



Research Paper

A tale of two *syn*-rifts: New age information and depositional environment interpretation for the North Falkland Basin *syn*-rift and implications for the rifting of Gondwana

Rory J. Sutton^{a,*}, Gayle E. Plenderleith^a, Thomas J.H. Dodd^a, Lorraine P. Field^b, Ian L. Millar^b, Dave J. McCarthy^a, Thomas A. Randles^a

^a British Geological Survey, the Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, United Kingdom

^b British Geological Survey, Nicker Hill, Keyworth, Nottingham NG12 5GG, United Kingdom

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ABSTRACT

The timing of North Falkland Basin (NFB) rifting, and how the wider Falkland Plateau fits into the history of the breakup of Southern Gondwana, has been a topic of debate and uncertainty. This has been exacerbated by a complete lack of direct geochronological age constraint on the sedimentary fill of the Early Syn-rift in the NFB. This study presents an analysis of well data, core from the Early Syn-rift interval, seismic interpretation, and new zircon U-Pb age dating. The resulting depositional model supports a revised understanding of the sedimentary environment and structural setting of the *syn*-rift of the NFB. The Early Syn-Rift strata infill a series of NW–SE striking sub-basins, which together comprise the Southern North Falkland Basin (SNFB). The overstepping Late Syn-rift rests unconformably above the lower *syn*-rift sequence, and is accommodated by a series of *syn*-depositional N–S trending fault-bounded basins that together form the Central North Falkland Basin (CNFB). The NFB Early Syn-Rift is characterised by ephemeral fluvial–fluvio-lacustrine and volcanoclastic intervals, with nine identified sedimentary facies assigned to five distinct facies associations. An analysis of ashfall tuffs identified in core from the 14/24–1 well yields a new LA-ICP-MS zircon U-Pb age determination of 175 ± 5 Ma (early to middle Jurassic) for the upper part of the Early Syn-rift. These results provide the first absolute age determination for Early Syn-rift strata in the NFB, and implies that they are substantially older than previous models suggest (by between 13.9–41 Ma). This suggests that the NW–SE striking basins of the SNFB developed as a result of Gondwana rifting during the early to middle Jurassic. The findings provide clear evidence for two distinct *syn*-rift packages in the NFB, with early to middle Jurassic (Gondwana) depocentres and associated faults overprinted by later N–S trending early Cretaceous sub-basins.

1. Introduction

The Falkland Islands and its territorial waters are located approximately 300 km to the south-east of South America. The islands are surrounded by four Mesozoic offshore sedimentary basins which developed through different deformation mechanisms. These basins include the North Falkland Basin (NFB), Falkland Plateau Basin, South Falkland Basin, and the Malvinas Basin (Fig. 1). The movement of the Falkland Plateau in relation to South Africa, South America, and East Antarctica has long been a topic of debate and uncertainty (Adie, 1952; Lohr and Underhill, 2015; Ramos et al., 2017; Stanca et al., 2019; Eagles and Eisermann, 2020; Stanca et al., 2022 and 2023). To this day the

tectonic history of the region, particularly the structural history of the Falkland Islands offshore basins, remains uncertain. There have been several studies that propose often-contrasting models for the structural history and multi-phase development of the *syn*-rift infill of the NFB (Brandsen et al., 1999; Richards and Hillier, 2000a; Lohr and Underhill, 2015; Jones et al., 2019). These previous interpretations, which are based on seismic data and limited age information, generally suggest that the NFB records two episodes of extensional faulting with contrasting trends: a NW–SE trend associated with Upper Jurassic rifting that is dominant in the Southern North Falkland Basin (SNFB); and a N–S trend associated with early Cretaceous rifting which is dominant in the Central North Falkland Basin (CNFB) (Lohr and Underhill, 2015).

* Corresponding author.

E-mail address: rsutton@bgs.ac.uk (R.J. Sutton).

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Prior to the breakup of Gondwana, the Falkland Islands lay to the south or south-east of South Africa (Fig. 2), its position having recently been revised by Stanca et al. (2019). However, the position of the Falkland Islands prior to the breakup of Southern Gondwana and its evolution remains a contentious issue. Different models have been put forward in order to determine the palaeoposition and orientation of the Falkland Islands. These models are the rotational model and the rigid model. The rotational model (adopted by this study; Adie, 1952; Mitchell et al., 1986; Marshall, 1994; Mussett and Taylor, 1994; Curtis and Hyam, 1998; Stone et al., 2009; Stanca et al., 2019, 2022, 2023; Malone et al., 2023) proposes that the islands are part of a separate microplate and were originally positioned to the east of South Africa in a rotated position. The rigid model (Richards et al., 1996b; Lawrence et al., 1999; Ramos, 2008; Ramos et al., 2017; Lovecchio et al., 2019; Eagles and Eisermann, 2020), argues that the Falkland Plateau was originally located to east of South Africa, not in a rotated position but instead fixed to the South American plate and thus did not undergo rotation during the breakup of Gondwana.

The earliest phase of rifting that created the NFB has been tentatively linked to the same phase of rifting which developed the Outeniqua Basin (Ramos et al., 2017; Stanca et al., 2019), located off the south coast of South Africa (Fig. 2). However, due to a lack of geochronological age constraint, this association remains poorly understood.

While the Cretaceous (Valanginian to Maastrichtian) post rift petroleum system (described in Richards and Hillier, 2000a; Richards and Hillier, 2000b; Farrimond et al., 2015; Holmes et al., 2015; Dodd et al., 2019; Dodd et al., 2020) has been targeted by a series of hydrocarbon exploration campaigns, only eight wells intersect the syn-rift (Table 1;

Fig. 3). Of these, five wells intersect the Early Syn-rift (Table 1; Fig. 3), but there has been no previous age dating of this interval prior to this study. Previous studies and well data show that Early and Late Syn-rift deposition occurred in a predominantly continental lacustrine setting (Richards and Hillier, 2000a; Lohr and Underhill, 2015; Dodd et al., 2019). However, the sedimentology and depositional history, when compared to the overlying post-rift in the NFB, is poorly understood (Bunt, 2015; Holmes et al., 2015; Dodd et al., 2019; Dodd et al., 2020; Plenderleith et al., 2022). A total of 18.7 m of core through the syn-rift interval was obtained from well 14/24–1.

This paper presents the results of a detailed analysis of the syn-rift of the NFB (Fig. 1). Available 2D and 3D seismic data have been used to map key syn-rift horizons (top Early Syn-rift, top Late Syn-rift and top basement) in order to constrain the distribution and stratigraphical relationship of the Early Syn-rift and Late Syn-rift intervals within the NFB. Detailed sedimentary logging and micro-facies descriptions of thin sections taken from the 14/24–1 core were carried out to examine the range of facies and facies associations present. Importantly, this study presents the results of new geochronological analyses, including LA-ICP-MS age determinations conducted on samples taken from the 14/24–1 Early Syn-rift core. Together, the results of these analyses support a revised understanding of the age and depositional environments of the NFB syn-rift.

This study answers the following questions:

- (i) what is the age of the syn-rift strata in the NFB and what are the implications of the new age determination from the 14/24–1 well

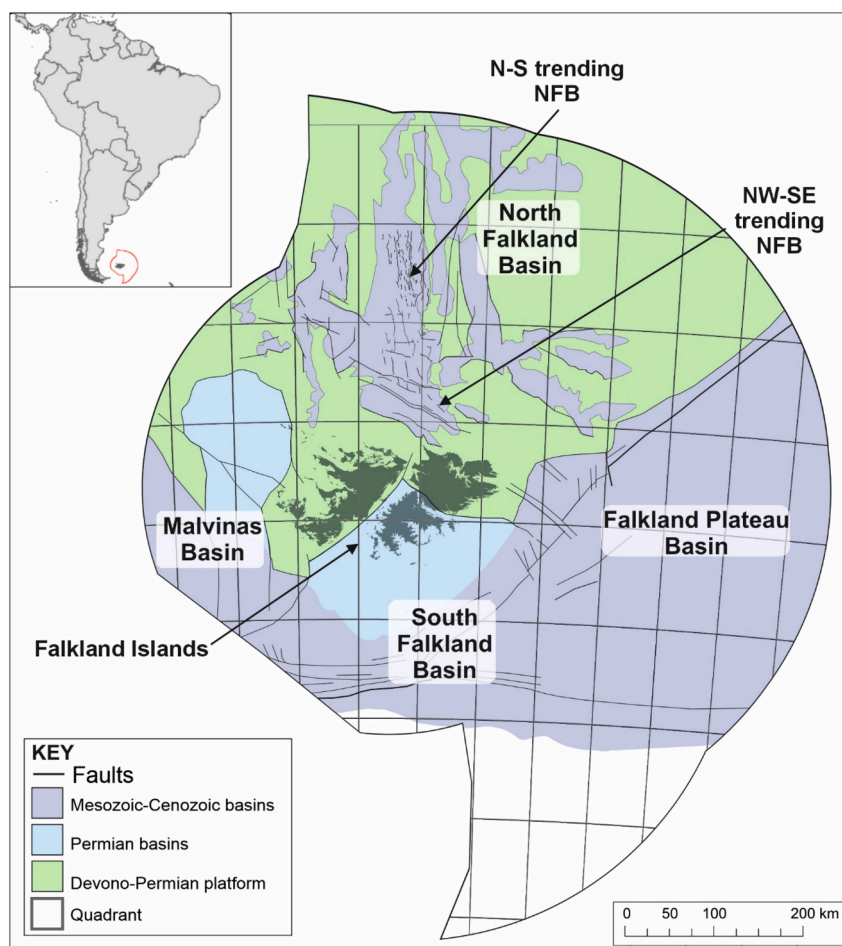


Fig. 1. Map showing the location of the Falkland Islands in the South Atlantic. The Falkland Islands are surrounded by four Mesozoic offshore basins: the North Falkland Basin (NFB), South Falkland Basin, Falkland Plateau Basin and the Malvinas Basin.

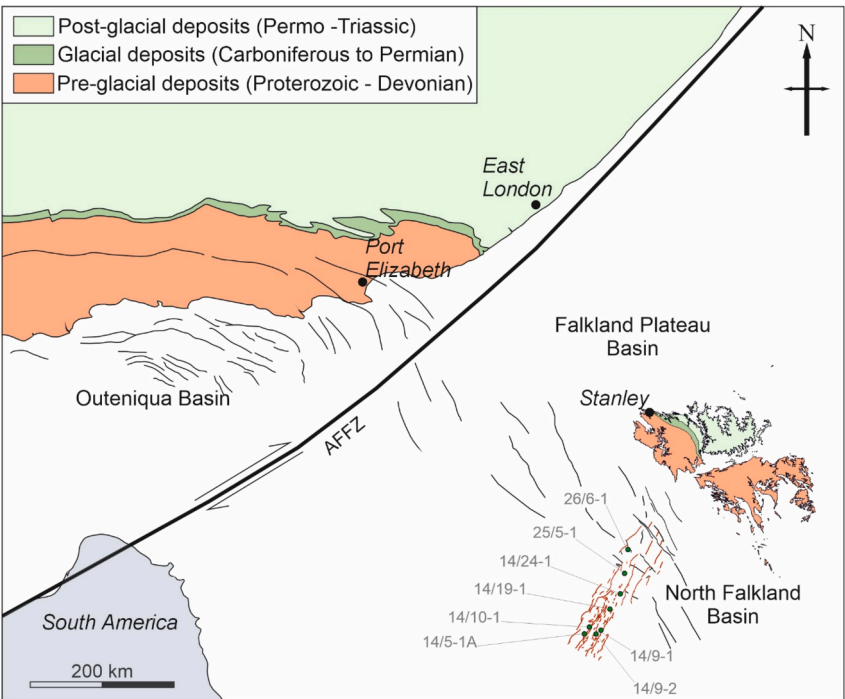


Fig. 2. The approximate position of the Falkland Islands at ~ 180 Ma modified from [Stanca et al. \(2019\)](#) based on the Falklands rotational model. The present-day position of N–S trending faults of the Central North Falkland Basin are shown in red. The present-day position of NW–SE trending faults of the Southern North Falkland Basin (from [Lohr and Underhill, 2015](#)) are shown in black. The faults in the Outeniqua Basin are modified from [Salomo et al. \(2024\)](#). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Exploration and appraisal wells drilled in the North Falkland Basin that penetrate the syn-rift strata. A total of eight wells penetrate either the Early Syn-rift or the Late Syn-rift. Depths are recorded in measured depth below rotary Kelly bushing (MDRKB).

Well	Operator	Date spudded	MDRKB (m)	Syn-rift encountered
14/09-1	Hess	27 Apr 1998	2615	Early Syn-rift
14/05-1A	Shell	04 Jul 1998	4525	Late Syn-rift
14/24-1	Lundin	16 Sept 1998	2938	Early Syn-rift & Late Syn-rift
14/09-2	Hess	13 Oct 1998	2371	Early Syn-rift
14/10-1	Shell	01 Nov 1998	3005	Late Syn-rift
14/19-1	Desire	22 Feb 2010	3667	Early Syn-rift & Late Syn-rift
26/06-1	Rockhopper	23 Jul 2010	2240	Early Syn-rift & Late Syn-rift
25/05-1	Desire	18 Dec 2010	1697	Late Syn-rift

- upon the regional geological understanding of the NFB and wider Falkland Plateau;
- (ii) what lithologies can be identified in the 14/24–1 core;
 - (iii) what sedimentary processes and depositional environments were present in the basin during syn-rift deposition; and
 - (iv) what impact does the new syn-rift age determination and depositional history have on the hydrocarbon prospectivity of the NFB?

2. Geological setting

2.1. Gondwana and South Atlantic rifting

The geological history of the Falkland Islands reflects the development of the Gondwana supercontinent, its initial breakup, and the subsequent opening of the South Atlantic. The scarcity of information regarding the deep structure of the Falkland Plateau in relation to South Atlantic spreading currently prevents accurate positioning of the Falkland Islands prior to the breakup of Gondwana ([Stanca et al., 2019](#)). [Adie \(1952\)](#) was the first to suggest that the islands may have originated from a position to the east of South Africa, having been rotated

approximately 180 degrees into their present-day position. This hypothesis was based on stratigraphic correlations of fossil assemblages and is supported by more recent palaeomagnetic, aeromagnetic, stratigraphic and structural data ([Mitchell et al. 1986](#); [Mussett & Taylor 1994](#); [Marshall 1994](#); [Curtis & Hyam 1998](#); [Trewin et al. 2002](#); [Stone et al. 2009](#)). The position of the Falkland Plateau was recently revised by [Stanca et al. \(2023\)](#) based on an analysis of open-source gravity, seismic reflection and well data ([Fig. 2](#)). Comparison of the local stress configuration of the Falkland Islands with a regional stress reconstruction for south-west Gondwana suggests that the rotation of the Falkland Plateau began during the middle Jurassic ([Stanca et al., 2019, 2022, 2023](#)). After the onset of South Atlantic rifting at ~ 135 Ma, the Falkland Plateau separated from South Africa via dextral strike-slip movement along the Agulhas-Falkland Fracture Zone ([Baby et al., 2018](#)).

The break-up of Gondwana began as early as the late Triassic, and continued throughout the Jurassic and into the early Cretaceous (~200–134 Ma; [Baby et al., 2018](#)). Initial Gondwana rifting associated with the breakup of Southern Gondwana began approximately 184 million years ago ([Bastias et al., 2021](#); [Macgregor and Reeves, 2025](#)). This initial Gondwana rifting was a precursor to the opening of the South Atlantic, and resulted in the formation of a series of basins

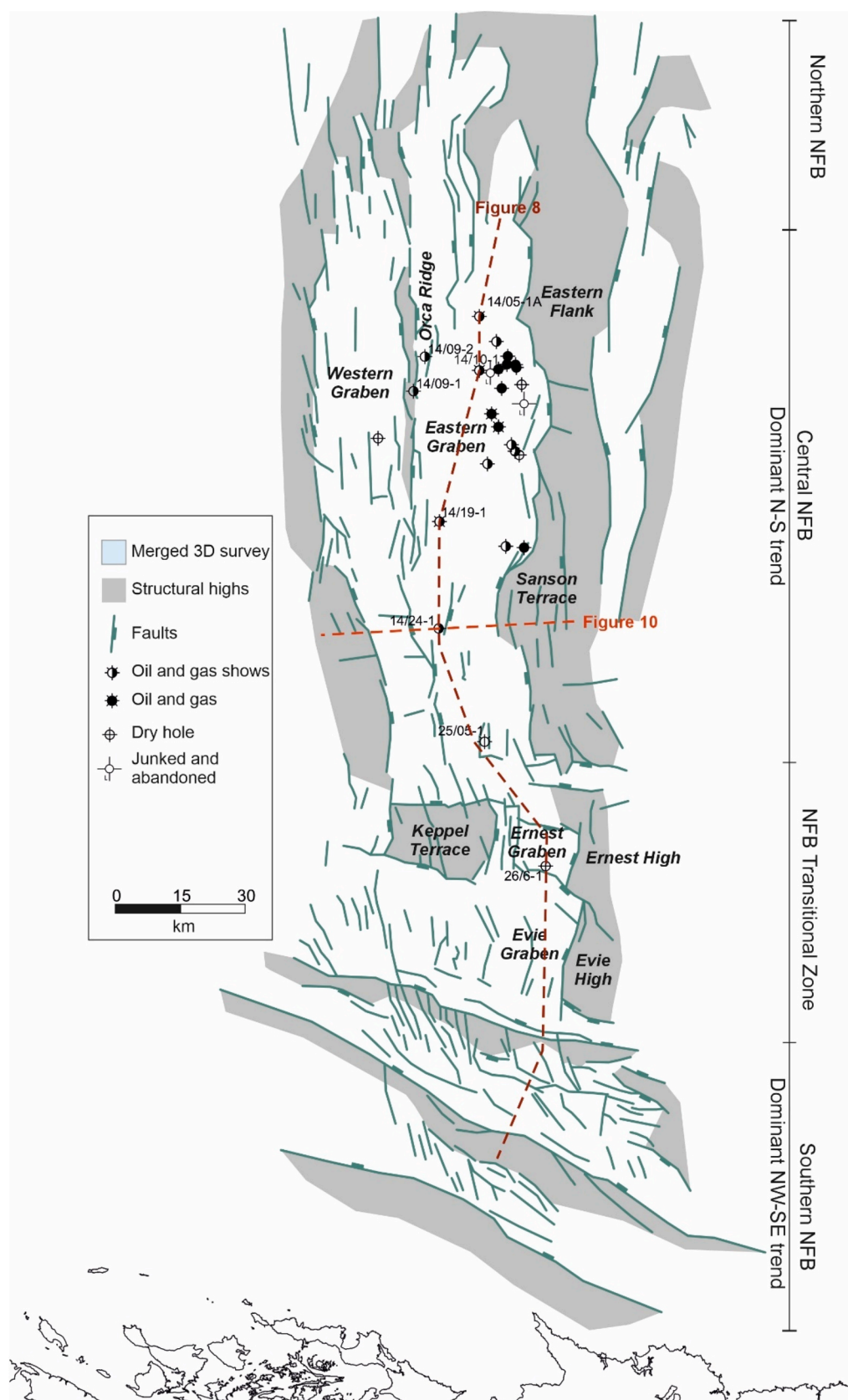


Fig. 3. Regional structure map of the extensional North Falkland Basin, highlighting the two regional trends present in the basin: the N–S trending Central North Falkland Basin and the NW–SE trending Southern North Falkland Basin, separated by a structurally complex transition zone. Existing hydrocarbon wells are shown, with the eight wells that intersect the syn-rift labelled. North Falkland Basin faults modified from [Lohr and Underhill \(2015\)](#).

along the proto-South Atlantic margins, including the NFB, Falkland Plateau Basin and the Outeniqua Basin (MacDonald et al., 2003).

Initial attempts to determine the age of the oldest parts of the South Atlantic oceanic crust, and thus constrain the timing of the onset of South Atlantic rifting, were made by Larson and Ladd (1973) and Rabinowitz (1976). However, these studies failed to obtain concordant results for the South African and South American margins. Since these initial studies, the South Atlantic is now inferred to have opened in the early Cretaceous, with suggested opening ages between 135 Ma (Valanginian) and 126 Ma (Hauterivian) (Rabinowitz and LaBrecque, 1979; Unternehr et al., 1988; Nurnberg and Muller, 1991; Gladchenko et al., 1997; Jokat et al., 2003; Heine et al., 2013), propagating from south to north along the entire length of the South Atlantic (Rabinowitz and LaBrecque, 1979; Austin and Uchupi, 1982; Uchupi, 1989; Eagles, 2007; Granot and Dymant, 2015; Jackson et al., 2000; Koopmann et al., 2014; Pérez-Díaz and Eagles, 2014). The oldest magnetic anomalies related to seafloor spreading are dated to ~ 135 Ma (Valanginian) for the Southern South Atlantic and it is now generally accepted that South Atlantic rifting began at around this time (Baby et al., 2018; Koopmann et al., 2014).

The NFB preserves evidence for both phases of rifting, during the Jurassic and the Cretaceous. CNFB rifting and Late Syn-rift deposition during the early Cretaceous is evidenced by available geochronological and biostratigraphic data (Richards and Hillier, 2000a). A paucity of data from the *syn*-rift has made age constraint challenging with uncertainty as to how the early development of the NFB (Early Syn-rift deposition) fits into the regional history of Gondwana rifting and continental breakup.

2.2. North Falkland Basin geological setting

The NFB is an extensional deep-lacustrine basin located 40 km north of the Falkland Islands (Fig. 3). It comprises a series of sub-basins which exhibit two main structural trends: NW–SE orientated basins in the south, and N–S orientated basins in the north (Lohr and Underhill, 2015). These two trends were first proposed to be an older Jurassic rift underlying a younger Cretaceous rift (Bransden et al., 1999); this was based on a regional study using 2D seismic data, which was agnostic of well data. This theory has been expanded on more recently by Lohr and Underhill (2015), using new 3D seismic data. The two structural trends are now considered to have been associated with two main phases of extension, depositing Jurassic and Cretaceous *syn*-rift megasequences (Bransden et al., 1999; Lohr and Underhill 2015). Lohr and Underhill's (2015) results refute a previous interpretation developed by Richards and Hillier (2000a, b), who suggested that the two differently oriented structural trends were active simultaneously. The NW–SE trend is dominant in the south of the basin (SNFB) and is associated with deposition of the Early Syn-rift strata. The Early Syn-rift is purported to be Jurassic in age (Richards and Hillier, 2000a; Richardson and Underhill, 2002; Lohr and Underhill, 2015; Stanca et al., 2019; Macgregor and Reeves, 2025), however until now there has been no geochronological evidence linking the Early Syn-rift to this period. For this study, this initial phase of Jurassic rifting is referred to as the Jurassic rift event. The N–S trend is dominant in the north (CNFB) and was active during deposition of the Late Syn-rift strata. The Late Syn-rift is attributed to a phase of early Cretaceous rifting (Lohr and Underhill, 2015; Richards et al., 1996b), referred to in this study as the Cretaceous rift event. The two *syn*-rift megasequences are separated by an unconformity which has been mapped using seismic reflection data (Lohr and Underhill, 2015).

The CNFB and SNFB are separated by the North Falkland Basin Transitional Zone (NFBTZ), where the intersecting N–S and NW–SE trends create alternating block and basin geometries (Fig. 3). Basement highs (blocks) include the Keppel Terrace, Ernest High, and Evie High, and basins include the Ernest Graben and Evie Graben (Fig. 3).

Deposition during both rifting events occurred in a dominantly

fluvio-lacustrine to lacustrine environment, with alluvial fans and ephemeral fluvial systems bringing sediment in from surrounding basement highs (Richards and Hillier, 2000a). This sediment input comprised both epiclastic and volcanoclastic intervals (Richardson and Underhill, 2002). Richardson and Underhill (2002) investigated Early Syn-rift aged core from well 14/24–1, identifying ashfall, volcanoclastic and conglomerate intervals in addition to lacustrine mudstones and epiclastic deposits. The overlying post-rift deposits consist of lacustrine claystones and deltaic intervals which pass into a succession of interbedded sandstones and mudstones, reflecting a gradual shift from a lacustrine to a marginal marine setting.

The SNFB is characterised by NW–SE trending faults and asymmetric half-grabens separated by basin highs (Fig. 3). The CNFB is sub-divided into two N–S trending depocenters: the Eastern Graben and the Western Graben (Fig. 3). The depocenters are separated by a prominent north–south trending intra-basinal high known as the Orca Ridge (Fig. 3). The Eastern Graben is the larger of the two basins and has a broadly asymmetrical profile controlled by a series of large westward-dipping normal faults that form its eastern margin. To the west it is bounded by a number of smaller eastward-dipping faults. This graben formed the main depocentre during the Cretaceous rift event. To the north, the Eastern Graben is partitioned into two depocenters by the Northern High (Fig. 3), a structural high that extends southward into the survey area (Lohr and Underhill, 2015). The smaller Western Graben is approximately 20 km across, 100 km long, and contains c. 2–4 km of sedimentary fill (Jones et al., 2019). The Western Graben has a similar asymmetrical profile to that of the Eastern Graben, with both the eastern and western margins bounded by normal faults, but preserves a much thinner sedimentary fill. The thickest Western Graben deposits are preserved towards the eastern side of the depocentre, adjacent to the Orca Ridge. The Western Graben fill thins to the south and eventually disappears south of well 14/19–1 (Fig. 3). Based on seismic interpretation, the sedimentary succession in the Western Graben is thought to be broadly age-equivalent to that in the Eastern Graben (Lohr and Underhill, 2015); however, the succession has not been drilled and remains poorly understood.

2.3. NFB tectonostratigraphy

Much (but not all) of the stratigraphy of the CNFB has been penetrated by hydrocarbon wells. Richards and Hillier (2000a) developed a tectonostratigraphic scheme for the NFB based on these well data and regional seismic reflectors. The scheme defines eight tectonostratigraphic units: the pre-rift/basement; Early Syn-rift; Late Syn-rift; Transitional/sag unit; Early Post-rift; Middle Post-rift; Late Post-rift; and a Post-uplift sag unit (Fig. 4). The scheme has been extended to areas outside of the CNFB based on seismic data, however due to the sparse well control there is considerable uncertainty in the stratigraphy in these areas.

The pre-rift basement is only encountered in well 14/09–1 of the CNFB, located over the Orca Ridge (Fig. 3). Approximately 50 m of *meta*-sediments, interpreted to be Devonian–Jurassic in age, were intersected by the well (Richards and Hillier, 2000a). There is considerable uncertainty as to the lithology of the basement away from this well.

The Early Syn-rift and Late Syn-rift units were defined by Richards and Hillier (2000a) as separate wedge-shaped packages observed on seismic data. They represent a progression from fluvial to lacustrine environments and are composed principally of conglomerates, organic-rich claystones, reworked tuffs and sandstones (Richards and Hillier, 2000a). The Transitional/sag unit consists of organic-rich claystones deposited in a lacustrine environment, interbedded with sandstones sourced from the basin margins (Richards et al., 1996a; Richards and Hillier, 2000a).

The Early Post-rift unit is characterised by a southward prograding delta system. Deltaic sandstones in the north of the basin transition

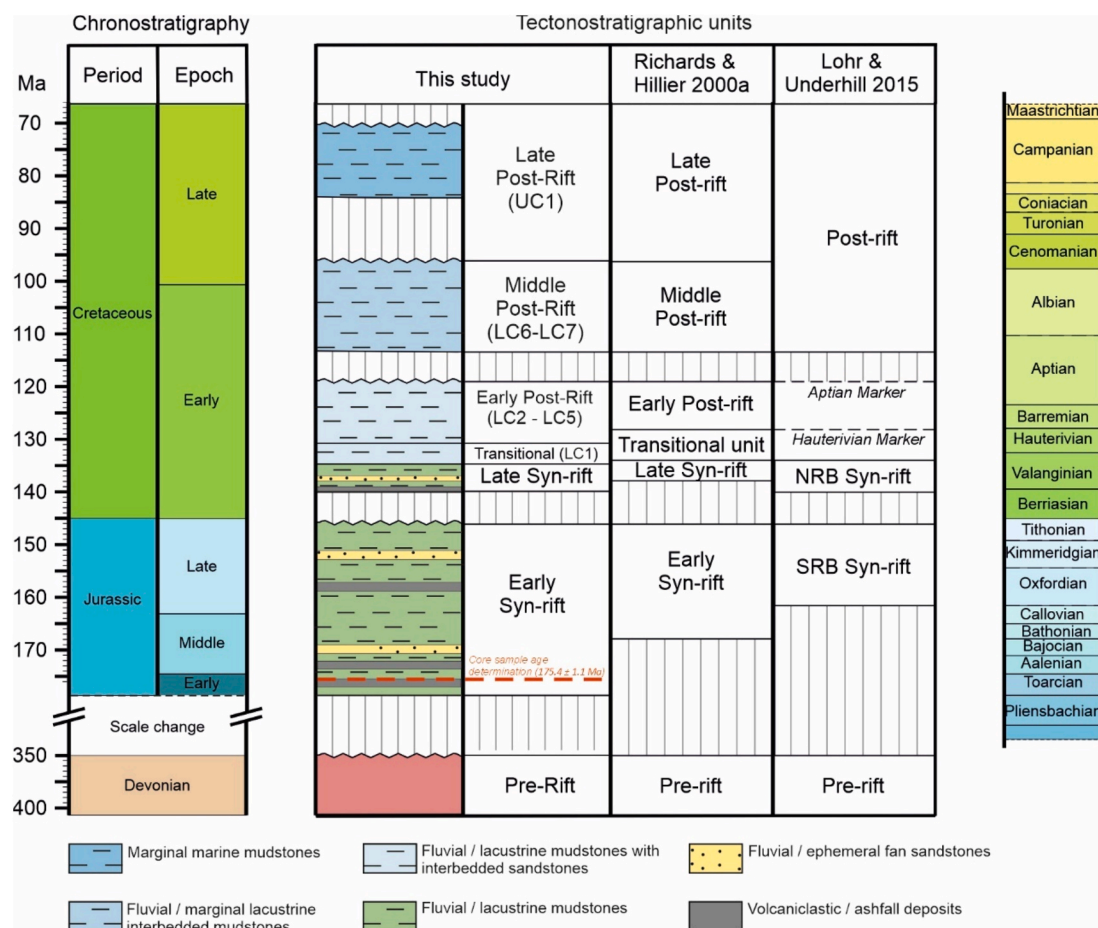


Fig. 4. Summary tectonostratigraphic chart highlighting the scheme used by this study, modified from Richards and Hillier (2000a). The scheme used by Lohr and Underhill (2015) is shown for comparison. The new core age determination is displayed, assigning at least part of the Early Syn-rift unit to the early Jurassic.

southward into organic-rich lacustrine claystones. These deposits are interbedded with turbidite fan systems derived from the basin margins. These turbidite fan systems resulted in a complex succession of sandstones interbedded with claystone facies (Dodd et al., 2019) and provide the primary reservoir units for discovered hydrocarbons in the NFB (e.g., Sea Lion, Isobel and Isobel Deep).

The Middle Post-rift contains sandstones, conglomerates, claystones and lignites, and marks a return to a terrestrial-fluvial depositional environment (Richards and Hillier, 2000a). The Late Post-rift unit contains sandstones and claystones deposited in a marginal-marine to marine setting (Richards et al., 1996a; Richards and Hillier, 2000a).

3. Data and methodology

This study used 3D and 2D seismic reflection, well, and core data supplied courtesy of the Falkland Islands Government. The seismic horizon interpretation was tied to existing syn-rift and basement well tops. The sedimentological interpretation was informed by core (from 14/24–1), geophysical well logs and cuttings descriptions, as well as seismic geometries and characteristics.

3.1. Seismic data and analysis

A comprehensive database of merged 3D seismic volumes and 2D seismic lines was available for this study. Approximately 4500 km² of 3D seismic data was acquired over the northern section of the NFB between 2007 and 2011 (Fig. 3; Fig. 5). In 2011, three of these surveys were reprocessed and merged along with new 3D acquisition to form a single contiguous seismic volume known as the ‘3D Company

Composite’ (Fig. 5). The merged seismic data was processed by Geotrace who performed manual velocity picking, 3D Kirchhoff Pre-Stack Time Migration (KPSTM), radon de-multiple, trim statics, offset scaling, spectral enhancement, and zero-phasing. The data is displayed with SEG normal polarity (an increase in acoustic impedance is displayed as a positive peak, in blue). No 3D seismic from the SNFB was used for this study. Here 2D seismic line surveys have been used to expand the interpretation south (Fig. 5). The 2D seismic line surveys, covering the SNFB (Fig. 5), were acquired between 1993 and 2006.

Three key regional horizons and associated basin bounding faults have been interpreted to define the Early Syn-rift and Late Syn-rift tectonostratigraphic megasequences: (i) top Late Syn-Rift; (ii) top Early Syn-rift and (iii) top basement. Time-thickness maps have been generated for each interval, based on the interpreted horizons, in order to highlight depositional trends and the distribution of the syn-rift deposits in the NFB.

3.2. Well data and sedimentary core logging

Well data is available from 26 wells in the NFB, including geophysical wireline, core and cuttings material. Eight of these wells penetrate the NFB syn-rift and were used for this study, (see Table 1; Fig. 5; Fig. 6). The well data used include gamma-ray and sonic wireline logs, cuttings descriptions and published composite lithology logs. Available wireline data from the mapped syn-rift interval were used to correlate the stratigraphy and to tie the seismic (Fig. 6). The seismic well ties for the eight syn-rift wells (Table 1) were used to identify three key seismic horizons (the top basement, the top Early Syn-rift and the top Late Syn-rift) that are presented in this paper. Gamma logs, sonic logs and cuttings

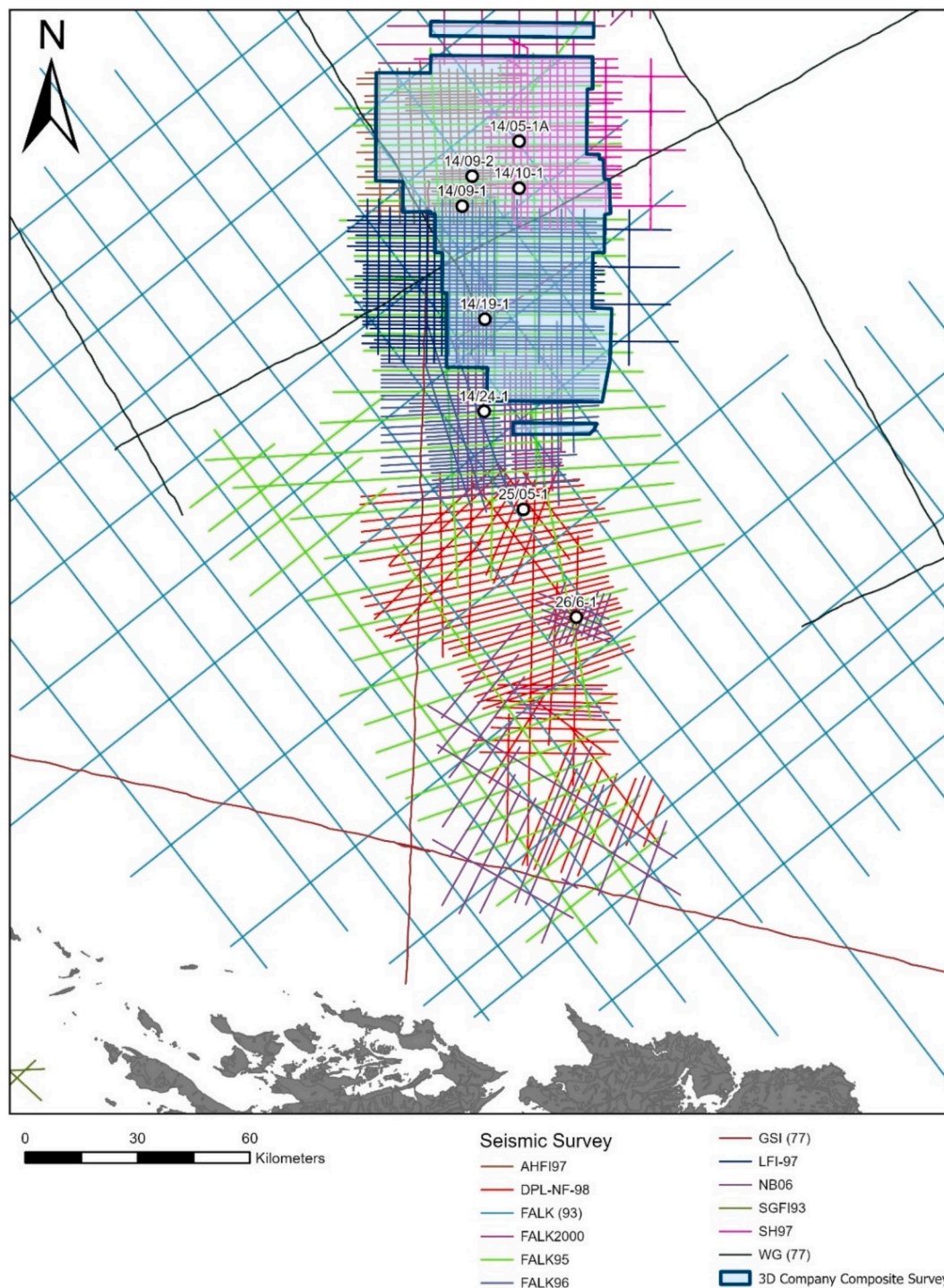


Fig. 5. 2D and 3D seismic reflection surveys available for the North Falkland Basin. Contains data © UKRI and Falkland Islands Government 1999. BGS © UKRI 2022.

descriptions from these wells also provided lithological information which was used for facies interpretation.

Well 14/24–1 is the only well to provide core through the *syn*-rift interval, with a total of 18 m of core available (retrieved from 2920.6 m and 2939.1 m MD RKB; Fig. 6). Sedimentary logs were produced, with data collected relating to lithology, grain size, grain sorting, grain angularity, clast size and composition, sedimentary structures and fracturing. This data was used to define a sedimentary facies scheme, and to group these into facies associations.

3.3. Thin section analysis

A total of 11 samples were taken from the 14/24–1 core for thin section (Table 2) and petrological analysis. Samples were selected for thin section analysis based on the preliminary core log interpretation. Polished thin sections were prepared using clear epoxy resin for optical microscopy (28 x 48 mm). The polished thin sections were initially imaged using a digital flatbed scanner to provide reference images for the whole section area. The polished sections were then examined by optical microscopy under plane-polarized light (PPL) and cross-polarized light (XPL) condition.

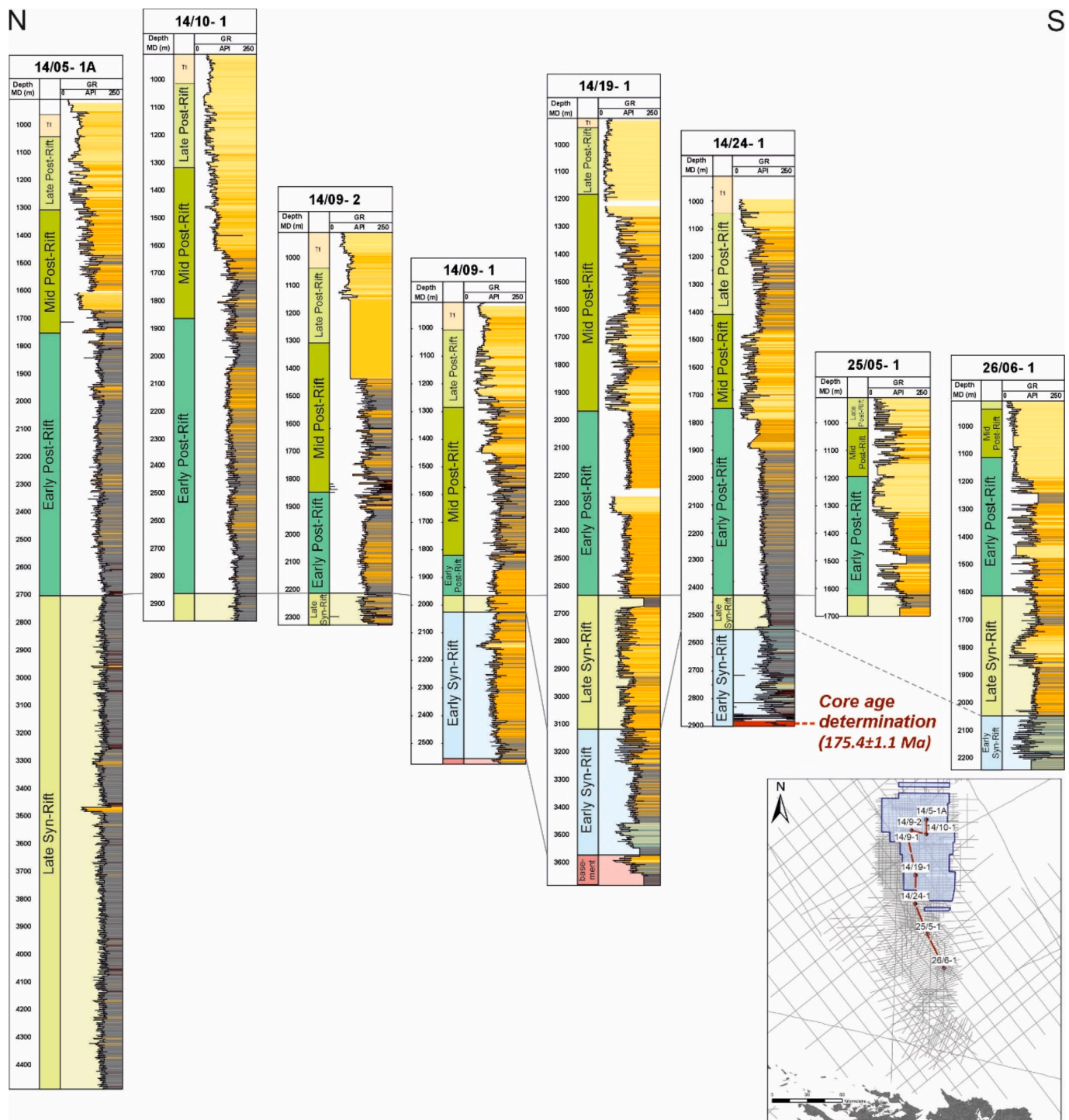


Fig. 6. North-south oriented well correlation panel showing wireline logs (gamma-ray), flattened on the top Late Syn-rift. Correlations are supported by seismic interpretation. Gamma-ray log scale on each well is 0 to 250 API. The Pre-rift, Early Syn-rift and Late Syn-rift units are indicated for each well. The cored interval of well 14/24-1 is highlighted in red. The Early Syn-rift succession partly comprises volcanics/volcaniclastics such as tuffs and tuffaceous claystones, in addition to interbedded sandstones and conglomerates. The Late Syn-rift succession is shown to comprise interbedded mudstone and sandstone intervals. Contains data © UKRI and Falkland Islands Government 1999. BGS © UKRI 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This analysis was undertaken to derive microfacies descriptions to supplement the grain size, sorting and sedimentary structure descriptions derived from the core analysis. These microfacies descriptions provided additional lithological information including mineral and clast composition. Note that not all sedimentary facies have corresponding thin section samples and associated descriptions.

3.4. Geochronology

Three additional samples were collected from the 14/24-1 core for age determination, recovered from three units of volcaniclastic rock (Sample 1–2936.75–2936.85 m; Sample 2–2930.30–2930.40 m; Sample 3–2922.10–2922.30 m). These samples were then thin sectioned.

Table 2

Thin section samples taken from the well 14/24–1 core. These samples are displayed in Fig. 10. Facies and Facies association analysis is provided in the results section of this study. Depths are recorded in measured depth below rotary Kelly bushing (MDRKB).

Sample number	MD RKB (m)	Facies	Facies association
62	2920.89	Fngt	5
66	2921.9	Fngt	5
60	2924.13	Fms	1
61	2924.94	Fiss	4
59	2929.64	Fcbt	3
58	2930.47	Fcbt	3
65	2930.47	Fcbt	3
57	2935.58	Fsd	2
56	2936.42	Fms	2
64	2936.42	Fms	2
55	2937.9	Fpxc	2

Zircon was separated using standard density and magnetic separation techniques, then hand-picked onto double-sided tape and mounted in epoxy, and polished to expose the interior of the grains. Cathodoluminescence (CL) imaging of zircon was carried out using an FEI Quanta 600 Scanning electron Microscope. U-Pb analyses were carried out using a multicollector Nu Plasma HR mass spectrometer coupled to a New Wave 193SS solid state laser, typically using a 20–25 μm laser spot, and fluence of c. 2.0–2.5 J/cm^2 . For zircon, three reference materials (Plešovice zircon; Sláma et al., 2008), 91,500 (Wiedenbeck et al., 1995), and GJ-1 (206Pb/238U 602.3 ± 1 Ma, 207Pb/206Pb 609.2 ± 0.7 Ma; Horstwood et al., 2016) were regularly analysed to correct the instrument mass bias and depth dependent inter-element fractionation of U and Pb. The 91,500 reference material was used as primary throughout, yielding a weighted average 206Pb/238U age of 1063.1 ± 4.3 Ma ($n = 31$). Secondary reference materials Plešovice and GJ-1 gave weighted average 206Pb/238U ages of 339.7 ± 1.7 Ma ($n = 27$) and 608.9 ± 2.4 Ma ($n = 28$) respectively. Data was reduced using Iolite (Paton et al.,

2010, 2011) and plotted using IsoplotR (Vermeesch, 2018). For samples, 206Pb/238U ages were used throughout, with discordance limit of $\pm 5\%$.

4. Results

4.1. Basin structure and tectonostratigraphy (2D and 3D seismic interpretation)

The below sections provide a description and interpretation of the basin structure and tectonostratigraphic sequences using the analysis of well data and both 2D and 3D seismic data. The descriptions are provided first, followed by a combined interpretation of the two outputs (time-structure maps and time-isochores).

4.1.1. Time-structure map descriptions

The top basement, Early Syn-rift and Late Syn-rift horizons have been picked across the extent of the Company Composite 3D Survey, as well as 2D surveys available for the SNFB. The SNFB is characterised by three NW–SE oriented grabens (Fig. 7). The northernmost of these grabens has an asymmetric profile and deepens to the southwest. The basement is downthrown by up to ~ 1750 ms two-way travel time (TWTT) across the southern bounding fault. The southernmost NW–SE oriented graben is bounded by faults on both its northeast and southwestern margins and, based on available seismic data, appears to have a more symmetrical profile in cross-section (Fig. 8). Transitional depocentres, located at the transition between the CNFB and the SNFB, such as the Ernest Graben and Evie Graben are also identified on the basement structure map (Fig. 7; Fig. 8). These two grabens are bounded by faulting on their eastern and western margins. The Ernest Graben is flanked by the Keppel Terrace to the west and the Ernest High to the east. The Ernest and Evie Grabens dip gently northwards, towards the CNFB. These SNFB structures are also visible within the top Early Syn-rift time structure map (Fig. 7). The NW–SE trending grabens that characterise the SNFB are not

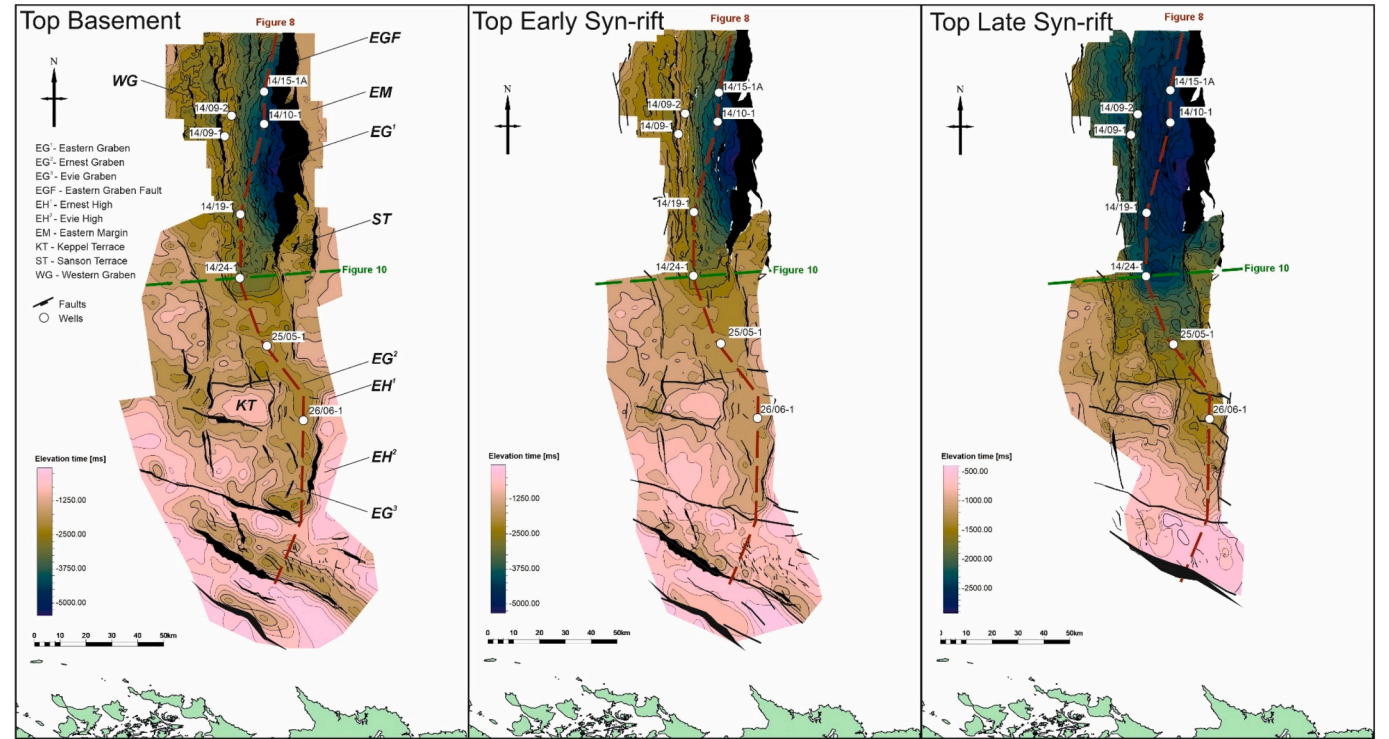


Fig. 7. Horizon time-structure maps for the top basement, top Early Syn-rift and top Late Syn-rift horizons. The top basement time-structure map clearly shows the N–S regional trend of the CNFB and the NW–SE regional trend of the SNFB. Basin highs such as the Orca Ridge and Keppel Terrace are visible on all three maps. The preserved top Early Syn-rift also highlights both regional trends.

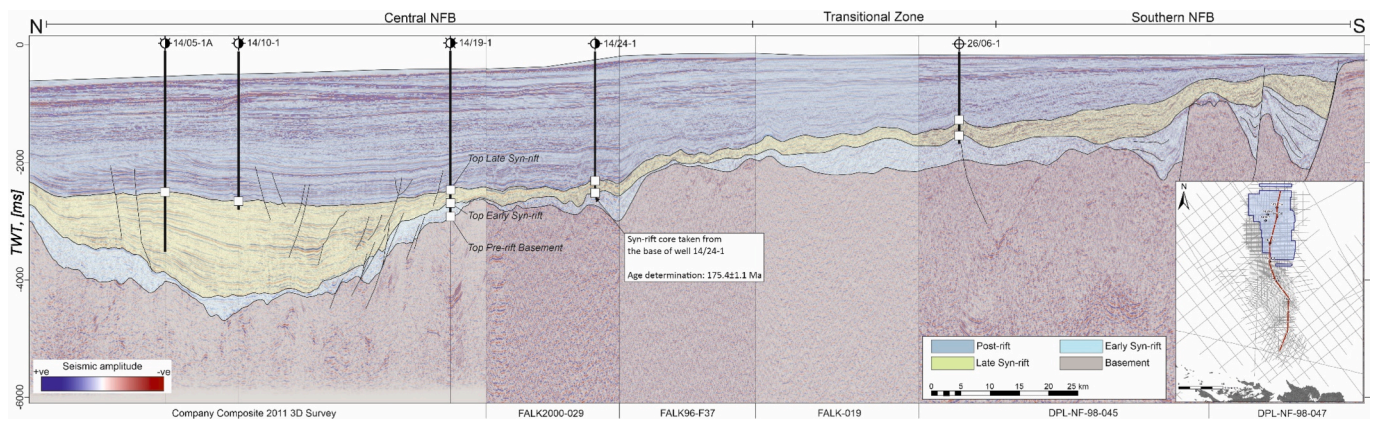


Fig. 8. Composite seismic section through the North Falkland Basin showing the N–S trending Central North Falkland Basin (CNFB) and the NW–SE trending, asymmetric grabens that comprise the Southern North Falkland Basin (SNFB). The section shows the interpreted basement, Early Syn-rift, Late Syn-rift and Post-rift sequences. The depth of the syn-rift basin fill increases notably to the north. The syn-rift in the North Falkland Basin Transitional Zone is interpreted here as the lateral continuation of the Early Syn-rift and Late Syn-rift megasequences identified in the CNFB and the SNFB. However, there is still uncertainty regarding the structural interpretation of this area, which is largely due to a combination of the data coverage, structural complexity, and orientation of available seismic lines relative to that structure. The location of the age determination obtained in this study is shown. The inset map contains data © UKRI and Falkland Islands Government 1999. BGS © UKRI 2022.

visible within the Top Late Syn-rift time structure map. Structures identified within the transition zone, such as the Ernest Graben and neighbouring Keppel Terrace, are represented but are less pronounced compared to the underlying Early Syn-rift and basement surfaces.

In the CNFB, the horizon structure maps for the basement, top Early Syn-rift and top Late Syn-rift highlight the N–S oriented asymmetrical Eastern Graben and Western Graben, which are separated by the Orca Ridge. Both half grabens deepen to the east, with the maximum burial depth attained in the Eastern Graben (Fig. 7). The basement is down-thrown by up to ~ 3,500 ms TWTT across the Eastern Graben Fault, where it reaches a maximum depth of ~ 5250 ms TWTT. The basement

forms a series of eastward dipping tilted fault blocks, which are accommodated by a series of westward dipping faults. These faults show listric geometries at depth. The rotated footwalls of these tilted fault blocks form the Orca Ridge and the Northern High, which both represent prominent intra-basinal highs in the northern part and along the western margin of the Eastern Graben.

The top Early Syn-rift is defined by a laterally continuous low amplitude reflector that is observed across the NFB. The horizon dips to the east, roughly sub-parallel to the profile of the underlying basement (Fig. 7). The depth of the surface ranges from approximately 2000 ms TWTT over the Orca Ridge, to a maximum of ~ 5200 ms TWTT in the

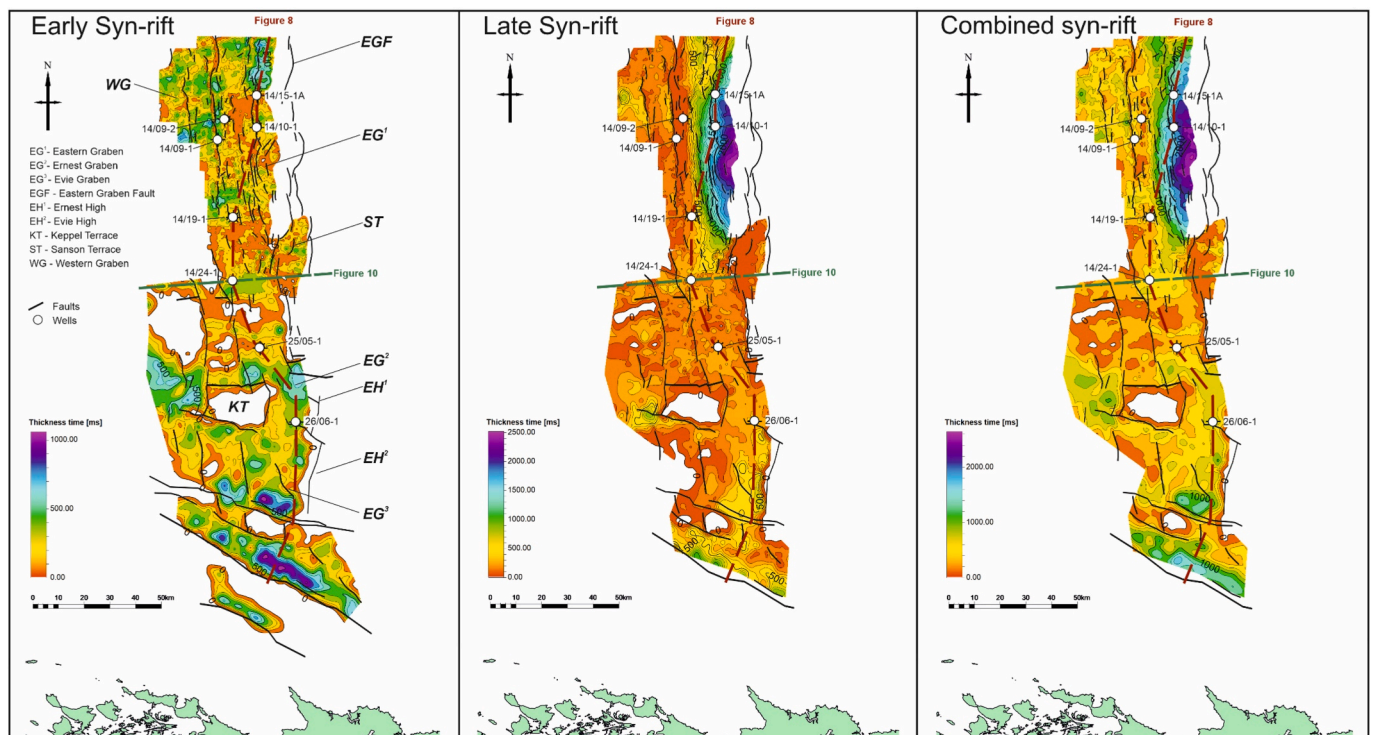


Fig. 9. Time isochores for the Early Syn-rift, Late Syn-rift and the complete syn-rift sequence. The Early Syn-rift isochore highlights the NW–SE trending half grabens of the SNFB that preserve the thickest Early Syn-rift packages. The Late Syn-rift reaches a maximum thickness in the Eastern Graben, with smaller packages preserved in the Western, Ernest and Evie grabens. No syn-rift is preserved over the Keppel Terrace.

centre of the Eastern Graben. The horizon is also interpreted to extend over the Sanson Terrace. The top Late Syn-rift reaches a maximum depth of ~ 2900 ms TWTT in the centre of the Eastern Graben, and approximately ~ 2400 ms TWTT in the Western Graben (Fig. 7). The Orca Ridge is picked out by this surface but is less prominent compared to the underlying surfaces for the top Early Syn-rift and basement (Fig. 7).

4.1.2. Syn-rift isochore descriptions

A maximum Early Syn-rift thickness of ~ 1000 ms (TWTT) is preserved in the SNFB depocentres (Fig. 9). Early Syn-rift thickness is inconsistent across the CNFB, reaching a maximum TWTT of ~ 800 ms in the Western Graben (Fig. 9). Sediment thickness within the Western Graben generally ranges between 200–500 ms. A thickness in excess of 500 ms is observed in parts of the Eastern Graben. Despite this, the unit is interpreted to thin significantly within the Eastern Graben (Fig. 9).

The sequence is absent over a number of SNFB and transitional highs, including the Keppel Terrace, Ernest High and Evie High. Up to 600 ms (TWTT) of Early Syn-rift is preserved in the Ernest Graben (Fig. 9). Up to 500 ms of the Early Syn-rift is preserved at the crest of the Orca Ridge. Here, the Early Syn-rift reflectors are shown to be truncated. Reflectors within the overlying Late Syn-rift onlap onto the top Early Syn-rift surface within the Eastern Graben and SNFB depocentres. Over 500 ms of Early Syn-rift sediments are interpreted to be preserved in places over the Sanson Terrace, onlapping onto the basement surface. The Early Syn-rift over the terrace is preserved as a wedge-shaped unit with diverging reflectors that truncate at the contact with the overlying Late

Syn-rift.

The Late Syn-rift forms an eastward diverging sedimentary wedge in both the eastern and western grabens, with the deposition controlled by faulting associated with E–W extension. In the CNFB the Late Syn-rift thins onto the Orca Ridge, and the Northern High, and is largely absent across the central part of the Orca Ridge. The Late Syn-rift sequence is considerably thinner in the Western Graben (<300 ms thick across the majority of the graben). Within the Western Graben the Late Syn-rift fill reaches a maximum thickness of ~ 750 ms against the western margin of the depocentre (Fig. 9).

A thin package of late syn-rift sediment is preserved across the SNFB and the transition zone (Fig. 8). Unlike in the CNFB, the Late Syn-rift isochore identifies few depositional trends across the SNFB. Late Syn-rift thickness in the SNFB ranges from 0 to 300 ms TWTT, a range comparable to that found in the Western Graben. A notable exception to this is a comparatively thick package of Late Syn-rift preserved in the Evie Graben. Late Syn-rift thicknesses in this transitional depocentre reaches a maximum of ~ 600 ms (time). The Late Syn-rift appears to largely pinch out over the Keppel Terrace, Ernest High and Evie High in the transition zone (Fig. 9).

4.1.3. Interpretation of time-depth maps and isochores

The Early Syn-rift was deposited on an erosional pre-rift surface, and consequently associated sedimentation was likely influenced by pre-existing pre-rift topography. The thickness of the unit varies across the basin (Fig. 9) and is influenced by both active faulting and topographical

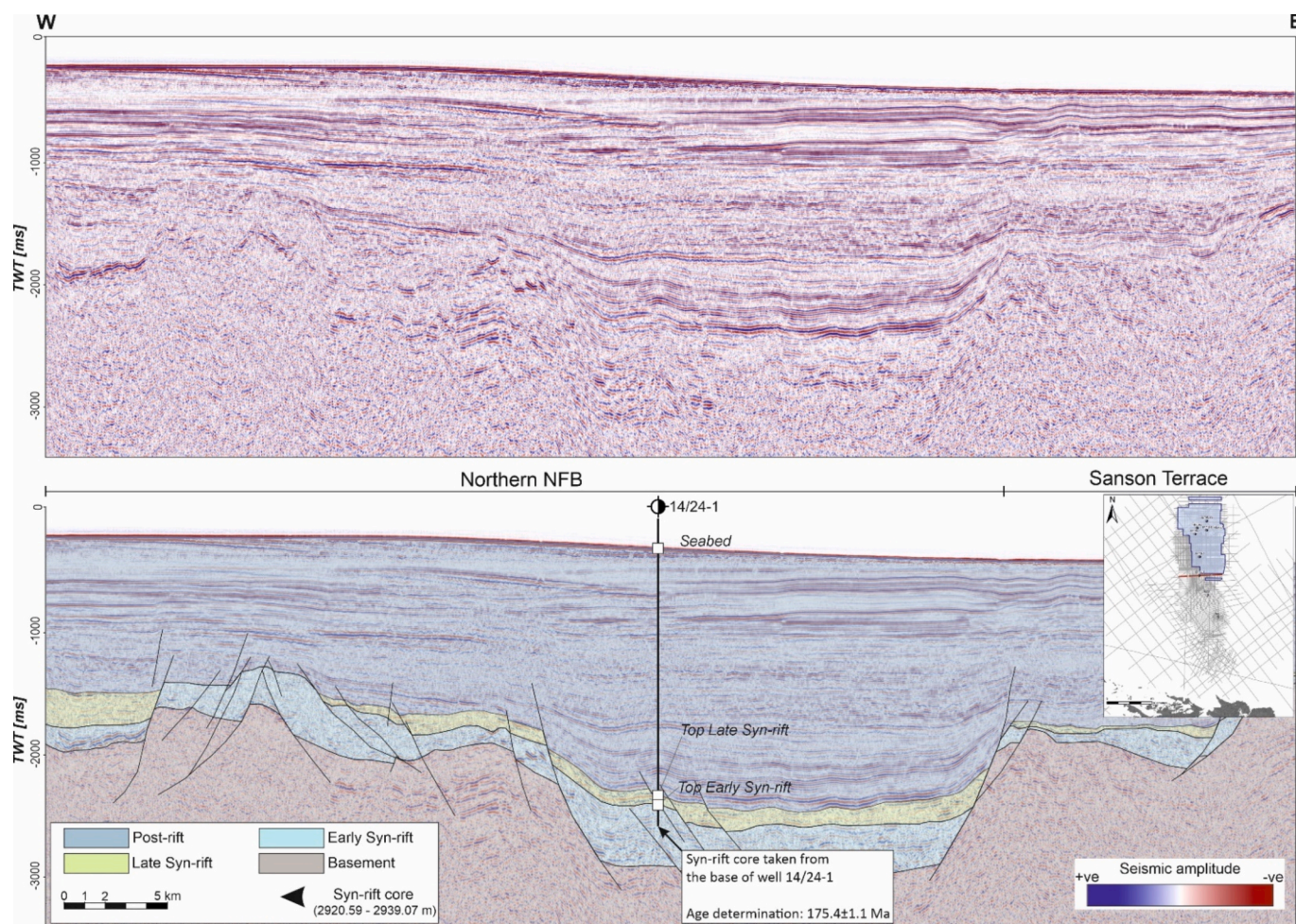


Fig. 10. Seismic section through the NFB showing an E–W cross-section of the CNFB and the location of well 14/24–1, which intersects both the Early Syn-Rift and Late Syn-rift. This 2D line was taken from the Spectrum_IPC_FALK_A1996 survey (FALK96-F20) and shows the interpreted basement, Early Syn-rift, Late Syn-rift and Post-rift sequences. On the basis of this seismic interpretation, the 14/24–1 core is from the Early Syn-rift.

controls. Depth-structure and thickness maps for the Early Syn-rift and the basement show a NW–SE and a NE–SW structural trend. This suggests that the structural domain characterising the SNFB is also present in the CNFB 3D survey area, expressed by deep-rooted faults (Stanca et al., 2019). The NW–SE structural domain associated with Jurassic extension and the deposition of the Early Syn-rift is interpreted to have been overprinted by the N–S structural domain that now characterises the CNFB, and which accommodated the deposition of the Late Syn-rift. During deposition, the thickness of the Early Syn-rift was influenced by the NW–SE striking structural trend. Deposition on the Sanson Terrace during Jurassic rifting appears to have been potentially influenced by pre-rift topography, as is indicated by the correspondence of Early Syn-rift thickness with mappable pre-rift topographic lows (Fig. 10), and/or evidence for erosion between rifting phases. The truncation of Early Syn-rift reflectors, particularly over the Sanson Terrace and the Orca Ridge, and the onlap of Late Syn-rift reflectors onto the Early Syn-rift points to the presence of an erosional unconformity separating the two syn-rift units. This unconformity evidences the partial erosion of the Early Syn-rift during the hiatus between the Jurassic and Cretaceous rift events.

Early extension associated with the second phase of rifting (Cretaceous rift event) was accommodated by the development of the Eastern Graben, which was facilitated by the growth of the Eastern Graben Fault System. Deposition within the northern part of the Eastern Graben was also influenced by development of the Northern High: a prominent topographical high located in the north of the study area, which formed during the Cretaceous rift event (Jones et al., 2019). The scale of subsidence during the Cretaceous rift event differs between the Eastern and Western Graben. Isochore analysis highlights that only a thin package of Late Syn-rift is preserved across the SNFB (Fig. 8). It is uncertain as to what extent this is due to reduced deposition or subsequent erosion. The syn-rift to post-rift boundary is hard to define in seismic data (Lohr and Underhill, 2015), particularly in the SNFB where there is less data. In the CNFB, the boundary appears to be transitional. The N–S structural trend visible in the CNFB gradually decreases in prominence and disappears in the transition zone between the CNFB and the SNFB.

4.2. Sedimentology and facies analysis

Nine facies have been identified in the Early Syn-rift core from well 14/24–1 (Table 3; Fig. 11; Fig. 12; Fig. 13), through core logging and thin section analysis. The facies were identified on the basis of recognising lithological variability within the core data and associated key sedimentary structures. The nine facies are described in detail at the –core-scale and are defined in Table 3. These facies are: Coarse-tail graded sandstone (*Fcs*), Planar cross-bedded conglomerate (*Fpxc*), Planar cross-bedded sandstone (*Fpxs*), Mottled siltstone (*Fms*), Interbedded sandstone and siltstone (*Fiss*), Structureless diamictite (*Fsd*), Compositionally banded tuff (*Fcbt*), Planar laminated tuffite (*Fpt*) and Mottled normally-graded tuffite (*Fngt*) (Table 3). Microfacies descriptions based on thin-section analysis are provided for six of the identified facies (Table 3; Fig. 11; Fig. 14). Microfacies descriptions are not provided for the *Fcs*, *Fpxs* and *Fpt* facies as the thin-section sampling was completed before final facies analysis of the logs was undertaken. The core-scale and microfacies descriptions have been interpreted to identify likely sedimentary processes that led to their deposition.

The nine facies have been grouped into five facies associations, based on common and/or successive sedimentary processes. Collectively, these processes represent the product of a particular environment of deposition (at the element scale).

4.2.1. Unconfined fluvial facies association (FA1)

4.2.1.1. Description. This facies association comprises coarse-tail graded sandstone (*Fcs*), mottled siltstone (*Fms*), and interbedded siltstone and sandstone (*Fiss*) (Fig. 11). The unconfined fluvial facies

association is the most prevalent facies association in the cored section of well 14/24–1, recurring several times (Fig. 11). The unconfined fluvial facies association comprises c. 8 m of the 18.41 m cored section (Fig. 11).

Stacked beds of *Fcs* commonly occur in this facies association, interrupted by *Fms* and/or *Fiss*. The base of *Fcs* has an erosive boundary with the underlying beds and coarse-tail grading above the contact; this is the case whether *Fms*, *Fiss* or *Fcs* is present above the contact. Beds of *Fms* or *Fiss* occur above *Fcs* and indicate a normal grading pattern from the coarse lag before the next *fcs* bed (or ensuing succession of stacked beds) (Fig. 11). Individual beds of *Fcs* are up to 0.6 m thick; stacked beds of *Fcs* are up to 1.29 m thick. Beds of *Fms* are typically around 0.25 m thick (with a maximum thickness of 0.96 m in this facies association), whilst beds of *Fiss* range between 0.25 m and 0.45 m in thickness (Fig. 11).

4.2.1.2. Interpretation. The unconfined fluvial facies association represents an immature, unconfined, fluvial-related environment, where flows may have had low water content resulting in the absence of crossbedding, imbrication, or other sedimentary structures. The facies association shows variation in flow energy and potentially in sediment supply/influx. *Fcs* was deposited by high-energy, ephemeral flows that carried reworked volcanoclastic material as a significant component of their load. Such flows may have taken place within an ephemeral or migratory fluvial environment. The base of *Fcs* are commonly defined by a coarse-tail lag, which can be seen clearly where *Fms* or *Fiss* are present below. This erosive boundary is less noticeable where it overlies another *Fcs* bed. Often, the *Fcs* bed fines upwards and is overlain by *Fiss* or *Fms*. Beds of *Fms* are interpreted to have been deposited in slack water environments, probably during periods between the ephemeral high-energy flows. Beds of *Fiss* are interpreted to represent deposition within a low-energy environment, where there was occasional influx of coarser material and variation in flow energy. Stacked beds of *Fcs* may indicate repeated influx of high-energy, ephemeral flows with little/no return to slack water conditions. It is likely that there was a return to background sedimentation between the ephemeral flows, with beds of *Fms*/*Fiss* deposited within these low-energy conditions, then subsequently eroded by the high-energy flow. Background sedimentation between ephemeral flows is evidenced by the occurrence of thin beds (10 cm) of *Fiss* and *Fms* preserved between beds of *Fcs* within the cored section.

4.2.2. Confined fluvial facies association (FA2)

4.2.2.1. Description. The confined fluvial facies association contains planar cross-bedded sandstone (*Fpxs*), planar cross-bedded conglomerate (*Fpxc*), mottled siltstone (*Fms*), and structureless diamictite (*Fsd*) (Fig. 13). It occurs once near the base of the cored section and is bound by intervals of unconfined fluvial facies association above and below (Fig. 11; Fig. 12).

The base of the facies association is erosive/irregular and comprises alternating beds of *Fpxs* and *Fpxc*. A 0.32 m thick bed of *Fms* containing planar lamination is identified at the top of the basal *Fpxs* and *Fpxc* interval, capping a normally graded sequence. This continues into a bed of *Fsd*, where clasts are scattered throughout the relatively homogeneous matrix of very fine-grained sand (Fig. 14C). Overall, the confined fluvial facies association fines upwards (Fig. 11; Fig. 12).

4.2.2.2. Interpretation. The confined fluvial facies association represents a mature fluvial environment, with channelised fluvial elements. Beds of *Fpxs* were deposited in a channel by a high-energy and low concentration flows which resulted in imbrication of clasts carried as bedload, and the formation of planar cross-bedding structures showing subaqueous dune migration. The lower bed of *Fpxs* is 14.5 cm thick and is directly overlain by *Fpxc*, however, the upper bed of *Fpxs* shows very

Table 3

Description and interpretation of the nine sedimentary facies identified in the core from well 14/24–1.

Facies code	Facies title	Facies description	Micro-description (thin section descriptions)	Interpretation
<i>Fcs</i>	Coarse-tail graded sandstone	Very fine-grained coarse-tail graded, sandstone. 1–20 mm wide typically sub-angular to rounded cobble to pebble-grade clasts at the base. The clasts are volcanic in origin. The matrix sometimes fines upwards from very fine-grained sandstone to siltstone at the top of the bed, with poorly-developed planar laminations. Smaller clasts (<1–5 mm) are scattered and suspended in upper parts of the facies beds (Fig. 11; Fig. 12).	No micro-facies description available.	An ephemeral high-energy, unconfined decelerating flow (Coronel et al., 2020). These flows deposited cobble to pebble grade lags, which are observed to erode into the underlying siltstone. Fine-grained sand and smaller clasts (<1–5 mm in width) settle out as energy dissipates due to flow deceleration. The clasts that are at the bed bases, or are suspended within the beds, are interpreted to be eroded volcanic rock (secondary volcanoclastic).
<i>Fpxc</i>	Planar cross-bedded conglomerate	Planar cross-bedded, conglomerate, with imbricated sub-angular to rounded pebbles (<35 mm in width), fining-upwards to coarse-grained sandstone. There can be breaks in the conglomerate where layers of fine- to medium-grained sandstone are deposited, draping the underlying clasts. Both clast supported and matrix supported intervals are identified. Clasts within the matrix supported conglomerate intervals are suspended in fine-grained or medium-grained sandstone layers (Fig. 11; Fig. 12).	Sub-rounded to rounded coarse-grained clasts (<10 mm), which are grain supported. The clasts, and rock have an igneous origin, with clasts containing interlocking crystals of quartz and felspar, or comprising crystal-rich ash. Around the grains, calcite is present as a pore-filling cement (Fig. 14A). Both matrix and grains contain chlorite and calcite, indicating extensive alteration of the sample.	An ephemeral, very high-energy, confined or unconfined flow deposit (Priddy and Clarke, 2020) with low sediment concentrations that deposited imbricated and planar cross-bedded pebbles and coarse-grained sand. Suspended clasts within the conglomerate indicate rapid deposition. The observed crossbedding indicates in-channel migration within combined flows.
<i>Fpxs</i>	Planar cross-bedded sandstone	Coarse- to fine-grained planar cross-bedded sandstone with < 35 mm wide, sub-angular to rounded, suspended clasts concentrated towards the base of the sandstone beds. The matrix fines to very fine-grained sand above the cross-bedded clasts (volcanoclastic) and sometimes fines upwards to siltstone at the bed tops. Volcanoclastic clasts also are present in the upper portions of beds, typically scattered and suspended in the matrix (Fig. 11; Fig. 12).	No micro-facies description available.	Ephemeral, high-energy, confined flow (fluvial) with high water content, depositing imbricated and planar cross-bedded clasts in a coarse- to fine-grained sand matrix (Priddy and Clarke, 2020). Observed crossbedding potentially points to deposition occurring in a fluvial system with sediment migrating in channel bedforms.
<i>Fms</i>	Mottled siltstone	Planar laminated or structureless grey/green mottled siltstone, with dark grey to white mottling, and isolated burrows that are up to 2 cm in diameter and form as discontinuous structures. Discrete lithic grains (<1000 µm) are visible in places. (Fig. 11; Fig. 12).	Discrete coarse grains (<1000 µm), largely composed of quartz with some feldspars and lithic fragments, are randomly oriented in a clay- to silt-grade matrix (Fig. 14B). The matrix exhibits extensive chlorite alteration. The siltstone matrix contains extensive sub-horizontal trails of iron oxide.	Suspension fallout in still water/lacustrine conditions (Dodd et al., 2019; Coronel et al., 2020). The planar laminated intervals within the siltstone are the result of gradational changes in grain-size as particles initially suspended within a flow settle out of the water column. Structureless intervals were potentially disturbed by bioturbation. Observed mottling textures may relate to a period of palaeosol development, with associated textures enhanced further by early diagenesis (Kraus, 1999).
<i>Fiss</i>	Interbedded sandstone and siltstone	Comprises two sub-facies: structureless beds of very fine-grained sandstone to siltstone, and discrete beds of coarse-grained sandstone with suspended pebble clasts. The very fine-grained sandstones to siltstones occasionally show planar laminations. Contains dark grey or white discoloured elongate features within the silt-grade sediments and very fine-grained sandstone beds. The coarse-grained sandstone beds are commonly isolated and thin (up to 7 cm, typically 1 to 3 cm). Sandstone intervals are generally poorly sorted. One bed (Fig. 11Ci; Fig. 12Ci) contains horizons of concentrated clasts (up to 5 mm in size) suspended in a poorly-sorted fine-grained sand to silt-grade matrix (Fig. 11; Fig. 12). Sand grains throughout are generally angular to sub-angular.	The matrix contains numerous angular quartz, and brown coloured grains (metamict subhedral titanite, opaque phases and volcanic glass) (Fig. 14E). The matrix has been extensively altered to chlorite. Some lithics also show extensive chlorite alteration (Fig. 14E). Some primary void spaces have been infilled with a fibrous secondary phase, which has grown into the void space from the surrounding material. Fine-grained, and coarse-grained anhedral patches of calcite are present throughout the matrix.	Low-energy lacustrine suspension fallout interrupted by periodic, slightly higher energy flows and often affected by post-depositional reworking (slumping and churning; Dodd et al., 2019). Periodic higher energy flows are responsible for bringing in coarser-grained sandstones with suspended clasts up to 5 mm across. The discoloured and elongate features potentially represent burrows or roots.
<i>Fsd</i>	Structureless diamictite	Dark grey structureless diamictite in which 1–2.5 mm angular- to sub-rounded clasts are suspended in a silt- to very fine-grained matrix (Fig. 11; Fig. 12). Clasts compositions include lithic fragments.	Fine-grained clasts with rare lithic clasts, up to 2.5 mm in diameter, are identified in thin section (Fig. 14C). The silt- to very fine-grained matrix exhibits extensive chlorite alteration, micaceous phases and secondary calcite.	The microfacies composition points to the <i>Fsd</i> facies having a volcanic source or a volcanic component. The lack of structure and presence of scattered and suspended clasts throughout the diamictite interval suggests reworking of existing very fine-grained volcanoclastic deposits, potentially as part of a mass flow.
<i>Fcbt</i>	Compositionally banded tuff	A compositionally banded tuff composed of fine-ash grade material with ‘wavy banding’ at the base, and pale green fine-ash grade material with persistent veining at the top. Overall, veining and mottling is most intense throughout the upper half of the facies. Contains grey < 5 mm	The visible colour change is caused by different mineral phases which have formed in distinct bands. EDXA spectra and BSEM imaging show that the three phases are adularia, calcite and quartz. These phases are also present around fractures, where precipitation has progressed	This compositionally banded tuff is interpreted as the product of ashfall resulting from volcanic activity (Bahk and Chough, 1996). The observed compositional banding is broadly parallel to the bedding, evidencing gradual accumulation rather than flow deposition. The ash has since been altered

(continued on next page)

Table 3 (continued)

Facies code	Facies title	Facies description	Micro-description (thin section descriptions)	Interpretation
<i>Fpt</i>	Planar laminated tuffite	wide circular mottled patches. A large vein is bordered by grey discolouration and infilled with chlorite (Fig. 11; Fig. 12). Planar laminated tuffite, composed of green to grey coloured silt-grade material, along with up to 4 mm long angular flat and elongate dark grey fragments. The grey tuffite bands preserve some potential flow structures/ripple laminations. Fiamme are present throughout the bed. Fiamme are curved or straight and scattered at different angles in the bed. White to light grey mottling near the top of the facies (Fig. 11; Fig. 12). Fiamme lack a welded texture at core-scale.	into the wall rock on either side of the fracture. The matrix is partially affected by secondary precipitation of adularia, quartz and calcite (Fig. 14D). No micro-facies description available.	to clays and carbonate. The banding and mottled discolouration appear to be the result of post-depositional alteration/diagenesis (alteration halos in the case of the mottled discolouration). The planar laminated tuffite is an epiclastic deposit. Deposition is interpreted to have occurred through the reworking of volcanoclastic material in a low-energy, lacustrine/marsh environment, or the distal regions of a fluvial system proximal to a volcanic source (Bartow, 1994). The proximity is indicated by intact but non-welded fiamme that would have had limited transport potential before being broken up by sedimentary transport processes. The observed non-planar laminations are interpreted as flow structures/ripple laminations, suggesting an aqueous deposition. The planar laminations indicate deposition as part of a non-turbulent flow (likely as flow energy decreased). Mottling is interpreted to represent a pedogenic texture, which was the result of subaerial exposure and enhanced by early diagenesis.
<i>Fngt</i>	Mottled normally-graded tuffite	A mottled normally-graded coarse-ash to fine-ash grade tuffite, with matrix suspended clasts. The sub-angular to rounded clasts (< 10 mm in width) are present throughout the bed but are mainly concentrated near the base of the bed. The clasts become more dispersed moving up through the bed. Overall, the bed is normally-graded (Fig. 11; Fig. 12). The fiamme appear to be limited to the coarser matrix, occurring lower in the bed. The fiamme are curved or straight and scattered with a variety of A-axis orientations within the bed. Fiamme lack an obvious welded texture at core scale.	The mottled texture of the facies is due to variations in grain size, and concentrations of different material phases (Fig. 14F), namely concentrations of secondary calcite and chlorite. Fine crystals of chlorite are often closely associated with the calcite. Some of the coarse-grained clasts are polymictic lithics comprising quartz and feldspar, with secondary clays and white mica, calcite and/or chlorite (Fig. 14G and H). Sample also contains rare zircons (Fig. 14H). Small-scale burrow-like features infilled with clay are visible in a thin section taken from the uppermost tuffite bed at the top of the core.	The <i>Fngt</i> facies is representative of deposition in an ephemeral, higher energy fluvial/alluvial environment, such as an alluvial or turbidite fan (Chun and Chough, 1995), which deposited coarse volcanoclastic material. Flow energy gradually decreased over time and sediment concentration and grain size within the flow decreased, evidenced by the normally-graded succession observed in the core, and a reduction in the number of clasts.

clear normal grading and fines upwards to *Fms*. *Fpxc* also shows imbrication and planar cross-bedding. The difference between the *Fpxc* and *Fpxs* facies is indicative of varying flow energies at the time of deposition. The *Fpxc* facies was deposited under high-energy flow conditions, forming migrating in-channel bars. The *Fpxs* facies was deposited under lower energy conditions, possibly as part of a point bar succession. This could indicate further maturity in the fluvial system, an increase in energy and/or a variation in sediment supply. *Fpxc* does not show a strong normal-grading pattern, unlike *Fpxs*, suggesting rapid deposition. The stacked beds of *Fpxs* and *Fpxc* are capped by beds of planar laminated *Fms*, which indicates a substantial reduction in flow energy and a change from a mature fluvial system to a low-energy, possibly lacustrine environment. This marks the abandonment of the fluvial system. *Fsd* overlies *Fms*, with a sharp, defined boundary between the two beds. The deposition of *Fsd* is interpreted to represent a reduction in water levels and subsequent onset of pedogenic processes, eventually leading to a formation of palaeosols.

This facies association represents a high-energy confined fluvial system, resulting in beds of *Fpxs* and *Fpxc*, the flows responsible for which being cut-off suddenly, resulting in the return to a still water environment. In some cases of FA2, subaerial exposure further dries out the deposit, eventually causing them to undergo pedogenesis to form a palaeosol (*Fsd*) at the top of the association.

4.2.3. Volcanic ashfall facies association (FA3)

4.2.3.1. Description. Facies association 3 is dominated by compositionally banded tuff (*Fcbt*), with a bed of mottled siltstone (*Fms*) at the top of the association (Fig. 11; Fig. 12). This facies association occurs once, between FA1 and facies association 4 (Fig. 13). The bed of *Fcbt* is 1.76 m thick, topped by a 0.13 m thick bed of *fcs*. The base of *Fcbt* is sharp and undulating with the underlying *Fms* that belongs to the

unconfined fluvial facies association (Fig. 11; Fig. 12). *Fcbt* is predominantly structureless, although is variable in colour, changing from white and then grey at the base and becoming greener in the middle and top (Fig. 11Bii; Fig. 14D). Veining or mottling is most intense throughout the upper half of the association, in both the *Fcbt* and *Fms*.

4.2.3.2. Interpretation. A 1.76 m thick bed of *Fcbt* is the major facies within FA3, accompanied by more minor *Fms* intervals. The volcanic ashfall facies association represents a hiatus in normal sedimentary processes and is instead represented by the deposition of *Fcbt*, which is interpreted as a result of volcanic ashfall. These volcanic ashfall processes led to the deposition of an extremely fine-grained and structureless unit, which has since been diagenetically altered to carbonate and clay (Fig. 14D). *Fms* overlies the *Fcbt* bed and is marked by an abrupt change to a darker coloured bed of planar/sub-planar laminated silt (Fig. 14B). The *Fms* bed represents the return to 'normal' sedimentary processes, that being epiclastic deposition in a low-energy environment.

4.2.4. Unconfined ephemeral facies association (FA4)

4.2.4.1. Description. This facies association contains mainly inter-bedded siltstone and sandstone (*Fiss*), with beds of planar cross-bedded sandstone (*Fpxs*) and planar cross-bedded conglomerate (*Fpxc*) (Fig. 11). It occurs once in this cored section, between FA3 below and unconfined fluvial facies association above (Fig. 11; Fig. 12Cii). Many of the beds of *Fiss* in this facies association exhibit faulting, which makes sedimentary logging and facies identification challenging.

4.2.4.2. Interpretation. The *Fiss* facies is the most prevalent facies within FA4, comprising two main subfacies; (i) siltstone to very fine-grained sand which is generally structureless; (ii) discrete beds of coarse-

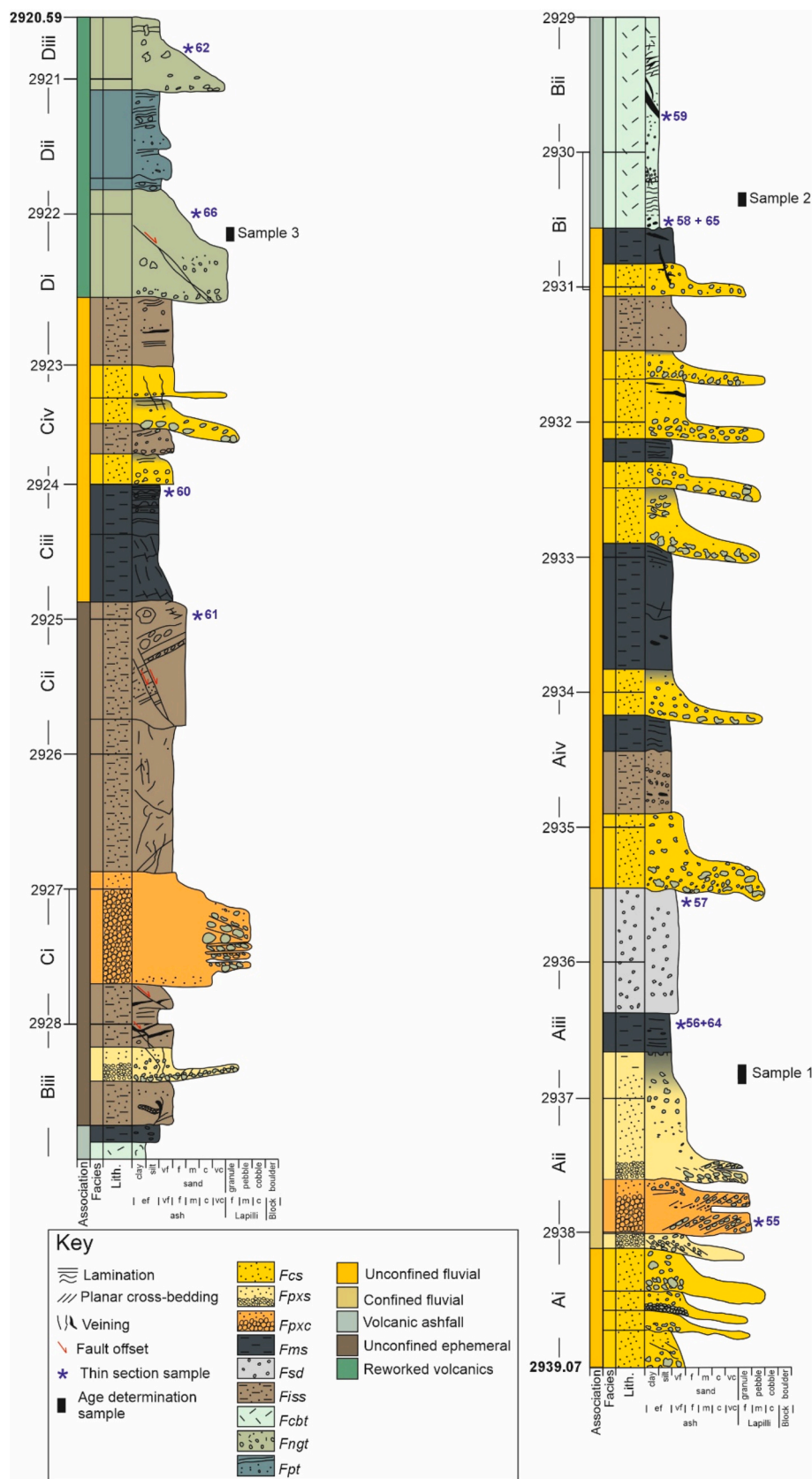


Fig. 11. Sedimentary log of the cored section from the Early Syn-rift in well 14/24-1. The log shows the character and distribution of the nine interpreted sedimentary facies, as well as the five interpreted facies associations. Both depositional and non-depositional structures (such as faults) are shown. Age determination sample locations are highlighted in black.

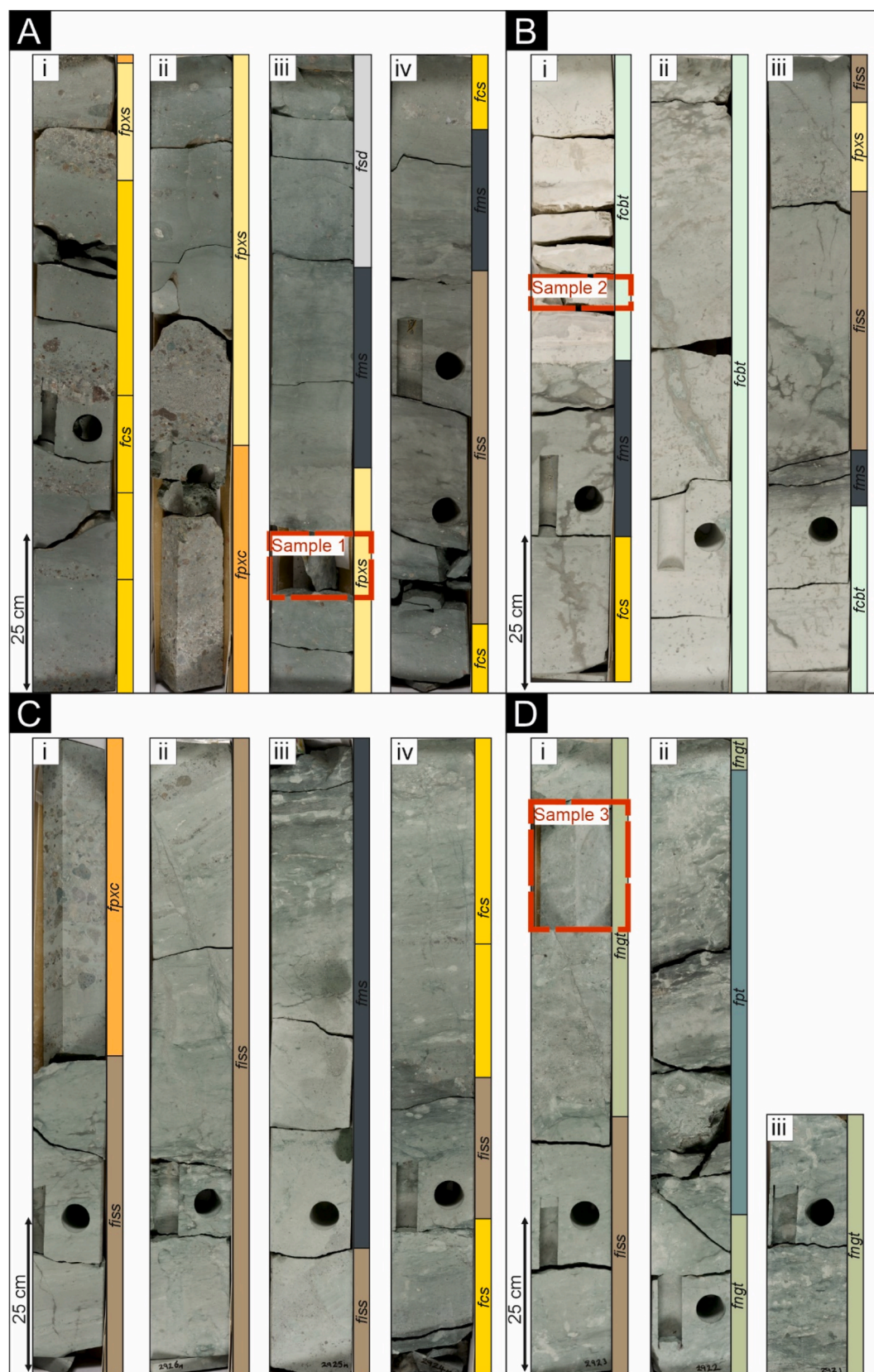


Fig. 12. Core panel photographs from the 14/24-1 well, showing reference examples of the nine interpreted lithofacies (for facies descriptions, see Table 1.), supplementing the sedimentary log presented in Fig. 12. A) 2939 m (i) (base depth) to 2934 m (iv); B) 2931 m (i) to 2928 m (iii); C) 2928 m (i) to 2923 m (iv); D) 2923 m (i) to 2920.59 m (iii) (top depth). Geochronology sample locations are outlined in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

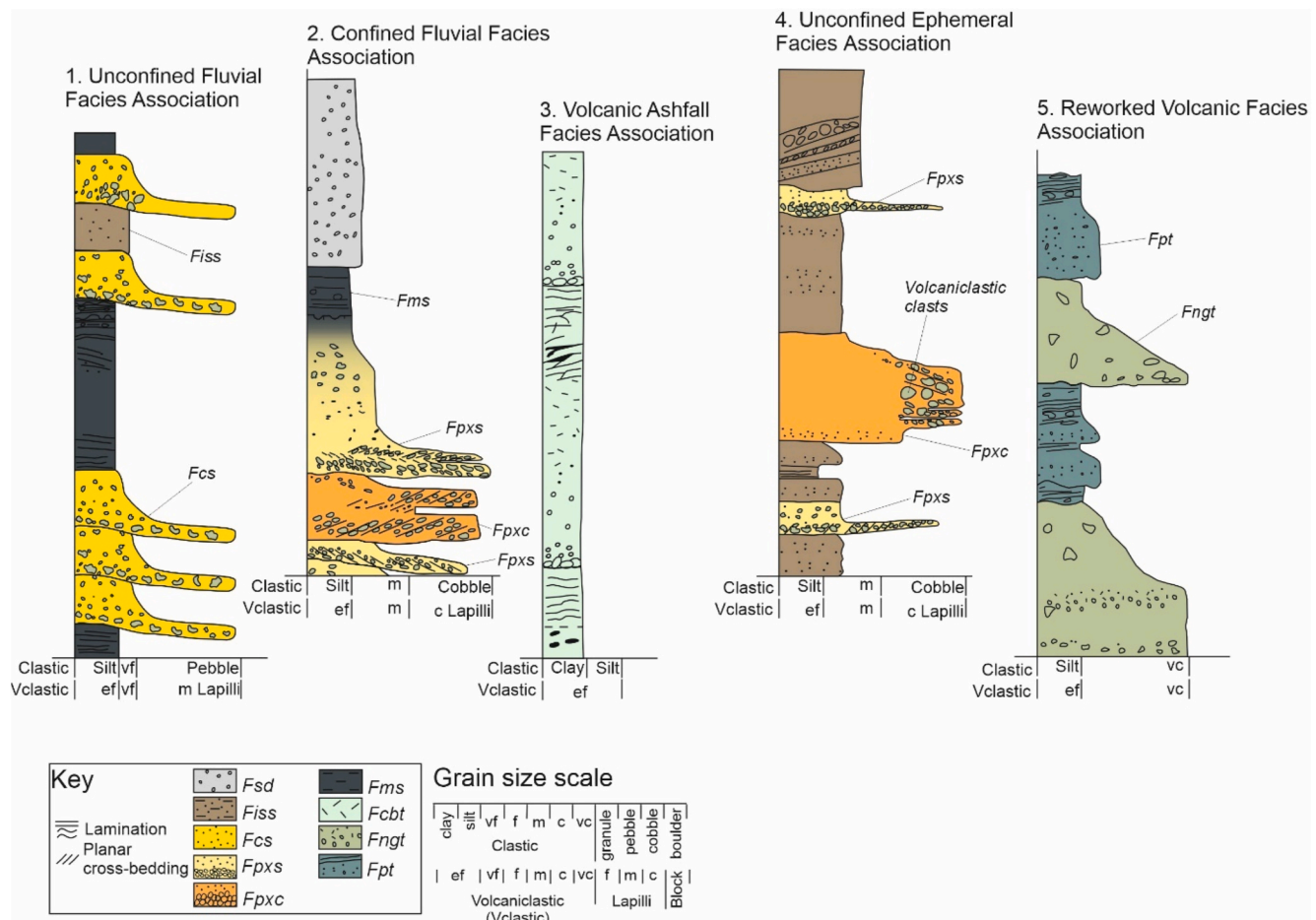


Fig. 13. The five idealised facies associations outlined in this study. These facies associations are based upon the interpretation of the cored section of well 14/24–1. The nine individual facies are described and interpreted in Table 3.

grained sand and clasts suspended in a fine matrix. In the lower part of the association, *Fiss* is mainly composed of the siltstone to very fine-grained sand component, with rare medium-grained sand beds. The top extent of *Fiss* in this association contains more discrete beds of coarse-grained sands and clasts suspended in a fine-grained matrix (Fig. 14E). These sandstone beds are poorly sorted and do not exhibit normal grading, indicating that they probably reflect periodic influxes of sediment laden flows across the underlying surface. The siltstone/very fine-grained sand between the discrete sand beds contain white/light grey circular and tubular features, which are interpreted as burrows or roots, potentially related to a pedogenic surface.

Beds of *Fpxc* and *Fpxs* within FA4 were deposited by unconfined high-energy, low sediment concentration ephemeral flows across the palaeosurface. This is indicated by imbrication and planar cross-bedding, but which lack amalgamation surfaces that would otherwise point toward channel deposition; instead, the deposits are interrupted by beds of *Fiss*. This facies association represents high-energy low sediment concentration ephemeral flows over an unconfined plain, which may have been exposed or at least were under very shallow waters. Later in the facies association, the flows are of lower energy and are more sediment laden, depositing discrete beds of coarse-grained sand and clasts that are suspended in a fine-grained matrix across the palaeosol.

4.2.5. Reworked volcanic facies association (FA5)

4.2.5.1. Description. Facies association 5 (Fig. 13) is composed of mottled, normal-graded tuffite (*Fngt*) and tuffaceous siltstone (*Fpt*)

(Fig. 11; Fig. 14D). This facies association occurs only once, at the top of the cored section, overlying FA1 (Fig. 11). The mottled appearance of the normal-graded tuff is due to grain size variations and the distribution of different mineral phases (namely the distribution of chlorite and calcite cement). Clay rich phases have a dark green–brown colouration. Coarse-grained lithic clasts, comprising quartz, feldspars, secondary clays and micas, are present throughout the tuff beds (Fig. 14G). Larger lithic clasts up to 5 mm in size are present in places. The *Fngt* is predominantly structureless, although it is quite varied in appearance and hosts numerous fractures and interconnected microfractures (Fig. 14F). Fiamme are present within areas of the *Fngt* beds. The *Fpt* facies, located between the two *Fngt* beds at the top of the cored section, is composed of generally dark grey, structureless or planar laminated siltstone. Fiamme are present throughout the facies, as well as angular inclusions up to 4 mm in length. There is significant mottling throughout *Fpt*, which displays an overall light grey colouration at bed tops.

4.2.5.2. Interpretation. FA5 represents a period of deposition within a low energy lacustrine to distal-fluvial environment interrupted by ephemeral fluvial and/or alluvial fan deposition. The normal grading of the *Fngt* tuff and the potential flow structures/ripple laminations visible in the *Fpt* tuffite are interpreted to be evidence of aqueous deposition. *Fpt* deposition likely occurred within a medial to distal unconfined flow such as a sub-lacustrine fan, or a distal deposit derived from a fluvial system entering a palaeo-lake. This deposition was punctuated by the reworking of volcaniclastic sediment derived from either ephemeral or migratory fluvial systems (or potentially alluvial systems). Decreasing flow energy within these systems has produced the normally graded *Fngt*

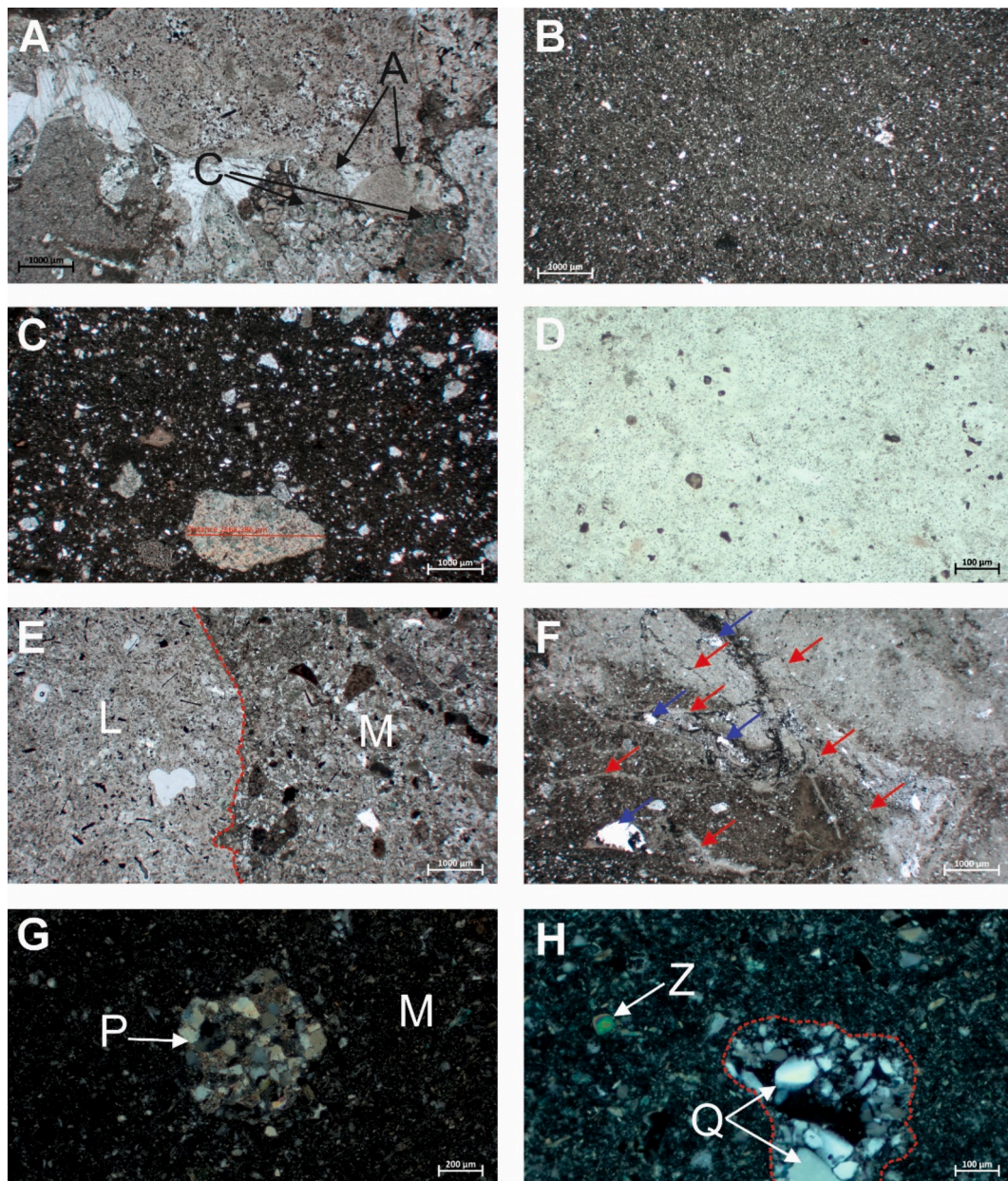


Fig. 14. Optical photomicrographs from thin section samples, core from well 14/24–1 (Fig. 11). Microfacies descriptions are provided in Table 3. A) Sample 55- Low magnification image of section in PPL, showing sub-rounded grains (<10 mm (A)) with interstitial chlorite (C). B) Sample 56 – Low magnification, PPL image showing the fine-grained nature of the sample. C) Sample 57 – Higher magnification PPL image showing a coarser grain (2570 μm), and finer grained matrix. D) Sample 65 – An image of the groundmass in PPL showing that it is generally fine-grained and reasonably homogenous. E) Sample 61 – Low magnification image, showing a large lithic grain (L) left and the poorly sorted matrix (M) right. F) Sample 62 – Low magnification PPL image showing the general texture of the sample, which is crosscut by a complex network of microfractures (e.g., red arrows). Large white features represent infilled voids and or replaced crystals/lithics (e.g., blue arrows). G) Sample 66 – XPL view of a polymictic clast (P) in a fine-grained matrix (M). H) Sample 66 – A lithic grain comprising angular quartz fragments (Q). A zircon is visible on the left side of the image (Z). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

facies identified in the 14/24–1 core. This facies association comprises reworked volcanoclastic material. The “burrow-like” features may be micro-burrows formed by organisms prior to lithification, infilled with layers of fine-grained material (clays).

The sedimentary processes evidenced within the *Fngt* and *Fpt* facies have similarities to those observed in the units of *Fcs* and *Fms* that comprise FA1. The main difference between the two facies associations is the presence of intact fiamme in FA5, as well as a greater volcanic ash component. It is therefore suggested that FA5 represents a continuation of a comparable/contiguous and dominantly fluvial depositional environment. FA5 represents a change of sediment source due to proximal

volcanic activity responsible for the presence of the *Fngt* and *Fpt* facies that comprise the facies association.

4.3. Depositional environment model

The results of the facies analysis have further informed the depositional environment and transport processes that influenced deposition during the Early Syn-rift. A schematic, intra-basin scale depositional model (Fig. 15) has been created based on these results.

Sediments entering the NFB were generally derived from two likely sources: volcanoclastic sediments from nearby volcanic systems (*Fcbt*,

Fngt and *Fpt*) active during the syn-rift, and clastic sediments (*Fcs*, *Fpxs*, *Fpxc*, *Fms* and *Fsd*) derived from surrounding topographic highs (this includes intra-basin highs and basin margins). Clastic deposition within the lacustrine system occurred via background sediment fallout forming lacustrine claystones, which was interrupted by high-energy lacustrine turbidite fan deposition depositing unconfined and partially confined sandstones (where influenced by bathymetric variability and pre-existing fan deposits) (Fig. 15).

Additionally, the 14/24–1 core preserves both confined and unconfined fluvial deposits. Overland, sediment transport into and within the NFB was facilitated by a combination of migratory fluvial, lacustrine fan and unconfined ephemeral flows (*Fpxs*, *Fpxc* and *Fiss*; Fig. 15). Overland, ephemeral flows were high-energy, depositing pebbly sandstones (*Fcs* and *Fpxs*) and conglomerates (*Fpxc*). Overbank flooding would also have led to the deposition of unconfined higher energy intervals like those observed in the *Fiss* facies. Palaeosol deposits were developed during periods of sub-areal exposure (Fig. 15).

4.4. Geochronology

Samples were recovered from three Early Syn-rift units of volcanoclastic rocks (Fig. 11). The full length of cored section shows evidence for alteration (fluid/diagenetic alteration), providing a pervasive green colouration. Based on the observations described in section 4.2, the clastic and volcanoclastic sediments exhibit sedimentary successions that are characteristic of terrestrial deposition, including deposition by fluvial to alluvial processes (probably ephemeral), with common pedogenic alteration of finer-grained intervals and of the upper parts of tuff beds. This suggests that the eruption and subsequent deposition of volcanogenic material was onto a palaeo-land surface, and therefore any significant re-working is unlikely. On this basis, any age determination obtained from these samples should be highly representative of true depositional ages for the NFB syn-rift.

All samples in the dataset exhibit a spectrum of detrital zircon dates (Fig. 16). As detrital zircon populations, individual grain dates cannot be related to each other to determine a population age. However, age assessment can be performed in order to note similarities between samples whilst then emphasising a date range within which age events

are likely to have occurred.

In this dataset, when focussing upon those data for each sample with U-Pb ratios representing ages < 200 Ma and within 5% of concordance, each sample shows a very similar distribution of dates (Fig. 16). Table 4 highlights a weighted mean calculation for each sample for the data as selected. Sample 1 shows a spectrum of points across the date range and is unlikely to represent a single igneous age event. Samples 2 and 3 could possibly represent single age events although only after omission of some points for sample 3 (Fig. 16).

The age determination for sample 1 is 175 Ma. The age determination for sample 2 is 176.6 Ma. The age determination for sample 3 is 173.4 Ma. The best overall estimate for age is given by the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age. The weighted mean for the pooled data is 175 ± 5 Ma (Fig. 16). This new age determination places the age of the Early Syn-rift in the Toarcian Stage of the Lower Jurassic. This is notably earlier than the Middle to Upper Jurassic estimates (namely the Upper Jurassic Oxfordian to Tithonian) previously suggested (Richards and Hillier, 2000a; Lohr and Underhill 2015; Stanca et al., 2022).

Long-term uncertainties in laser ablation U-Pb studies, representing the reproducibility of the technique, are usually around 2%. Propagating this uncertainty into the results for each sample, it is clear that the younger data sets for these samples are equivalent within uncertainty (3.6–3.8 Ma). The three sample dates and their uncertainties cover a range of 10 Ma (170–180 Ma). As such an overall uncertainty of ± 5 Ma is given for the overall age determination (175 ± 5 Ma, Fig. 16). The uncertainty associated with the new age determination covers the Toarcian – Aalenian boundary (174.7 ± 0.8 , Cohen et al., 2025), meaning that the Early Syn-rift sample could therefore be assigned to the lower-most part of the Middle Jurassic or to the Early Jurassic.

5. Discussion

This section discusses the updated depositional model presented for the NFB syn-rift, based on the analysis of seismic, well, core and thin section data. Block diagrams have been created to illustrate this updated understanding (Fig. 17, Fig. 18). The implications of the new age determination from the Early Syn-rift core in well 14/24–1 regarding the timing of SNFB rifting and how it fits into the breakup of Gondwana are

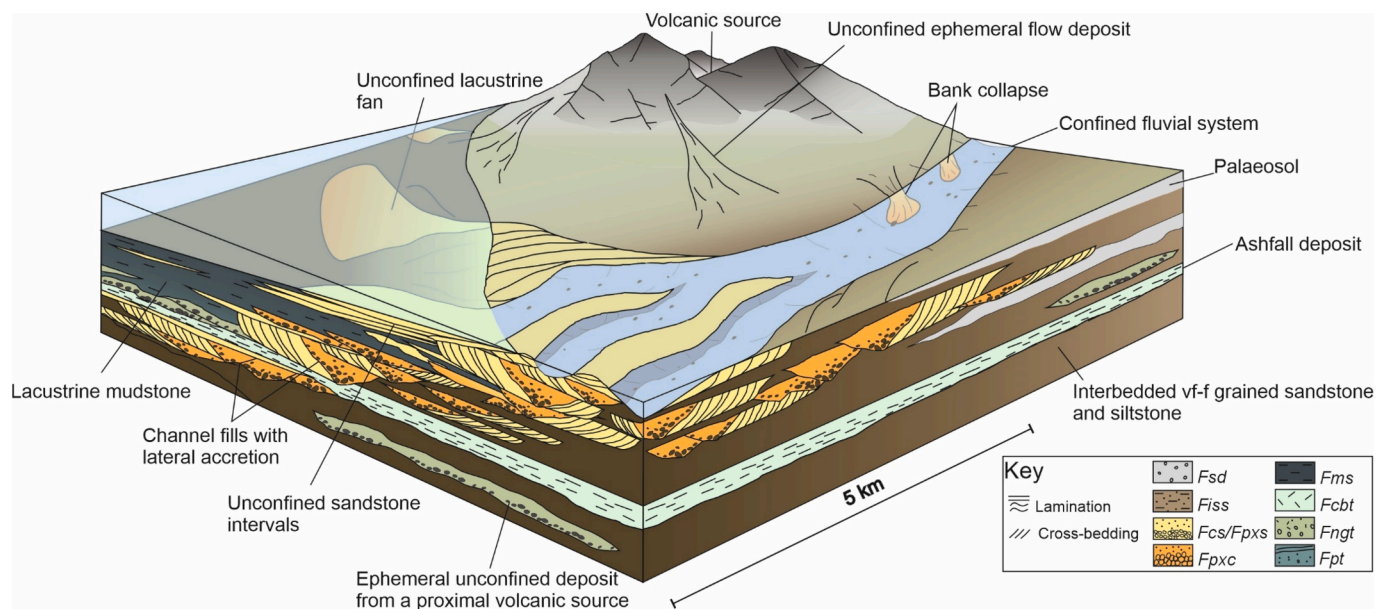


Fig. 15. Schematic depositional model for the ephemeral fluvial to lacustrine environment of the North Falkland Basin during the Jurassic rifting event based on the interpretation of the Early Syn-rift core from well 14/24–1. Active depositional mechanisms occurred in a combination of both fluvial and lacustrine environments. The model shows detailed sedimentology, as well as the interaction between the fluvial and lacustrine environments. This model is likely comparable to the depositional environment that was active during the early Cretaceous within the developing N–S trending depocentres.

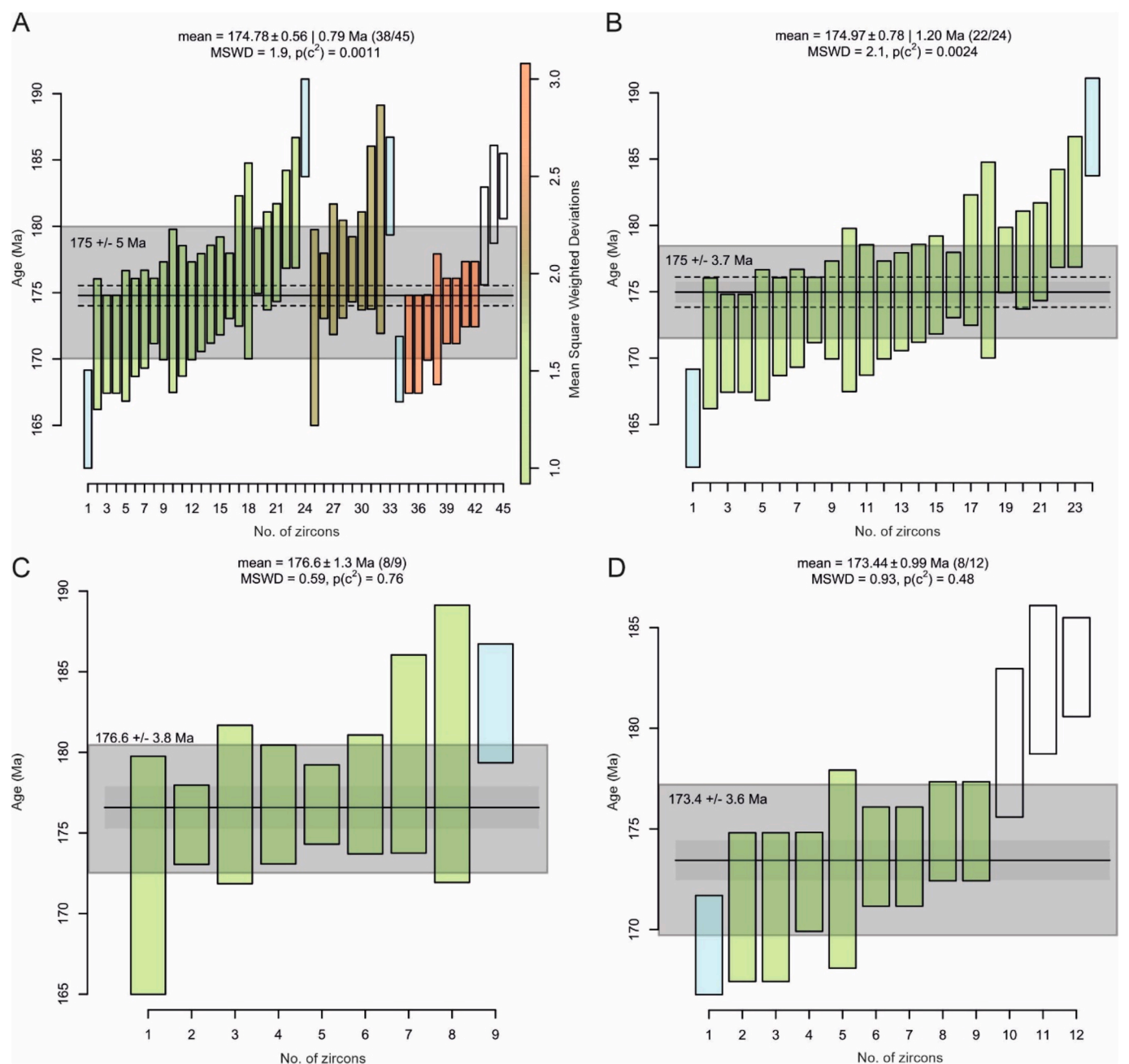


Fig. 16. $^{206}\text{Pb}/^{238}\text{U}$ weighted average age plots for: A) all three samples taken from the well 14/24-1 core, illustrating the similarity in the spectrum of dates for each; B) sample 1 – sandstone; C) sample 2 – tuff and D) sample 3 – tuffite, showing the omission of three zircons (Fig. 11). Plots display age on the y-axis (filtered to 165–190 Ma) with the mean values highlighted in grey. Weighted averages were determined for each sample. Concordant values are shown in green, rejected discordant values in blue. Values omitted from the study, based on the interpretation that they are part of a separate population not under consideration in this study, are shown in white. These dates and their uncertainties cover the range of 170–180 Ma. As such, a value of 175 ± 5 Ma is presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
An overview of the three age determination samples and their associated uncertainties.

	Date	Weighted mean uncertainty	Propagated uncertainty	MSWD, p value (%), n	Comments
Sample 1	175.0	1.2	3.7	2.1, 0.24%, 22	Exhibits excess scatter. Unlikely to be a single population
Sample 2	176.6	1.3	3.8	0.59, 76%, 8	Potentially a single population
Sample 3	173.4	1.0	3.6	0.93, 48%, 8	Potentially a single population
All samples	174.8	0.8	3.6	1.9, 0.11%, 38	Exhibits excess scatter. Unlikely to be a single population

also discussed. These new findings potentially have wider implications for the hydrocarbon prospectivity of the Falkland Islands. In order to better understand these implications, comparisons are made between

the *syn-rift* strata of both the NFB and the Outeniqua Basin. An updated depositional model for the NFB *syn-rift*. This study builds upon the current understanding of NFB *syn-rift*

deposition (Richards and Hillier, 2000a; Lohr and Underhill, 2015). The analysis of the 14/24–1 core, provides evidence for a range of depositional environments and processes that were active during Early Syn-rift deposition (Fig. 17). This study has identified and described a total of nine depositional facies; these have been grouped into five facies associations (Fig. 13) which are proposed to represent depositional processes active during rifting in the Early to Middle Jurassic. The newly defined facies associations present in well 14/24–1 provide new understanding of the Early Syn-rift of the NFB, which updates previous regional scale depositional models for the basin that have focussed upon the Late Syn-rift and Early Post-rift fill. These presented depositional facies models have additionally been informed by well log analysis from the other wells that penetrate the NFB syn-rift, as well as the findings of previous studies (Richards and Hillier, 2000a; Lohr and Underhill, 2015; Dodd et al., 2019; Macgregor and Reeves, 2025). The depositional facies analysis in this study supports the interpretation put forward by Richards and Hillier (2000a) that the NFB, during active rifting, was host to a dominantly fluvio-lacustrine to lacustrine environment.

During the first phase of rifting in the Jurassic (Toarcian), the resulting series of half grabens that comprised the NFB at the time were primarily host to ephemeral fluvial depositional environments (Fig. 17) with examples of fluvial, debris and nascent still-water/lacustrine deposition (Richards and Hillier, 2000a). Based on the results of this study, as well as previous investigations (Richards and Hillier, 2000a; Lohr and Underhill, 2015), it is understood that as the basin developed over time, these fluvial systems gradually developed into more perennial fluvio-lacustrine and lacustrine depositional environments. These environments facilitated the deposition of coarse-tail graded sandstones (an example of which is identified in the 14/24–1 core; Fig. 12), which were deposited by high sediment load, unconfined ‘sheet’ flows/fans entering the basin. Between these ephemeral flows, deposition occurred in a low-energy lacustrine environment, depositing lacustrine shales and siltstones. These sandstones and low-energy siltstones define FA1, the dominant facies association in the 14/24–1 core (Fig. 11; Fig. 12; Fig. 13). As rifting continued more perennial, mature fluvial systems

developed within the basin, as evidenced by the normally graded sandstone channel sequence (FA2) identified in the 14/24–1 core (Fig. 12). The migration of these systems resulted in the deposition of channel sandstones across marginal lakeshore areas (Fig. 15; Fig. 17). A combination of perennial fluvial systems and ephemeral flows were the primary mechanism for the transport of sediment (including epiclastic volcanics) into the NFB.

The presence of palaeosol deposits (FA2) points to periods of sub-aerial exposure and terrestrial deposition during Early Syn-rift deposition. Further work is needed in order to determine whether such periods are represented in the seismic data. Such episodes would potentially have been influenced by tectonic activity associated with basin development leading to periods of emergence. However, it could also have been the result of temporary retreat/shrinking of the lacustrine system brought about by changes in climate.

Another important factor considered when modelling the depositional environment is the influence of volcanism and the mechanisms by which volcanoclastic sediments were transported into the NFB. Active volcanism proximal to the NFB (and the Falkland Plateau more generally) during the Jurassic is evident based on the facies analysis of the Early Syn-rift core from well 14/24–1 (Fig. 11; Fig. 13), as well cuttings analysis from company reporting for wells 14/24–1, 14/9–2 and 26/06–1. This is congruent with previous studies, with sites of volcanic activity proximal to (and possibly linked to) the developing NFB having already been considered (Richardson and Underhill, 2002; Lohr and Underhill, 2015). The facies analysis presented in this study shows that a nearby palaeo-eruption was responsible for the deposition of the extremely fine-grained and structureless volcanic ashfall facies association. The normally-graded tuff and tuffaceous siltstones that comprise the reworked volcanic facies association were likely deposited by unconfined ephemeral flows and ephemeral fluvial systems. The reworked volcanoclastic sediments were probably eroded and redeposited from a nearby volcanic source such as the those in the Karoo Basin, the Chon Aike Igneous Province (Muir et al., 2020), or perhaps more locally from within the NFB itself.

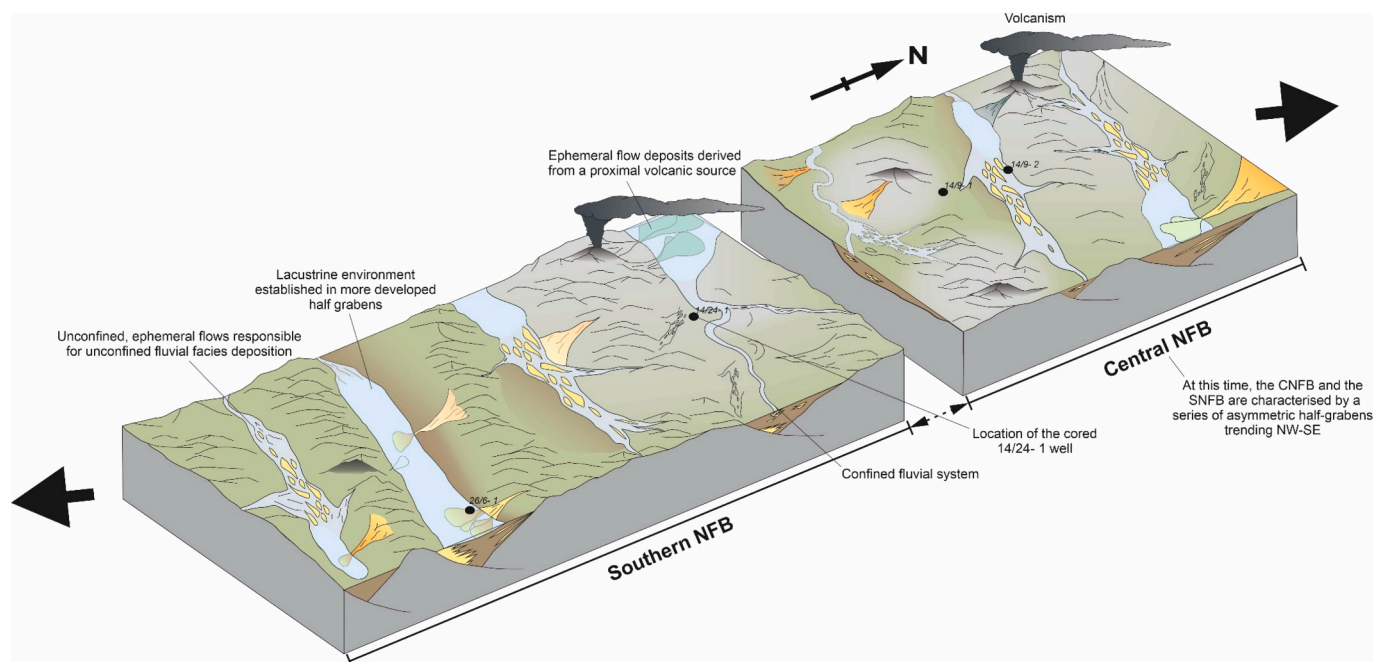


Fig. 17. Schematic regional depositional environment for the North Falkland Basin (NFB) during the early to middle Jurassic and the deposition of the Early Syn-rift. During this time, NE–SW extension is accommodated by a series of NW–SE trending half grabens, which host developing fluvio-lacustrine and perennial lacustrine systems. Ephemeral flows and perennial fluvial systems fed into the basins from surrounding and intra-basin highs and are responsible for the deposition of the fluvial facies interpreted as part of this study (facies associations 1, 2, 4 and 5). Active volcanism in the region is the source of the volcanoclastic facies associations (facies associations 3 and 5).

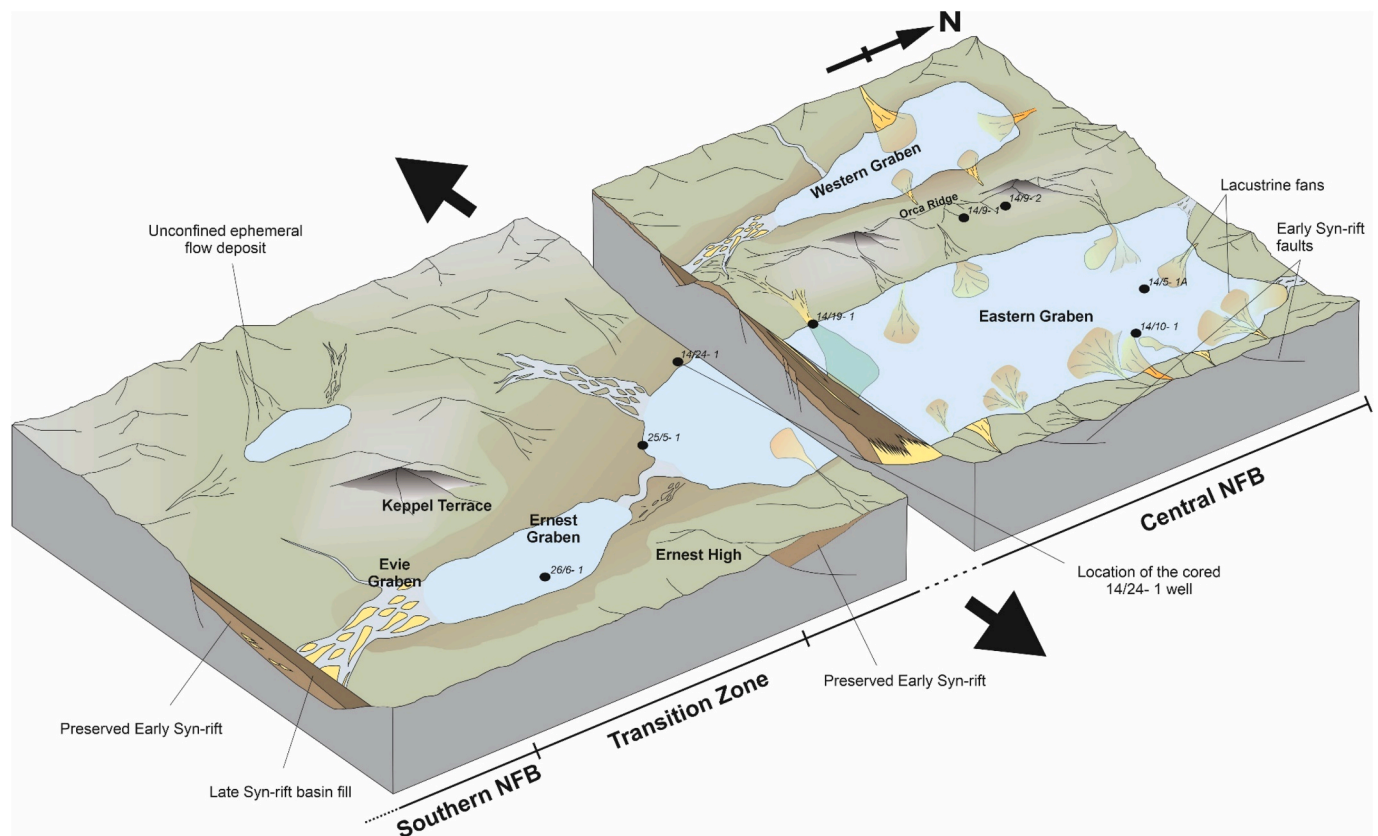


Fig. 18. Schematic regional depositional environment for the North Falkland Basin (NFB) during the early Cretaceous and the deposition of the Late Syn-rift. During this time, E–W extension is accommodated by the N–S oriented asymmetric half-grabens such as the Eastern Graben and Western Graben. The approximate locations of the eight wells that intersect the syn-rift are shown.

The Karoo Basin was a site of active volcanism during the early Jurassic (Macgregor and Reeves, 2025). Furthermore, volcanism in the neighbouring Mozambique Basin, located to the northeast of the Karoo Basin and the palaeoposition of the Falkland Plateau, is understood to have begun 177 million years ago and continued into the middle Jurassic (170 ± 5 Ma) (Macgregor and Reeves, 2025). Recent U–Pb and Lu–Hf isotope analysis of Permian-aged sedimentary formations present on the islands links the Falkland Islands to the volcanoclastic units present in the South African Karoo Basin (Riley et al., 2025). These findings support the revised Falkland Plateau palaeoposition model presented by Stanca et al. (2022, 2023).

Alternatively, volcanism associated with the Chon Aike Magmatic Province may be a possible volcanic source (Richardson and Underhill, 2002; Muir et al., 2020; Bastias et al., 2021). Recent geochronology work by Bastias et al. (2021) suggests active magmatism associated with the Chon Aike Magmatic Province during the Jurassic (~145–225 Ma). Further work, such as major and trace element geochemical analysis, is needed to constrain the source of Early Syn-rift volcanoclastics of the NFB.

The second phase of rifting during the early Cretaceous (Berriasian to Hauterivian; Lohr and Underhill, 2015) resulted in the development of depositional environments/systems comparable to those present during the Jurassic (Fig. 15; Fig. 18). This hypothesis is based on well logs, cuttings and sidewall core analysis first carried out by Richards and Hillier (2000a) as part of their tectonostratigraphic review of the NFB. The pre-existing Jurassic NW–SE oriented structural framework was overprinted by N–S oriented structures, resulting from an E–W extensional regime associated with the opening of the South Atlantic (Macgregor and Reeves, 2025). The Eastern Graben (a sub basin of the CNFB) was the primary depocentre during this period, with sediment influx from the surrounding topographic highs, as well as intra-basin

highs such as the Orca Ridge (Fig. 18), a newly emergent high during the early Cretaceous (Cretaceous rifting event). Based on seismic, well log, cutting and sidewall core analysis (Richards and Hillier 2000a), deposition likely would have occurred via similar depositional mechanisms to those during the Jurassic, initially occurring in an ephemeral fluvial environment with examples of sheet and channelised flows. Gamma ray wireline logs from the NFB wells show that as the basin developed, deposition gradually shifted to that of a fluviolacustrine environment (Richards and Hillier, 2000a), with examples of perennial fluvial systems and ephemeral fans feeding into a growing lake (Fig. 15; Fig. 18). By the Hauterivian, the palaeo-lake environment filled the entire Eastern Graben. The seismic mapping of the basement and top syn-rift surfaces indicates that Late Syn-rift strata is preserved in the Ernest Graben and Evie Graben (Fig. 18). This mapping combined with core facies analysis further helps to understand deposition within the NFB during the early to middle Jurassic, and the early Cretaceous. Mapping of the top Early Syn-rift and top Late Syn-rift horizons has helped to further elucidate the timing of sub-basin development within the NFB; confirming that the NW–SE trending basins that characterise the SNFB developed during an initial first phase of rifting (early to middle Jurassic; Fig. 17). These were subsequently overprinted by the N–S trending Eastern and Western Grabens in the CNFB during a second phase of rifting (early Cretaceous; Fig. 18). The two distinct syn-rift megasequences, defined by seismic mapping, core analysis and the new age determination, are represented in seismic cross-sections that transect the NFB (Fig. 8; Fig. 10). There remains uncertainty as to how far south the early Cretaceous N–S structural domain extended. Another source of uncertainty is in the mapping of the syn-rift in the transitional zone between the SNFB and the CNFB, which is covered by relatively sparse seismic data of variable quality having been processed differently across multiple surveys. Further work is required to more accurately

constrain the *syn*-rift strata in the transition zone between the SNFB and the CNFB.

5.1. Implications of the new core age determination on South Atlantic palaeogeographies

The movement of the Falkland Islands and the development of the NFB in relation to the breakup of Gondwana and the opening of the South Atlantic has been the subject of much investigation and debate (Lawver et al., 1985; Marshall, 1994; Richardson and Underhill, 2002; Lohr and Underhill, 2015; Stone, 2016; Ramos et al., 2017; Stanca et al., 2019, 2022). Constraint of the precise timing of NFB rifting in the Jurassic has been an ongoing challenge due to paucity of data for the Early Syn-rift.

The close relationship between the Falkland Islands and South Africa is supported by detrital zircon, Lu–Hf isotopic and heavy mineral analysis (Mussett and Taylor, 1994; Craddock et al., 2019; Malone et al., 2023; Riley et al., 2025; Henderson et al., 2026). As an example detrital zircon data suggests a strong correlation between the Bay of Harbours Formation (upper Lafonia Group) of the onshore Falkland Islands and the sedimentary and volcanoclastic units from the Karoo Basin (Riley et al., 2025). These findings fit best within a Gondwana reconstruction that includes the Falkland Islands as a rotated microplate adjacent to the southern Cape of South Africa (Adie, 1952; Johnston, 2000; Stone et al., 2009; Stanca et al., 2019; Malone et al., 2023).

The new zircon dates presented by this study from the top of the Early Syn-rift strata, intersected in well 14/24–1, suggests that SNFB rifting occurred earlier than originally estimated. Well 14/24–1 is interpreted to intersect both the Early and Late Syn-rift, with the core taken from the Early Syn-rift in the base of the well. This is based on this study's regional mapping of the basement, top Early Syn-rift and top Late Syn-rift horizons (Fig. 7). The Early Syn-rift core from 14/24–1 was found to have an age of 175 ± 5 Ma, placing it in the Toarcian of the Lower Jurassic (or Aalenian of the Middle Jurassic, within error). This new age determination suggests that the Early Syn-rift is at least 15 Ma older than originally thought (based on the ICS international Chronostratigraphic Chart; Cohen et al., 2025). This in turn suggests that the extension responsible for the NW–SE trending faults (Jurassic rift event) occurred much earlier (Richards and Hillier, 2000a; Lohr and Underhill, 2015; Stanca et al., 2022), and is closer in timing to the volcanic episodes related to the initial break-up of Gondwana (during the early Jurassic; Macgregor and Reeves, 2025).

Previous models had interpreted that this initial extension was associated with the opening of the South Atlantic around 138 million years ago (early Cretaceous; Macgregor and Reeves, 2025). Whilst the age determination suggests *syn*-rift deposition occurring in the Toarcian, it is acknowledged that the analytical uncertainty of ± 5 Ma associated with the results could push the timing into the Aalenian (Middle Jurassic).

The NFB is host to two distinct structural trends (Brandsen et al., 1999; Richardson and Underhill, 2002; Lohr and Underhill, 2015; Dodd et al., 2019; Jones et al., 2019; Plenderleith et al., 2022; Stanca et al., 2022), however the age determination of the Early Syn-rift succession presented here provides evidence that the Early Syn-rift and Late Syn-rift megasequences are the result of two distinctly separate periods of rifting, one beginning in the early to middle Jurassic and the other during the early Cretaceous, respectively. The NW–SE faulting of the SNFB is thought to have occurred during the period of early Jurassic-aged extension associated with the initial rifting of Gondwana. The N–S trend of the CNFB was formed by an early Cretaceous phase of rifting (Lohr and Underhill, 2015).

5.2. Implications for hydrocarbon exploration in the NFB

The NFB is a frontier basin for hydrocarbon exploration. To date, the best understood reservoir intervals are contained within the overlying

Early Post-rift, which has been the target of exploration drilling campaigns and is host to the Sea Lion Discovery (Dodd et al., 2019). Despite the successes in the Early Post-rift, the *syn*-rift has been relatively under-explored. A key factor in *syn*-rift hydrocarbon prospectivity is the uncertainty over the presence of suitable source rock and reservoir intervals. The key data available for *syn*-rift source intervals have been analysed in wells 14/05-1A and 14/10-1 from the CNFB, which encountered lacustrine claystone-dominated units, with average TOC values of 0.76%, ranging up to 1.6% (Richards and Hillier, 2000b; Jones et al., 2019). Fluvial sandstones within the NFB *syn*-rift have the potential to act as hydrocarbon reservoirs (Richards and Hillier, 2000b; Jones et al., 2019). The Early Syn-rift play in the NFB strata, specifically in the CNFB, has been identified as potentially being host to source intervals (Richards and Hillier, 2000b). However, the character and distribution of Early Syn-rift strata and its hydrocarbon play potential in the SNFB is more uncertain. To provide some perspective for hydrocarbon exploration potential in the SNFB, this study compares the age dating and palaeogeographical implications for *syn*-rift prospectivity with the neighbouring Outeniqua Basin (i.e., neighbouring prior to South Atlantic rifting), and its associated sub-basins (Fig. 2).

The Outeniqua Basin is composed of a series of *en-echelon* half-grabens that formed during the early Jurassic to middle Cretaceous (Ramos et al., 2017; Stanca et al., 2019; Muir et al., 2020), linked to Jurassic inversion of compressive structures (Muir et al., 2020). Sedimentation occurred in four main depocentres: the Bredasdorp, Pletmos, Gamtoos and Algoa basins, as well as a number of southern Cape onshore basins (Muir et al., 2020). These half-grabens are bounded by broadly westward-dipping normal faults, with displacements in excess of 10 km in places (Stanca et al., 2019). U–Pb radioisotope dating of zircons from pyroclastic deposits within the Uitenhage Group, which is a widely distributed succession of *syn*-rift deposits preserved across the southern Cape of South Africa and within the Outeniqua Basin (Muir et al., 2020), indicates that *syn*-rift deposition probably began in the latest part of the early Jurassic. Zircon ages for the Uitenhage Group ($172.6 \pm 0.6/-0.9$ Ma in the Mossel Bay Basin, and 170.5 ± 0.6 Ma in the Heidelberg Basin) provide evidence for rifting that predates the Aalenian and probably began shortly after Karoo volcanism in the Toarcian (Muir et al., 2020). Continued displacement facilitated a protracted > 40 Ma period of deposition that continued into the early Cretaceous, recorded in the Uitenhage Group (Muir et al., 2020). These age determinations from the *syn*-rift of the southern Cape basins (and by extension the Outeniqua Basin), and the Early *syn*-rift of the NFB (this study) indicates that initial rifting within the two basins occurred contemporaneously.

Additionally, the southern South African onshore to offshore margin exhibits a similar deformation style to the transition from the Falkland Islands to the NFB. Observations made by Stanca et al. (2019) suggest that normal faulting in the SNFB could be analogous to the deformation domain between the St. Croix and Gamtoos faults of the Outeniqua Basin. The timing, combined with the proximity of the two basins prior to, and during, the earliest stages of continental separation suggest that the Outeniqua Basin and SNFB structures may have formed as contiguous basins hosting similar fluvio-lacustrine to lacustrine systems (Muir et al., 2020; Salomo et al., 2024), which are analogous in both age and character. Studies conducted in the Outeniqua Basin conclude that existing hydrocarbon reservoirs in the Pletmos Basin are charged from Jurassic and early Cretaceous lacustrine source intervals (Salomo et al., 2024). The presence of these lacustrine source rocks has also been proven in the neighbouring Gamtoos sub-basin. Therefore, as an initially contiguous basin, the NFB–Outeniqua system was probably host to a similar petroleum play configuration. Given the hydrocarbon exploration successes in the Outeniqua Basin, these observations and correlations in geological processes provide only positive indications for hydrocarbon potential in the *syn*-rift strata of the NFB.

6. Conclusions

This study has interpreted and integrated seismic mapping, core and thin section analysis, and zircon age data into a revised basin scale model and depositional history for the NFB during the Jurassic rift event (early Jurassic) and the Cretaceous rift event (early Cretaceous).

An updated depositional model is presented for the Early Syn-rift and the Late Syn-rift. Key sedimentary and volcanic/volcaniclastic facies associations, identified through the analysis of the core from well 14/24–1, evidence a dynamic fluvial to fluvio-lacustrine environment that was at least proximal to a region of active volcanism.

Seismic mapping of the basement and key *syn*-rift horizons identified primary depocentres active during Jurassic and Cretaceous rift events. This mapping indicates that the Early Syn-rift is present in both the CNFB and the SNFB. Regional extension during the Jurassic was focused within the proto/nascent NFB, as well as the neighbouring Outeniqua Basin. After a hiatus in active rifting, regional Cretaceous rifting resulted in the overprinting of the Jurassic structural domain in the CNFB. However, uncertainty still remains regarding the regional extent of extensional faulting during the Jurassic and Cretaceous rifting events. Further investigation is required to constrain the extent of the Cretaceous overprinting as it is uncertain whether the Early Syn-rift of the SNFB was also overprinted, with the overlying evidence having since been eroded or not picked up on the available seismic.

In addition to the facies analysis, this study presents direct evidence to support an updated understanding of the timing of deposition of the Early Syn-rift in the NFB. The new LA-ICP-MS 206Pb/238U data zircon age determination of 175 ± 5 Ma reveals that Jurassic rifting (and the associated development of the NW–SE structural domain of the SNFB) likely began during the early Jurassic, around 15 Ma earlier than previously estimated. Initial Jurassic rifting is now interpreted to have begun in the Toarcian (Lower Jurassic) and likely continued into the Middle Jurassic. This links this first phase of *syn*-rift basin development closely with the initial break-up of Southern Gondwana.

The contemporaneous development of the SNFB and its South African counterpart, the Outeniqua Basin, has potential implications for hydrocarbon prospectivity in the NFB *syn*-rift. The new age determination means that Jurassic-aged source intervals, equivalent to those with proven hydrocarbon prospectivity in the Outeniqua Basin, could be present within the Early Syn-rift of the NFB. Further investigation would be required to determine whether such intervals, that could potentially charge overlying *syn*-rift fan and wedging reservoir intervals, are indeed present.

Data availability statement

The data that support the findings of this study are available upon request from the Falkland Islands Government Department of Mineral Resources. Restrictions may apply to the availability of these data.

CRediT authorship contribution statement

Rory J. Sutton: . **Gayle E. Plenderleith:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Thomas J.H. Dodd:** Conceptualisation, Methodology, Writing – original draft, Writing – review & editing. **Lorraine P. Field:** Investigation, Resources, Writing – original draft. **Ian L. Millar:** Investigation, Resources, Writing – original draft. **Dave J. McCarthy:** Writing – review & editing, Writing – original draft. **Thomas A. Randles:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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