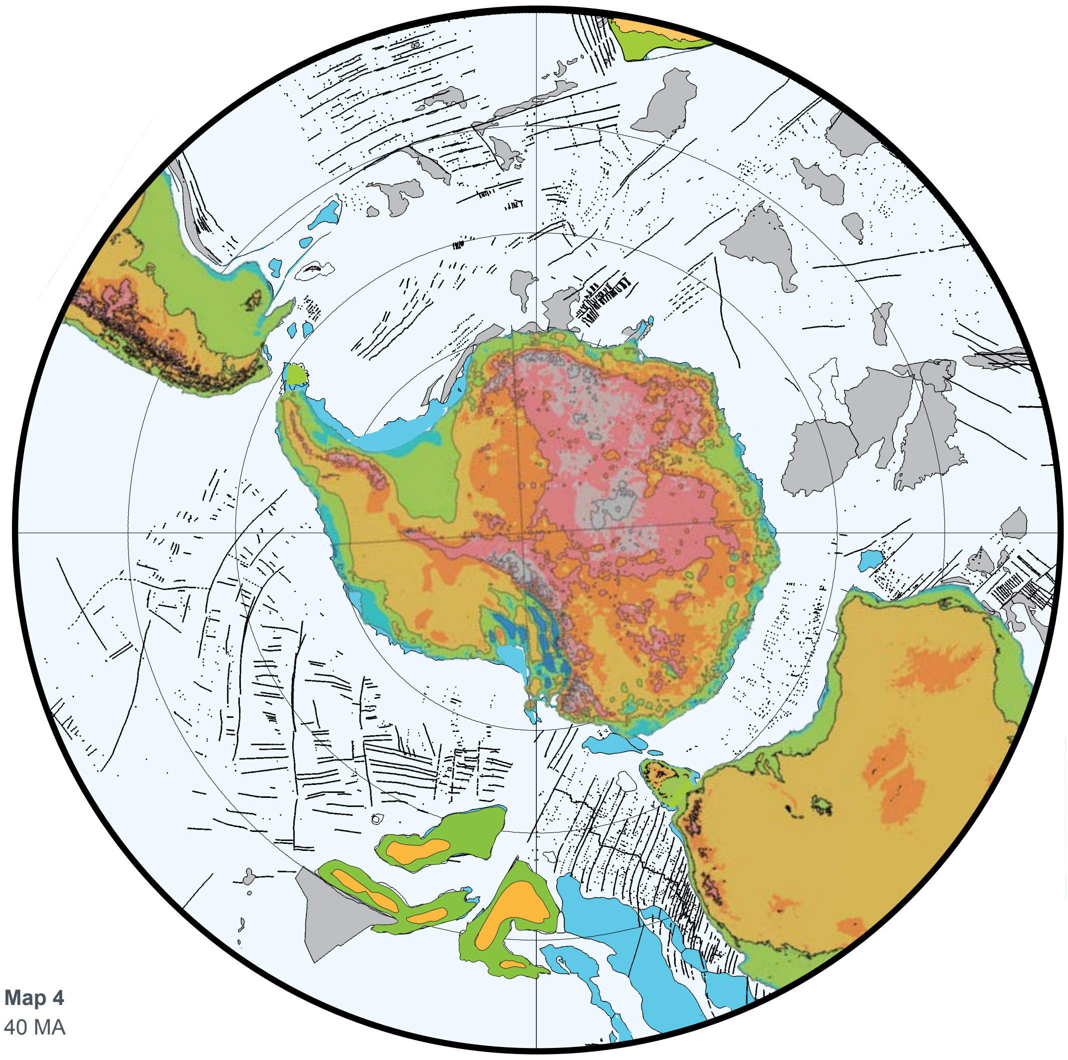
4. Late Cretaceous (70 Ma) reconstruction (Map 2)

Major plate motions indicate that the Tasman Gateway was still blocked during the Maastrichtian, while major plate motion assuming present day configurations of southern South America and the Antarctic Peninsula indicate a small gap between the two. Many have speculated that continental fragments that have been dispersed over the region of the Scotia Sea would have effectively blocked any such gateway (Barker & Thomas 2004 and references therein) but even more important are two events, the time of the closure of the Rocas Verdes Basin in southern Patagonia and the opening of the Powell Basin and motion of the South Orkney block. Most estimates of opening of the Powell Basin put it sometime during the Oligocene (Lawver & Gahagan 1998, Eagles & Livermore 2002). Consequently, the South Orkney block in the 70 Ma reconstruction (Map 2tt) and the other pre-Oligocene reconstructions are based on the pre-breakup configuration determined by King & Barker (1988) and Powell Basin has been closed according to King *et al.* (1997). It is quite possible that the severe closure that we show for the Antarctic Peninsula and the South Orkney block in the reconstructions at 70 and 55 Ma may have been more relaxed and the "tip of the Peninsula" was perhaps elongated from what is shown in Map 2.

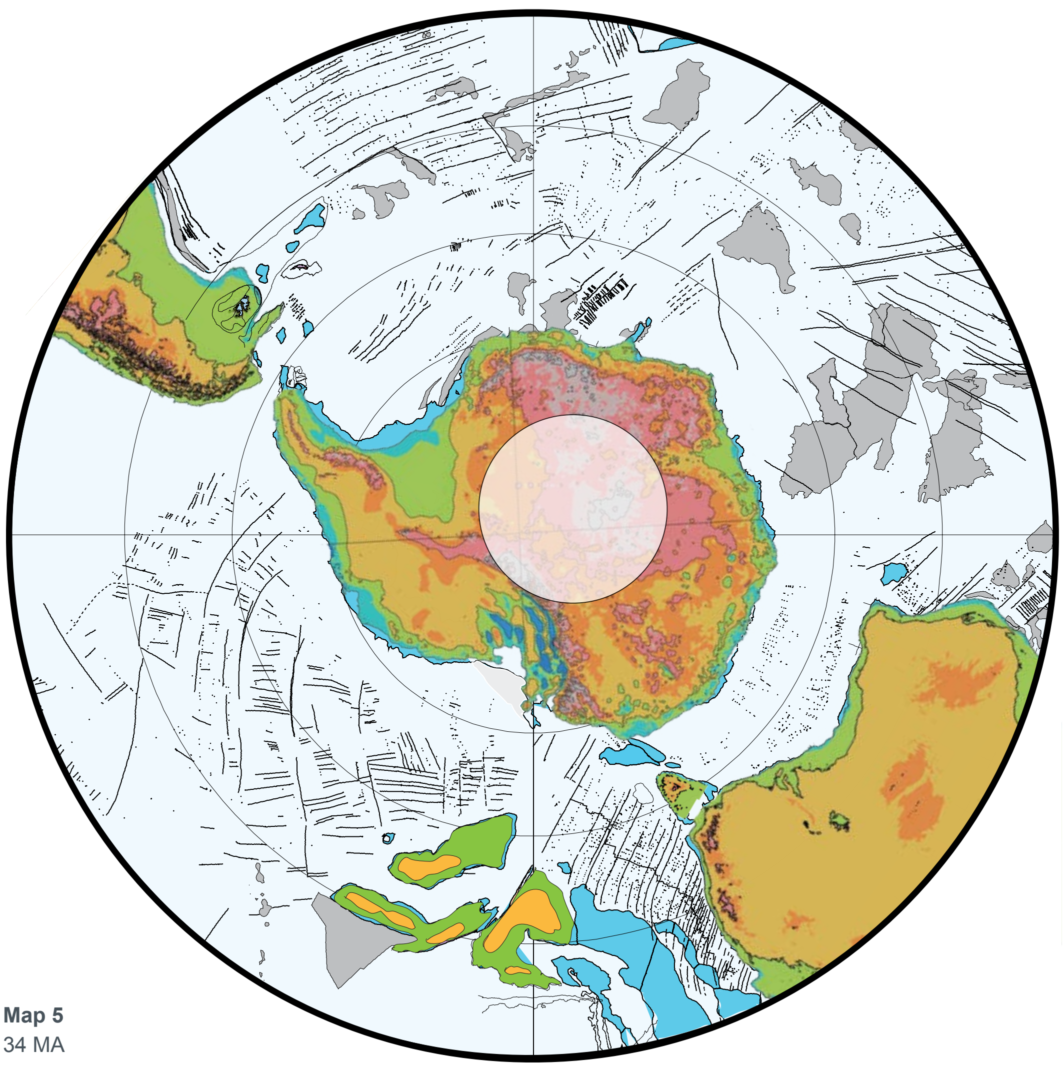
The Rocas Verdes Basin in southern South America was the westerly continuation of the initial rifting between West [Africa, South America and the Antarctic Peninsula] and East Gondwana [East Antarctica, India, Australia and other pieces] and was floored by basaltic crust with mid-ocean ridge affinities (Dalziel *et al.* 1974, Stern 1980, Alabaster & Storey 1990, Mpodozis & Allmendinger 1993, Calderón *et al.* 2007). Opening in the Rocas Verdes Basin dates from the Late Jurassic but stopped when rifting in the South Atlantic began in Early Cretaceous, ~132 Ma (Rabinowitz & LaBrecque 1979, Lawver *et al.* 1998, Ghidella *et al.* 2006, Moulin *et al.* 2010, Contreras *et al.* 2010). This led to a three plate problem and the reorganization of seafloor spreading in the Weddell Sea. Of critical importance to opening of Drake Passage is when the Rocas Verdes Basin closed, resulting in subduction of the seafloor of the Rocas Verdes Basin to the west that began about late Albian [~115 Ma] and continued until at least Campanian [~72 Ma] based on the ages of potassic volcanism found by González-Guillot *et al.* (2012) in the Fuegian Arc. Klepeis *et al.* (2010) date the closure at sometime after ~82 Ma and Torres-Carbonell *et al.* (2013) have continued contraction into the Danian. In the reconstruction for 70 Ma, it is assumed that the Rocas Verdes Basin may have a wider extent than it has presently and consequently some or all of the gap left by major plate motions may have been accounted for. It should be noted that the tip of the Antarctic Peninsula in earlier reconstructions, suggests a scenario where the tip of the Antarctic Peninsula produces transpression along the Fuegian Arc starting in the Albian or perhaps earlier which may be the closure mechanism needed. It should be noted that vertebrate Paleontologists (Reguero *et al.* 2013, and references therein) feel that there was a landbridge between Patagonia and the Antarctic Peninsula region, particularly Seymour Island that allowed interchange from the Late Cretaceous through the end of the Paleocene.

5. Early Eocene (55 Ma) reconstruction (Map 3)

At the beginning of the Eocene, the tip of the Antarctic Peninsula appears to be a very small distance from the southern margin of South America, see Map 3. Within a million years, the major plate motions between South America, Africa and Antarctica bring the reconstructed continental margins of the Antarctic Peninsula and southernmost South America into conjunction where they remain until almost 40 Ma. The caveats expressed for the 70 Ma reconstruction apply although the Rocas Verdes Basin is considered to be fully compressed by the beginning of the Eocene. If our reconstruction of the South Orkney block and a very tight closure of Powell Basin is too conservative then the gap shown might not have been present. If a gap was present, it was more likely to be a shallow seaway than a deep



Map 4
40 MA



Map 5
34 MA

Plate Tectonics Maps 4–5 Map 4. Plate reconstruction of the Southern Ocean region at 40 Ma (Bartonian, Middle Eocene). — Map 5. Plate reconstruction of the Southern Ocean region at 34 Ma (Priabonian, Late Eocene). See Map 2 for explanation.

gateway. With respect to the Tasman Seaway, it does not appear that the South Tasman Saddle had yet cleared the margin of East Australia by the beginning of the Eocene. The possible presence of a fixed Balleny hotspot under the South Tasman Rise would certainly have contributed to a barrier at this time. In addition, the seafloor spreading center to the west of the Tasmania block might have produced a small amount of thermal uplift but any lateral flow would have been minor.

Broken Ridge to the west of Australia is shown contiguous with the Kerguelen Plateau in both Map 1 and Map 2. Broken Ridge is dated at 95–94 Ma (Duncan 2002) and is believed to have formed as part of the Kerguelen Large Igneous Province [LIP] based on ODP drilling results (Frey *et al.* 2000). After subduction of the spreading center between Australia and Eurasia to the north of the Kerguelen Plateau/ Broken Ridge, the Southeast Indian Ridge jumped southward just prior to chron C18 (~41 Ma) to between Broken Ridge and the Kerguelen Plateau.

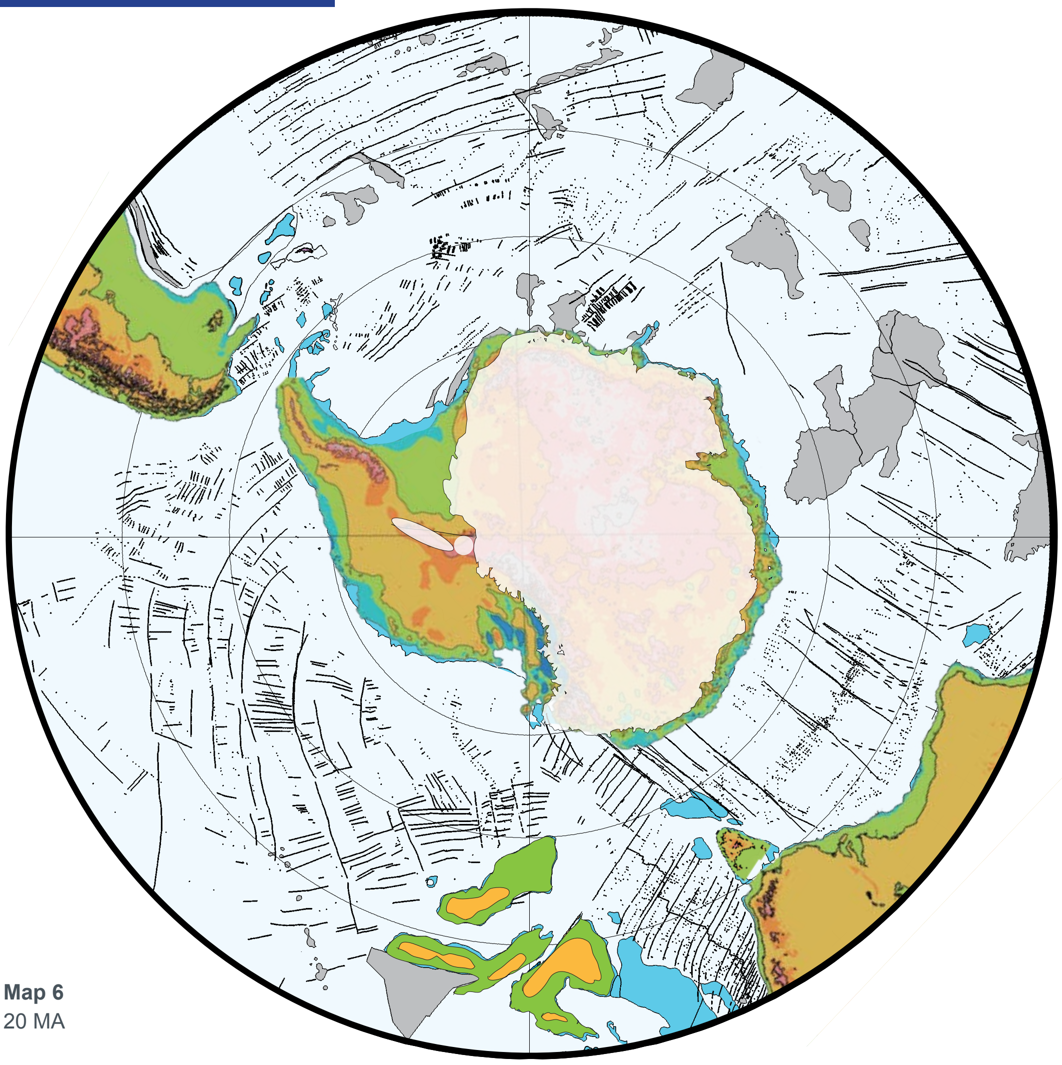
6. Late Eocene (40 Ma) reconstruction (Map 4)

By the end of the middle Eocene, the initial Drake Passage, defined as a lasting separation between the margin of South America and the tip of the Antarctic Peninsula began to form (Map 4). It is unclear as to the exact location of Terror Rise, believed to be a thinned continental fragment by both Eagles *et al.* (2006) and Galindo-Zalvidar *et al.* (2006). If it was farther south from were it is shown as a small fragment off the tip of Tierra del Fuego, it could easily have blocked a deepwater passage between South America and Antarctica. It is reasonably certain though that a shallow seaway was in existence by the middle Eocene due to the increased distinction between the Patagonian fauna and the La Meseta fauna of Seymour Island (Woodburne & Zinsmeister 1984, Woodburne & Case 1996, Reguero & Marenssi 2010). While Barker & Burrell (1977) show Elephant Island, the northernmost part of the Antarctic Peninsula adjacent to the southern tip of South America at chron C8 (27 Ma), in a later paper, Barker & Thomas (2004) show those two points significantly separated both latitudinally and longitudinally. At chron C18 (~40 Ma) they show a reconstruction of those two points very close to what is shown here in Map 4 although they show a fully extended South Orkney block by this time with a closed Powell Basin.

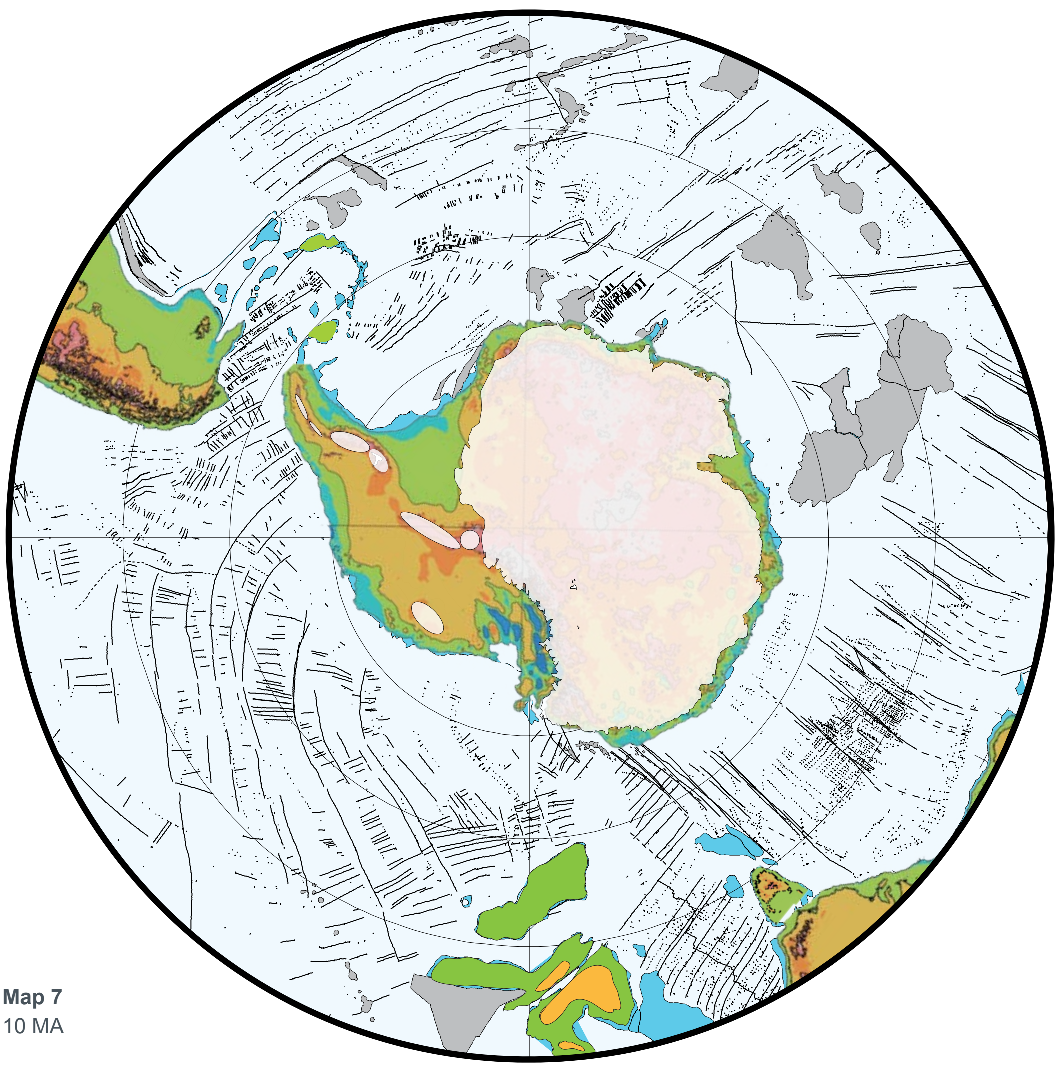
By 40 Ma, the South Tasman Saddle would have cleared the Antarctic margin and would have been a medium depth seaway up to 3000 m deep and at least 200 km wide. Even if it were still slightly thermally uplifted by either an adjacent spreading center to the west or by the lingering effects of the Balleny Islands hotspot, there would have been a significant seaway that would effectively bar large mammal dispersal between Antarctica and Australia. Also, by 40 Ma, the Southeast Indian Ridge [SEIR] spreading center would have jumped to between Kerguelen Plateau and Broken Ridge to the west of Australia but continued activity by the Kerguelen hotspot at the western end of Broken Ridge dated at ~38 Ma by Frei & Weis (1995) would probably have blocked major flow between the two parallel, high ridges.

7. Eo/Oligocene (34 Ma) boundary reconstruction (Map 5)

As discussed above, the dramatic change in $\partial^{18}O$ at the Eocene-Oligocene boundary (Zachos *et al.* 2001) is taken as a proxy to a significant chilling of the world's oceans and many authors have suggested that a final opening to complete a circum-Southern Ocean deepwater pathway was the likely cause of such a significant change. Major plate motions though indicate that the only particular seaway or gateway in the path of the present-day ACC that had yet to fully open was the one between the Kerguelen Plateau and Broken Ridge. The present-day ACC is shown in Sandwell & Zhang (1989) in the figure where they have derived the root-mean-square [rms] slope variability for the first year of Geosat/ERM satellite altimetry data. From their figure it is clear that the ACC which extends from the sea surface to the seafloor is steered by shallow to mid-depth seafloor features including such



Map 6
20 MA



Map 7
10 MA

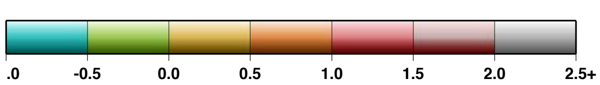


Plate Tectonics Map 6–7 Map 6. Plate reconstruction of the Southern Ocean region at 20 Ma (Burdigalian, Early Miocene). — **Map 7**. Plate reconstruction of the Southern Ocean region at 10 Ma (Tortonian, Late Miocene).

highs as the Campbell Plateau south of New Zealand, the Falkland Plateau, and such lows as the deepest sill along the Pacific–Antarctic Ridge, and through a passage in the North Scotia Ridge as documented by Naveira Garabato *et al.* (2002). While a deepwater passage may have developed between the tip of South America and the Antarctic Peninsula by 40 Ma, Dalziel *et al.* (2013) show that an ancestral South Sandwich Arc would have been a barrier to the ACC and delayed development of a vigorous ACC until a deep water Drake Passage opened in the Miocene. In addition to possible shallow seaways or even deep gateways, the last evidence of an indigenous Antarctic mammal is known from a well-preserved, Upper Eocene ungulate tooth from the uppermost level of the Submeseta Formation (TELM 7) reported by Vizcaino *et al.* (1997).

8. Early Miocene (20 Ma) reconstruction (Map 6)

By the Middle Miocene there seem to be significant gateways all around the circum-Antarctic region. While there may have been an ancestral South Sandwich Arc (Dalziel *et al.* 2013) that would have diverted or even hindered the ACC between South America and the Antarctic Peninsula, it is possible that the ACC did not become a vigorous and significant current until both the gateway between New Guinea/Australia and Southeast Asia closed in the middle Miocene and the late Miocene or Pliocene closure of the Isthmus of Panama. By 20 Ma, it is believed that East Antarctica and the Ellsworth-Whitmore Mountains were mostly but not totally covered by the East Antarctic icesheet (Pekar & Christie-Blick 2008, Passchier *et al.* 2011). Pekar & Christie-Blick (2008) show an ice volume ≥ the present day East Antarctic Ice Sheet [EAIS] just prior to 20 Ma and a short time after 20 Ma. Based on the ANDRILL drilling in the western Ross Sea, Passchier *et al.* (2011) concluded "*that the Antarctic ice sheets were dynamic, with grounding lines south of the modern location at ca. 20.1–19.6 Ma and ca. 19.3–18.7 Ma and during the Miocene climatic optimum, ca. 17.6–15.4 Ma, with ice-sheet and sea-ice minima at ca. 16.5–16.3 Ma and ca. 15.7–15.6 Ma*". They found glacial minima

Table 1 Finite rotation poles relative to a fixed Antarctica as calculated from the PLATES global plate model.

Plate	Age (Ma)	Latitude + °N	Longitude + °E	Angle °
Australia	10	12.2	38.5	-6.28
	20	13.4	34.6	-12.07
	34	13.5	33.7	-20.72
	40	14.3	31.8	-23.17
	55	12.5	32.8	-24.96
	70	11.5	33.0	-26.35
Africa	10	8.2	-49.4	-1.54
	20	10.7	-47.9	-2.76
	34	12.7	-48.2	-5.64
	40	17.0	-46.6	-7.19
	55	6.1	-39.4	-10.21
	70	0.3	138.5	12.54
India	10	21.6	16.2	-5.01
	20	27.2	4.8	-8.86
	34	21.6	20.2	-17.09
	40	24.1	19.2	-20.19
	55	17.7	11.4	-33.11
	70	13.6	7.4	-50.84
Pacific	10	70.4	-77.0	8.86
	20	74.0	-69.6	16.77
	34	74.5	-62.6	27.81
	40	74.9	-54.2	32.53
	55	73.1	-53.3	41.06
	70	68.8	-52.4	53.07
South America	10	84.0	37.5	2.70
	20	76.3	-10.5	6.02
	34	73.0	2.8	10.63
	40	73.5	9.3	12.13
	55	80.3	38.4	18.18
	70	79.5	60.1	23.44

at ca. 20.1–19.6 Ma that are characterized by temperate margins, an increased abundance of gravelly facies and diatomaceous siltstone. They concluded that a lack of meltwater plume deposits suggested a cooler and drier climate. Even so, Passchier *et al.* (2011) concluded that there was a fully developed EAIS between 20.2 and 20.1 Ma with the WAIS labeled as WAIS? and a EAIS/WAIS for the period 19.6 to 19.3 Ma. Figure 6 shows a nearly complete EAIS and an icesheet covering parts of the Ellsworth/Whitmore Mountains.

9. Late Miocene (10 Ma) reconstruction (Map 7)

By the late Miocene, both the Tasman Gateway and Drake Passage were fully operational as deepwater passageways. Based on magnetostratigraphy for the lower part of the ANDRILL 1-B hole (Wilson *et al.* 2012b), it appears that at 10 Ma, the drill hole was subglacial so a larger than present EAIS might have existed. Passchier *et al.* (2011) interpret the facies associations and chronology found in the ANDRILL 2-A hole to indicate that from 14 Ma until sometime after the end of the middle Miocene (younger than 11 Ma), the depositional environment indicated it was a cold marine environment as well as there having been both an EAIS and WAIS. We use these results to presume that the EAIS was at least equivalent to its present day form and that fragments of a WAIS or even more may have been in existence by 10 Ma.

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THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

Scope

Biogeographic information is of fundamental importance for discovering marine biodiversity hotspots, detecting and understanding impacts of environmental changes, predicting future distributions, monitoring biodiversity, or supporting conservation and sustainable management strategies.

The recent extensive exploration and assessment of biodiversity by the Census of Antarctic Marine Life (CAML), and the intense compilation and validation efforts of Southern Ocean biogeographic data by the SCAR Marine Biodiversity Information Network (SCAR-MarBIN / OBIS) provided a unique opportunity to assess and synthesise the current knowledge on Southern Ocean biogeography.

The scope of the Biogeographic Atlas of the Southern Ocean is to present a concise synopsis of the present state of knowledge of the distributional patterns of the major benthic and pelagic taxa and of the key communities, in the light of biotic and abiotic factors operating within an evolutionary framework. Each chapter has been written by the most pertinent experts in their field, relying on vastly improved occurrence datasets from recent decades, as well as on new insights provided by molecular and phylogeographic approaches, and new methods of analysis, visualisation, modelling and prediction of biogeographic distributions.

A dynamic online version of the Biogeographic Atlas will be hosted on www.biodiversity.aq.

The Census of Antarctic Marine Life (CAML)

CAML (www.caml.aq) was a 5-year project that aimed at assessing the nature, distribution and abundance of all living organisms of the Southern Ocean. In this time of environmental change, CAML provided a comprehensive baseline information on the Antarctic marine biodiversity as a sound benchmark against which future change can reliably be assessed. CAML was initiated in 2005 as the regional Antarctic project of the worldwide programme Census of Marine Life (2000-2010) and was the most important biology project of the International Polar Year 2007-2009.

The SCAR Marine Biodiversity Information Network (SCAR-MarBIN)

In close connection with CAML, SCAR-MarBIN (www.scarmarbin.be, integrated into www.biodiversity.aq) compiled and managed the historic, current and new information (i.a. generated by CAML) on Antarctic marine biodiversity by establishing and supporting a distributed system of interoperable databases, forming the Antarctic regional node of the Ocean Biogeographic Information System (OBIS, www.iobis.org), under the aegis of SCAR (Scientific Committee on Antarctic Research, www.scar.org). SCAR-MarBIN established a comprehensive register of Antarctic marine species and, with biodiversity.aq provided free access to more than 2.9 million Antarctic georeferenced biodiversity data, which allowed more than 60 million downloads.

The Editorial Team

Claude DE BROYER is a marine biologist at the Royal Belgian Institute of Natural Sciences in Brussels. His research interests cover structural and ecofunctional biodiversity and biogeography of crustaceans, and polar and deep sea benthic ecology. Active promoter of CAML and ANDEEP, he is the initiator of the SCAR Marine Biodiversity Information Network (SCAR-MarBIN). He took part to 19 polar expeditions.

Huw GRIFFITHS is a marine Biogeographer at the British Antarctic Survey. He created and manages SOMBASE, the Southern Ocean Mollusc Database. His interests include large-scale biogeographic and ecological patterns in space and time. His focus has been on molluscs, bryozoans, sponges and pycnogonids as model groups to investigate trends at high southern latitudes.

Cédric d'UDEKEM d'ACOZ is a research scientist at the Royal Belgian Institute of Natural Sciences, Brussels. His main research interests are systematics of amphipod crustaceans, especially of polar species and taxonomy of decapod crustaceans. He took part to 2 scientific expeditions to Antarctica on board of the *Polarstern* and to several sampling campaigns in Norway and Svalbard.

Bruno DANIS is an Associate Professor at the Université Libre de Bruxelles, where his research focuses on polar biodiversity. Former coordinator of the scarmarbin.be and antabif.be projects, he is a leading member of several international committees, such as OBIS or the SCAR Expert Group on Antarctic Biodiversity Informatics. He has published papers in various fields, including ecotoxicology, physiology, biodiversity informatics, polar biodiversity or information science.

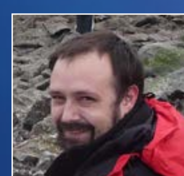
Susie GRANT is a marine biogeographer at the British Antarctic Survey. Her work is focused on the design and implementation of marine protected areas, particularly through the use of biogeographic information in systematic conservation planning.

Christoph HELD is a Senior Research Scientist at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven. He is a specialist in molecular systematics and phylogeography of Antarctic crustaceans, especially isopods.

Falk HUETTMANN is a 'digital naturalist' he works on three poles (Arctic, Antarctic and Hindu-Kush Himalaya) and elsewhere (marine, terrestrial and atmosphere). He is based with the university of Alaska-Fairbank (UAF) and focuses primarily on effective conservation questions engaging predictions and open access data.

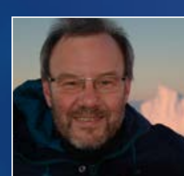
Philippe KOUBBI is professor at the University Pierre et Marie Curie (Paris, France) and a specialist in Antarctic fish ecology and biogeography. He is the Principal Investigator of projects supported by IPEV, the French Polar Institute. As a French representative to the CCAMLR Scientific Committee, his main input is on the proposal of Marine Protected Areas. His other field of research is on the ecoregionalisation of the high seas.

Ben RAYMOND is a computational ecologist and exploratory data analyst, working across a variety of Southern Ocean, Antarctic, and wider research projects. His areas of interest include ecosystem modelling, regionalisation and marine protected area selection, risk assessment, animal tracking, seabird ecology, complex systems, and remote sensed data analyses.



Anton VAN DE PUTTE works at the Royal Belgian Institute for Natural Sciences (Brussels, Belgium). He is an expert in the ecology and evolution of Antarctic fish and is currently the Science Officer for the Antarctic Biodiveristy Portal www.biodiversity.aq. This portal provides free and open access to Antarctic Marine and terrestrial biodiversity of the Antarctic and the Southern Ocean.

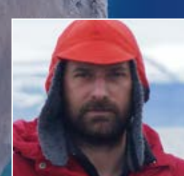
Bruno DAVID is CNRS director of research at the laboratory BIOGÉOSCIENCES, University of Burgundy. His works focus on evolution of living forms, with and more specifically on sea urchins. He authored a book and edited an extensive database on Antarctic echinoids. He is currently President of the scientific council of the Muséum National d'Histoire Naturelle (Paris), and Deputy Director at the CNRS Institute for Ecology and Environment.



Julian GUTT is a marine ecologist at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, and professor at the Oldenburg University, Germany. He participated in 13 scientific expeditions to the Antarctic and was twice chief scientist on board Polarstern. He is member of the SCAR committees ACCE and AnT-ERA (as chief officer). Main focii of his work are: biodiversity, ecosystem functioning and services, response of marine systems to climate change, non-invasive technologies, and outreach.

Graham HOSIE is Principal Research Scientist in zooplankton ecology at the Australian Antarctic Division. He founded the SCAR Southern Ocean Continuous Plankton Recorder Survey and is the Chief Officer of the SCAR Life Sciences Standing Scientific Group. His research interests include the ecology and biogeography of plankton species and communities, notably their response to environmental changes. He has participated in 17 marine science voyages to Antarctica.

Alexandra POST is a marine geoscientist, with expertise in benthic habitat mapping, sedimentology and geomorphic characterisation of the seafloor. She has worked at Geoscience Australia since 2002, with a primary focus on understanding seafloor processes and habitats on the East Antarctic margin. Most recently she has led work to understand the biophysical environment beneath the Amery Ice Shelf, and to characterise the habitats on the George V Shelf and slope following the successful CAML voyages in that region.



Yan ROPERT COUDERT spent 10 years at the Japanese National Institute of Polar Research, where he graduated as a Doctor in Polar Sciences in 2001. Since 2007, he is a permanent researcher at the CNRS in France and the director of a polar research programme (since 2011) that examines the ecological response of Adélie penguins to environmental changes. He is also the secretary of the Expert Group on Birds and Marine Mammals and of the Life Science Group of the Scientific Committee on Antarctic Research.