Research Update No. 13, September 2020

The Weddell Sea, Scotia Sea, Patagonia and the Antarctic Peninsula

Context

The latest animation of Gondwana dispersal may be found on the website www.reeves.nl/gondwana. The model is undergoing repeated refinement but has recently reached the end of a long cycle of adjustment in recent months. The following text refers specifically to model CR20ABHK (and the fixed-Africa version CR20AAHK) compiled on 2020 September 9.

Conceptually the model defines, first, the motion of **South America** (SAM) against **Africa** (AFR) and then that of **Antarctica** (ANT) against **Africa**, both of which are only slightly refined versions of those demonstrated in other animations launched within recent months and years. Once both these trajectories are defined, the relative motion of South America and Antarctica is also defined since, geometrically, this is the closing of the plate circuit SAM-AFR-ANT and we should know everything there is to know geometrically about the ocean between Antarctica and South America. But that assumes there are only these three continental fragments, Africa, Antarctica and South America.

I argue here for a fourth fragment. I call it Hoorn and it is physically that part of Patagonia lying south of the San Matias fault, as defined in Research Update No.11. This still leads to a simple solution, even for the complexity evident in the ocean-floor data between South America and Antarctica. It also gives an elegant fit for Hoorn within reassembled Gondwana (Figure 1). This model avoids the overlap of Patagonia and the Antarctic Peninsula that has thwarted simple closure models for the South Atlantic for 50 years (e.g. Smith & Hallam, 1970) as well as explaining simply the features of the ocean south of South America. The San Matias fault that separates Hoorn from the rest of South America is defined (Research Update No.11) from purely geometrical constraints. It does not correspond to any major fault feature yet recognised in the continent but runs through an area devoid of both outcrop and potential field survey data.

The mid-ocean ridge(s) between Antarctica and South America may be somewhat subordinate globally since the relation between Africa-Antarctica and between Africa-South America are both by way of great lengths of mid-ocean ridge with thousands of km of ocean growth while the relative movement between Antarctica and South America is much smaller, more complex and undoubtedly a consequence of the motions of larger plates rather than a major driving force in the global scheme of things. Nevertheless, the Weddell mid-ocean ridge now has a length of about 2600 km that effectively extends the South-West Indian Ridge (SWIR) by a significant amount beyond the 6600 km distance from the triple junction in the Indian Ocean to the Bouvet triple junction for a total of over 9000 km. The SWIR is also of particular interest because, of all the ridges in the southern hemisphere, it alone has remained fixed with respect to the global hotspot reference frame I have used throughout Gondwana dispersal. This may well be on account of the Bouvet mantle plume which, in this and similar models, retains a dominant position between Africa and Antarctica throughout Gondwana disruption, following its initial outbreak at about 183 Ma.

Features of the SAM-ANT ocean

Understanding the growth of the SAM-ANT Ocean is complicated by the advent of a new spreading ridge in the Scotia Sea in Cenozoic times and the unknown amount of crustal consumption achieved by the Scotia Arc (South Sandwich Islands) and along the margins of the Scotia Sea. I have been concentrating on the record of events in the Weddell Sea which evidently preserves at least one half of the SAM-ANT Ocean (Figure 2). The Weddell Sea, in fact, offers a clear record of much of the movement of SAM vs ANT, with a fan-shaped array of former ridge positions and a good supply of marine magnetic anomaly picks (Konig & Jokat, 2006) to date the rapid and important early ocean growth process, particularly in the interval 144.32 (M18) to 126.11 Ma (M0) (Berriasian to Barremian) which is shown to be a period of profound changes in Gondwana dispersal.

From the vicinity of the present-day Bouvet triple junction and for a distance of about 900 km to the west of it, the whole ocean is virtually complete, lying east of the Scotia Arc on its South America flank. Most of it, however, is relatively young since the ridge has grown longer as both South America and Antarctica have moved away from the triple junction.

The middle section of about 1000 km, to a point about 650 km east of the South Orkney Islands, is fully 'half-complete' and lacks complications apart from the destruction of its conjugate half.

The remaining 900 km, closest to the Antarctic Peninsula, is complicated by the tectonic history of the South Orkney micro-fragment. This fragment lay beyond the western end of the mid-ocean ridge in the early phases of ocean growth and rotated counter-clockwise away from the Antarctic Peninsula (Figure 3), probably until about the start of spreading in the Scotia Sea. This latter event seems to have trapped the most recent (and minor) positions of the Weddell Sea mid-ocean ridge south of the South Orkney micro-fragment.

First opening of the Weddell Sea

Perhaps the clearest feature of the topographic pattern of the Weddell Sea is Anomaly-T (Figure 2) which marks the start of the conspicuous 'fan' feature (Livermore and Hunter, 1996) and which is also virtually coincident with magnetic Anomaly M0 (126.11 Ma). M0 marks the start of the Cretaceous Quiet Zone (KQZ) that continued until 83.64 Ma. Ocean topography shows a clear change in ocean-growth direction at Anomaly-T. Before that time, however, the growth direction is defined clearly by M-series anomalies (Konig & Jokat, 2006) from 126.11 Ma back to 144.32 Ma (Figure 2) when a 'fit' is proclaimed by these authors between South America and Antarctica. In the present study we claim that this was only an intermediate stage fit that came at the end of earlier, Jurassic extension in the Weddell Sea, determined by the known movements of East and West Gondwana before 144.32 Ma (i.e. in Jurassic times).

Our fourth fragment, Hoorn, we define as all of Patagonia lying south of the San Matias Fault as defined in Research Update No. 11. This fragment (about the size of peninsular India, much of it by area offshore) we consider as the first large part of Gondwana to lead an existence separate from either East or West Gondwana. We argue here that there is sufficient information to define the movements of this fragment all the way back to a full Gondwana 'fit' position at 182.7 Ma. Since about 117 Ma, we have Hoorn retaining the position it has today as a part of the large South America plate.

Before 117 Ma we envisage two distinct movements of Hoorn against South America. Going backwards in time, the more recent, 117 to 138 Ma approximately, is the closure of the Colorado and Salado rifts with the San Matias fault remaining tight, thus shortening South America by the amount (approximately 180 km) necessary for the San Matias fault to become coincident with the Agulhas fault once closure is complete (Figure 4). The eastern margin of South America thus attains the same length as the distance on Africa from the Gulf of Guinea to its SW extremity off South Africa.

In times before this (138 to 165 Ma approximately), the motion of Hoorn was pure strike slip along the Agulhas fault and its 'San Matias' extension into South America. This extension was once thought to be the Gastre fault (Rapela & Pankhurst, 1992; Watkeys & Soukoutis, 1998), the existence of which has been disputed. The more precise reconstruction of the South Atlantic presented here places this fault feature several hundred km further north than the postulated Gastre.

The position of Hoorn at all times may be determined by confining it to these two movements with respect to South America while satisfying the magnetic anomaly evidence in the Weddell Sea. This has been done as follows.

First consider the fragment Hoorn in our Gondwana assembly to be defined by three arcuate margins: (1) a northern margin formed by the San Matias Fault, the northern margin of the Malvinas plateau and (eventually) its extension into Africa, the Agulhas fault; (2) a southern margin formed by the southern escarpment of the Malvinas plateau as far east as a point about 250 km SE of the Falkland Islands; and (3) a western margin that now lies somewhere within the Andes, approximately coincident with the political boundary between Argentina and Chile.

We have used the magnetic anomaly and satellite gravity information in the Weddell Sea to derive a set of interval rotations solely for the **mid-ocean ridge of the SAM-ANT Ocean** against Antarctica for the period starting at 144.32 Ma and continuing until 126.11 Ma (and less certainly to more recent times). The shape of (much of) the ridge – particularly the 1500 km closest to the Antarctic Peninsula) - can be shown to have remained constant over this interval, evidenced, for example, by the consistently parallel traces of the M-series anomalies reported (Konig and Jokat, 2006) and the reproduction of this shape in what we interpret as hiatuses in later spreading and its record in ocean-floor topography and post-KQZ magnetic anomalies. If it is assumed that this ridge remained central in the (early) SAM-ANT Ocean, then the position of the conjugate margin to this ridge, namely the southern margin of Hoorn in the Early Cretaceous, may be estimated (Figure 2).

Of particular concern in Gondwana reconstruction are events immediately before and during the Early Cretaceous. The magnetic anomaly data is particularly well-defined for the period from about 150 Ma until the start of the KQZ at 126.11 Ma. With these constraints it is possible to derive a series of positions for Hoorn such that its southern margin makes a good approximation to a conjugate margin, a similar distance from the Weddell mid-ocean ridge as the ridge, as defined in the previous paragraph, is from the 144.32 Ma 'start' position defined on Antarctica. In fact, this is the closure of our whole plate circuit, ANT-AFR-SAM-Hoorn-ANT. Perhaps the greatest uncertainty then is whether or not other features (such as the Burdwood Bank and South Georgia) should also be added to the southern margin of Hoorn before making these reconstructions (Figure 2).

Before 144.32 Ma, the well-defined movements of East and West Gondwana can be used to constrain the independent movements of Hoorn back to an Early Jurassic reassembly. This is consistent with our systematic fitting of 'gravity margins' throughout Gondwana (Research Update No.11). Hoorn, we postulate, originally occupied precisely the embayment of Antarctica now describing the Weddell Sea. Its southern margin, south of the Malvinas Plateau, finds its Gondwana 'home' against the Coats Land coast of Antarctica. Geometrically, this join is parallel to the earliest phase of disruption between East and West Gondwana as defined in the Africa-Antarctica corridor (AAC) so would have undergone strike slip and perhaps mildly-transtensional rifting in the first 25 myr of disruption. By coincidence or otherwise, the Magellanes fault of Patagonia is coincident with this regime of faulting in our reconstruction and could be a re-activated relic of this early rifting.

At about 157.5 Ma, the well-established change in direction of spreading between East and West Gondwana (Reeves & Teasdale, 2019) was not possible while Hoorn remained in its 'fit' position. Consistent with the age of first rifting in South Africa's Outeniqua basin, we have Hoorn starting to move west along the Agulhas fault at about 165 Ma and gaining pace (to about 30 k/myr) after 157.5 Ma. A distance of about 670 km is covered by about 138 Ma when the Agulhas fault goes into transtension and a number of other events occur simultaneously in the broader region. Hoorn starts to rotate slightly clockwise away from South America, opening the Salado and Colorado rifts, and the earliest opening of the South Atlantic Ocean is linked via the Agulhas fault (now a leaky transform) to the Bouvet triple junction.

To the east of Hoorn we can expect a simple relationship to exist with the position of the Maurice Ewing Bank, the position of which is well-defined from 138 to 125 Ma (approx.) by marine magnetic anomalies in the so-called Natal Valley off SE Africa. Our positions for Hoorn indicate that, before about 138 Ma, crustal extension occurred between MEB and Hoorn but, after that time, a new mid-ocean ridge was established to the east of MEB and relative movement between Hoorn and MEB was minimal.

There is no need to invoke further movements of the various constituent fragments of southern South America after 117 Ma.

Hoorn and the Antarctic Peninsula

The western margin of Hoorn has its Gondwana 'home' against the Antarctic Peninsula and its extension offshore below the Larsen Ice Shelf. This contact zone would have undergone normal faulting and extension by rifting during the earliest phase of Gondwana disruption, 182.7 to 157.5 Ma in our EGO-WGO model determined from well-defined magnetic anomalies in the AAC (Mueller and Jokat, 2019).

After about 157.5 Ma the rifted zone or proto-ocean became a zone of sinistral strike-slip that continued for a further 40 myr. By the end of this period, and after about 750 km of strike-slip, the southern margin of Hoorn was well clear of the tip of the Antarctic Peninsula. The clear change of spreading direction at about 117 Ma in the South Atlantic Ocean led to the onset of westward movement of Hoorn, along with the rest of South America, along the Shackleton Fault Zone and faults parallel to it, a process that has continued now for almost 120 myr with rapid acceleration since about 35 Ma .(Figure 5).

Note that, in our model, the Antarctic Peninsula has remained firmly attached to the rest of Antarctica throughout Jurassic and more recent times. We could imagine many earlier movements since West Antarctica, unlike East Antarctica, is an assembly of fragments in a collisional environment, but we would confine these movements to the extensive compressional tectonism that affected the whole of Gondwana's Pacific margin in Permian and Triassic times. We do not need to invent such movements in Jurassic times to build a workable model.

The Scotia Sea

Events younger than about 50 Ma are much more complicated and have not received the same attention here since it is presently the reconstruction of Gondwana that is of primary interest. Suffice it to say now that most of the post-50 Ma growth in area between South America and Antarctica has been achieved by growth of the Scotia Sea about a new central ridge, accompanied by a certain amount of compression and subduction around the margins of that new sea.

An appreciation of our model is most easily achieved by watching the animation launched on 2020 August 6 (www.reeves.nl/gondwana, Model CR20ABHC) rather than by reading a long dissertation on what happened in this text.

Initiation of rapid growth of the Weddell Sea

At about **144 Ma** it should be noted that the earliest magnetic anomalies off Coats Land (Antarctica) follow the same geometry as the Euler latitude lines defined by the relative motion of Antarctica and Africa at that time. This is interpreted as showing an interval in which there was dextral strike-slip between Antarctica and Hoorn (still in contact with Africa along the Agulhas fault) along their line of contact in the pre-existing ocean crust of the Weddell Sea, giving a distinctive shape to the subsequent magnetic anomalies once that strike-slip fault line (transform) became a new ridge/spreading axis after about 144 Ma. It has been noted some time ago (Reeves *et al*., 2016) that this geometry is identical to that of the outboard margin of the Mozambique Rise – also a strike-slip feature in the same Africa-Antarctica ocean-growth regime. As with the Davie Fracture Zone off east Africa, this long transform appears to have been activated just as soon as it was geometrically possible to make this connection active as a transform entirely within oceanic crust.

We suggest that, before 144 Ma and consistent with magnetic anomaly evidence in the AAC, growth of the Weddell Sea was in two phases separated at 157.5 Ma. This model is derived from the model of spreading between Africa and Antarctica of Mueller and Jokat (2019). These two fragments represent the still-intact West Gondwana and East Gondwana respectively. Most of the ocean crust created in these two phases was abandoned on the Antarctic side of the new ridge created at about 144 Ma, filling the interior of the Weddell Sea embayment. The post-144 Ma period of rapid spreading between Hoorn and Antarctica continued up until Anomaly-T time (126.11 Ma, M0) and was the most rapid period of ocean growth recorded in this ocean, namely about **20 km/myr** half-spreading rate (40 km/myr full rate).

Movements on the San Matias-Agulhas Fault

A model for the movements of Hoorn must conform to a credible record of what happened on the well-known Agulhas fault and its postulated San Matias extension into South America. Our model has this fault behaving as follows.

Before 157.5 Ma there is only minimal movement (<70 km) between Hoorn and southern Africa (strictly speaking our Southern Kalahari fragment, south of the Mwembishi fault (Reeves & Teasdale, 2019)); the initial movements between East and West Gondwana can occur without significant disruption of Hoorn and the Maurice Ewing Bank (MEB) from the 'fit' positions we give them in Gondwana.

Our model has the onset of dextral movement of Hoorn (but not MEB) along the Agulhas fault at 165 Ma with acceleration to about 27 km/myr 157.5 to 145 Ma and 44 km/myr thereafter. Following the ridge reorganisation at 144.32 Ma, the area between the Malvinas Plateau and the Agulhas fault became transtensional and opened progressively in the later stages of contact between South America and Africa, 137 to 117 Ma. This clockwise rotation of Hoorn away from South America is necessary to achieve, finally, the amount by which the margin of South America is longer than the conjugate margin of Africa (about 180 km). The space created between Hoorn and rigid South America is taken up by westward movement and clockwise rotation of the two continental blocks south of Buenos Aires and creation, by scissor-like opening, of the Salado and Colorado basins that separate these blocks, keeping the San Matias fault closed. We propose that the whole assembly of South America had acquired its present-day configuration by 117 Ma (Figure 4).

We positioned MEB independently of Hoorn as determined by the magnetic anomalies recorded in the so-called Natal valley. Reassuringly for the validity of our model, this resulted in the growth of space between MEB and Hoorn in the interval 157.5 to 138 Ma, after which time there is minimal movement between the two. Stated simply, crustal extension/ocean creation occurred between Hoorn and MEB before 138 Ma and east of MEB after that time.

Before about 138 Ma, there was extension of about 670 km between Hoorn and MEB while the latter stayed almost stationary with respect to Africa. With reorganisation of the triple junction in its vicinity at about 138 Ma, ocean growth started east of the MEB (i.e. in the Natal Valley) and subsequent relative movements between MEB and Hoorn became minimal, though the two were doubtfully fully rigid, given the complexity of the tectonic environment at the time. We have assumed full rigidity of South America only after 117 Ma at which time we have the long term (117-80 Ma) spreading direction in the South Atlantic established. By 117 Ma, the total dextral displacement between Hoorn and the rest of South America is about 870 km.

The Hauterivian sidestep

Several lines of evidence point to important tectonic events occurring over a wide region within a few myr of about **135 Ma** (Reeves & Teasdale, 2019). In global terms, pre-135 Ma tectonism within Gondwana is predominantly the dextral movement of East Gondwana (EGO = ANT+AUS+IND+MAD) against West Gondwana (WGO = SAM+AFR). After about 135 Ma, however, this movement, while continuing, was secondary in magnitude to the separation of 'North Gondwana' (AFR+MAD+IND) from 'South Gondwana' (SAM+ANT+AUS) [with Sri Lanka 'jumping ship' from ANT to IND at the last minute]. In a short period of time, 12 000 km of new ocean ridge became active all the way from West Africa to Western Australia, following this 'sidestep' event. The event is traced by sigmoidal shapes in the ocean-floor topography in the Africa-Antarctica corridor (AAC) (described in Reeves & Teasdale, 2019).

In the AAC the pre-sidestep spreading direction was re-established by about 128 Ma. The Hauterivian sidestep is not evident in the record of the Weddell Sea, we think because the Weddell Sea was separated from the AAC by the head of the Bouvet plume in a position that it retains to the present day, half way between Africa and Antarctica. During the sidestep it was below several smaller continental fragments (MEB, South Georgia, etc) that it appears to have separated effectively from the larger continental masses.

At about 135 Ma we have the outbreak of the Tristan mantle plume and the start of rifting in the South Atlantic, north of the Mwembishi fault, with the consequent eruption of the Parana and Etendeka basalts (recently re-timed to 135 Ma – Renne, 2015). Marine magnetic anomalies off Argentina, South Africa and Namibia show that ocean growth was already well established further south (but north of the Agulhas-Falkland FZ) by this time. By 117 Ma, the pattern of continental dispersion between Africa and South America was established, though the Cretaceous Quiet Zone regrettably does not allow us to constrain the timing of movements well until it ends with Anomaly 34 at 83.64 Ma.

The 126 Ma change in mid-ocean spreading in the Weddell Sea involved changes in both speed and direction. Subsequently only about 300 km of half-growth is seen between well-defined magnetic anomalies M0 (126.11 Ma) and C34 (83.64 Ma) amounting to only about **7.1 km/myr** of half-growth in this interval, about one third of the speed of Weddell Sea growth immediately before 126.11 Ma.

Antarctica and South America

Watching the relative motion of South America and Antarctica since Gondwana break-up in the animation (www.reeves.nl/gondwana;. CR20ABHK, 2020 September 7) shows that the movement of the Patagonian Andes relative to the Antarctic Peninsula may be described in three phases. Before about 117 Ma (i.e. while South America was hingeing away from Africa about a pole near the present-day Gulf of Guinea and before that, while South America was still fixed to Africa) relative displacement between SAM and ANT was achieved by sinistral strike-slip along an alignment west of the Andes and east of the Antarctic Peninsula. This occurred along a line of rifting that developed there in the first of the two pre-144 Ma regimes in the Weddell Sea, starting at the time of Gondwana disruption (about 182 Ma). Hoorn was still attached to Africa at this time.

With the direction change between EGO and WGO at about 157.5 Ma, Hoorn stood in the way of a more southerly progress of Antarctica and was consequently dislodged from Africa and pushed west along the Agulhas fault. This continued until a second ridge reconfiguration occurred at about 144 Ma when accelerated separation between Hoorn and Antarctica commenced and continued until 126.11 Ma. After about 117 Ma, however, the point of contact between continental Antarctica and South America was north of the tip of the Antarctic Peninsula. At this point South America started rounding this tip and moving west with respect to the Antarctic Peninsula by sinistral strike-slip on what is now the Shackleton FZ. This movement was slow at first but then accelerated after about 35 Ma with onset of spreading in the Scotia Sea and, by the present day, has totalled about 1900 km of movement. Oceanic crust of the Antarctic plate totalling about 1000 km has been subducted below the Patagonian Andes by the present day.

We have used the Shackleton FZ as a reference for the relative position of Antarctica and South America as an additional constraint to adjust very slightly the spreading rates in the South Atlantic Ocean (SAM-AFR) and the Africa-Antarctica corridor (AAC) within the accuracy of positions defined in both these trajectories. In other words, we have refined the movements of SAM vs AFR and ANT vs AFR to ensure that the Shackleton FZ remains intact, without lateral compression or extension. The fact that this was possible without offending the accuracy of data in the South Atlantic Ocean and the Africa-Antarctica corridor affirms that the Antarctic Peninsula was an important and rigidly fixed part of Antarctica, at least from the start of the Jurassic, with South America's motion relative to it defined first by N-S dextral strike-slip, turning gradually to E-W directed strike slip (Figure 5).

After about 40 Ma, the westward movement of South America with respect to Antarctica creates space that is taken up mostly by growth of new ocean in the Scotia Sea. Activity in the Scotia Sea was at the expense of growth between the South Orkney Micro-fragment and Antarctica (i.e. the innermost part of the Weddell Sea).

The origin of the sub-Antarctic islands?

Any model of continental dispersion off South America has to be compatible with the geology observed in rare exposures afforded by the few islands in this large area of ocean.

While long the subject of discussion, it now seems evident (from marine seismic data) that the Falkland Islands are not isolated continental fragments in a large area of oceanic crust but merely local outcrops in a large area of otherwise unexposed terrane that is probably contiguous with the continental terranes of southern Patagonia on the South American mainland. The Falkland Islands do, however, lie towards the eastern limit to this terrane and seismic data shows considerable extension in the crust that now joins the Malvinas plateau to the MEB. Our reassembly places the Falkland Islands adjacent to the Coast Land coast of Antarctica. This is about 400 km SE (Africa coordinates) from the often-favoured position off the Natal coast of South Africa. This more northerly position cannot be reconciled with the presence of known continental crust (hosting the North Falkland basin) now known to extend more than 350 km north of the Falkland Islands. Interpretation of a 180 degree rotation of the Falkland Island (Stanca *et al.,* 2019) appears increasingly untenable.

The South Orkney islands have already been discussed and consist of a fragment from the Jurassic rift zone between the Antarctic Peninsula and the Patagonian Andes that rotated counter-clockwise until stranded in its present position south of the more active mid-ocean ridge of the Scotia Sea. The geology of the small islands outcropping off the northern margin of the micro-continent (Trouw *et al.,* 1997) should be compared with that of the two present-day localities with which it should share a common origin on both continents, in the Andes and the Antarctic Peninsula of **West** Antarctica (Figure 3).

By contrast, the island of South Georgia and the submerged banks of Burdwood, Barker, etc would appear to have their Gondwana origin in the rift zone between the southern margin of Hoorn and the Coats Land coast of **East** Antarctica. It is not clear when they were separated from Hoorn. This could have happened, conceivably, immediately after the ocean growth episode at 144 Ma, or much later with the onset of rifting in the Scotia Sea. Both processes could exploit weaknesses resulting from the 182-157.5 Ma dextral rifting we envisage in this area and which follows major known faults such as the Magellanes fault that are known in this area. This area of uncertainty is the ultimate closure of our plate circuit and leads to uncertainty in where exactly we should draw the conjugate margin of Hoorn to the 144.32 margin in the Weddell Sea.

South Atlantic off Brazil

Our earlier models of the closed South Atlantic have drawn criticism on account of the tightness of our fit between Brazil and Angola which does not leave enough room for the known structures of extended continental crust of the Brazilian coast. Our latest model (CR20ABHK) has added extra space in this area by starting the separation of less-tightly closed South America and Africa north of the Mwembishi only at 135.62 Ma. To do this while retaining all the results obtained for reconstructions further south, we have extended the dextral strike-slip we propose for the Mwembishi structure into South America at the latitude of Porto Alegre. At 98 km, this exceeds the 72 km movement on the Mwembishi argued in Reeves & Teasdale (2019). The resulting model retains the sequence of events suggested earlier, namely (1) opening of the South Atlantic south of Rio de la Plata starting before 137 Ma with the onset of transtension in the Agulhas-San Matias fault system; (2) onset of extension north of the Mwembishi-Porto Alegre fault at about 135 Ma; (3) onset of extension between the South American margin between Porto Alegre and Rio de la Plata and the African margin of Namibia as the most recent phase.

We have not invoked any movement on the Orange-Limpopo fault shown in the animation. However, this alignment shows evidence of Karoo-aged (Permian-Triassic) movement in southern Africa. Its extension into South America may be correlated with the earliest rifting in the Salado rift. Similarly, the extension of the Karoo STASS (southern trans-Africa shear system) into South America could have determined the earliest trace of the Colorado rift.

Some 'take-home' points

(a). The Antarctic Peninsula, in its present position with respect to the rest of Antarctica, may be interpreted as a fixed part of Antarctica at least as far back as the 182.7 Ma Gondwana reconstruction, though it was undoubtedly involved in the extensive Gondwanide tectonism in pre-Jurassic times that extended along the whole Pacific margin of Gondwana and particularly West Antarctica.

(b). The Antarctic Peninsula does not lie in the way of dispersing Gondwana while retaining that position; Patagonia (Hoorn, to be precise) can escape from Antarctica past it in a sinistral fashion over the last 180 Ma (Figure 5) as best seen in the animation. These movements are a consequence of the precisely determined positions of Hoorn against Africa, South America and East Antarctica and have not been used as a constraint in our model, apart from a check on the positions of Antarctica and South America with respect to Africa to preserve the integrity of the Shackleton fault in the broader dispersion model.

(c). Only with a careful and tight reconstruction of the whole of the South Atlantic margins can the well-defined geometry of the Agulhas fault be extended meaningfully into South America. Earlier attempts to do this led to the 'invention' of the 'Gastre fault' that was not substantiated in the field and does not conform to careful geometrical analysis (e.g. Watkeys and Soukoutis, 1998). Our San Matias fault is at least 400 km further north and appears, at least at first sight, to fit well with (lack of) outcrop information and gravity and magnetic survey coverage. The fact that it has not yet been discovered is not an argument, then, that it does not exist. The Agulhas fault is an iconic feature of oceanic structure and must have a unique extension into South America. Once the combined structure became transtensional (about 137 Ma), there are more possibilities for multiple faults within South America. The Salado and Colorado systems may be only the main ones. Logic demands a single fault before this time.

(d). The earliest movements of Hoorn involved prolonged dextral strike-slip between the southern margin of Hoorn (the 'sole' of the Malvinas plateau) and Coats Land, Antarctica while the former was part of West Gondwana (WGO) and the latter of East Gondwana (EGO). When the WGO-EGO spreading direction changed, at about 157 Ma, Hoorn was dislodged from its position with respect to Africa and started moving west (i.e. dextrally) along the Agulhas fault while its opposite edge moved sinistrally against the Antarctic Peninsula, exploiting the zone of rifting and/or ocean growth of the earlier regime as a zone of weakness.

(e). Movement of Hoorn along the San Matias-Agulhas FZ may be estimated using the constraints we have used in the model and amounts to about 860 km with respect to the rest of South America. *Evidence for the existence of the San Matias fault is necessary to support our model*.

(f). The Falkland Islands/Malvinas are part of an extensive and integral terrane of continental crust that extends over the area of Patagonia defined here as Hoorn. Only to the east of the Falkland Islands is there crustal extension that now separates this terrane form the MEB and South Georgia.

(g). The South Orkney Islands are part of a small terrane that initially moved away from an origin between the Antarctica Peninsula and the Patagonian Andes and travelled as far north as the tip of the Antarctic Peninsula.

(h). It may be important to note that, at the start of movement of Hoorn against Africa, Hoorn moved to the west in the hotspot reference frame just as fast as Africa moved to the east. This pattern continued even once opening of the South Atlantic had started with the Tristan plume head retaining a central position between Africa and South America in the same way that Bouvet remained central between Africa and Antarctica in the early dispersal process.

(i). Review the animation again (www.reeves.nl/gondwana) to see the way in which all this hangs together!

Brief chronology of events as shown in model CR20ABHK

Gondwana disruption started at **182.7 Ma** with NW-SE-directed extension between EGO and WGO. Geometrically, south of Africa, this would have been pure strike-slip between Antarctica (Coats Land) and Hoorn.

At **157.5 Ma** the direction of EGO-WGO separation changed to a more southerly direction (Africa coordinates). This was not possible without dislodging Hoorn from its original position against Africa. Hoorn started moving west along the Agulhas FZ while the Maurice Ewing Bank stayed in place. About 700 km of new extended crust was created between MEB and Hoorn on the crest of the Bouvet plume.

A maximum of 700 km of extension between Hoorn and Antarctica had been achieved by the end of the Jurassic but most of this oceanic/stretched continental crust was abandoned to Antarctica with the advent of a new mid-ocean ridge, formerly a transform in the Mozambique ocean-Weddell Sea spreading system at about 144.32 Ma (Figure 2).

At about **144.32 Ma** a long transform in the Weddell Sea became a new mid-ocean ridge close to the margin of the Malvinas plateau (Hoorn) and initiated the clearly-defined M-series magnetic anomalies in the Weddell Sea. The active ridge between Africa and Antarctica jumped to outboard of the Mozambique Rise position at about 137 Ma. Identical ridge geometry existed north and south of Limpopia where a 500 km southward ridge jump was achieved by the first ridge to separate Limpopia from Antarctica. Perpendicular spreading between Hoorn and Coats Land started shortly before this time. The ridge between Hoorn and MEB jumped to **east** of MEB (i.e. the Natal Valley) at about 137 Ma.

Several events are determined in time by anomaly M18, 144.32 Ma, after which time major reorganisation of ocean growth takes place in the interval 138-128 Ma. We see the Bouvet plume-head as central to these events. It appears to anchor the SWIR in its vicinity and it always has above this head the smaller fragments of continental material such as Limpopia, MEB, South Georgia, etc . The Bouvet plume remains centrally between Africa and Antarctica and close the Bouvet triple junction throughout the Cretaceous.

It may be speculated that the major meteorite impact at Morokweng (145.1 Ma, Maier et al, 2006) - which was centred only about 1000 km from the centre of the Bouvet plume head - could have acted as the trigger for some or all of these plate margin reorganisations around southern Africa at this time.

After about **135 Ma,** the main (northern) section of the South Atlantic Ocean started rifting but was not yet joined to the southern parts on account of dextral movement on the Mwembishi FZ moving southern Africa westward by about 75 km, despite ocean already existing further south. By this time Hoorn was about 750 km west of its original position with respect to South America in the Gondwana assembly. This increased to about 850 km by 117 Ma

At about **126 Ma** (M0) the ridge in the Weddell Sea was coincident with Anomaly-T. The position of the main South American block immediately north of Hoorn is well-determined at this time by M0 anomalies in the Atlantic Ocean.

By **117 Ma**, all fragments of mainland South America (including the Falkland Islands, the MEB and the two blocks separated by the Salado and Colorado rifts) were in their present-day positions as part of the South America plate. Growth of the whole South Atlantic, south of the Gulf of Guinea, became margin-normal.

At about **30 Ma** the Drake Passage opened with consequences for global ocean circulation and the climate of a newly-isolated Antarctica in particular.

Colin Reeves

Delft, 2020 September `15.

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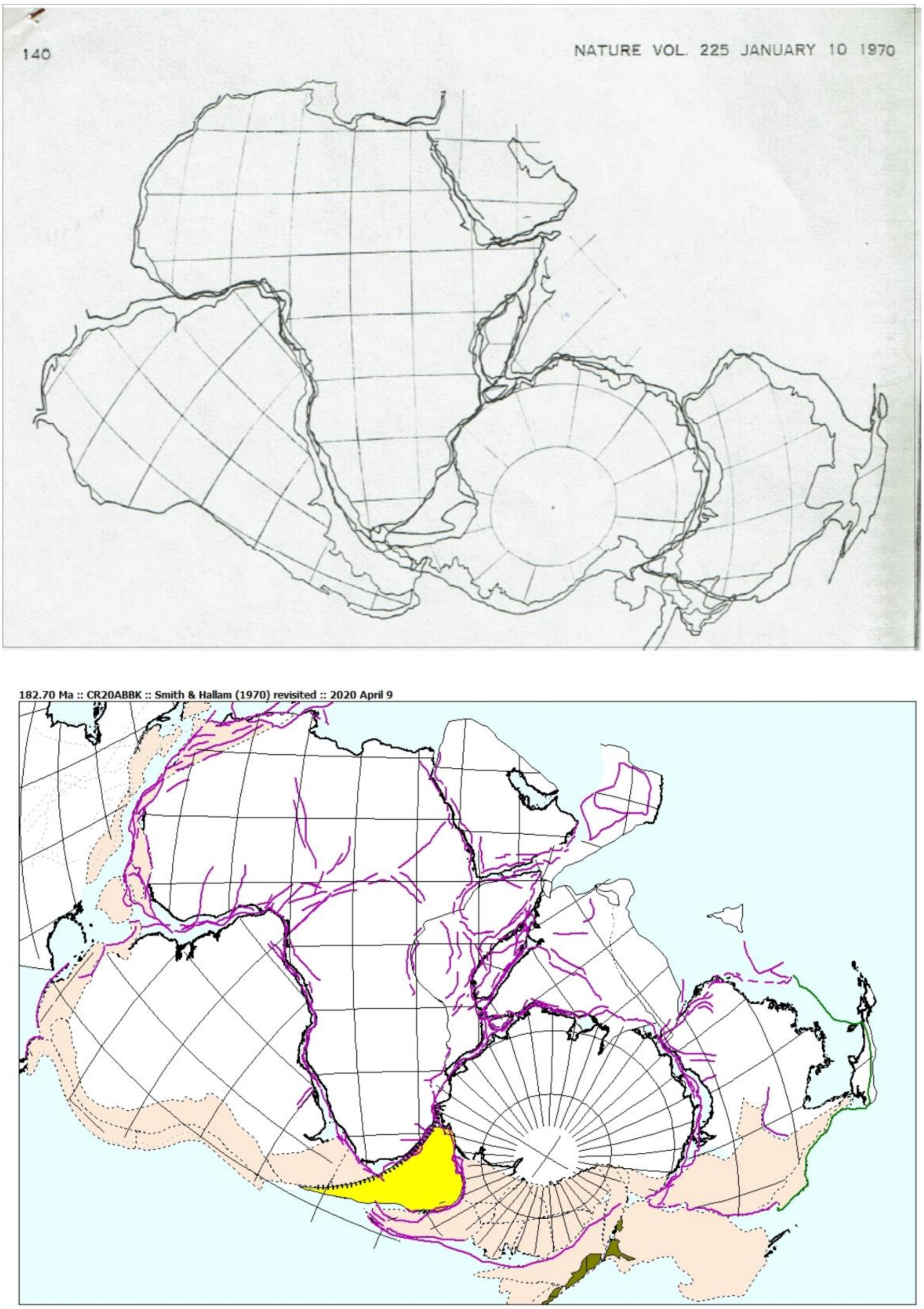

Figure 1. *Above:* The fit of the southern continents from Smith & Hallam, 1970. *Below:* the fit advocated in this paper with 'Hoorn' – that part of Patagonia lying south of the postulated San Matias fault in Patagonia – shaded in yellow.

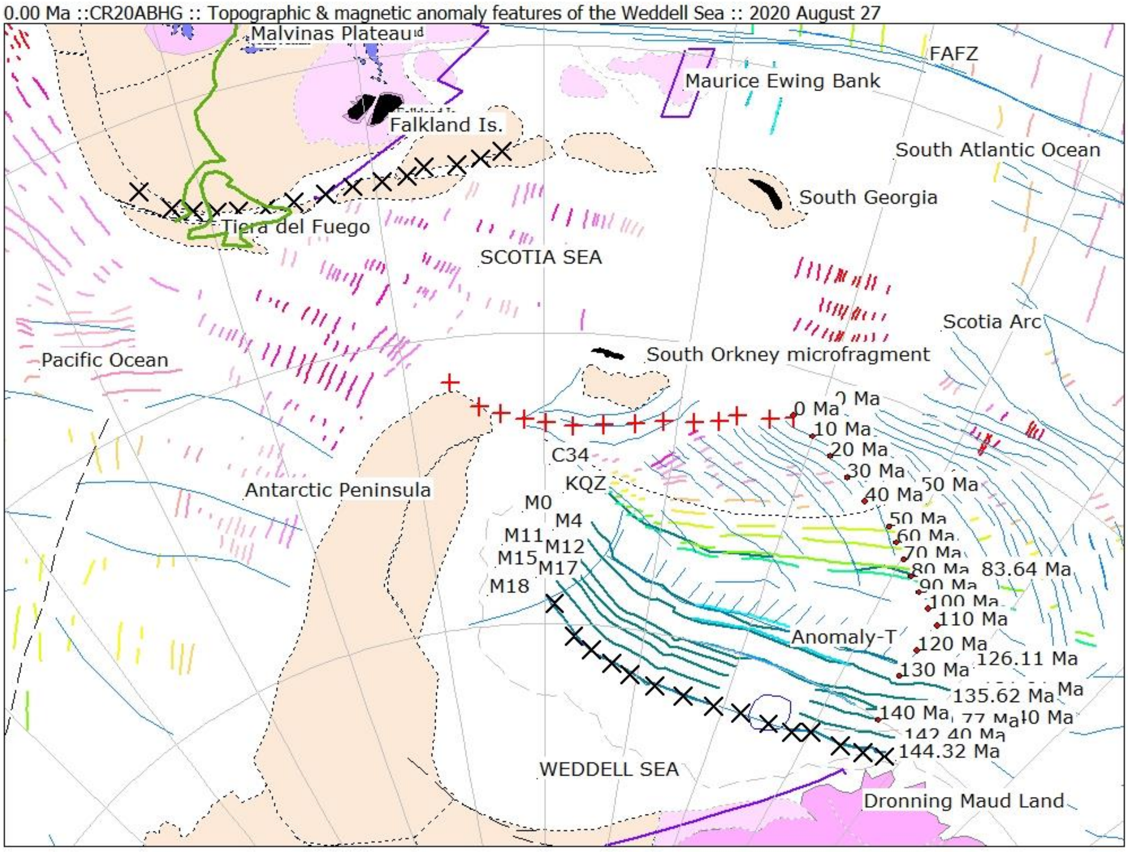

Figure 2. Main features of the Weddell Sea. Thin blue lines are the topographic expression of fracture zones and transforms. Short coloured lines are picks of marine magnetic anomalies, coloured by age. Thick dark green lines closest to Antarctica are the magnetic anomalies (Konig & Jokat, 2006) used to derive paleo ridge positions between 145 and 125 Ma in this study. The two rows of black diagonal crosses off Antarctica and Patagonia were conjugate at 144.32 Ma (M18). The vertical red crosses belong to the mid-ocean ridge that was originally created between these two conjugate margins at that time and that has subsequently created the fan-shaped topographic features that characterise the Weddell Sea, outboard of Anomaly-T, as South America moved first north and then west with respect to Antarctica. Mid-ocean ridge positions at intervals of 10 myr are shown as red dots.

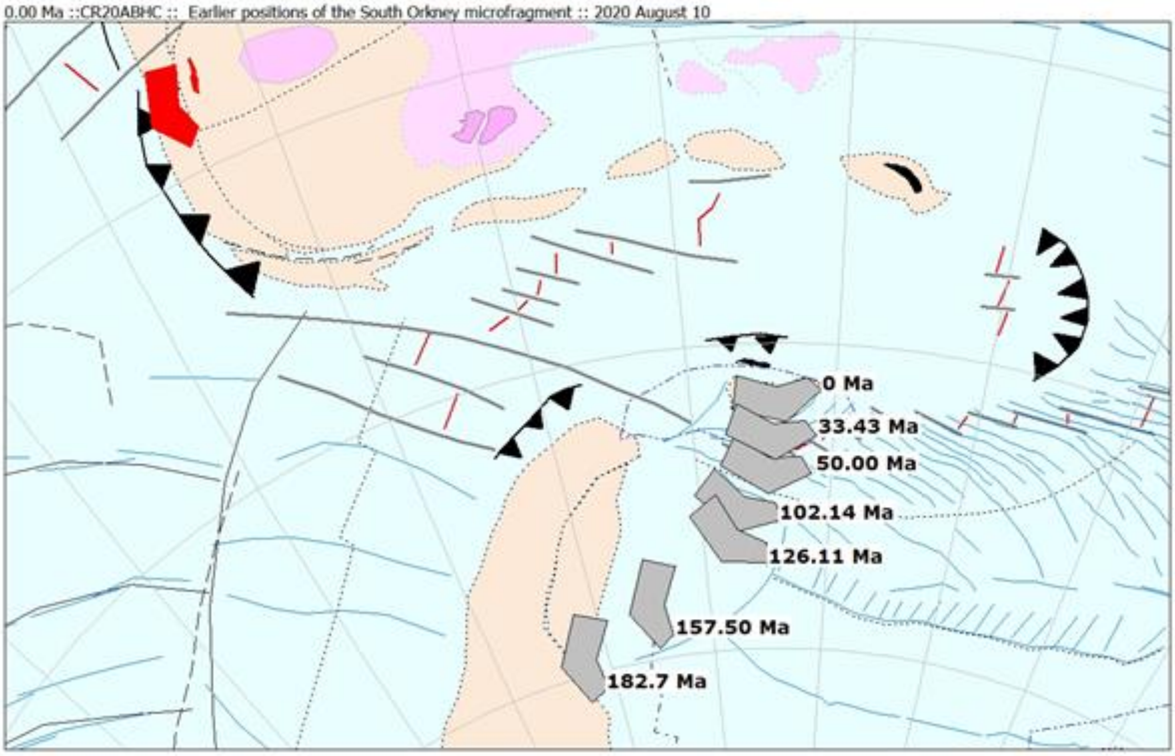

Figure 3. The anti-clockwise rotation of the main outboard part of the South Orkney microfragment away from the Antarctic Peninsula during opening of the Weddell Sea. The position of the same fragment is shown in red for the position with respect to South America at the Gondwana 'fit' position. The outline of the South Orkney Islands themselves is shown in black, just to the north of the main fragment.

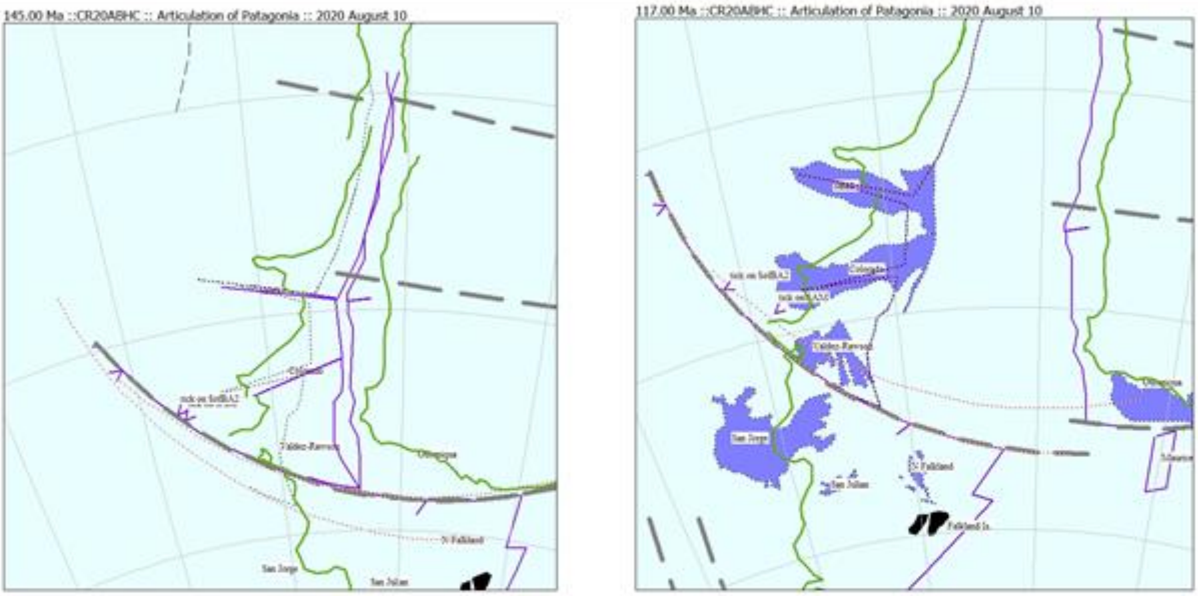

Figure 4. Left: Patagonia rifts closed, South Atlantic re-assembled. Purple lines mark block margins, green lines the coastlines of South America and South Africa/Namibia. Dashed lines show the positions of the purple lines once rifts are fully opened, as at 117 Ma (right). Outlines of basins in Patagonia and offshore South Africa in blue.

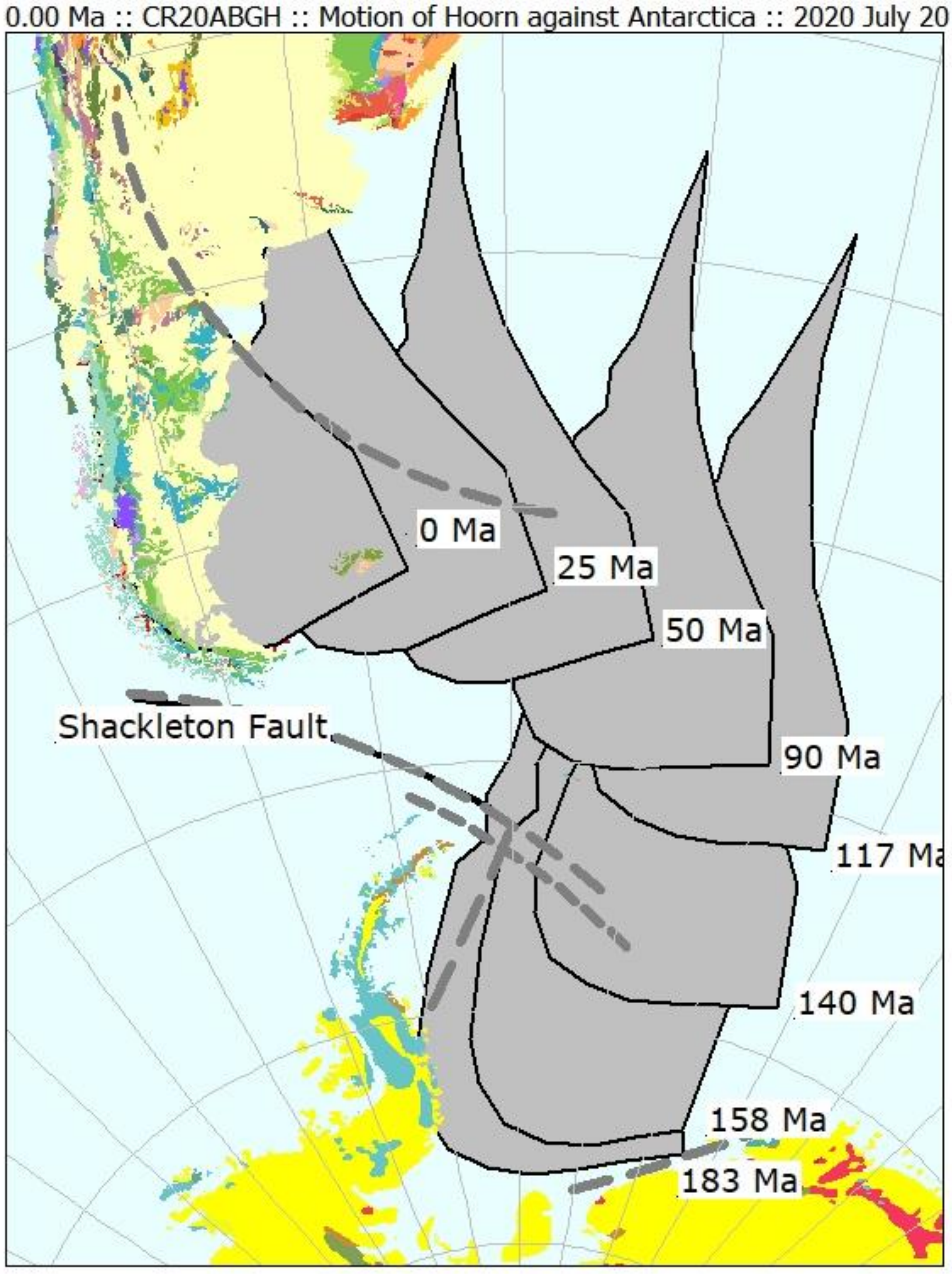

Figure 5. The movement of Hoorn against Antarctica from Gondwana break-up to the present day.