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The heterogeneous crustal architecture of the Falkland Plateau Basin

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Abstract

Continental break-up can be oftentimes associated with intracontinental wrenching that can lead to the generation of transform margins and transform marginal plateaus. The wrenching phase can be accompanied by complicated processes, which result in heterogeneous structural and crustal architectures. This makes understanding the evolution of such tectonic settings challenging. The Falkland Plateau is an example of a transform marginal plateau where regional wrenching accompanied the incipient stages of Gondwanan continental break-up to result in a mosaic of crustal types underlying its largest basin: the Falkland Plateau Basin (FPB). The uncertainties in crustal boundaries have led to several models for the evolution of the plateau, which hinder the development of a reliable plate reconstruction of Southern Gondwana. We integrate seismic reflection, gravity and magnetic data to propose an updated crustal architecture of the FPB. The results show that extended continental crust underlies the basin in the west and north. The eastern and central parts consist of a juxtaposition of intruded and underplated continental crust which transitions southwards to a thick oceanic domain. The basin is crosscut by three main NE–SW trending shear zones which facilitated the development of the contrasting crustal and structural domains interpreted across the plateau. This integrated reassessment of the FPB provides new insights into the tectonic evolution of the plateau, the deformation associated with wrenching and transform margin formation and our understanding of the tectono-stratigraphic evolution of such areas.

KEYWORDS
crustal architecture, Falkland Plateau Basin

1 | INTRODUCTION

Continental break-up can be accompanied by intracontinental wrenching and the development of transform margins, which in turn can be associated with the formation of transform marginal plateaus (Loncke et al., 2020; Mercier de Lépinay et al., 2016). Typically, these types of tectonic settings display complicated tectono-stratigraphic architectures due to high degrees of faulting and fragmentation of the crust, volcanism, localized tectonic, thermal and/or flexural uplift (Attoh et al., 2004; Basile, 2015; Basile & Allemand, 2002; Mascle & Blarez, 1987; Scrutton, 1979). The resulting tectono-stratigraphy provides a heterogeneous record of the evolution of such areas. Their assessment is challenging, and an integrated approach to analysis is crucial to understand the structure of these environments.

The Falkland Plateau is an example of a transform marginal plateau (sensu Loncke et al., 2020), bounded to the north by a transform fault (Figure 1a), which formed at the junction between Africa, South America and Antarctica during the break-up and dispersal of Gondwana (Figure 2b). Numerous studies, based on seismic reflection and refraction, gravity and magnetic data, have documented offshore fault networks and developed stratigraphic and crustal models for the plateau (Baristeas et al., 2013; Bry et al., 2004; Del Ben & Mallardi, 2004; Eagles & Eisermann, 2020; Kimbell & Richards, 2008; Lohr & Underhill, 2015; Lorenzo & Mutter, 1988; Ludwig et al., 1978; Schimschal & Jokat, 2017, 2019a, 2019b; Schreider et al., 2011). However, there are still uncertainties regarding the distribution of crustal types across the plateau, which limits the elucidation of the evolution and reconstruction of the Falkland Plateau Basin (FPB). This in turn hinders reconstruction of the prebreak-up plate configuration in south-western Gondwana.

We integrate regional 2D and 3D seismic reflection data, global open-source gravity data (Sandwell et al., 2014) and magnetic data (Eagles & Eisermann, 2020) to assess the crustal architecture of the FPB. We discuss the implications of the results on the overall crustal architecture and evolution of the Falkland Plateau.

Highlights

- The Falkland Plateau Basin is underlain by a mosaic of continental to oceanic crust.
- The crustal architecture suggests a complicated Jurassic tectonic history of the plateau.
- The interpreted crustal extents highly impact the plate reconstruction of the plateau.

2 | GEOLOGICAL BACKGROUND

2.1 | Tectonic context of the Falkland Plateau

The Falkland Plateau is a transform marginal plateau extending eastward from the continental shelf of South America (Figure 1a). The northern boundary of the plateau corresponds to the Agulhas-Falkland Fracture Zone (AFFZ), which is a long dextral strike-slip fault that accommodated the opening of the South Atlantic (Ben-Avraham et al., 1993). To the south, the plateau is bounded by the sinistral North Scotia Ridge (Ludwig, 1983), and to the east, it merges with the Georgia Basin (Lorenzo & Mutter, 1988; Figure 1a,b).

The formation of the present-day configuration of the Falkland Plateau started during the incipient stages of south-western Gondwanan break-up (Figure 3). The plateau was subsequently affected by the opening of the Atlantic Ocean in the Mesozoic and Late Cretaceous—Cenozoic oblique compression from the south related to the development of the North Scotia Ridge (Bry et al., 2004; Cunningham et al., 1998; Eagles, 2000; Lorenzo & Mutter, 1988). These tectonic events resulted in a series of crustal and structural provinces along the plateau: the Falkland Islands surrounded by the Malvinas Basin, the North Falkland Basin, the South Falkland Basin and the FPB to the west, north, south and east, respectively (Figure 1b), and the Maurice Ewing Bank (Figure 1b), which is the easternmost province of the plateau. The North Falkland Basin is further subdivided into the Jurassic Southern North Falkland Basin and the Upper Jurassic–Lower Cretaceous North Falkland Graben (Lohr & Underhill, 2015; Stanca et al., 2019). The FPB consists of the Volunteer sub-basin to the northwest and the Fitzroy sub-basin in the west and southwest; the two sub-basins are separated by the Berkeley Arch basement high (Dodd & McCarthy, 2016; Rockhopper Exploration Plc., 2012).

Some authors argue that the Falkland Islands are part of a separate microplate (the Falkland Islands Microplate, FIM sensu Richards, Gatliff, Quinn, & Fannin, 1996; Stanca et al., 2019, 2021, and this paper; the Falkland Platform sensu Marshall, 1994; the Falkland Islands Block sensu Storey et al., 1999; the Lafonia Microplate sensu Ben-Avraham et al., 1993; Dalziel et al., 2013). This microplate would represent a domain of the Falkland Plateau, has a debatable extent (inset in Figure 1a) and is believed to have undergone a vertical-axis clockwise rotation during the break-up of south-western Gondwana (Adie, 1952; Curtis & Hyam, 1998; Macdonald et al., 2003; Marshall, 1994; Mitchell et al., 1986; Mussett & Taylor, 1994; Stanca et al., 2019, 2021; Stone et al., 2009; Storey et al., 1999; Trewin et al., 2002). The existence of this microplate and its evolution are, however, not unanimously accepted (Eagles & Eisermann, 2020; Lawrence et al., 1999; Lovecchio et al., 2019; Ramos, 2008; Ramos et al., 2017).

The nature of the crust underlying the Falkland Plateau was directly influenced by the evolution of the FIM during the fragmentation of south-western Gondwana and remains subject to debate. Correlations between geological and geophysical data from the Falkland Islands and South Africa led to the development of the rotational theory that argues for a clockwise rotation of the proposed FIM of up to 120° (configurations [1] and [3] in Figure 2a; Adie, 1952; Crowell & Frakes, 1972; Curtis & Hyam, 1998; Dalziel et al., 2013; Frakes & Crowell, 1967; Macdonald et al., 2003; Marshall, 1994; Mitchell et al., 1986; Mussett & Taylor, 1994; Stanca et al., 2019, 2021; Stone et al., 2009; Storey et al., 1999; Thomson, 1998; Thomas et al., 1997; Trewin et al., 2002). The lack of documented evidence for this rotation in the sedimentary infill of the basins surrounding the islands (Richards, Gatliff, Quinn, Fannin, & Williamson, 1996) and the absence of a mechanism to accommodate this rotation led several authors to favour a nonrotational model (Figure 2a [2]; Eagles & Eisermann, 2020; Lawrence et al., 1999; Lovecchio et al., 2019; Ramos, 2008; Ramos et al., 2017). In this model, the Falkland Islands were in a similar position relative to South America prior to the break-up of Gondwana as today (Eagles & Eisermann, 2020; Lawrence et al., 1999; Lovecchio et al., 2019; Ramos, 2008; Ramos et al., 2017), and the fragmentation of the supercontinent was recorded by extension in the sedimentary basins around the islands.

2.2 | Architecture of the Falkland Plateau Basin

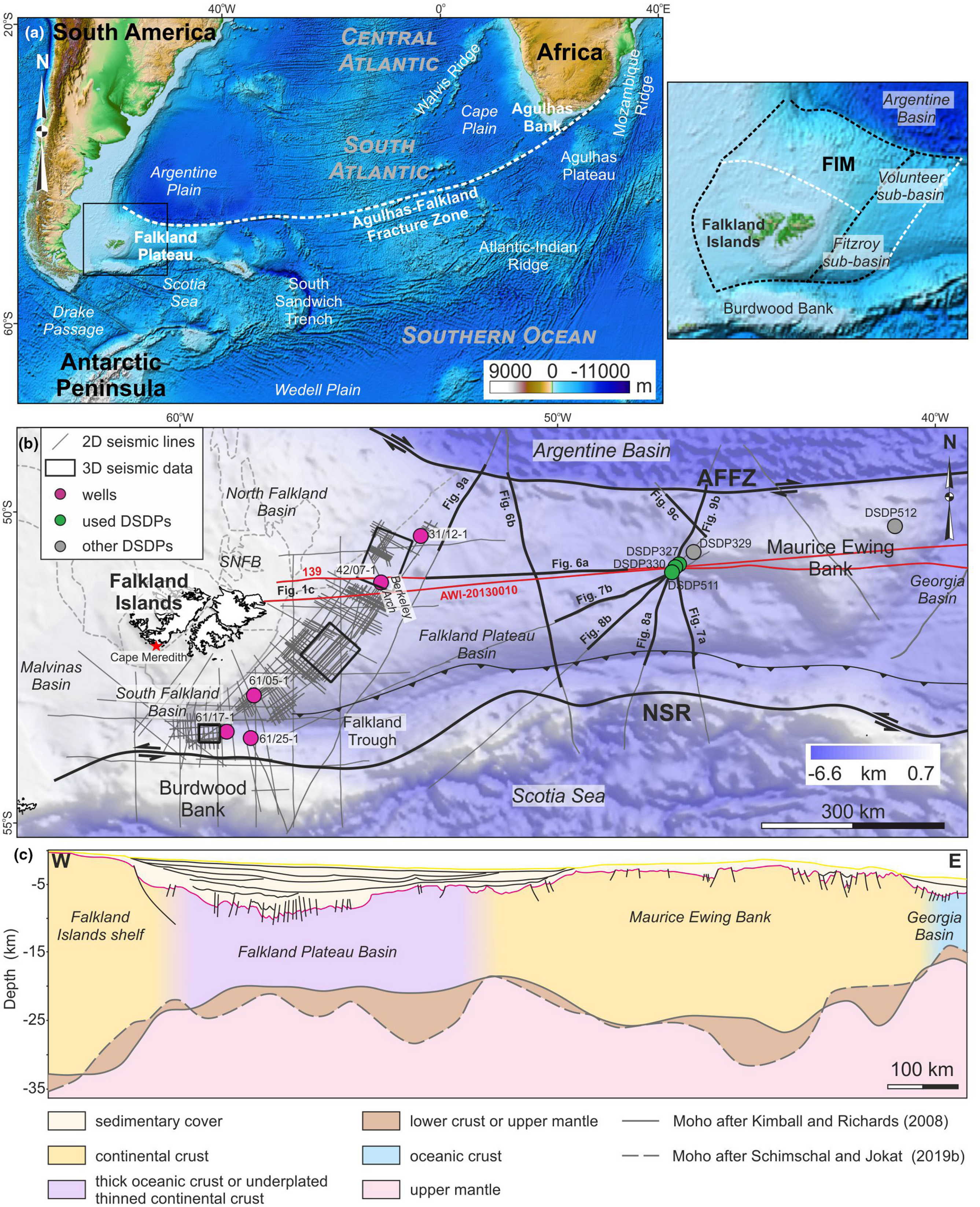
2.2.1 | Tectono-stratigraphy of the Falkland Plateau Basin

The present-day tectono-stratigraphic architecture of the Falkland Plateau is the result of multiple tectonic events that started as early as the Permian and has been most recently affected by the formation of the Scotia Sea (Cunningham et al., 1998; Hodgkinson, 2002; Stone, 2016). Evidence of the Permo-Triassic collisional episode, which resulted in the formation of the trans-Gondwanian orogen, seen today in the Sierra de la Ventana (South Argentina), Cape Mountains (South Africa) and Ellsworth Whitmore Terrane / Ellsworth Mountains Block and Pensacola Mountains (Antarctica), was recorded by the onshore geology of the Falkland Islands (Dalziel et al., 2000; Du Toit, 1937; Thomas et al., 1993; Trouw & De Wit, 1999) and influenced the architecture of the offshore Mesozoic sedimentary basins that formed during the break-up of Gondwana (Richards & Fannin, 1997).

Currently, the only area of the Falkland Plateau that crops out above sea level are the Falkland Islands, which range in age from Neoproterozoic gneisses (Cape Meredith Complex) through Siluro-Devonian quartz-rich sandstones and conglomerates with intercalated siltstones and mudstones (West Falkland Group) to Permo-Carboniferous glacial deposits and mudstone-dominated successions (Lafonian Supergroup; Figure 2a; Aldiss & Edwards, 1999; Curtis & Hyam, 1998). The architecture of the islands was strongly influenced by Permo-Triassic folds and thrusts associated with compression and dextral transpression (Aldiss & Edwards, 1999; Curtis & Hyam, 1998; Stone, 2016). The inheritance of this structural grain played a major role in the formation of the Southern North Falkland Basin and the western margin of the FPB (Lohr & Underhill, 2015; Richards & Fannin, 1997; Stanca et al., 2019, 2021). During and following the fragmentation of Gondwana, the Falkland Plateau underwent extension which resulted in the formation of four sedimentary basins: the Malvinas Basin, the North Falkland Basin, the South Falkland Basin and the FPB (Figure 1b).

The FPB extends east of the islands and comprises two sub-basins nearshore: the Fitzroy and Volunteer sub-basins. Its western margin consists of a series of NE–SW trending normal faults (Richards, Gatliff, Quinn, & Fannin, 1996; Richards, Gatliff, Quinn, Fannin, & Williamson, 1996; Figure 2b), and to the east. the basin terminates against the Maurice Ewing Bank. Seismic reflection data interpretation suggests that the youngest deposits affected by major normal faults within the basin fill are of Late Jurassic age (Lorenzo & Mutter, 1988; Richards, Gatliff, Quinn, Fannin, & Williamson, 1996). FPB rifting was interpreted to have occurred during the Permo-Jurassic (Richards, Gatliff, Quinn, Fannin, & Williamson, 1996), although some authors postulate a continuation of the rifting up to the Early Cretaceous (Lorenzo & Mutter, 1988). However, no well data exist for the oldest syn-rift deposits from the distal parts of the basin to constrain the ages of the deformation. Seismic reflection

FIGURE 1 (a) Present-day configuration of the South Atlantic region showing the location of the Falkland Plateau and the extent of the Agulhas-Falkland Fracture zone; ETOPO1 global relief model (Amante & Eakins, 2009; NOAA National Geophysical Data Center, 2009); dashed lines in the Falkland Plateau inset mark the approximate extent of the potential Falkland Islands Microplate (FIM); white dashed lines show alternative interpretations of the northern and eastern extents of the FIM (Richards, Gatliff, Quinn, & Fannin, 1996; Stanca et al., 2021; Storey et al., 1999). (b) Present-day extent of the Falkland Plateau showing the bounding fracture zones (the dextral Agulhas-Falkland Fracture Zone and sinistral North Scotia Ridge [NSR] along with the NSR thrust front) overlain by the available seismic reflection data and wells used in this study. Bathymetry from GEBCO Compilation Group (2020). DSDP, Deep Sea Drilling Project; SNFB, Southern North Falkland Basin. (c) Alternative interpretations of profile 139: thick oceanic crust or underplated thinned continental crust underlying the Falkland Plateau Basin. Two interpretations for depth to the Mohorovičić (Moho) discontinuity are also shown; the Moho after Schimschal and Jokat (2019b) is estimated along profile AWI-20130010 in (b) and projected along profile 139 for comparison. Line position is shown in (b).



data, presented and interpreted by Stanca et al. (2021), show the presence of Jurassic NE–SW and WNW–ESE trending faults in the northern part of the margin (along the Berkeley Arch and in the Volunteer sub-basin; Figure 2b). These faults are superimposed by Jurassic to Early Cretaceous N–S striking en-échelon normal faults extending into the Fitzroy sub-basin (Figure 2b), suggesting a wrenching element associated with the Mesozoic break-up and extension.

The fragmentation of Gondwana was also associated with extensive volcanism, both onshore and offshore the islands. The Palaeozoic succession cropping-out onshore was intruded by predominantly E–W and NE–SW trending Jurassic dykes, coeval to the Karoo-Ferrar large igneous province formation, and N–S striking Early Cretaceous dykes related to the opening of the South Atlantic (Hole et al., 2016; Mitchell et al., 1999; Mussett & Taylor, 1994; Richards et al., 2013; Stone, 2016; Stone et al., 2008; Figure 2b), although bigger variations in dyke orientations were observed locally. N–S trending Early Cretaceous dykes and sills have been interpreted nearshore and offshore the Falkland Islands, in the Fitzroy and Volunteer sub-basins (Barker, 1999; Richards et al., 2013; Stanca et al., 2021; Figure 2b).

2.2.2 | Crustal distribution along the FPB

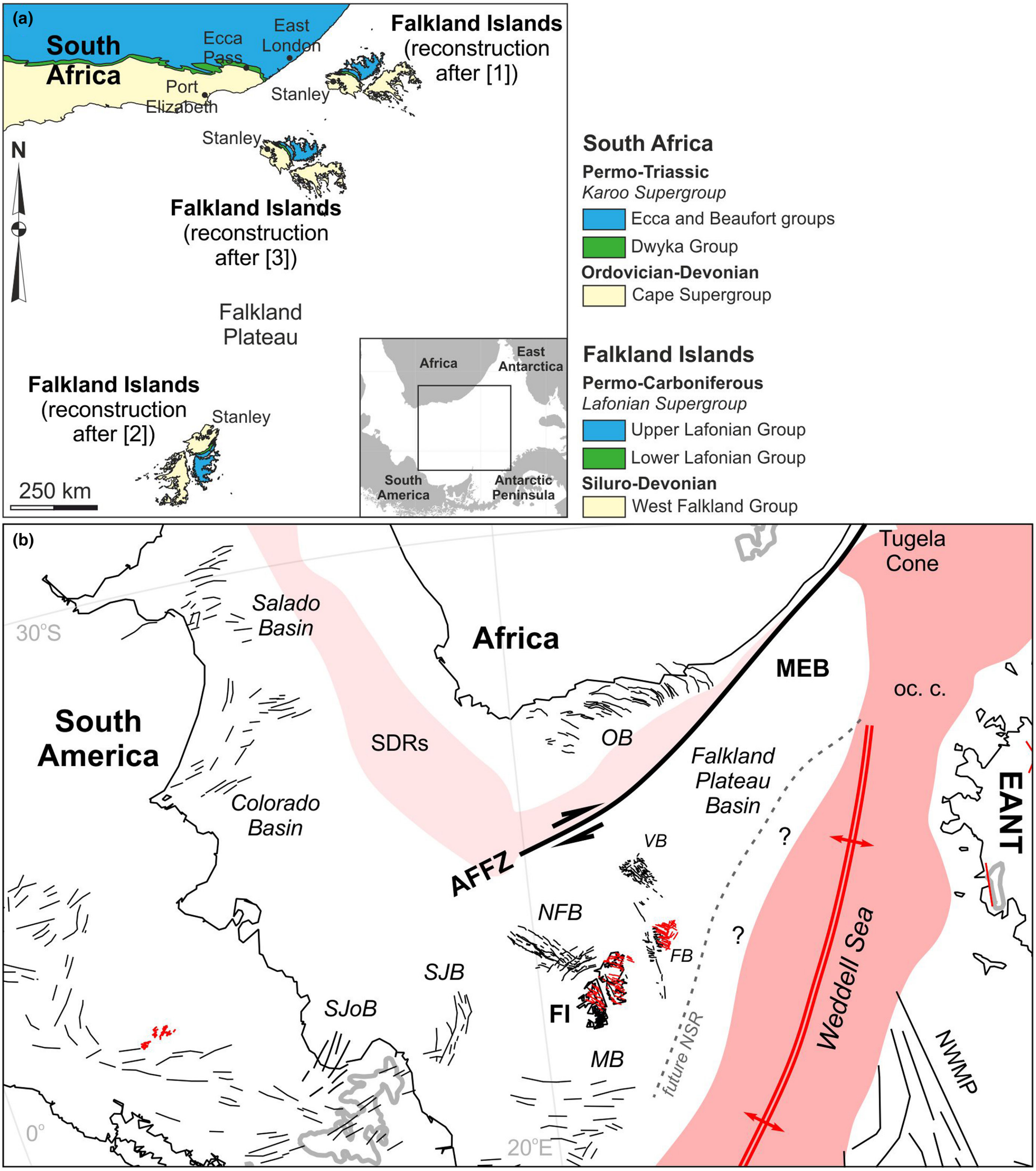
The fragmentation of Gondwana, interpreted by some authors to have been associated with the rotation of the FIM (Adie, 1952; Curtis & Hyam, 1998; Macdonald et al., 2003; Marshall, 1994; Mitchell et al., 1986; Mussett & Taylor, 1994; Stanca et al., 2019, 2021; Stone et al., 2009; Storey et al., 1999; Thomson, 1998; Trewin et al., 2002), resulted in a highly variable tectono-stratigraphy along the Falkland Plateau and a conflicting interpretation of the crustal architecture, particularly across the FPB.

Deep Sea Drilling Project (DSDP) site 330 cored metamorphic and igneous rocks on the western flank of Maurice Ewing Bank (Beckinsale et al., 1977), supporting a continental nature of the block. The cored granites and gneisses are comparable with the ones cropping out in the western part of the Falkland Plateau, onshore the Falkland Islands at Cape Meredith (Beckinsale et al., 1977; Tarney, 1977; Figure 1b), suggesting that the islands and the Maurice Ewing Bank originated from a continuous continental block that underwent extension and/or potential break-up during the fragmentation of Gondwana. This is supported by geochemical and isotopic analyses of their basement lithologies (Chemale et al., 2018).

The seismic refraction study across the Falkland Plateau and Scotia Sea by Ewing et al. (1971) is amongst the first attempts to describe the nature of the crust under the FPB. Based on the estimated velocities, Ewing et al. (1971) interpreted oceanic crust under the Falkland Trough, continental crust in the central part of the FPB (Ewing et al., 1971), whilst the northern escarpment bounding the basin showed velocities corresponding to continental basement. The latter interpretation remains uncertain due to the existence of steeply dipping structures and intense faulting (Ewing et al., 1971).

Further multichannel seismic reflection and sonobuoy reflection/refraction data were acquired during the cruises carried out by the Lamont-Doherty Geological Observatory. Analysis of these data suggested the presence of thick oceanic crust or highly attenuated continental crust underlying the FPB (Lorenzo & Mutter, 1988; Ludwig, 1983). Richards, Gatliff, Quinn, Fannin, and Williamson (1996) interpreted a 16 km thick continental crust in the western part of the basin based on gravity modelling, and Barker (1999) placed the continent–ocean boundary along the NE–SW gravity high SE of the Falkland Islands. Based on gravity inversion and flexural modelling, Kimbell and Richards (2008) interpreted continental crust in the northern part of the FPB along the AFFZ, whereas the rest of the basin was interpreted as being underlain by thick oceanic crust or underplated thinned continental crust (Figure 1c). Schimschal and Jokat (2017, 2019b) used wide-angle seismic data and potential field data modelling along an E–W trending section to confirm the presence of 35 km thick continental crust nearshore East Falkland, followed by a 90 km wide continent–ocean transition zone and a high velocity (up to 7.4 km/s) 11–20 km thick crust underlying the FPB, which was interpreted as thick oceanic crust (Figure 1c). The same authors proposed an interpretation in which the entire FPB is underlain by oceanic

FIGURE 2 (a) Jurassic prebreak-up rotational ([1] and [3]) and nonrotational [2] reconstruction models of the Falkland Islands after [1] Trewin et al. (2002), [2] Ramos (2008) and [3] Stanca et al. (2019). Africa is fixed in its present-day position. (b) Early Cretaceous configuration of south-western Gondwana (base plate model after Müller et al., 2019). Black lines—faults; red lines—dykes; double red line and double arrows—oceanic ridge and spreading direction; grey lines—extent of Chon Aike and Karoo—Dronning Maud Land—Ferrar volcanics. Question marks in the Falkland Plateau Basin mark its uncertain southern extent and relation to the Weddell Sea oceanic crust. Northern Weddell Magnetic Province (NWMP) from Jordan et al. (2017); East Antarctica dykes after Curtis et al. (2008); Patagonia dykes after Rapalini and Lopez de Luchi (2000); Falkland Islands onshore dykes after Stone et al. (2009); FB and VB dykes and faults after Stanca et al. (2021); NFB faults after Lohr and Underhill (2015) and Stanca et al. (2019); South America fault network after Lovecchio et al. (2019); Karoo lavas extent after Jourdan et al. (2007); Chon Aike lavas extent after Bouhier et al. (2017); DML-Ferrar lavas extent after Elliot (1992) and Elliot et al. (1999); Outeniqua Basin fault network after Paton et al. (2006) and Parsiegla et al. (2009); AFFZ, Agulhas-Falkland Fracture zone; EANT, East Antarctica; FB, Fitzroy sub-basin; FI, Falkland Islands; MB, Malvinas Basin; MEB, Maurice Ewing Bank; NFB, North Falkland Basin; NSR, North Scotia Ridge; NWMP, Northern Weddell Magnetic Province; OB, Outeniqua Basin; oc. c., oceanic crust; SDR, seaward dipping reflectors; SJB, San Julian Basin; SJoB, San Jorge Basin; VB, volunteer sub-basin.



crust. Recent aeromagnetic data acquired along the FPB show the presence of linear magnetic anomalies interpreted as reversal isochrons in the south-eastern part of the FPB (Eagles & Eisermann, 2020). Based on this, and the information from the refraction study of Schimschal and Jokat (2017), Eagles and Eisermann (2020) also interpreted a FPB underlain by oceanic crust. However, the seismic refraction survey of Schimschal and Jokat (2017, 2019b) comprises a single profile, which makes extrapolation of the interpretation across the entire FPB unreliable, whereas the aeromagnetic data from the study of Eagles and Eisermann (2020) indicated the presence of oceanic crust with certainty only in the south-eastern corner of the FPB.

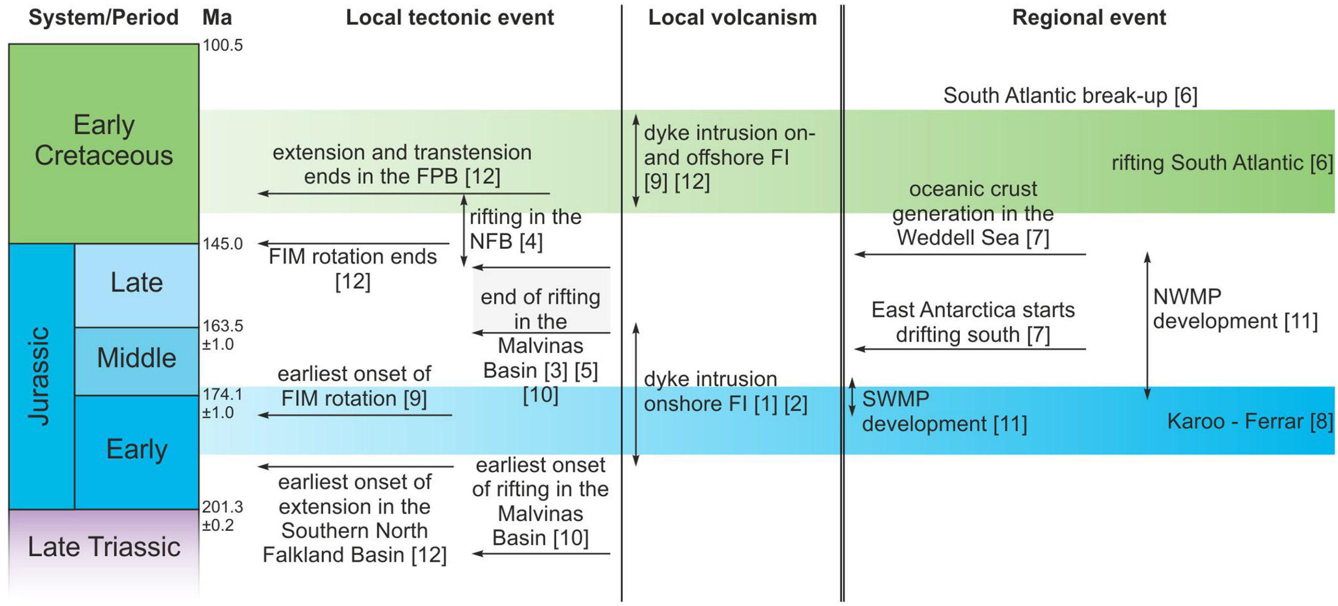


FIGURE 3 Timeline of the main events affecting SW Gondwana from Late Triassic to Early Cretaceous; [1] Mussett and Taylor (1994), [2] Thistlewood et al. (1997), [3] Galeazzi (1998); [4] Richards and Hillier (2000), [5] Baristeas et al. (2013), [6] Heine et al. (2013), [7] König and Jokat (2006), [8] Jourdan et al. (2007), [9] Stone et al. (2008), [10] Lovecchio et al. (2019), [11] Riley et al. (2020) and [12] Stanca et al. (2021). FI, Falkland Islands; FIM, Falkland Islands Microplate; FPB, Falkland Plateau Basin; NFB, North Falkland Basin; NWMP, Northern Weddell Magnetic Province; SWMP, Southern Weddell Magnetic Province.

3 | DATA AND METHODOLOGY

3.1 | Gravity and magnetic data and interpretation

The gravity data consist of the V24.1 1-min satellite altimetry free-air gravity anomaly grid of Sandwell et al. (2014) for the entire Falkland Plateau. We use magnetic data from the AIRLAFONIA aerogeophysical survey (Eagles & Eisermann, 2020) acquired along the FPB by the Alfred Wegener Institute in 2017–2018. The computation of derivatives and testing of filters were carried in Geosoft's Oasis Montaj. Gravity and magnetic lineaments were mapped using the total horizontal derivative (Cordell & Grauch, 1985) and the tilt derivative (function of the ratio between the vertical and horizontal derivatives) (Miller & Singh, 1994; Oruç & Keskinsezer, 2008; Verduzco et al., 2004) of the free-air gravity anomaly and the reduced to pole total magnetic anomaly for the Falkland Plateau. A Butterworth bandpass filter with cut-off wavelengths of 5–70 km (chosen by trial to resolve regional structures constrained by literature or seismic data) was applied to the free-air gravity anomaly data to enhance structural features and delineate areas with potentially different crustal types along the FPB.

3.2 | Seismic reflection data and interpretation

We use 2D and 3D seismic reflection data from seven surveys acquired between 1977 and 2014 by Falklands Oil and Gas Limited, WesternGeco, Noble Energy, Lamont-Doherty Earth Observatory and Geophysical Service Incorporated (Figure 1b). All seismic reflection data have a vertical scale in two-way time (TWT), and the maximum recorded length varies between 6 and 12 s TWT for the 2D data and is equal to 9 s TWT for the 3D data.

Five exploration wells (31/12-1, 41/07-1, 61/05-1, 61/17-1 and 61/25-1) and three DSDP boreholes (sites 327, 330 and 511) were tied to the seismic reflection data for the horizon interpretation stage (Figure 1b). Seismic reflection and well data, with the exception of the open-source Lamont-Doherty Earth Observatory 2D seismic reflection lines and the DSDP borehole data, were provided courtesy of the Falkland Islands Government.

The seismic reflection data were used to interpret the top acoustic basement (or the base of the area characterized by coherent reflectivity, here corresponding to the base of the Mesozoic section), near top Jurassic, and intra-Cretaceous and Cenozoic mega-sequences based on stratal terminations and seismic facies analysis (Hubbard et al., 1985a, 1985b; Mitchum Jr. et al., 1977). Well data directly tied to the seismic reflection data were available nearshore the Falkland Islands and on the Maurice Ewing Bank. Lower levels of certainty characterize the interpretation away from the wells, within the central part of the FPB, particularly for the deeper horizons. Middle Jurassic deposits were only documented by DSDP site 330, on the Maurice Ewing Bank. A Middle Jurassic interface could be interpreted only locally due to the poor quality of the seismic reflection data at depth.

The westward and southward extents of these deposits remain highly uncertain.

Two-dimensional regional seismic reflection lines from the surveys acquired by Lamont-Doherty Earth Observatory, WesternGeco and GSI were used to validate the distribution of crustal types interpreted from gravity and magnetic data. This was carried out by evaluating changes in the seismic character across the Falkland Plateau and changes in amplitude considered a function of volcanism.

4 | RESULTS

4.1 | Gravimetric signature

The bandpass-filtered free-air gravity anomaly shows a mosaic of regions with different gravimetric signatures. In the southern part of the North Falkland Basin, an alternation of linear positive and negative gravity anomalies follows a WNW-ESE strike (Figure 4a). This trend is mapped in the Volunteer sub-basin, ca. 300 km off the coast of East Falkland, where the wavelength of the anomalies is relatively higher (Figure 4a). Underneath the Fitzroy sub-basin, this trend is not readily identifiable. NE–SW oriented anomalies, cross-cutting the entire width of the FPB, are seen along the shelf break (S1) but also truncating the NW-SE trend of the Volunteer sub-basin to the east (S2; Figure 4a). The remainder of the FPB displays a chaotic distribution of gravimetric anomalies which transition eastward to the Maurice Ewing Bank, which is bounded by NW–SE and NE–SW trending lineaments (Figure 4a).

The tilt derivative displays a similar distribution to the bandpass-filtered free-air gravity anomaly, but with a few additions. A third basin-wide break in the gravity response following the same NE–SW trend as S1 and S2 in Figure 4a is identified on this derivative (S3; Figure 4b). This results in a separation of the FPB in two narrow slivers to the west (domains A and B) and a triangular domain to the east (domain C; Figure 4). Another characteristic readily visible on the tilt derivative is a negative, E–W trending anomaly in the northern part of the FPB, parallel to the AFFZ and just south of it (Figure 4b), the nature of which will be addressed in the following sections.

4.2 | Magnetic signature

The available magnetic data show a high amount of variability in the magnetic response from west to east (Figure 5). The region from the eastern coast of the Falkland Islands to the hinge line (S1 in Figure 4a,b) displays N–S, NW–SE and NE–SW trending anomalies (Figure 5a). The hinge line displays isolated NE–SW striking linear magnetic anomalies (Figure 5) which follow the trend of the S1 gravity lineament in Figure 4.

East of S1 (domain A), isolated negative anomalies are separated by a WNW–ESE striking positive magnetic anomaly (Figure 5a,b). These are underlying the Volunteer and Fitzroy sub-basins and the Berkeley Arch, respectively. The areas east and south of the Fitzroy sub-basin show a high positive magnetic response (Figure 5). The magnetic anomaly corresponding to the Berkeley Arch is truncated eastwards (Figure 5b). The location of the truncation corresponds to the S2 in Figure 4a,b.

The remainder of the basin shows two distinct domains separated by S3 in Figure 4. The first one, west of S3 (domain B), shows medium to high positive magnetic anomalies and a chaotic distribution of magnetic lineaments, with trends ranging from NE–SW and N–S to NW–SE (Figure 5). The domain east of S3 (domain C) corresponds to the triangular zone delineated on gravity data west of the Maurice Ewing Bank (Figure 4). This region shows NW–SE to WNW–ESE magnetic stripes in the central and southern part of the domain (Figure 5) which are truncated to the west by S3. The northern part shows predominantly negative anomalies with weak NW–SE lineaments switching to a more WNW–ESE orientation in the vicinity of S3 (Figure 5).

4.3 | Seismic character of the crust

Regional 2D seismic reflection data have been used to constrain the different crustal domains based on gravity and magnetic data. A seismic characterization of the S1 shear zone is reported by Stanca et al. (2021). Based on their interpretation, multiple episodes of roughly E–W-directed extension and dextral transtension and NE–SW sinistral transtension occurred along the S1 from Lower Jurassic to Lower Cretaceous (Stanca et al., 2021). To describe the remainder S2 and S3, two sub-orthogonal seismic profiles crossing these two shear zones are shown in Figure 6, with each one intersecting domain C, between S3 and the Maurice Ewing Bank, in different points. The profiles show a change in the seismic character of the crust underlying the FPB between each of the three domains.

A thick succession of deformed sedimentary deposits of (pre?) Jurassic age are interpreted to extend up to 300 km offshore in the Volunteer sub-basin (Figure 6a). Along and east of the S2 the seismic reflection data show evidence of a high degree of faulting resulting in depocentres infilled by Jurassic and potentially older sediments (Figure 6a). The remainder of the crust up to the Maurice Ewing Bank is characterized by high amplitudes

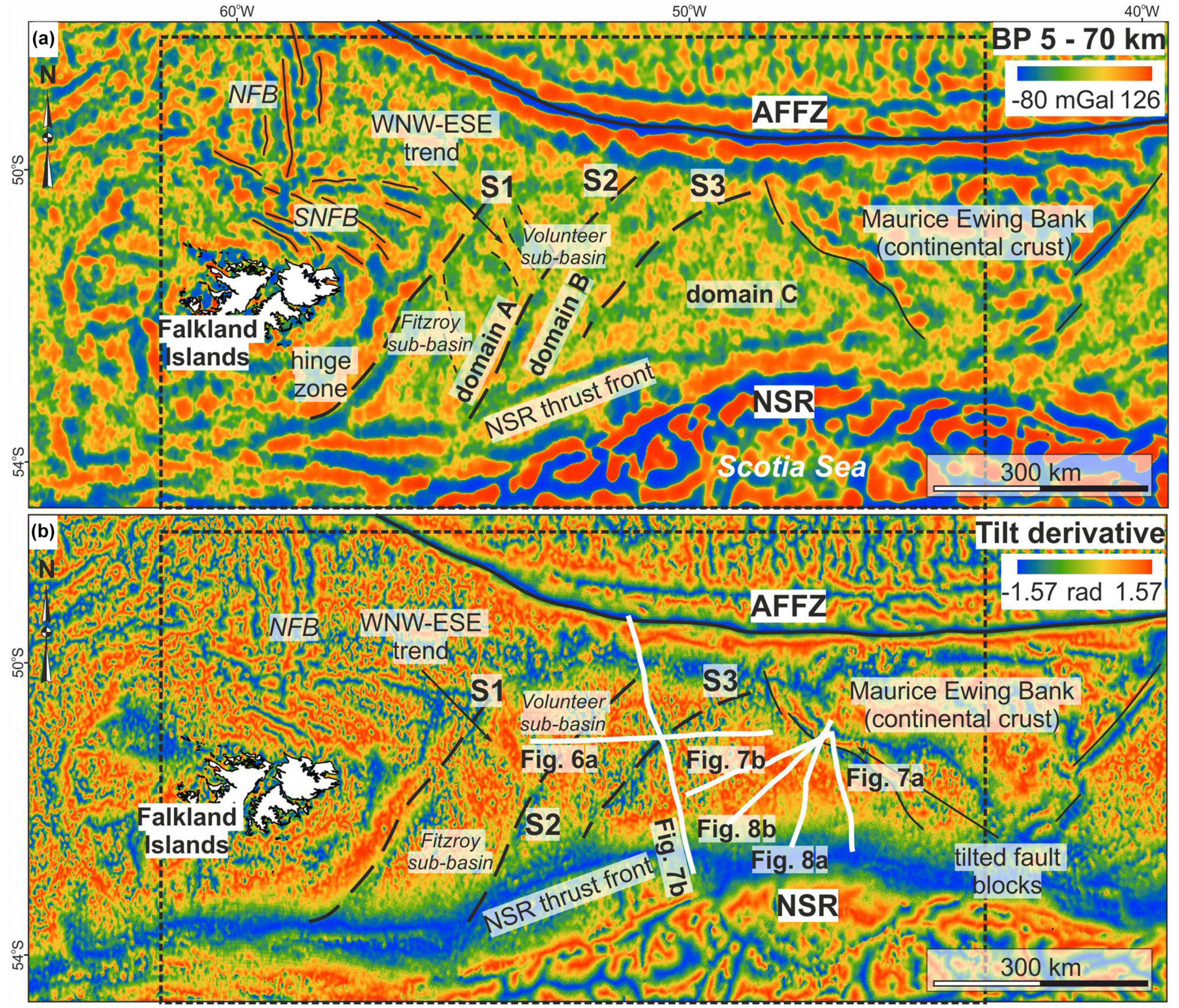


FIGURE 4 (a) Bandpass-filtered free-air gravity anomaly showing the trend of the North Falkland Basin (NFB) and Southern North Falkland Basin (SNFB; Stanca et al., 2019) and the NE–SW potential shear zones (S1–S3). (b) Changes in the gravity signature as shown by the tilt derivative. Black dashed lines mark potential fracture zones/crustal block boundaries. White lines—seismic reflection data cross sections in Figures 6–8; dashed rectangle—extent of maps in Figure 5. Free-air gravity anomaly data source: Sandwell et al. (2014).

in the uppermost part and seismic transparency at depth. The crust is in an elevated position relative to the rest of the basin on the E–W striking seismic line and covered by a thin veneer of Jurassic sediments (Figure 6a). This segment corresponds to the northern part of domain C in Figures 4 and 5 which is associated with a negative magnetic response. A mound was identified in the eastern part of the section (Figure 6a), which correlates with a magnetic lineament on the magnetic data (Figure 5a). Thicker deposits are readily visible on either side of this features with potentially Middle Jurassic deposits onlapping its eastern flank (Figure 6).

The ~N–S trending seismic line crosses the S2–S3 shear zones and terminates in the southern part of domain C, characterized my magnetic stripes (Figure 6b). The architecture of the basin fill and the seismic character varies abruptly southwards. A highly elevated, transparent crustal block is juxtaposed against the AFFZ and represents the northern boundary of a ca. 8 s TWT deep depocentre infilled by Jurassic and potentially older sediments. Further south, the infill of this depocentre onlaps a crustal domain characterized by high amplitudes and covered by a thin layer of pre-Upper Jurassic (?) deposits bounded at the top by an erosional unconformity (Figure 6b).

The seismic response at S2 is either associated with high degrees of faulting (Figure 6a and the shallow part of section in Figure 6b) or seismic transparency (deeper

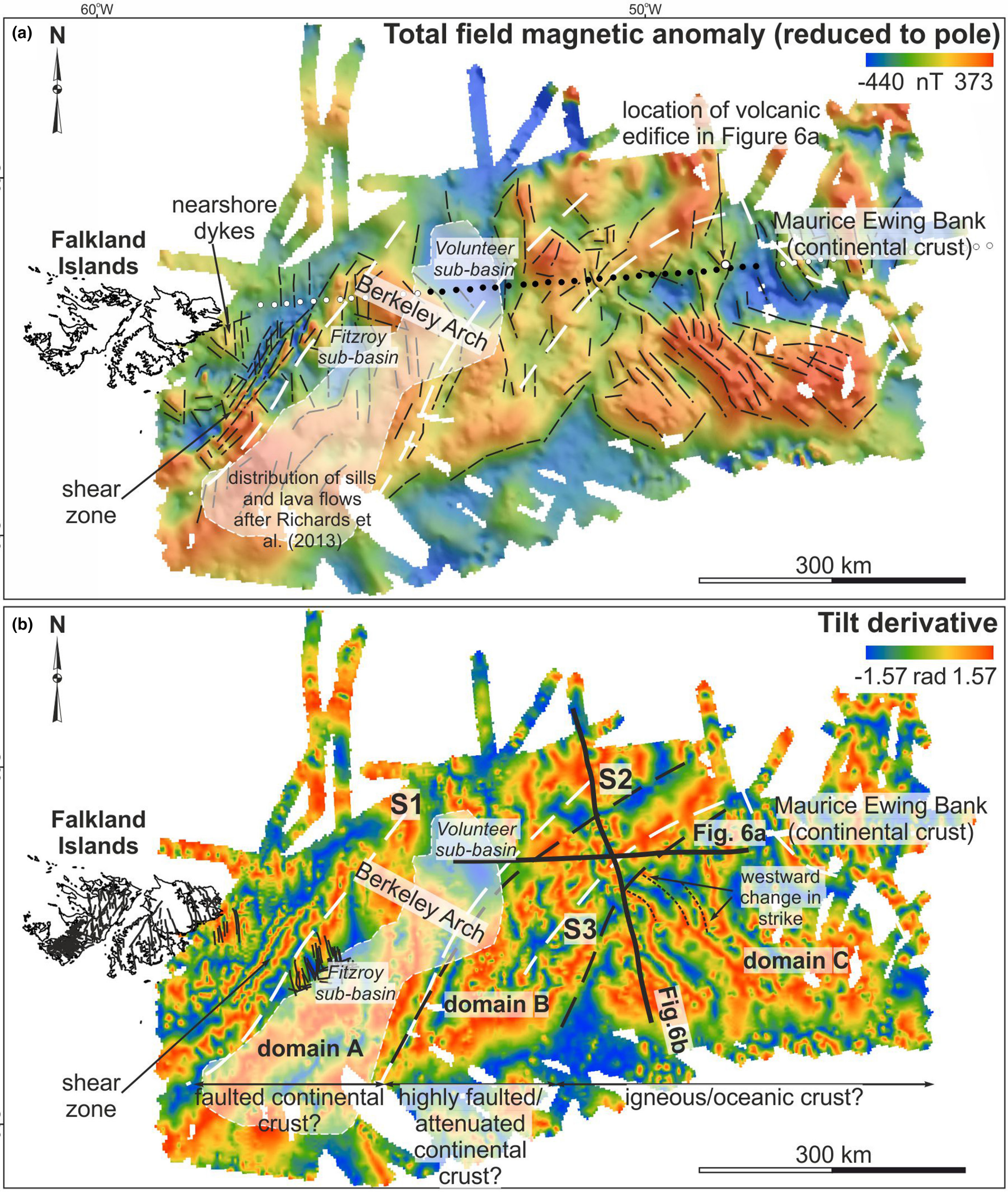


FIGURE 5 (a) Reduced to pole total magnetic anomaly overlain by magnetic lineaments. Dots mark locations of ocean bottom seismometers from Schimschal and Jokat (2019b) with the black ones marking locations where oceanic crust was interpreted in the same study. (b) Tilt derivative along with the on- and nearshore dykes after Barker (1999) and Stone et al. (2009) and offshore dykes from Stanca et al. (2021), and the distribution of sills and lava flows (white shaded area) after Richards et al. (2013). White and black dashed lines mark the shear zones as interpreted on gravity and magnetic data, respectively. Aeromagnetic data source: Eagles and Eisermann (2020).

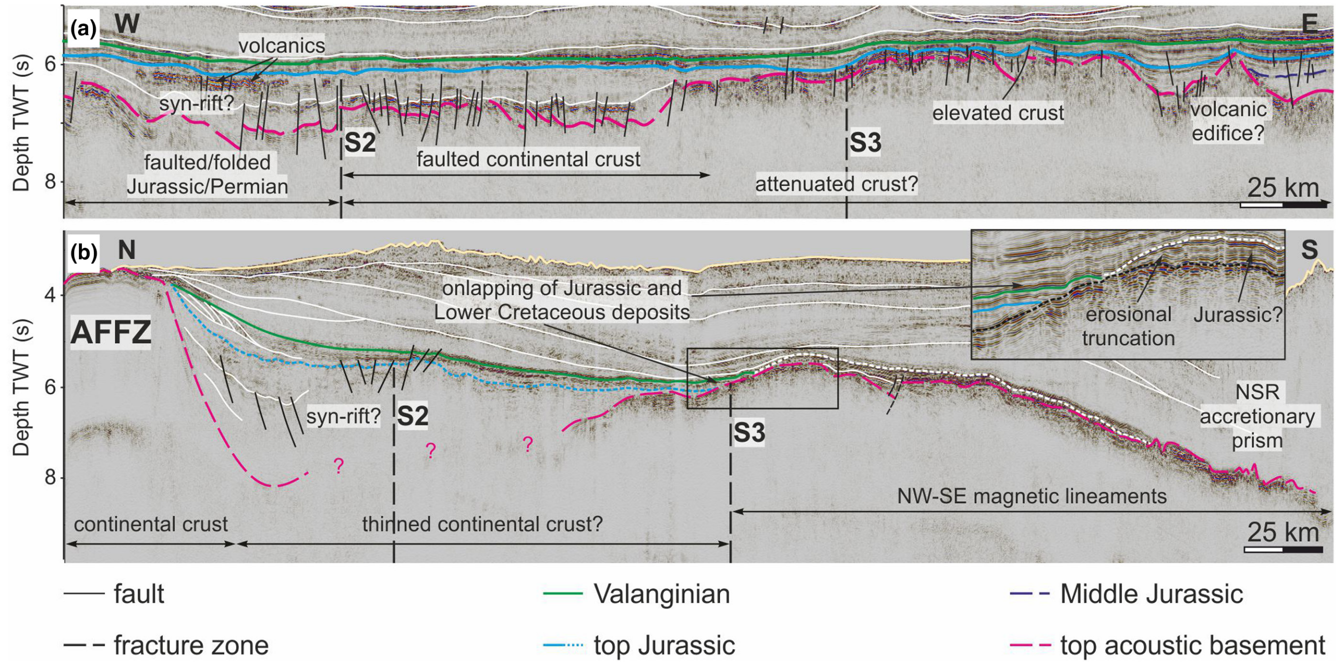


FIGURE 6 (a) Seismic reflection data cross section showing the E–W transition from Jurassic/Palaeozoic deposits to highly faulted crust and to an elevated domain; (b) seismic reflection cross section showing the N–S variation in crustal architecture in the FPB with uplifted continental crust to the north, and a Jurassic depocentre and potentially oceanic crust to the south. Location of lines is shown in Figure 1b, and in Figures 4b and 5b relative to the gravity and magnetic data, respectively. AFFZ, Agulhas-Falkland Fracture Zone; NSR, North Scotia Ridge.

section of Figure 6b), whereas no clear contact is seen around the location of S3.

The area lying between S3 and the Maurice Ewing Bank (domain C) shows a N–S variation on the magnetic data and requires further analysis based on seismic data. Four additional regional lines crossing the magnetic lineaments east of S3 were used for this analysis and paired based on the presence of inverted Mid(?)-Jurassic depocentres (Figures 7 and 8). These show a varied stratigraphic architecture and seismic response of the crust.

The seismic character of the basement is chaotic (Figures 7 and 8b) to transparent (Figure 8a), with areas of high amplitudes in the upper section (Figure 8). Locally, reflectors dipping north-eastward are described (Figure 8b), but the poor imaging at depth and the presence of multiples mask the overall character of the crust. A depocentre was documented in the northern part of domain C where a negative magnetic anomaly was identified (Figures 6a, 7 and 8). Based on the currently available well data, a ca. 0.8–0.9 s TWT thick sequence of Jurassic deposits infill this depocentre, with Middle Jurassic strata interpreted to be confined to this region (Figures 6a, 7 and 8). The northernmost and easternmost regional seismic profiles show Jurassic and Lower Cretaceous strata onlapping an older sediment section bound at the top by an erosional unconformity (Figure 7). This is relatively thick and narrow on the easternmost section (Figure 7a) and thins and extends across a wider region on the northern profile (Figure 7b). These deposits are the same for sections in Figures 6b and 7b, but it is unclear if they are coeval with the ones in Figure 7a due to the sparse distribution of seismic lines. This section of older sediments is not seen on the two seismic lines crossing the central part of the magnetic lineaments where Upper and Middle Jurassic strata are interpreted to directly overlie the acoustic basement (Figure 8). Lower Cretaceous strata onlap onto the Jurassic section in the SW of each section (Figure 8a,b), and erosional truncations of the Jurassic and Lower Cretaceous sequences are interpreted in the southern part of the profile in Figure 8a (seismic inset).

Evidence of uplift of the Cretaceous and Lower Cenozoic sections was identified locally (Figure 7a). On three of the four sections, the northern limit of the positive and striped magnetic area corresponds to elevated features on the top acoustic basement (Figures 7a,b, and 8a). These are between 10 and 15 km wide and do not correspond to anomalies on the magnetic map. Jurassic strata thin above these features (Figures 7a and 8a) and further folding and faulting of the Lower Cretaceous section is observed (Figures 7a,b and 8a).

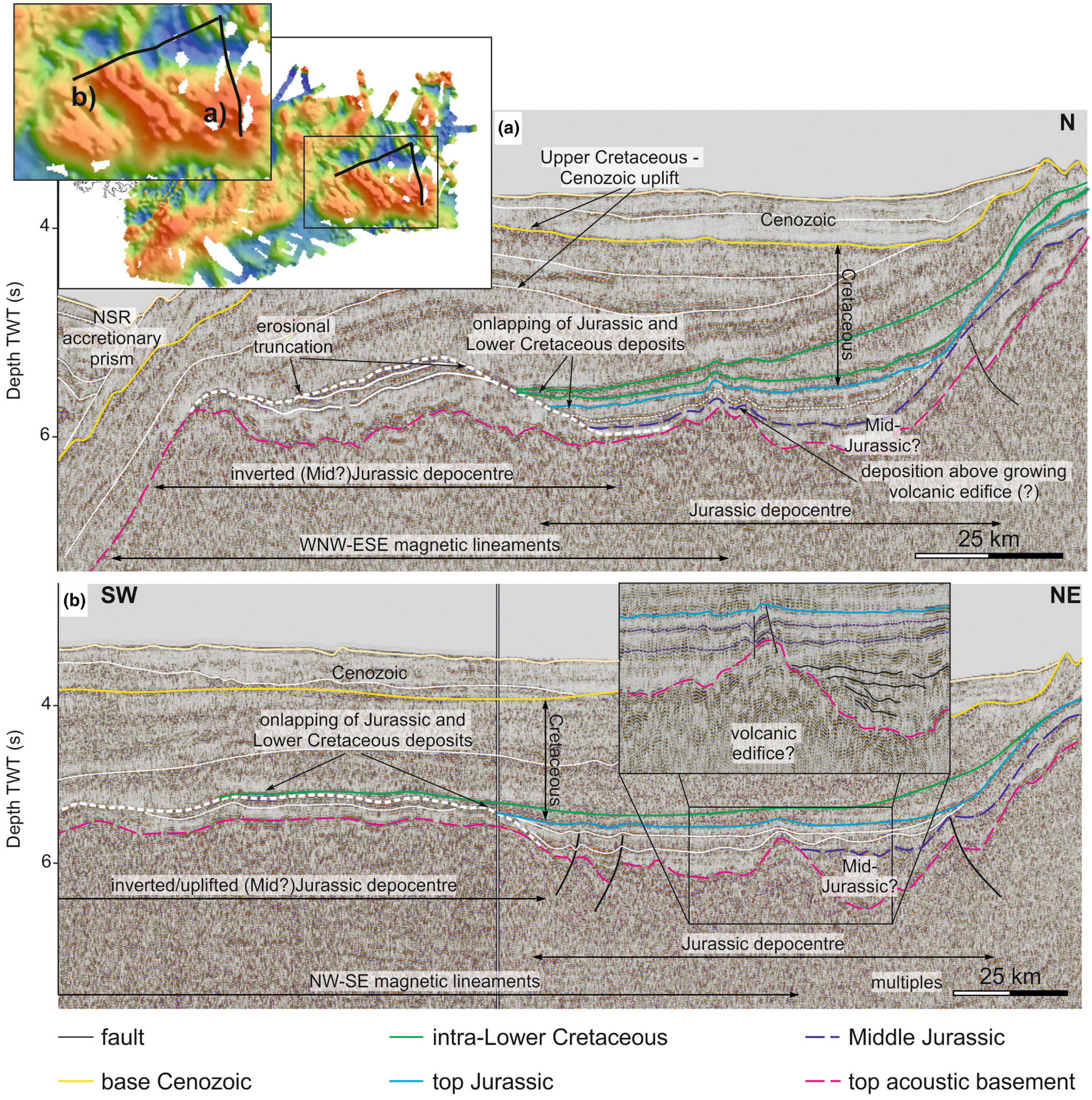


FIGURE 7 Seismic reflection data cross sections across the northern and eastern regions of the magnetic lineaments showing older uplifted Jurassic deposits onlapped by younger sediments and potential volcanic edifices bounding the northern extent of the magnetic lineaments. Location of lines is shown in Figure 1b. Inset map shows seismic lines location relative to the magnetic lineaments on the total field magnetic anomaly map. NSR, North Scotia Ridge.

A narrow negative gravity anomaly running parallel to the AFFZ in the northern part of the FPB has been identified and mentioned in the previous section (Figure 4b). On seismic reflection data, this area corresponds to a series of Jurassic half-grabens overlying intensely faulted crust (Figure 9).

5 | CRUSTAL ARCHITECTURE ACROSS THE FALKLAND PLATEAU BASIN

The crustal architecture underlying the FPB has been associated with high degrees of uncertainty. The integration

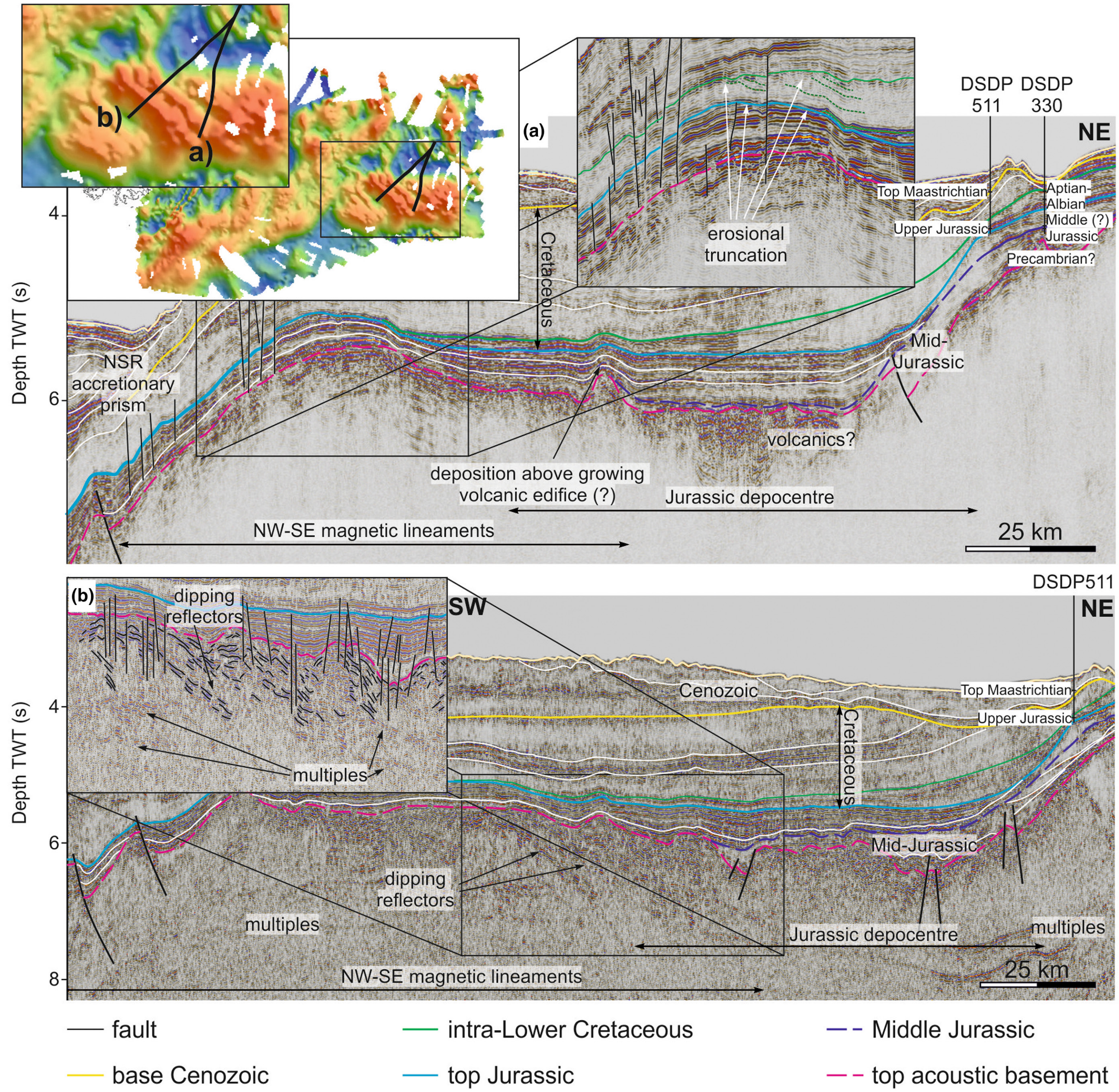


FIGURE 8 Seismic reflection data cross sections across the central part of the magnetic lineaments showing continuous deposition during the Jurassic and areas of high amplitudes (a) and dipping reflectors (b) within the acoustic basement. Location of lines is shown in Figure 1b. Inset map shows seismic lines location relative to the magnetic lineaments on the total field magnetic anomaly map. NSR, North Scotia Ridge.

of geophysical data supports a separation of the basin into three domains (A–C). The NW–SE trending lineaments separating these domains have been previously interpreted as shear zones (Stanca et al., 2021). Although no clear evidence of a shear zone is seen on the seismic reflection data at the location of S3 (Figure 6), a clear truncation of the magnetic stripes east of it are seen on the magnetic data (Figure 5), which supports the presence of a tectonic contact.

5.1 | Domain A (S1 to S2)

The WNW–ESE trend of the reactivated Palaeozoic thrusts in the Southern North Falkland Basin north of the Falkland Islands is truncated eastwards by S1 (Figure 4). Localized evidence of a similar trend is noticeable in domain A which could suggest a continuation of these reactivated thrusts in the western part of the FPB. However, the wavelength of the anomalies increases eastward (Figure 4a). This change

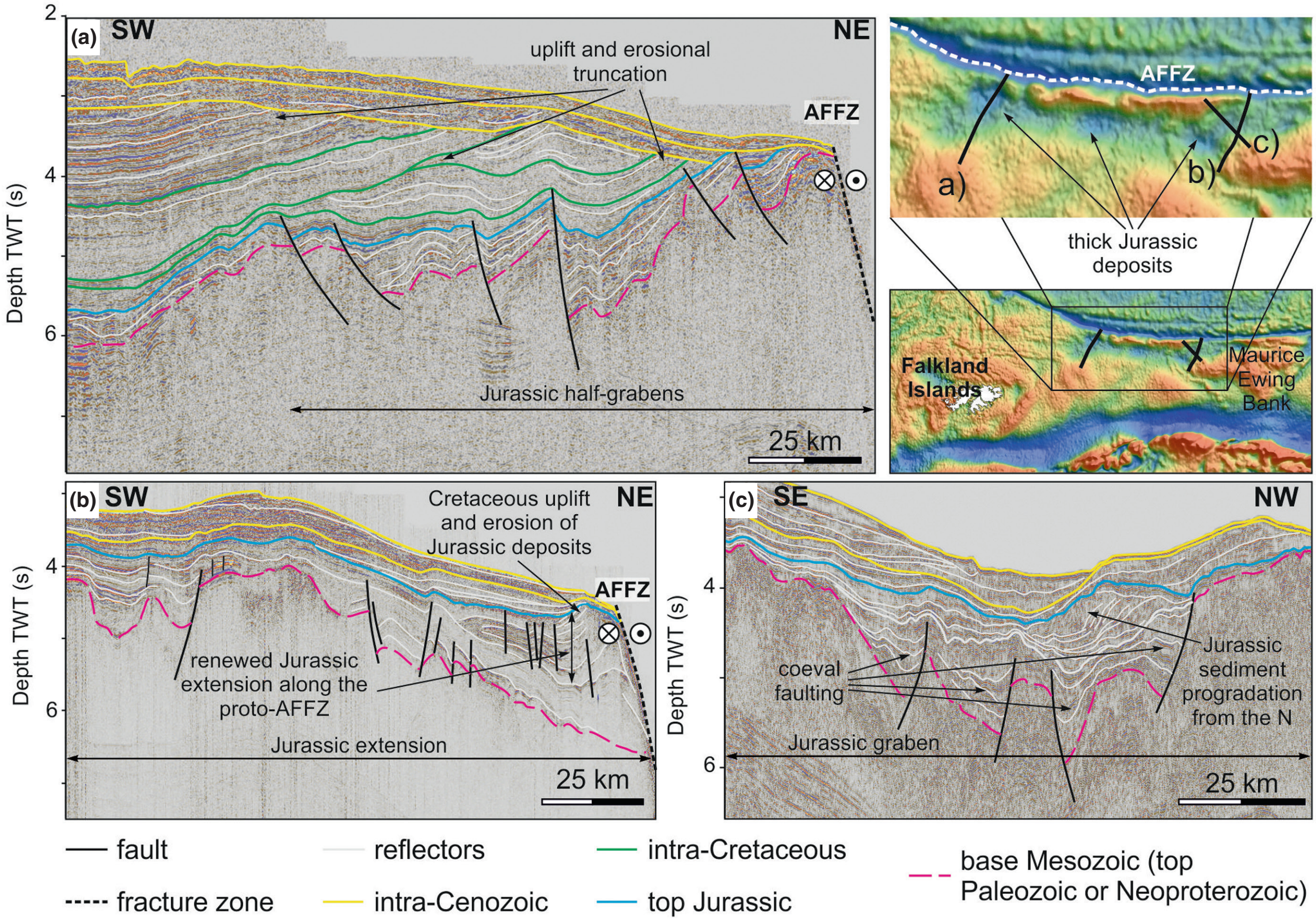


FIGURE 9 (a–c) Seismic reflection data cross sections across the E–W trending negative gravity anomaly in the northern FPB showing Jurassic grabens and half-grabens. Evidence of several unconformities and sediment deformation can be seen. Location of lines is shown in Figure 1b. Inset maps show line location relative to the free-air gravity anomaly low in the FPB; AFFZ, Agulhas-Falkland Fracture Zone.

could be the result of an increase in the burial depth of the fold and thrust belt or could be related to larger-scale variations in the basement topography and/or composition (Figure 4a). Furthermore, the lack of a similar trend underneath the Fitzroy sub-basin can be related to the sediment thickness, a change in the nature of the crust or a change in the pre-Mesozoic distribution of the deformation.

The elevated crust and succession of half-grabens interpreted in the northern part of domain A (Figures 6b and 9a) are correlated here with deformation occurring in the continental domain. The presence of a thick section of Jurassic and pre-Jurassic sediments on the regional seismic lines (Figure 6a,b), which show wedge-like geometries in the lower part, support syn-rift sedimentation (Figure 6a), and the gravimetric anomalies, reminiscent of buried reactivated Palaeozoic thrusts, support the continental nature of the crust underlying this portion of the FPB. This is consistent with the seismic reflection data presented by Stanca et al. (2021).

The N–S trending magnetic anomalies identified in the vicinity of S1 were correlated with the dyke swarm from Barker (1999). This is consistent with the trend of the youngest dyke swarm identified onshore the Falkland Islands (Stone et al., 2009) and the dykes mapped in the Fitzroy sub-basin (Stanca et al., 2021). The positive magnetic anomalies identified along S1 could suggest a further potential magmatic enrichment concentrated along this deformed margin of the basin (Figure 5a,b) as evidence of significant magmatism has been interpreted basinward (Richards et al., 2013; Richards, Gatliff, Quinn, Fannin, & Williamson, 1996; Stanca et al., 2021). Additional evidence of the sills and dykes complex interpreted by Stanca et al. (2021) and the magmatic and volcanic province defined by Richards et al. (2013) is given by the high positive magnetic anomalies east and south of the Fitzroy sub-basin (Figure 5), which suggest a significant magmatic enrichment of the continental crust underlying domain A.

5.2 | Domain B (S2 to S3)

The thick section of Jurassic and potentially pre-Jurassic sediments interpreted as overlying extended continental crust in domain A extend and taper in domain B (Figure 6) with no syn-rift sedimentation being interpreted in the easternmost part of domain B (Figure 6a). The high degree of faulting (Figure 6a) in combination with evidence of sill intrusions (Figure 6a), chaotic gravity signature and relatively high positive magnetic anomalies, could point to potentially attenuated continental crust. High P-wave velocities have been reported by Schimschal and Jokat (2017) across the eastern part of domain A, and domains B and C and previously interpreted as oceanic crust (black dots in Figure 5a). However, where available, seismic reflection data support the presence of syn-rift deposits (Figure 6; Stanca et al., 2021), indicative of deposition above thinned continental crust. Nevertheless, seismic reflection data are scarce, and the characterization of domain B remains limited. The domain could represent a mosaic of oceanic and highly deformed continental crust with significant magmatic and volcanic additions, sheared between the two fracture zones, with the oceanic component more predominant towards the south where domain B is adjacent to the oceanic subdomain C3 (Figure 10).

5.3 | Domain C (S3 to Maurice Ewing Bank)

The potentially attenuated continental crust of domain B transitions eastwards into the highly reflective and elevated domain C (Figure 6a). The high amplitudes are interpreted to be the result of volcanic and magmatic additions, whereas the elevation could suggest underplating or a transition to thick oceanic crust (Figure 6a). Further evidence of volcanism is given by the presence of volcanic ridges/edifices (Figures 5a and 6a). The volcanic and magmatic enrichment is supported by the P-wave velocities reported by Schimschal and Jokat (2017).

This domain most likely comprises several subdomains as the seismic and magnetic data reveal the presence of a heterogeneous crust (Figures 5–8).

Subdomain C1 displays negative magnetic anomalies, different to the southern adjacent subdomain, which could be attributed to the thicker sedimentary succession (Figures 7 and 8). Magnetic lineaments were mapped in

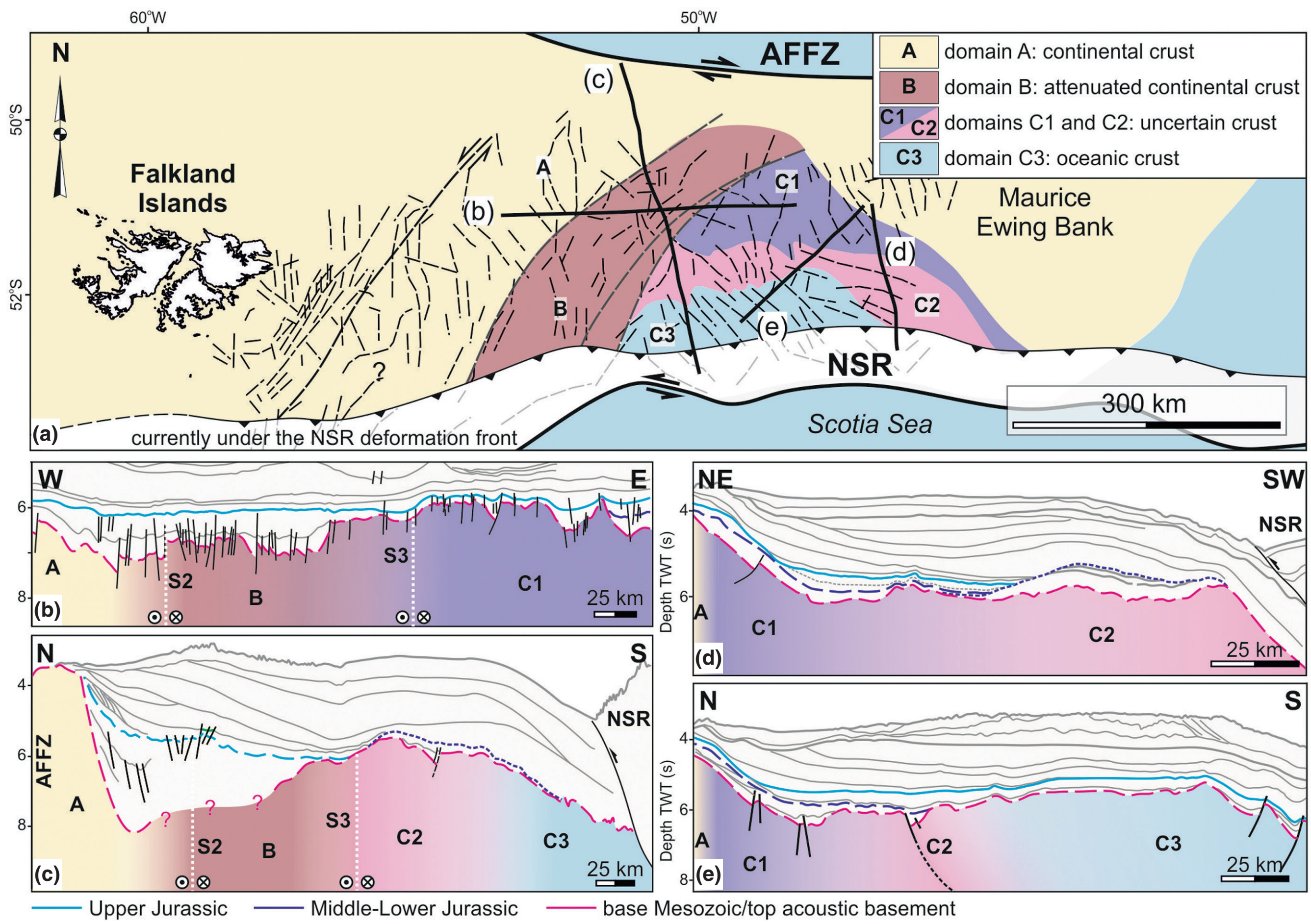


FIGURE 10 (a) Model of the distribution of crustal types along the Falkland Plateau Basin based on gravity, seismic reflection and magnetic data overlain by the mapped magnetic lineaments; (b–e) line drawings of seismic sections in Figures 6a,b, 7a and 8b, respectively; letters in the legend relate to domain numbers (domains A to C3); AFFZ, Agulhas-Falkland Fracture Zone; NSR, North Scotia Ridge.

this subdomain (Figure 5) and were locally associated with volcanic edifices on seismic reflection data (Figure 6). The lineaments change their strike from NW–SE to WNW–ESE towards the west (Figure 5b), possibly due to shearing along the S3. These linear magnetic anomalies have been previously interpreted as magnetic reversal isochrons (Eagles & Eisermann, 2020), which would indicate oceanic crust is underlying subdomain C1.

The geophysical signature of subdomain C1 transitions southward to high positive magnetic anomalies (Figure 5). These display a linear geometry and have been previously interpreted as magnetic reversal isochrons (Eagles & Eisermann, 2020), characteristic of oceanic crust. Syn-rift deposits spanning domains A and B (Figure 6b) onlap onto a highly reflective crust interpreted to have a significant igneous component, which supports a potential transition to oceanic crust southwards. In addition, potential volcanic edifices mark the northern termination of subdomain C2 (Figures 7a,b and 8a). The strata above these edifices suggest a Jurassic to Early Cretaceous activity.

All these observations could suggest that domain C is underlain by oceanic crust. However, inverted depocentres with strata older than Middle Jurassic have been identified within subdomain C2 (Figure 7) and do not extend in subdomain C3 (Figure 8). This suggests that domains C2 and C3 had a different evolution, with C2 being a fully formed domain much earlier than C3. An alternative interpretation of subdomain C2 is that it consists of continental crust, and the magnetic lineaments readily seen along it (Figure 5) represent a continuation of the Early Jurassic linear magnetic pattern of the Weddell Sea Rift System (Southern Weddell Magnetic Province in Jordan et al., 2017; Figure 3). In this case, the depocentres identified in Figure 7 would be coeval with the Weddell Sea Rift. This interpretation does not support the presence of oceanic crust in subdomain C1, which in turn would suggest that the magnetic lineaments identified in this area were generated during extension in the FPB and acted as magma conduits, rather than representing magnetic reversal isochrons.

Full oceanic crust is interpreted to occur with a higher degree of certainty only in subdomain C3. DSDP site 330 cored Oxfordian-Middle Jurassic sediments on the western slope of the Maurice Ewing Bank (Barker et al., 1977). Although difficult to map and extrapolate across the sparse seismic reflection data, there are areas where these deposits were not interpreted (Figure 8), which would suggest oceanic crust generation occurred after their deposition. The presence of Upper Jurassic deposits overlying the oceanic crust in subdomain C3 narrows the window for oceanic crust generation to the Late Jurassic. However, as the interpretation of the Middle Jurassic interface is poorly constrained, an earlier onset of oceanic crust generation should not be discounted.

5.4 | Summary and implications

A summary interpretation of the crustal distribution as constrained by gravity, magnetic and seismic reflection data is shown in Figure 10. The seismic reflection data were not diagnostic for the nature of the crust in the distal part of the FPB or for the location of crustal type boundaries, but nonetheless provided insights into the evolution of this part of the basin and the timing for oceanic crust generation. Based on the analysed data, the crust architecture underlying the FPB is characterized as follows:

- continental crust in the region between S1 and S2 (domain A) and adjacent to the AFFZ (1—yellow in Figure 10);
- a mosaic of faulted and potentially attenuated and underplated continental crust and sheared oceanic crust between S2 and S3 (domain B—brown in Figure 10);
- uncertain crust comprising:
  - the northern region of domain C (between S3 and the Maurice Ewing Bank; subdomain C1—purple in Figure 10) where the seismic reflection data suggests the presence of thicker or elevated magma-enriched crust with a magnetic signature different than the interpreted oceanic crust to the south;
  - the central and eastern regions of domain C (subdomain C2—pink in Figure 10) where magnetic lineaments were mapped indicative of magnetic reversal isochrons and oceanic crust, but pre-Middle Jurassic inverted basins were identified on the seismic data across these lineaments;
- an oceanic domain corresponding to the southern part of domain C (subdomain C3—light blue in Figure 10).

The interpretation of a highly heterogeneous crust underlying the FPB suggests a more complicated tectonic evolution than pure extension during the opening of the South Atlantic. The crustal architecture, along with the postulated shear zones, and evidence of strike-slip deformation presented by Stanca et al. (2021) along the western margin of the FPB, suggests that wrenching represented an important component in the tectonic evolution of the basin. Some of this deformation can be attributed to the shearing between East Antarctica and western Gondwana, and subsequently the Falkland Plateau and Africa. However, when considered in association with studies like the ones of Adie (1952), Mitchell et al. (1986), Mussett and Taylor (1994), Curtis and Hyam (1998), Trewin et al. (2002), Stone et al. (2009), Stanca et al. (2019, 2021) and more, the crustal and structural architecture of the plateau points towards a complex movement of its sub-blocks during the fragmentation of Gondwana. Furthermore, the integration of seismic reflection, gravity and magnetic data allows the

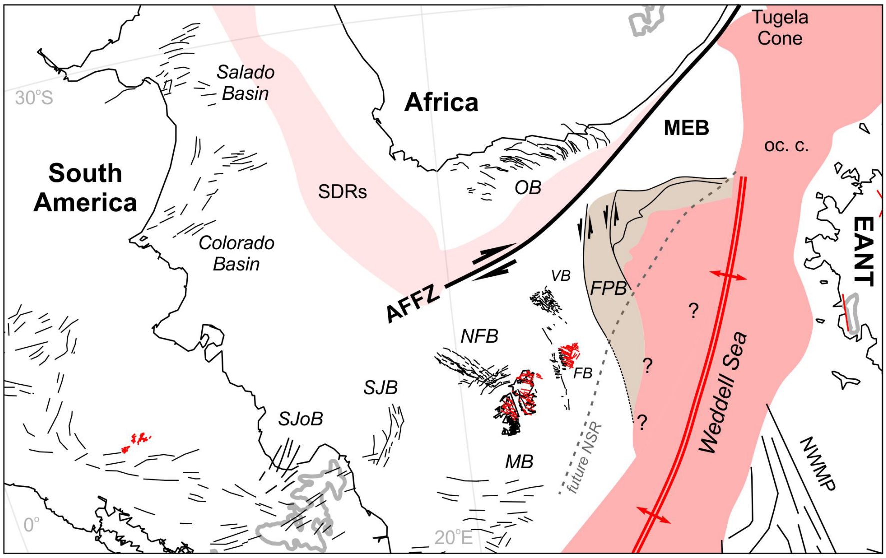


FIGURE 11 Updated Early Cretaceous configuration of south-western Gondwana (base plate model after Müller et al., 2019) including the distribution of crustal types in the FPB. Black lines—faults; red lines—dykes; double red line and double arrows—oceanic ridge and spreading direction; grey lines—extent of Chon Aike and Karoo—Dronning Maud Land—Ferrar volcanics. Question marks in the Falkland Plateau Basin oceanic domain mark its uncertain southern extent and relation to the Weddell Sea oceanic crust. Brown shades mark the interpreted intruded and underplated continental crust in the Falkland Plateau Basin. EANT, East Antarctica; FB, Fitzroy sub-basin; FPB, Falkland Plateau Basin; MB, Malvinas Basin; MEB, Maurice Ewing Bank; NFB, North Falkland Basin; NSR, North Scotia Ridge; NWMP, Northern Weddell Magnetic Province; OB, Outeniqua Basin; oc. c., oceanic crust; SDR, seaward dipping reflectors; SJB, San Julian Basin; SJoB, San Jorge Basin; VB, Volunteer sub-basin; NWMP from Jordan et al. (2017); East Antarctica dykes after Curtis et al. (2008); Patagonia dykes after Rapalini and Lopez de Luchi (2000); Falkland Islands onshore dykes after Stone et al. (2009); SNFB and NFB faults after Lohr and Underhill (2015) and Stanca et al. (2019); FB and VB dykes and faults after Stanca et al. (2021); South America fault network after Lovecchio et al. (2019); Karoo lavas extent after Jourdan et al. (2007); Chon Aike lavas extent after Bouhier et al. (2017); DML-Ferrar lavas extent after Elliot (1992) and Elliot et al. (1999); Outeniqua Basin fault network after Paton et al. (2006) and Parsiegla et al. (2009).

FPB crustal domains to be delineated in more detail than previously. The newly defined extents of oceanic and continental crust (Figures 10 and 11) impact the overall area the plateau occupied prebreak-up. This needs to be considered in the interpretation of the fragmentation and plate reconstruction of the plateau, particularly when constraining the location of the Falkland Islands in a regional plate model of south-western Gondwana. In summary, the FPB is a well-preserved example of complex tectono-stratigraphic architectures that result from wrenching occurring during continental break-up, with a range of structural styles documented, which affect a highly heterogenous crust with variable magmatic and volcanic additions.

6 | CONCLUSIONS

This study integrated seismic reflection, gravity and magnetic data to provide an assessment of the distribution of crustal types underlying the FPB, the largest basin of the Falkland Plateau. The interpreted crustal architecture of this transform marginal plateau that formed during regional wrenching that accompanied the continental break-up of Gondwana shows a higher degree of complexity than previously envisaged.

The east-central region comprises a mosaic of crustal types that resulted from the fragmentation of Gondwana. Typical continental crust, with varying degrees of extension, underlies the western domain of the FPB, up to the S2 shear zone, and the region just south of the Agulhas-Falkland Fracture Zone. A sliver of highly faulted and potentially attenuated and underplated continental crust is located between S2 and S3. The remainder of the FPB comprises the area most affected by the break-up of Gondwana. Magma-enriched and underplated continental crust underlies the northern and central parts of this region, transitioning to the south to an oceanic domain.

The findings reported in this study support a complex tectonic history of the Falkland Plateau and its constituent crustal domains. The newly defined crustal boundaries have implications on the reconstruction of the plateau in a Gondwana prebreak-up configuration. Additionally, the updated model presented in this study provides more insights into the varied structural styles and crustal architectures that can develop during wrenching associated with continental break-up.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Falkland Islands Government. Restrictions apply to the availability of these data, which were used under licence for this study. Data are available from the author(s) with the permission of Falkland Islands Government.

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