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- First vibroseis exploration of Antarctic sub-ice geology
- Explora Wedge enables first tight fit of South Africa and East Antarctica

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Reassembling Gondwana: A new high quality constraint from vibroseis exploration of the sub-ice shelf geology of the East Antarctic continental margin

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Abstract The breakup of Gondwana is manifested by coeval early Jurassic Karoo magmatism in South Africa and East Antarctica. In South Africa, the large volumes of volcanic rocks of the adjoining Lebombo and Mwenetzi-Save monoclines represent a volcanic rift margin, and in East Antarctica, a corresponding feature, the Explora Wedge is buried below sediments and floating ice shelves on the continental margin of Dronning Maud Land. We use the seismic vibrator source to explore the sub-ice geology in Antarctica, and the new seismic reflection and available regional aeromagnetic data enable us to outline a dogleg landward extent of the Explora Wedge in Dronning Maud Land. The congruent inboard wedge geometries on the two continents define a high quality constraint, which facilitate for the first time, a geologically consistent and tight reconstruction of Africa relative to East Antarctica within Gondwana. The uncertainties in correlations of major geological features (mobile belts) from one continent to the other may now be of the order of ten's of kilometers rather than hundreds of kilometers.

1. Introduction

Our efforts to reconstruct the initial position of Africa relative to East Antarctica with sufficient fidelity have been limited to oceanic areas and the presence of magnetic lineations correlatable to the geomagnetic polarity time scale [*Norton and Sclater*, 1979; *Martin and Hartnady*, 1986; *König and Jokat*, 2006; *Leinweber and Jokat*, 2012]. The main uncertainties east of South Africa are the nature of the crust forming the submarine Mozambique Ridge [*Thompson et al.*, 1982; *Ben Avraham et al.*, 1995; *König and Jokat*, 2010; *Leinweber and Jokat*, 2011], basement below the submarine Northern Natal Valley [*Goodlad et al.*, 1982; *Tikku et al.*, 2007] and below the Mozambique Coastal Plain [*Gwavava et al.*, 1992; *Leinweber and Jokat*, 2011] (Figure 1). Along the East Antarctic continental margin, the issues have been the extent of a volcanic wedge generated through Jurassic rifting and seafloor spreading [Hinz, 1981; *Hinz and Krause*, 1982; *Cox*, 1992; *Hinz et al.*, 2004], the boundary between continental and oceanic crust [*Hübscher et al.*, 1996; *Leitchenkov et al.*, 1996; *Jokat et al.*, 1996, 2004] or conjugate geological [*Wolmarans and Kent*, 1982; *Barton et al.*, 1987; *Groenewald et al.*, 1995; *Luttinen and Furnes*, 2000; *Frimmel*, 2004; *Grosch et al.*, 2007; *Grantham et al.*, 2011; *Marschall et al.*, 2013] and geophysical markers [*Corner*, 1994; *Sahu*, 2000; *Golynsky and Aleshkova*, 2000; *Riedel et al.*, 2012a, 2012b] such as outline of the Archean Grunehogna Craton, the continuation of the Mozambique Belt, and the East African-Antarctic orogeny into Antarctica [*Groenewald et al.*, 1991; *Jacobs et al.*, 1993, 1998; *Shackleton*, 1996; *Engvik et al.*, 2007]. The consequence of considering areas of unknown thick crust as either extended continental or transitional has been "loose" fits [*Martin and Hartnady*, 1986] and implied that the onset of seafloor spreading was delayed by 25–30 million years relative to the Jurassic volcanic event [*Watkeys*, 2002]. On the other hand, the "tight" fit of *Lawver et al.* [1998] obtained by matching the Lebombo monocline of volcanics in South Africa with the easternmost occurrence of Jurassic volcanics of Heimefrontfjella in Dronning Maud Land, East Antarctica (Figure 1), produces an unacceptable overlap between the East Antarctic Grunehogna Craton and its African counterpart, the Kapvaal Craton west of the Lebombo monocline. *Reeves et al.* [2002] tentatively assume that the initial position of known Precambrian crust of the two continents should be no more than 50–100 km apart.

Here, we image the landward extent of the Explora Wedge below a floating ice shelf on the continental margin of East Antarctic (Figure 2) by seismic reflection measurements using a vibroseis source—a first on the

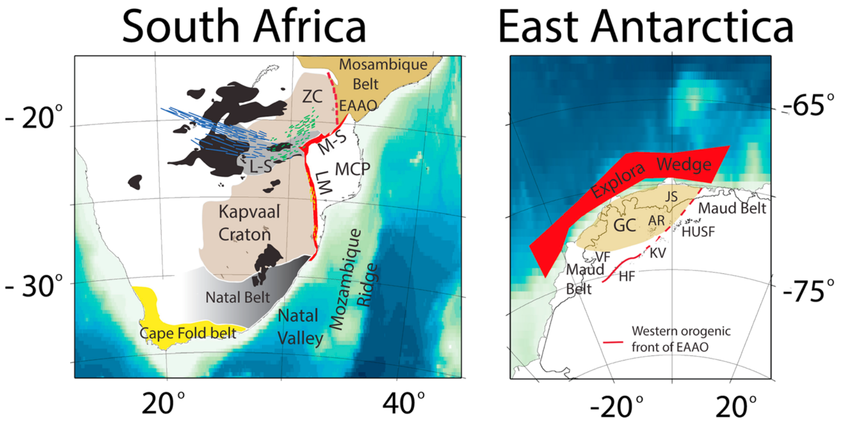

Figure 1. Location of outcrops of the Jurassic rift volcanics, the Lebombo (LM), and Mwenetzi-Save (M-S) monoclines (red) in South Africa and the submarine extent of the Explora Wedge (red) offshore East Antarctica. Outcrops of other Karoo volcanics in South Africa shown by black color. The Kapvaal Craton in South Africa and the Grunehogna Craton (GC) in East Antarctica are considered geological equivalents. Dyke swarms in South Africa are the Okavango (blue), the Limpopo-Save (green), and the Lemombo (yellow) dyke swarms. Other features are L-P; Limpopo-Save structural belt, MCP; Mozambique Coastal Plain, ZC; Zimbabwe Craton, and in East Antarctica: VF; Vestfjella, HF; Heimefrontfjella, KV; Kirwanveggen, AR; Ahlmanryggen, HUSF; H.U. Sverdrupfjella; and JS; Jutulstraumen ice stream. The domain of the East Africa-Antarctica Orogen (EAAO) is shown by dashed red line separating the Mozambique Belt and the Zimbabwe Craton in Africa and the Maud Belt from the Grunehogna Craton in Antarctica.

Antarctic continent. We use the seismic results in combination with regional aeromagnetic data to define a quality constraint for a tight and geologically consistent reassembly of the two continents.

2. Geological Setting

2.1. South Africa

In eastern South Africa, the N-S trending Lebombo monocline [*du Toit*, 1929; *Bristow and Saggerson*, 1983; *Klausen*, 2009], a 700 km long and 20–50 km wide exposure of east dipping volcanic strata and the adjoining south-dipping Mwenetzi-Save monocline (+250 km long, <40 km wide exposure) in the northeast [*Cox et al.*, 1965] are widely considered the trace of the final Gondwana breakup (Figure 1). These monoclines form a dogleg, coherent geologic unit of lower Jurassic volcanic flows with associated dykes and intrusions that were emplaced within a time span of less than 10 million years after ~184 Ma [*Duncan et al.*, 1997; *Jourdan et al.*, 2007]. A transect of the Lebombo monocline at 24°S (Olifant River) shows nearly 5 km of basalts interbedded with an overlying >3.5 km thick section of rhyodacites [*Klausen*, 2009]. The associated monocline-parallel feeder dyke swarm show a steep oceanward increase in crustal dilation (from <10% to >30%) about 10–12 km east of the landward lava limit, a situation which closely resembles the tectono-magmatic characteristics of the narrow East Greenland volcanic margin [*Klausen*, 2009]. Thinning of the crust at the Lebombo and Mwenetzi-Save monoclines toward the east and south is indicated by the gravity data [*Darracott*, 1974; *Gwavava et al.*, 1992; *Watts*, 2001]. A more comprehensive study by *Leinweber and Jokat* [2011] suggests the Mozambique Coastal plain and the northern Natal Valley are most likely floored by thickened oceanic crust. The Mozambique Ridge has geophysical characteristics [*König and Jokat*, 2010] of a volcanic feature and oceanic basalts have been recovered at DSDP Site 249 and in dredges at four locations over a distance of about 500 km along the southern part [*Thompson et al.*, 1982]. However, the ridge most likely also includes rafts of continental rocks as documented by dredge hauls at other locations over the same part of the ridge [*Ben Avraham et al.*, 1995; *Jokat and the Shipboard Scientific Party*, 2006].

2.2. East Antarctica

The Explora Wedge [*Hinz and Krause*, 1982; *Hinz et al.*, 2004] of seaward dipping reflectors extends over a distance of 1.700 km along the continental slope of Dronning Maud Land, Antarctica from 20°E to 30°W (Figure 1). Its landward extent is unknown and covered by floating ice shelves along the continental margin. The marine seismic reflection images of the Explora Wedge are characterized by an oceanward dipping,

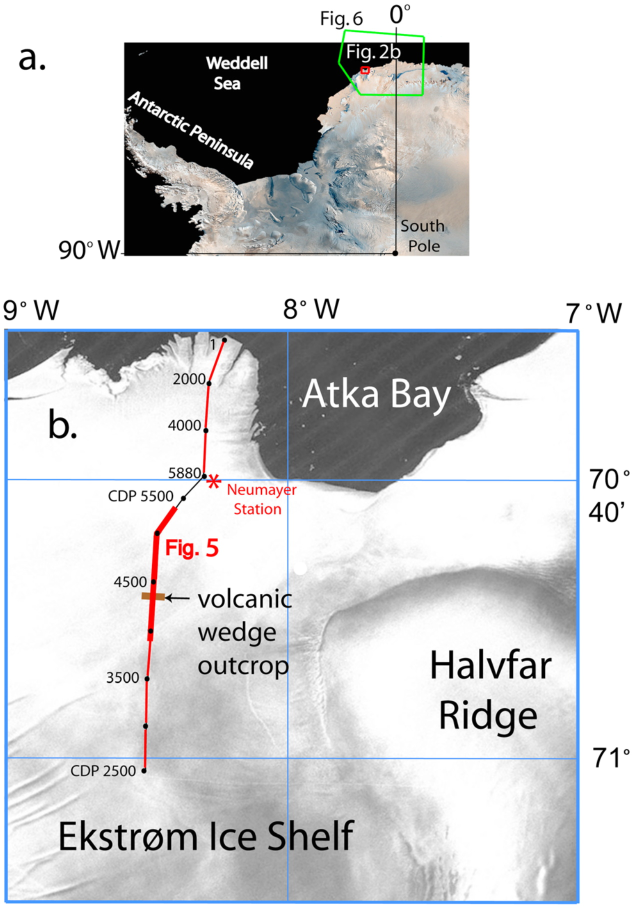

Figure 2. (a) NASA satellite image over the Weddell Sea sector and location of work area. (b) Satellite image (TerraSAR-X 21.01.2011 (c) DLR, 2011) over Ekström Ice Shelf and location of seismic transect. The location of the seismic section shown in Figure 4 is indicated by the thin red line, and details of the Explora Wedge in Figure 5 are shown by heavy red line.

divergent reflector pattern where the upper boundary forms a distinct unconformity to younger deposits while the base of the wedge is difficult to define. The seismic velocities increase with depth from 3 to 4 km/s in the upper part of the wedge to 5 km/s in the lower part. Occasional deeper reflector segments below the continental slope suggest that the wedge thickness may be >5 km. Above the wedge is more than 1.5 km of well stratified sediments which display strong progradation below the shelf edge and upper continental slope [*Hinz and Krause*, 1982].

The general coincidence between the Explora Wedge and magnetic anomalies has been noted by *Johnson et al*. [1992], *Hunter et al*. [1996], and *Riedel et al*. [2012a]. *Leitchenkov et al*. [1996] assigned the landward gradient of a long wavelength magnetic anomaly trend to the transition between thickened igneous crust of the Explora Wedge and "normal" continental crust. *Golynsky and Aleshkova* [2000] explored forward models of possible magnetic source configurations and preferred a scenario where the magnetic signature was predominantly a result of magmatic intrusions into basement rather than a wedge-shaped stack of volcanic flows. The nature of the Explora Wedge has never been tested by scientific drilling, but is inferred to be volcanic based on the combined acoustic and magnetic characteristics and analogy to similar wedges drilled on other continental margins [*Hinz*, 1981; *Menzies et al*., 2002].

The similarity in nature and geometry between the African monoclines and the Explora Wedge offshore East Antarctica [*Cox*, 1992] is considered to be a manifestation of a common origin associated with the Gondwana breakup (Figure 1).

3. Methods

3.1. Field Procedure

The seismic reflection data were acquired using a 16 ton truck-mounted seismic vibrator (Failing Y-1100) as source and recording the signal via a 1500 m long, 60 channel snow streamer, all pulled by a track vehicle (Figure 3a). An essential field party of three produced about 20 line kilometer of eightfold seismic reflection data pr. day.

The first 17 km of profile from the ice shelf terminus to Neumayer III Station (Figure 2b) was covered using the snow streamer configured in a loop with one half of the streamer staggered to obtain a 12.5 m group separation [*Eisen et al*., 2010]. Together with a 6.25 m move-up at each shot point, this yielded a composite record of 120 traces at each shot point along the profile. The distance between shot locations was half the effective streamer length (375 m) to give single fold coverage. The linear sweeps were 10–100 Hz over 10 s. All data south of Neumayer III Station were acquired in 2011 with a straight 1500 m long snow streamer and 100 m move-up between shots to give eightfold data.

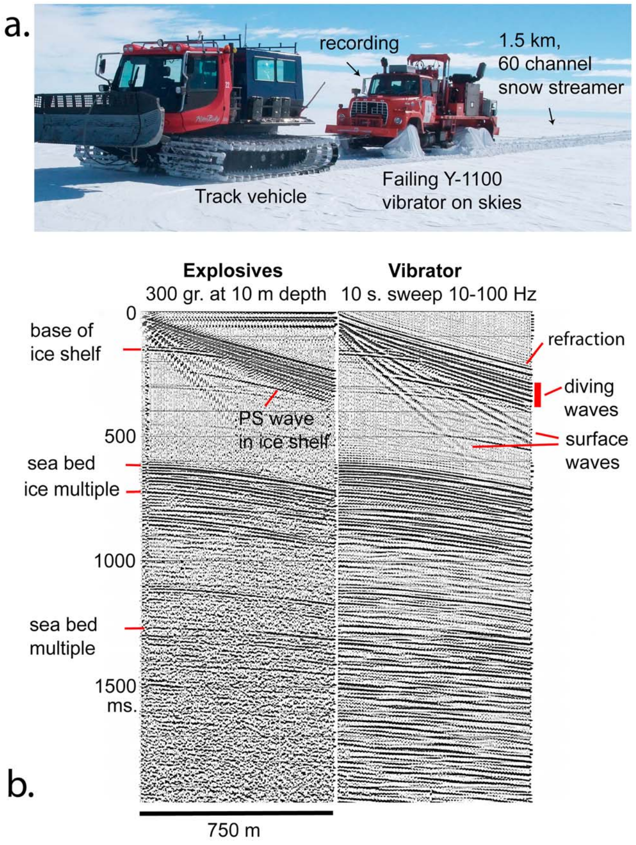

Figure 3. (a) The field unit consisting of a track vehicle towing a seismic vibrator and a 1.5 km long cable consisting of 60 groups of eight gimballed geophones distributed over 25 m along the cable. (b) Comparison of the shot record from an explosive charge of 0.3 kg explosives at 10 m depth and a deconvolved 10 s long vibrator sweep over the frequency range 10–100 Hz. Vertical axis is two-way travel time in ms.

3.2. The Seismic Signal

The field data from each vibrator location were ordered into proper shot-offset geometry and pre-whitened with a 1 s window to improve resolution [*Çoruh and Costain*, 1983]. Only one of the two sweeps recorded at each shot point was used instead of their sum in order to avoid any signal inequalities arising from undetected irregular subsidence of the vibrator pad during a sweep. To obtain a reflection record in the absence of any recorded pilot sweep, the data was cross correlated with a linear synthetic source sweep 10–100 Hz, 10 s long, tapered at both ends (0.5 s) with a Hanning window. The low fold and relatively short offset vibroseis data place limits on processing options. In the case of single fold data, normal move-out velocities were constrained by aligning corresponding reflection events in adjacent shot records, and for the low fold (8) data by visual inspection of scans over a range of move-out velocities. The NMO-corrected single fold data were band pass filtered (40–90 Hz) and deconvolved with a zero phase operator before display, while the stacked eightfold data in addition had Kirchhoff time migration applied.

The efficiency of energy transfer into an accumulating ice sheet is critical to the usefulness of an acoustic surface source. The surface snow in the upper 50–80 m thick firn layer is gradually transformed with depth into glacier ice accompanied by an increase in compressional velocity from about 1 to 3.7 km/s and increase in density from 0.4 to over 0.8 g/cm^3. At low energy densities, the close correspondence between output signal amplitudes of reflected seismic energy recorded by geophones on snow and adjacent geophones planted in permafrost has been documented by *Eiken et al.* [1989]. The vibrator base plate (2.5 m × 1 m) also represents a relatively low energy density stress perturbation where the mesh of snow crystals in the surface layer may respond in a quasi-elastic way and enable relatively efficient energy transfer at least within the frequency range 10–100 Hz. The peak force per unit area (ca. 500 g/cm^2) is roughly equivalent to the force exerted by a heavy person standing on one foot. Walking over the windblown surface of the Ekströmisen Ice Shelf, the boots of an average person sank less than 10 cm into the snow. In this environment, the vibrator pad usually made a 10–20 cm deep depression during an initial unrecorded sweep made to pack the snow, and only a small increment during the subsequent two recorded sweeps. The vibrator drive level was kept constant but reduced to avoid further sudden drops of the pad during the recorded sweeps. A comparison of records from the seismic vibrator and a 0.3 kg charge at 10 m depth at the same location is shown in Figure 3b. The explosive source is richer in higher frequencies relative to the band-limited vibrator source and better resolves acoustic impedance contrasts. The first 0.5 s (two-way travel time) of the cross-correlated record is dominated by a surface refracted arrival (3.6 km/s), multiple surface-reflected diving waves, and dispersive surface waves. Two multiple *P* wave reflections from the base of the floating ice shelf are present and for non-vertical offsets, the arrival following the first *P* wave reflection is converted energy travelling as an *S* wave from the ice-water contact back to the surface (Figure 3b). Below the seabed reflection are superimposed delayed events representing multiple reflections from the base of the ice shelf.

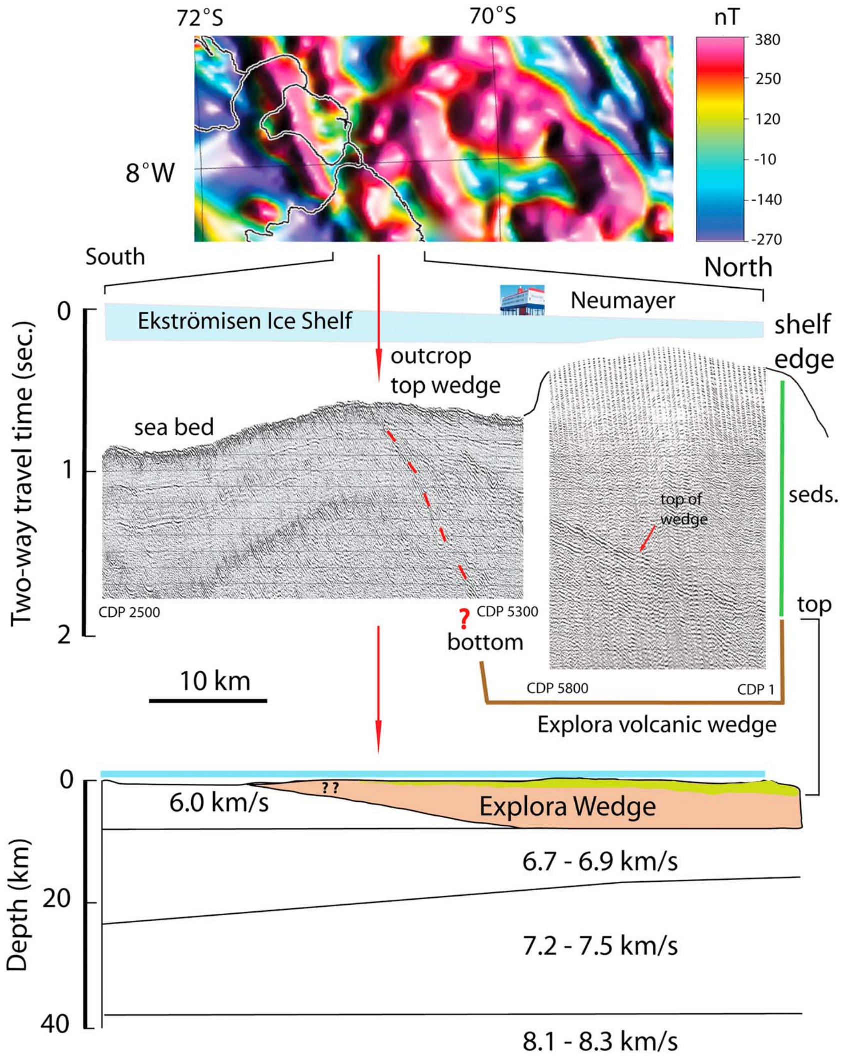

Figure 4. Upper panel: Section of aeromagnetic map across the continental margin at Neumayer III Station from *Golynsky et al.* [2007]. Location of the magnetic data strip is shown by white rectangle in Figure 6. Middle panel: Seismic transect across the continental shelf covered by the Ekström Ice Shelf. Migrated section of eightfold data south of Neumayer III and joined single fold shot panels from Neumayer III to the ice shelf front. Location of seismic sections indicated by thin red line in Figure 2b. Lower panel: Seismic refraction results from *Hübscher et al.* [1996] with same general location as the seismic transect.

4. Results

The seismic reflection transect crosses the East Antarctic continental shelf in Dronning Maud Land over the Ekström Ice Shelf at the German Neumayer III research station (Figure 2). Marine surveys [*Hinz and Krause*, 1982] have defined the Explora Wedge as an oceanward dipping, divergent reflector pattern with a distinct unconformity at the upper boundary about 17 km (from CDP 1 Figure 2) north of the front of the Ekström Ice Shelf. The unconformity at the top of the wedge is at about 2.0 s below the uppermost continental slope with overlying low velocity sequences ($v_p < 3$ km/s) of marine sediments (Figures 4 and 5). A similar acoustic pattern is observed in the vibroseis data at 1.8 s below the front of the Ekström Ice Shelf (Figure 4, CDP 1). The pattern shallows steadily to outcrop at the seabed about 36 km landward of the shelf edge or 14 km south of Neumayer III (Figures 4 and 5). Seaward of the outcrop, discernable irregular reflections appears within the first 0.5 s below the top of the wedge, while acoustic interfaces landward of the outcrop have steeper dips and cannot be followed to greater depths, i.e., >0.3 s below the seabed. These two domains are separated by a distinct steeply dipping reflection (Figure 5). No seismic velocities are obtained from the low fold vibroseis data. *Hübscher et al.* [1996] have carried out an unreversed seismic refraction

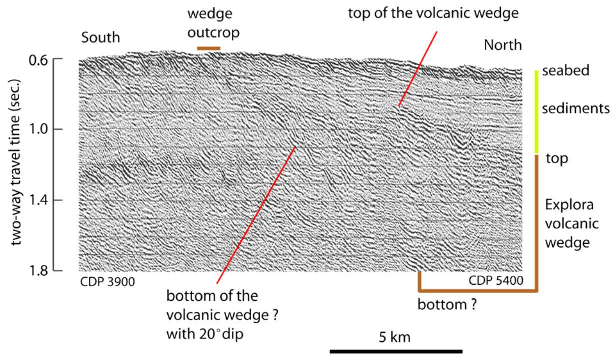

Figure 5. Migrated seismic section showing the outcrop area of the Explora Wedge. Location of section is indicated by heavy red line in Figure 2b.

experiment using a marine seismic source shooting a profile perpendicular to the ice shelf in line with the vibroseis profile and recording with six seismic stations scattered across the Ekström Ice Shelf. Their velocity model shows the top of a wedge-shaped body with $v_p = 4.0–5.4$ km/s tapering out southward north of 71°N (Figure 4). The upper crust below the wedge has velocities in the range of 6.7–6.9 km/s.

5. Interpretation and Discussion

The seismic image of the top of Explora Wedge defined in the marine data is carried to outcrop on the middle continental shelf (Figures 4 and 5). The base and true present landward extent of the Explora Wedge is less clearly defined from the vibroseis data. From the difference in coherency of the sub-bottom reflectivity north and south of the outcropping top of the wedge and the presence of a penetrating distinct reflection event with an apparent dip of 20° (assuming $v_p = 4$ km/s) to the north, we suggest the present wedge apex to be outcropping on the seafloor (Figures 4 and 5). Further support for a thin wedge at this area is the direct coincidence of the wedge outcrop with a linear coast-parallel, positive magnetic anomaly (Figures 4 and 6). The gradient between large positive (red color) and lesser negative (deep blue color) values at the landward edge is positioned directly over the acoustically mapped seabed outcrop. This supports the concept of the magnetic anomaly representing the edge effect of a vanishing magnetization contrast between the weakly magnetized continental crust and an overlying basalt wedge of with higher magnetization. Similar coinciding transitions from low to high amplitude magnetic anomalies and volcanic wedge onsets are observed along the Lebombo monocline [*Leinweber and Jokat*, 2011], continental margin segments off Argentina [*Hinz et al.*, 1999], Namibia [*Bauer et al.*, 2000], and Norway [*Olesen et al.*, 2007]. The refraction results of *Hübscher et al.* [1996] indicate that the Expora Wedge may outcrop across a much wider zone of about 7 km. However, we note that the constraints on this part of the crustal velocity model are limited to two stations south of Neumayer III one being 55 km off-line to the west, and the other 25 km off-line to the east, respectively, relative to the back-projected air-gun shooting direction. Therefore, their sampling of the seismic wave field may be insufficient to yield a representative crustal velocity distribution. Alternatively, the steeply dipping acoustically layered sub-bottom rocks landward of the assigned wedge outcrop (Figure 5) may also include rock assemblages with velocities >5.5 km/s, indistinguishable from the wedge proper. This could be Permian sediments like those outcropping at Vestfjella, Heimefrontfjella, and Kirwanveggen more than 300 km to the south [*Peters*, 1989].

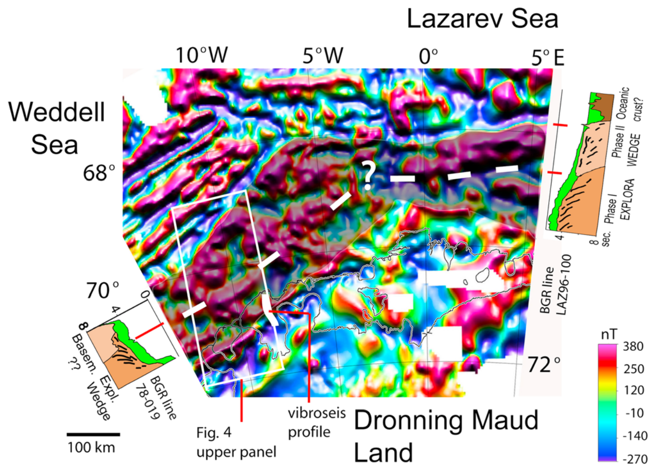

Figure 6. Excerpt of magnetic anomaly map of *Golynsky et al*. [2007] with proposed outline of Explora Wedge indicated by shaded overlay. Location of vibroseis line shown by heavy white line. Line drawing of seismic section in the Lazarev Sea based on *Hinz et al.* [2004] and *Jokat et al.* [2004] and in the eastern Weddell Sea continental margin from *Hinz and Krause* [1982]. Possible continuity of features internal to the Explora Wedge indicated by bold white dashes. Data within rectangle of thin white line is shown in Figure 4 upper panel.

Using the correlation between the distinct linear magnetic anomaly trend and the landward extent of the Explora Wedge below the Ekström Ice Shelf (Figure 4), we may extrapolate the

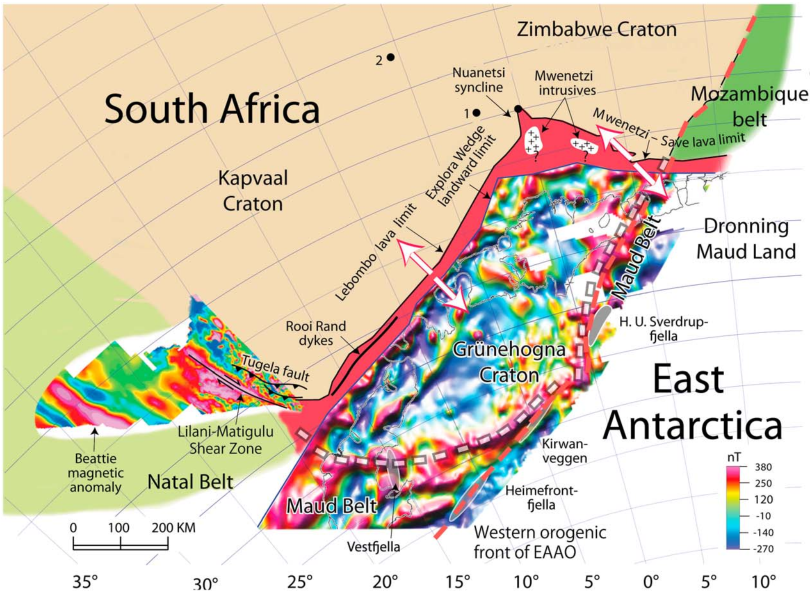

Figure 7. Reconstructed position of South Africa relative to East Antarctica at the time of initial rifting (182 Ma) with an average separation of ~30 km between the landward edges of lava flows of the respective continents (red area). Magnetic anomalies over East Antarctica from *Golynsky et al*. [2007] and from southeast South Africa from *Barritt* [1993]. For comparison, the reconstructed position of the apex of the Nuatensi syncline (black dot) is marked by location 1 in the extrapolated best fit of *Leinweber and Jokat* [2012] and location 2 by the fit of *König and Jokat* [2006]. The calculated direction of initial relative motion (182–159 Ma) shown by white arrows. Suggested limit of Grunehogna Craton from *Marschall et al.* [2013], *Grantham et al*. [2011], *Golynsky and Jacobs* [2001], *Luttinen and Furnes* [2000], and *Corner* [1994] shown by white rectangular dashes.

landward termination of the Explora Wedge along the coast out to about 315 km north-eastward from the vibroseis transect (Figure 6). Here the magnetic anomaly changes to an east-west trend which at 6° E again coincides with the seaward part of the wedge as defined by the marine seismic reflection data [*Hinz et al*., 2004; *Jokat et al*., 2004]. Toward the southwest, the magnetic signature and its associated Explora Wedge termination may be traced for another 350 km from the vibroseis profile passing 8° W about 100 km seaward of the Jurassic volcanics exposed on Vestfjella (Figure 7) and merging with a broader positive magnetic anomaly associated with the eastern flank of the postulated failed rift in the Weddell Embayment [*Kristoffersen and Hinz*, 1991; *Jokat et al*., 2003]. The seaward extent of Explora Wedge is the transition to seafloor spreading type anomalies given by *Jokat et al*. [2003] in the eastern Weddell Sea and in the Lazarev Sea represented by the contrast in crustal structure observed by *Jokat et al*. [2004]. The extent of the Explora Wedge between 15°W and 6°E as outlined by seismic reflection and aeromagnetic data is shown by light shaded overlay in Figure 6, and its inboard geometry mirrors the geometry of the combined Lebombo and Mwenetzi-Save monoclines (Figure 7).

The Explora Wedge includes an inner and outer wedge at 5°E [*Hinz et al*., 2004 LAZ96-100, Figure 6] but abuts a feature interpreted as basement (BGR line 78–019, Figure 6) below the continental slope in the Weddell Sea [*Hinz and Krause*, 1982]. We note an associated change in margin-parallel magnetic anomaly signature (Figure 6, white dashed bold lines) where the amplitudes on the landward side are relatively lower, suggesting a common history in the development of the wedge over its entire length. We speculate that the basement structure shown on BGR line 78–19 [*Hinz and Krause*, 1982] could possibly be of volcanic origin and the contrasting magnetic amplitude domains (relatively low amplitude inner part, high amplitude outer part) of the Explora Wedge along the Dronning Maud Land continental margin could reflect a bimodal pile of contrasting volcanic compositions by analogy with the geology of its pre-drift conjugate, the Lebombo monocline in South Africa. The Lebombo monocline has a landward exposure of nearly 5 km thick basalt underlying more than 3.5 km thick felsic lavas [*Klausen*, 2009]. These magmatic phases are separated in time by 4–5 million years [*Jourdan et al*., 2007]. Development of seaward dipping volcanic wedges tends to occur during distinct episodes as observed along the volcanic Atlantic margins [*Planke et al*., 2000; *Hopper et al*., 2003; *Franke et al*., 2007].

6. Landward Limits of the Juxtaposed Volcanic Wedges: A Quality Constraint for Reassembling Gondwana

To define the pre-breakup position of undeformed continental crust, we need to account for any subsequent magmatic dilation and tectonic extension. The rift process tend to be symmetric along volcanic margins [*Menzies et al*., 2002]; however, the present landward edge of volcanic flows along the rift margin is not a very accurate definition of where continent-ocean transitions begin. Lavas may flow laterally for ten's of kilometers away from and within an initial rift. In addition, the magnitude of subsequent erosion is largely unknown. A more direct and robust measure of magmatic dilation is the lateral increase in the number of dykes feeding the volcanic flows [*Klausen and Larsen*, 2002; *Klausen*, 2009]. *Klausen and Larsen* [2002] used the well-exposed coast-parallel dike swarms of the south-east Greenland volcanic margin to compensate for magmatic and tectonic dilation. They estimated the initial width from an inland hinge zone to the continent-ocean boundary to be no more than ~10 km, suggesting a total initial rift zone ~20 km wide between the Greenland and European plates. The increase in dyke densities at the inland margin of the Northern Lebombo dyke swarm is even greater than in southeast Greenland which could imply an even narrower rift zone, even if the edge of the Lebombo lava pile extends up to ~10 km landward of the maximum curvature of crustal downwarp from the lava load [*Klausen*, 2009]. Following the work of *Klausen* [2009] and *Klausen and Larsen* [2002], we tacitly assume the initial rift zone along the South Africa-East Antarctic plate boundary to be ~20 km wide as inferred from the dikes and furthermore assume the present edge of the conjugate lava piles to extend ~5 km on the average to either side of that, i.e., 30 km between the present day landward lava limits of an initial 20 km wide rift. We recognize that Miocene and younger glacial erosion in East Antarctica may have shifted the landward limit of the Explora Wedge, but the effect would be reduced due to the relatively steep dip (20°) of the interpreted base of the wedge (Figure 5). Keeping East Antarctica fixed, we have reconstructed the relative position of the congruent present edges of the Lebombo/Mwenetzi-Save monoclines and the Explora Wedge assuming an average separation of ~30 km between the respective landward flow limits (Figure 7). The parameter for the total rotation is a pole at 15.4° S, 27.7° W and an angle of 62.12°. The fit between South Africa and Antarctica in the corner region where the Lebombo and Mwenetzi-Save meets shows a discrepancy of ~75 km. This area includes the Nuanetsi syncline of volcanics and the ~40 km wide Mwenetzi granitic and gabbroic intrusions dated at 178–174 Ma [*Jourdan et al*., 2007]. One possibility is that the lava pile here is thicker than elsewhere along the margin and the present landward extent therefore exposed farther inland. Three large contemporary dyke swarms also cross each other in the corner region: the Save-Limpopo (N70°E), the Lebombo (180°), and the Okavango dyke swarms (N110°E) (Figure 1). The Save-Limpopo swarm does only partly follow the Mwenetzi monocline but has the same trend (Figure 1). The Save-Limpopo and the Okavango swarms are synchronous (179 Ma; *Le Gall et al*., 2002), while the plate boundary developed following the Save-Limpopo and the Lebombo trends. To obtain the initial motion of South Africa relative to Antarctica, we subtract the total rotation required to match the oldest marine magnetic isochrones (M33n, 159 Ma, (*Leinweber and Jokat*, 2012) from the total rotation generated by the new fit. The result is shown in Figure 7 by white diverging arrows and predicts near perpendicular rifting at the Lebombo monocline and more oblique rifting at the Mwenetzi-Save rift segment. Field observations by *Le Gall et al*. [2002] also estimate initial unidirectional extension (N160°) from the thickness variations between the N110°E and the N70°E swarms as well as the component of shear observed along dykes of the Okavango swarm. The calculated initial motion covers a time span from c. 182 Ma to Chron M33 (159 Ma), and intervals of more complex motion are very likely as argued by *Klausen* [2009].

The Lebombo- and Mwenetzi monoclines have similar volcanic stratigraphy (Klausen, pers. comm.), but current radiometric age dates suggest that formation of the volcanic rifted margin started with buildup of the main part of the Lebombo monocline within 1–2 million years at c. 182 Ma [*Riley et al*., 2004] followed by magmatism at the Mwenetzi monocline 181–177 Ma [*Jourdan et al*., 2007]. The main dyke swarms (Okavango and Save-Limpopo swarms) were intruded inside the craton and not along its margin within 1–2 million years around 179 Ma and signal onset of significant NNW-SSE extension [*Le Gall et al*., 2002]. Silicic magmatism started at c. 182 Ma at the Lebombo monocline shortly after eruption of the basalts [*Riley et al*., 2004].The emergence of the Rooi Rand dykes (174–172 Ma) with MORB-affinity may be a signal of full oceanization [*Jourdan et al*., 2007].

7. South Africa and East Antarctica United—Continuity of Geological Trends

The ~3.1 Ga. [*Barton et al*., 1987; *Marschall et al*., 2010] Grunehogna Craton in East Antarctica is considered to have been part of a larger entity which included the >3 Ga. old Kapvaal- and Zimbabwe cratons in South

Africa. The Grunehogna Craton is bordered to the east and south by arc-related high grade meta-igneous and meta-sedimentary rocks of the ~1.1 Ga Maud Belt formed during a continental collision [*Arndt et al.*, 1991; *Jacobs et al.*, 2003; *Bisnath and Frimmel*, 2005; *Grosch et al.*, 2007; *Ravikant et al.*, 2007]. The boundary of the craton is constrained by isolated nunataks to the east of Ahlmann-ryggen, west of Kirwanveggen, and north of Heimefrontfjella, a domain framed by a prominent arcuate magnetic anomaly [*Golynsky and Aleshkova*, 1997; *Golynsky and Jacobs*, 2001] (Figure 7). In the new reconstruction, the boundary between the Zimbabwe craton and the Mesoproterozoic Báruè Complex of the Mozambique Belt [*Manhica et al.*, 2008; *Koistinen et al.*, 2008] projects directly into the southwest trend of positive magnetic anomalies at 70°S, 6°E in Dronning Maud Land (Figure 7). This boundary also coincides with the western limit of the late Neoproterozoic-early Paleozoic East African-Antarctica orogeny (EAAO; [*Jacobs et al.*, 2008]). In East Antarctica, this geophysical anomaly may relate to an eastern limit of the Grunehogna craton east of Jutulstraumen as argued by *Grantham et al.* [2011] and *Marschall et al.* [2013], based on similar trace element characteristics of the Mesoproterozoic rocks, and on the geochemical provinciality of Jurassic lavas *Luttinen et al.* [2010]. Alternatively, it could represent the rear end of a Mesoproterozoic continental volcanic arc or simply a major thrust fault formed during the EAAO [*Grosch et al.*, 2007].

In the west, the Tugela Fault and the Lilani-Matigulu Shear Zone [*Jacobs et al.*, 1993; *Watkeys and Sokoutis*, 1998], which mark the transition from the ~1.1 Ga Natal metamorphic province to the Kapvaal Craton (Figure 7), project into the central part of East Antarctica's Vestfjella region as suggested earlier from limited gravity and magnetic data [*Corner*, 1994] and trace element signatures of the Jurassic lavas [*Luttinen and Furnes*, 2000]. Thus, the first direct evidence for a tight fit, inferred from the inland feather-edge of the Exlora Wedge, provides the best correlations of major geological features (mainly mobile belts) across the two craton fragments, with uncertainties in the order of only ten's, rather than hundreds, of kilometers. Also, magmatic and tectonic dilation appears highly symmetric over distances of more than thousand kilometers along the initial plate boundary as suggested by the exposed geology of the South African volcanic monoclines and the highly congruent extent of the East Antarctic counterpart, the Explora Wedge.

8. Conclusions

Reconstruction of South Africa and East Antarctica in Gondwana requires an ensemble of conjugate geological markers but is hampered by the scarcity of accessible geological outcrops on the Antarctic continent. However, geophysical surveys offshore Dronning Maud Land have outlined a wedge of seaward dipping reflectors (the Explora Wedge) which extends for $>$1.700 km along the continental margin. The nature of the wedge has never been tested by drilling but inferred from its geophysical characteristics to have been formed by volcanism and crustal extension during breakup between South Africa and East Antarctica. The Explora Wedge has its conjugate counterparts in the Lebombo and Mwenetzi-Save monoclines of South Africa, and the unknown landward extent of Explora Wedge is critical for a tight reconstruction between South Africa and Antarctica.

We have carried out the first seismic reflection measurements in Antarctica using a vibroseis source across the Ekström Ice Shelf in Dronning Maud Land to extend the offshore marine seismic stratigraphy on to the continental shelf.

The acoustic patterns which define the top of the Explora Wedge below the continental slope outcrop at the seabed below the floating ice shelf about 14 km south of the German Neumayer III station. The base of the wedge is poorly imaged but is interpreted from the seismic and magnetic data to merge with the top interface near the outcrop location and thereby define the landward extent of the presumed volcanic? wedge. A well defined, near coast-parallel linear magnetic anomaly coincidental with this wedge outcrop represents a transition between a landward low amplitude domain and a seaward domain of linear anomalies (southern end of shaded zone in Figure 6). These geophysical characteristics are used to trace the continued landward limit of the Explora Wedge, along the Dronning Maud Land continental margin between 20°W and 7°E. The extent of this landward limit forms a dogleg geometry conspicuously congruent with the Lebombo and Mwenetzi-Save monoclines of South Africa and presents a new constraint for reconstructing the relative position of South Africa and East Antarctica in Gondwana. We assume a 30 km wide symmetric initial rift estimated from the magmatic dilation observed by the lateral increase in the number of dykes observed in the Olifant section of the Lebombo monocline [*Klausen*, 2009] and assume the present edge of the conjugate lava piles to extend ~5 km on the average to either side of the location of maximum dyke density. The new fit provides good correlations of juxtaposed age-equivalent mobile belts and craton fragments on the two continents, with uncertainties on the order of only ten's, rather than hundreds, of kilometers. Furthermore, juxtaposition of the South African and East Antarctic wedges documents the high degree of symmetry in development of a volcanic margin. The average initial motion during the time span between breakup (c. 182 Ma) and Chron 33 (159 Ma) is perpendicular rifting along the Lebombo segment and oblique motion along the Mwenetzi-Save segment but has most likely been more complex.

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