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FIFTY YEARS OF GEOLOGICAL RESEARCH IN AND AROUND THE FALKLAND ISLANDS

by

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To mark the 50th issue of *The Falkland Islands Journal*, this article reviews the progress that has been made in understanding the archipelago's geology since the first issue was published in 1967. Several different factors have interacted to make progress possible. A scientific revolution – plate tectonics – fundamentally altered the way in which regional geological evidence was assessed, huge technical advances led to hitherto unimaginable datasets, the political landscape was transformed by the events of 1982 and, not least, the economic potential of the offshore sedimentary basins (Figure 1) has been recognised and investigated.

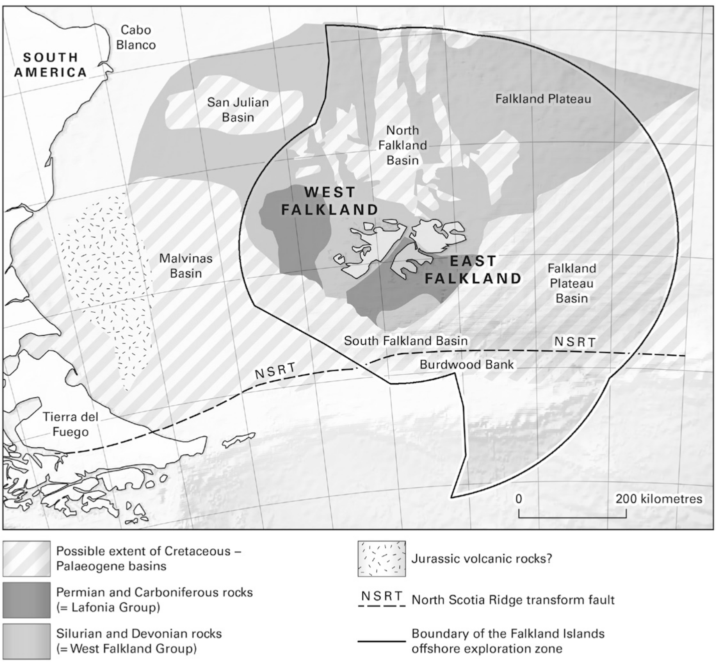

Figure 1. The regional setting of the Falkland Islands and the locations of their surrounding Mesozoic to Palaeogene sedimentary basins.

Geological reconnaissance

At the beginning of the 1970s, whilst the geology of the Falkland Islands was known in broad outline, that knowledge was largely based on investigations carried out at least 50 years previously. Charles Darwin (1846) had provided the first description of Falkland Islands rocks and fossils after his visits in 1833 and 1834 aboard HMS *Beagle*. Thereafter, it was not until 1902 that serious geological investigation was resumed when the geologist Johan Gunnar Andersson spent some time in the Falklands whilst waiting to rendezvous with the ship supporting the 1901–1903 Swedish South Polar Expedition. Andersson's (1907) work in the islands was subsequently extended by his colleague Thore Halle (1911) during the Swedish Magellanic Expedition, 1907–1909.

Shortly after Halle's departure an unlikely collaboration between Constance Allardyce (wife of the Governor, William Allardyce) and the eminent American palaeontologist John Clarke led to what is still the most extensive published description of the Falklands' fossil fauna (Clarke 1913); it was based largely on particularly well-preserved specimens from Pebble Island. Next, and despite the absence of detailed topographical base maps, an attempt at a regional geological survey was made between 1920 and 1922 by Herbert Baker during what was primarily a search for economically important resources. Although unsuccessful in that respect, his geological map and report of 1924 were not superseded until 1972 when a photogeological reinterpretation by Mary Greenway was published by the British Antarctic Survey (BAS). Greenway utilised the aerial photography flown in 1956 that had formed the basis of the first detailed topographical maps of the islands, a series of 29 sheets published in 1961 at a scale of 1:50 000.

Introducing the onshore geology

Baker initiated a comprehensive nomenclature for the Falklands succession of distinctive rock units, and the terms that he coined were adapted by Greenway before being assimilated with modifications into the modern, formally defined stratigraphy established during a 1996 to 1998 geological mapping project carried out by Don Aldiss and Emma Edwards. Given the large area covered and the inherent logistical difficulties this was an outstanding achievement: their results were published for the Falkland Islands Government by the British Geological Survey as a geological map at a scale of 1: 250 000 and a comprehensive geological report (Aldiss & Edwards 1998, 1999); a shorter, popular booklet followed (Stone *et al*. 2005), with some more recent developments discussed by Stone (2014, 2016). For this account, Figure 2, summarising the onshore geology of the archipelago, is largely derived from the Aldiss & Edwards (1998) map. The overall geological development is summarised in its regional context in Figure 3. The following brief summary of the onshore geology will provide context for the first part of this review, with the offshore geology dealt with in later sections.

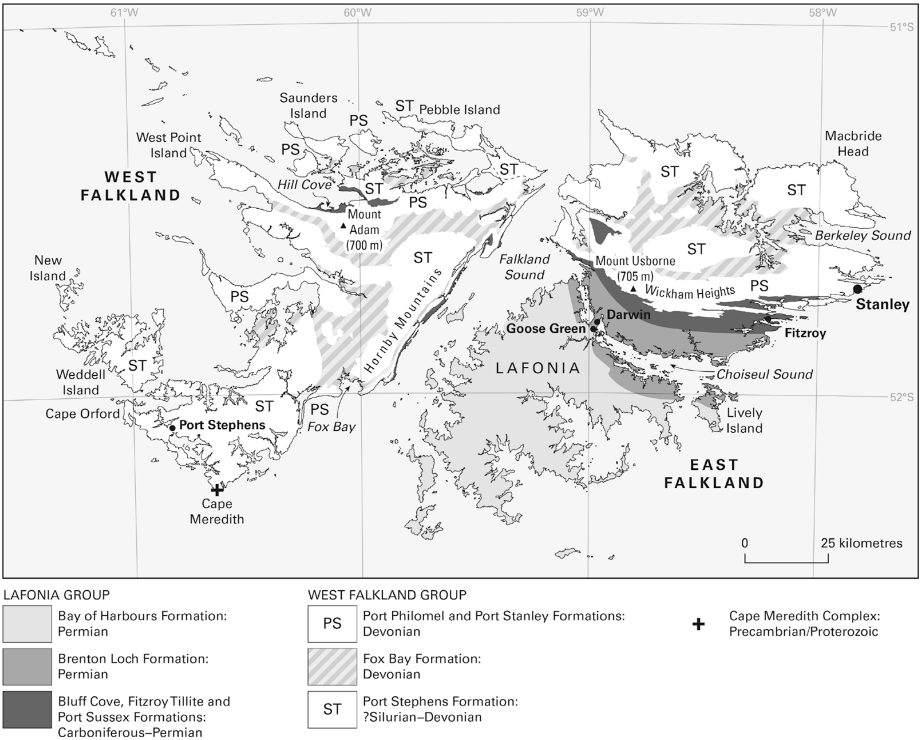

Figure 2. An outline of the onshore, bedrock geology of the Falkland Islands after Aldiss & Edwards (1998 & 1999).

The oldest Falkland Islands rocks are the *ca* 1000 million years old, granite and gneiss of the Proterozoic **Cape Meredith Complex**, which has a restricted coastal outcrop on the southernmost point of West Falkland. This 'basement' complex is unconformably overlain by the **West Falkland Group**, a thick succession of fluvial and near-shore to shallow-marine, clastic strata ranging in age from Silurian to Devonian. The age is defined by several assemblages of Devonian microfossils (pollen and spores), whilst Early Devonian macrofossils (trilobites and brachiopods) known only from the Fox Bay Formation in the middle of the group are about 405 million years old. The West Falkland Group forms most of West Falkland and the northern part of East Falkland. In the southern part of East Falkland a younger succession of strata, the **Lafonia Group**, has near its base a Permo-Carboniferous rock unit (Fitzroy Tillite Formation) that was deposited beneath an ice-sheet during a glaciation of the Southern Hemisphere about 300 million years ago. It passes upwards into a thick succession of Permian, deltaic and lacustrine strata. The Lafonia Group was deposited in a subsiding basin formed ahead of a developing fold-and-thrust belt that concurrently deformed the Silurian to Devonian West Falkland Group.

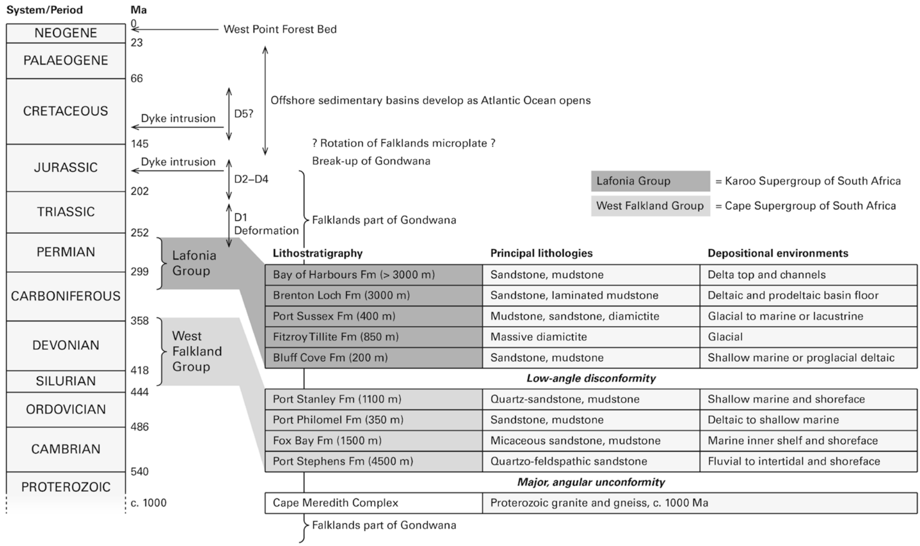

Figure 3. A summary of the geological history of the Falkland Islands and their offshore environs. The onshore stratigraphical thicknesses shown (after Aldiss & Edwards 1998 & 1999) are for East Falkland; the West Falkland succession is significantly thinner.

A multitude of sub-vertical dolerite sheets (known as dykes) were intruded into all of the older rocks during Jurassic and Cretaceous times, between about 190 and 120 million years ago. The dykes range in width from a few centimetres to tens of metres, form intersecting swarms running in several different directions and are particularly abundant in the southern half of West Falkland.

Across much of the Falkland Islands the bedrock is covered by extensive and varied superficial deposits. Evidence for glaciation is restricted to small cirques and associated moraine on the highest hills, but in places on the lower ground are developed spectacular periglacial blockfields – the ‘stone runs’. The widespread peat accumulations commonly range up to about 10 m in thickness. Coastal features are apparently contradictory, with the drowned ria-type coastline (the result of a relatively rising sea-level) replete with raised beaches and wave-cut rock terraces (left behind by a relatively falling sea level). Research into the landscape history is beyond the scope of this review but, that said, the stone runs are such an iconic feature of the Falkland Islands that they cannot be passed over without some comment.

The stone runs are composed of hard, quartzite boulders derived from the Port Stanley Formation and to a much lesser extent from the Port Stephens Formation. Both of these formations are parts of the West Falkland Group (Figure 3) and it is their outcrop (Figure 2) that controls the distribution of the stone runs. There is a range in form from extensive spreads of boulders covering thousands of square metres to spectacular arrays of multiple parallel strips of boulders wherein each individual strip runs for hundreds of metres but may be only a couple of metres wide. An excellent account of the stone runs and the history of research devoted to them was provided in the 2008 issue of *The Falkland Islands Journal* by Richard Clark and Peter Wilson, who focussed particularly on three important studies published earlier that year. The consensus view had previously seen the stone runs as arising from the innumerable freeze-thaw cycles in the periglacial environment that pertained in the Falklands between about 26 000 and 13000 years ago, during the coldest phase of the most recent ice age. However, the application of modern isotopic dating techniques (Hansom *et al*. 2008; Wilson *et al*. 2008) has thrown some contradictory light on the exposure history of the boulders and shown that development of the stone runs was a polyphase phenomenon spread over, at least, the last 700 000 years and several glacial episodes. The third study (André *et al*. 2008) speculated that the origin of the boulders owed more to deep tropical weathering 25 million years ago than to much more recent frost action. Nobody pretends that the enigmatic stone runs have yet surrendered all their secrets.

Regional correlations and widening interest

Prior to Greenway's work, Baker's (1924) stratigraphical terminology had been adopted in a 1963, Spanish-language review by the Argentine geologist Angel Borrello. He reproduced Baker's map and cross-section but emphasised perceived geological correlations with South America from which '*Las Malvinas*' were figured as a continental promontory. This interpretation ran contrary to the general view of those geologists who had worked in the Falkland Islands, including Baker, who had invoked continental drift to explain the remarkably close correspondence of Falkland Islands geology with that of South Africa. However, continental drift was regarded sceptically at that time and the idea did not find general favour despite the recognised contradictions between Falkland's geology and the archipelago's geographical position. The South African geologist, Raymond Adie, proposed a radical solution to this dilemma in a remarkably prescient contribution published in 1952. Adie had spent time in the Falklands in 1950 and used the data that he had gathered there to support his proposal that during the Mesozoic opening of the Atlantic Ocean the Falklands had been rotated, clockwise, by 180° from an original position adjacent to the *east* coast of South Africa (Figure 4). Rotation would have occurred in two phases: 150° during the Late Jurassic fragmentation of Gondwana, and a further 30° during opening of the South Atlantic Ocean from the Early Cretaceous onwards when the Falklands had transferred to the incipient South American continental margin.

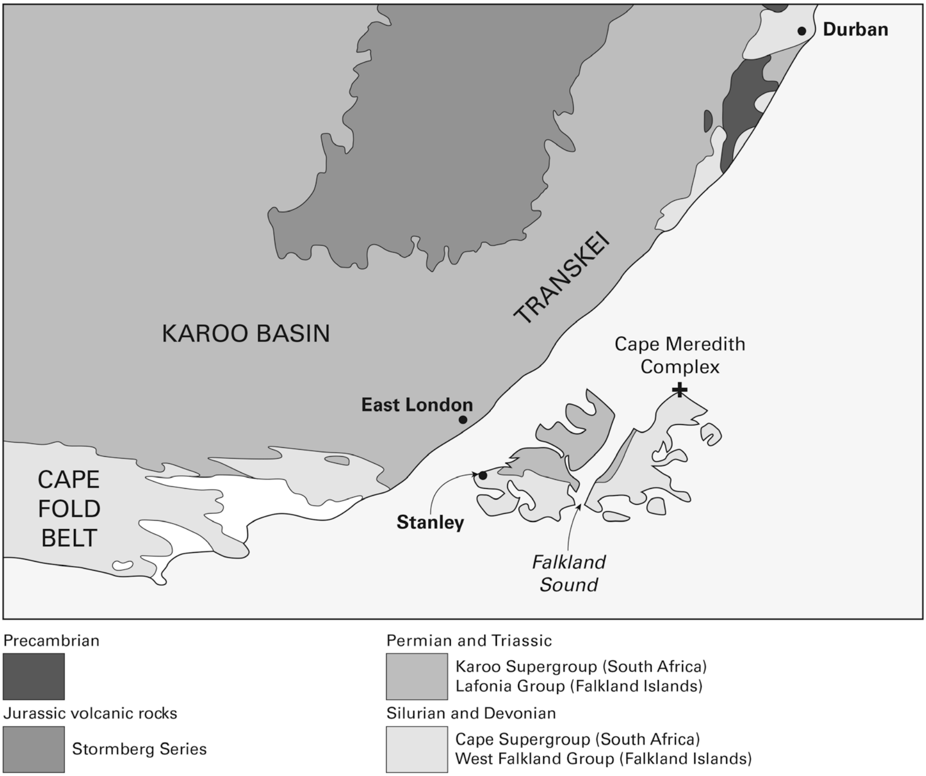

Figure 4. The radical solution to the problem of the Falkland Islands' apparently misplaced geology illustrated by Adie (1952), in which the islands are rotated through 180° to an original position adjacent to the SE coast of South Africa.

Adie's 'continental drift' solution to the geographical enigma of Falkland Islands geology was disregarded for the next thirty years, but was then 'rediscovered' as the plate tectonic revolution swept through geology. It is now widely accepted in principle, with the West Falkland Group and Lafonia Group seen as the originally eastward extensions of, respectively, the Cape Fold Belt and the Karoo Basin successions. When Greenway was working on her photogeological interpretation for the British Antarctic Survey, Adie had become that organisation's Chief Geologist and *de facto* Deputy Director. He contributed a section on economic geology to Greenway's report.

Publication of Greenway's map and report was followed during the 1970s by a series of visits to the Falkland Islands by Argentine geologists. Detailed work was done at a number of different localities with the most important results probably those derived by Cingolani & Varela (1976) from the first radiometric dating analyses of rocks from the Cape Meredith area. There, the metamorphic and granitic rocks of the Cape Meredith Complex were confirmed as Proterozoic and shown to range in age between about 980 and 1100 Ma; an Early Jurassic age of about 190 Ma was established for one of the many intrusive dolerite dykes in the vicinity. Complementing these results, the Cape Meredith Complex had been sampled for dating purposes some years earlier, in 1969, by BAS geologists. The results, ages of about 950 to 980 Ma were presented at a scientific conference in 1977, but the conference proceedings (including Rex & Tanner 1982) were slow to appear.

The Argentine invasion and short-lived military occupation of 1982 abruptly terminated the involvement of that country's geologists. Instead, there was a general increase in interest in the Falkland Islands and the archipelago's geology was no exception. In part this renewed interest was driven by the increasing awareness of offshore hydrocarbon potential, but some was academic research attracted by the opportunities then opening-up in what had previously been a logistically difficult region. First on the scene in the latter category was the 1989 'Cumberland and Lancashire Expedition' led by Richard Clark. The expedition's focus was primarily on geomorphology and ecology, but some bedrock geology observations were also made; Clark led two subsequent expeditions with similar aims in 1994 and 1997. The expeditions' principal geological contribution was a scientific review paper (Clark *et al*. 1995) written in collaboration with two Falkland Island students who had recently graduated in geology at UK universities: Emma Edwards (Belfast) and Stephen Luxton (Durham). Edwards subsequently worked with Don Aldiss on the 1996-1998 Falkland Islands Geological Mapping Project; Luxton went on to become the Director of the Falkland Islands Government's Department of Mineral Resources. Richard Clark provided an informed valedictory review of Falklands geomorphology for the 2008 issue of *Falkland Island Journal*.

Gondwana

Once peace had been re-established in the South Atlantic, the Falkland Islands were reintroduced to the geological community by the paper in the prestigious international journal *Nature* (Mitchell *et al*. 1986) that 'rediscovered' Adie's rotational model in terms of the modern concept of plate tectonics and a small Falklands 'microplate'. By then, it was universally accepted that the southern continents had drifted to their current locations following the break-up of a pre-existing 'super-continent', Gondwana (Figure 5). The new evidence (obtained by researchers from several British universities including Oxford, Liverpool and Cardiff) was derived from a study of the intrusive dolerite dykes that cut across West Falkland, and in particular the palaeomagnetic information that could be extracted from them using modern techniques. The dykes were known to be of broadly the same age and composition as similar swarms in South Africa, yet the new information showed that they had preserved very different magnetic histories, differences compatible with the rotation history that Adie had suggested (Taylor & Shaw 1989). At about the same time, new results on the age and compositions of dykes became available. Innovations in radiometric dating enabled relatively precise ages of about 188 and 190 Ma (Early Jurassic) to be established (Mussett & Taylor 1994) whilst the detailed geochemical composition of the rock confirmed associations with the coeval dykes of South Africa and Antarctica (Mitchell *et al.* 1999). At the time of intrusion these regions would have been in close proximity to each other and to the Falklands microplate, all within the supercontinent of Gondwana (Figure 5).

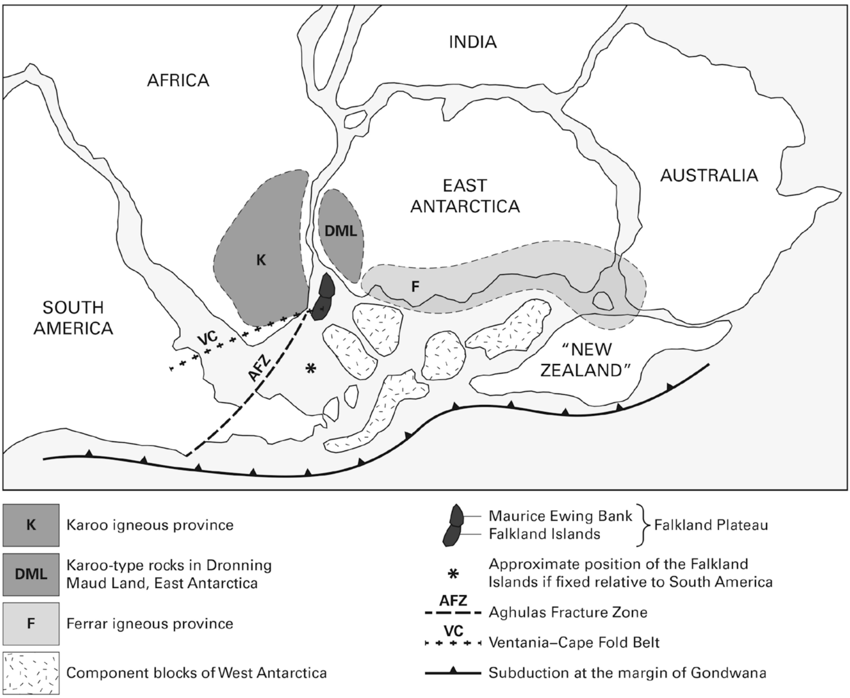

Figure 5. A representative reconstruction of the southern sector of the Gondwana super-continent immediately prior to the Jurassic commencement of its break-up.

Another part of the Gondwana jigsaw was addressed in the late 1990s with renewed work on the Proterozoic rocks of the Cape Meredith Complex by an international team (South Africa, Germany, Australia: Thomas *et al*. 1997; Jacobs *et al*. 1999). New radiometric dating techniques were applied and established precise ages in the range 1000 to 1100 Ma. These ages, and the nature and orientation of the tectonic fabrics within the rocks, were used to re-emphasise the South African correlation (with similar rocks in the Natal-Transkei region) and to support a rotational history for the Falkland microplate. More regional structural considerations, together with the marked contrast between West and East Falkland in the numbers of Early Jurassic dykes, suggested that the two main islands of the Falklands archipelago were much farther apart at the time of dyke intrusion. Sideways movement of tens of kilometres along a major fault coincident with Falkland Sound brought them together during the early stages of the break-up of Gondwana.

The role of the Falkland Islands microplate as the fragments of Gondwana drifted apart had also attracted other interest. Shortly after fieldwork in the islands John Marshall from the University of Southampton had proposed, in 1994, dextral sideways displacement along a Falkland Sound Fault, citing the contrast in the intensity of tectonic deformation between East (more deformed) and West (less deformed) Falkland. Marshall's interest in the way in which this contrast could be restored in a Gondwana reconstruction was maintained by his research student, Danny Hyam, who particularly compared the structural detail of the Falkland Islands with that of the Cape Fold Belt in South Africa. The latter is a north-directed fold and thrust belt which merges to the north into the less deformed strata of the Karoo Basin. The direct correlatives in the Falkland Islands are the fold and thrust belt affecting the West Falkland Group (most emphatically on East Falkland) which merges south into the much less deformed strata of the Lafonia Group. The rotation of a Falklands microplate from a position adjacent to the east coast of South Africa was supported and linked with considerable sideways (dextral) movement along the Falkland Sound Fault. Hyam (1998) published a general account of his interpretations and collaborated with Mike Curtis of the British Antarctic Survey in a comparison of the detailed structural history of the Falklands with that of comparable parts of South Africa (Curtis & Hyam 1998). Several episodes of deformation were described. East Falkland is dominated by the east-west, early fold-and-thrust, and although the effects of this deformation are more subdued on West Falkland, there they have been superimposed by subsequent effects parallel to the Falkland Sound Fault. The combination is responsible for large-scale interference structures around Bold Cove, and for the dramatic configuration of the Coast Ridge (formed by near-vertical beds of quartzite). In a later assessment that took into account offshore seismic data, Hyam *et al*. (2000) modified the idea of a major fault coincident with Falkland Sound, and instead proposed that a major, subterranean fault with a large down-to-the-east sense of movement underlay the eastern margin of West Falkland, beneath the Hornby Mountains. Nevertheless and despite that alternative, the evidence for substantial faulting at the north-west margin of Falkland Sound remains persuasive.

Palaeozoic stratigraphy and structure

The late 1990s proved to be a particularly productive period for onshore geological work in the Falkland Islands, as its importance for establishing the underlying control of the offshore geology became clear. Offshore seismic exploration was well underway by then and realising the deficiencies in the existing geological maps, Falkland Islands Government commissioned the survey carried out between 1996 and 1998 by Don Aldiss and Emma Edwards. Their stratigraphy has been utilised in figures 2 and 3 but their work also encompassed the geological structure with several episodes of deformation recognised (D1 to D5: Figure 3). The first, the south-directed fold-and-thrust belt, was developed in the northern parts of both East and West Falkland but its most intense affects were seen in the East; these structures correlated with those of the eastern end of the Cape Fold Belt in South Africa. Superimposed on those east-west structures was a series of large-scale faults and folds trending approximately NE-SW, the folds thought to be the surface expression of deep-seated faulting. Three further episodes of fault-dominated deformation followed and produced a variety of both compressional and extensional features, some of which were thought to have developed during rotation of the Falklands microplate as Gondwana fragmented. Some differences in interpretation from the structural proposals of Curtis & Hyam (1998) are unsurprising, but all concerned acknowledged the benefits of the discussions they had enjoyed during their concurrent fieldwork. In subsequent analysis as part of a PhD study based at the University of Birmingham, Richard Hodgkinson (2002) dated minerals formed during the earliest deformation episode at about 278 Ma.

As the geological mapping project came to and end, the Permian Lafonia Group was the subject of a PhD project undertaken by Chris Thomas at the University of Aberdeen, again with an emphasis on comparisons with the equivalent strata in South Africa. This detailed study allowed Thomas, together with his academic supervisors Nigel Trewin and David Macdonald, to establish an exceptionally close correlation with the South African succession (Trewin *et al*. 2002). Trewin (2000) also published an analysis of an unusual assemblage of fossilised traces produced by the fins of fish trailing across a wet sediment surface; again the similarity to examples from South Africa was emphasised. It is worth noting that all of this work arose as part of a broader geological investigation, onshore and offshore, carried out by a large team of university researchers and commercial consultants and funded by a consortium of oil companies; some of the results remain commercially confidential. Despite the evidence of a Lafonia Group fish fauna detailed by Trewin, body fossils of any kind remained elusive until a sparse bivalve assemblage was discovered in 2001 at Rory's

Creek, on the south shore of Choiseul Sound, as first reported in *The Falkland Islands Journal* by Stone & Rushton (2003). This find attracted the attention of Brazilian palaeontologists who visited the islands in 2011, extended the collection, and published an environmental interpretation (Simões *et al*. 2012).

With the general increase in geological interest in the South Atlantic during the late 1990s, the British Antarctic Survey expanded a long-standing interest in the break-up history of Gondwana. BAS geologists published a reconstruction and break-out model for the Falklands microplate (Storey *et al*. 1999) and this was followed-up by a detailed study by one of that team, Morag Hunter, of the Port Stephens Formation, the lowest unit of the West Falkland Group. The study topic was chosen as the relatively undeformed state of the Port Stephens Formation on West Falkland had allowed the preservation of sedimentological data that had been tectonically obscured in most of the equivalent South African rocks. Hunter & Lomas (2003) described the accumulation of the Falklands formation in terms of terrestrial and shallow marine sedimentation on an extensive and gently shelving, alluvial to coastal plain. The main depositional basin lay to the present-day NE, consistent with South African data once the Falklands were rotated into the preferred position off the south-east coast of that continent.

Hunter's work did not provide any new palaeontological evidence for the age of the Port Stephens Formation. At Cape Meredith it unconformably overlies the ancient 'basement' rocks and the unconformity also cuts across a number of mafic dykes intruded into them. An imprecise radiometric age from one of the dykes (Thistlewood *et al*. 1997) suggests that the base of the Port Stephens Formation might be no older than Late Ordovician, ca 460 Ma. The upper part of that formation is known from its content of fossil spores and pollen to be of Early Devonian age (c. 415 million years old) with similar evidence showing that the rest of the West Falkland Group extends upwards through the Devonian (Marshall 1994, 2016); at the top of the West Falkland Group the Port Stanley Formation is of Late Devonian age (c. 360 million years old). That range includes the age determined from the well-known trilobites and brachiopods found in the Fox Bay Formation, for which the best current estimate is about 405 million years.

Because of the collaboration mentioned earlier between the American palaeontologist John Clarke and governor's wife Constance Allardyce, until recently the best-described collection of Devonian macrofossils from the Fox Bay Formation was held by the New York State Museum in Albany, NY (Clarke 1913; Edgecombe 1994). Another New York institution, the American Museum of Natural History, supplemented that archive in 2000 during a fossil-collecting expedition to the Falklands led by John Maisey. From the material gathered were described a sparse fish fauna (Maisey *et al*. 2002) and an expanded assemblage of trilobites (Carvalho 2006).

Late Palaeozoic glaciation

Another of the Falkland Islands stratigraphical units to receive much recent attention is the Fitzroy Tillite Formation, one of the lower divisions of the Lafonia Group. Geologists from the University of California visited the Falkland Islands in the 1965-1966 austral summer to study this ancient glacial deposit (Frakes & Crowell 1967) and concluded that its deposition was transitional from terrestrial in the west to glaciomarine in the east, with overall ice movement (in present-day terms) from west to east. Greenway incorporated these findings into her 1972 report but the more recent reinterpretation by Aldiss & Edwards (1999) favoured a largely terrestrial origin throughout. An Early Permian age is generally accepted for the extensive glacial deposition of the Fitzroy tillite but it is worth noting that traces of an earlier, Carboniferous glaciation survive in a few places, as described by Hyam *et al* (1997).

The nature of the Fitzroy tillite had been recognised by Halle (1911) and reiterated by Baker (1924), and both had stressed the correlation with the Dwyka tillites of the Karoo Basin in South Africa. This association has been recently strengthened by the discovery of fossiliferous limestone blocks within the Fitzroy tillite's erratic clast assemblage. The fossils proved to be archaeocyaths (extinct sponge-like organisms) together with a few small trilobites (Stone & Thomson 2005; Stone *et al*. 2012) of Early Cambrian age, much older than any of the sedimentary rocks known from the Falklands where, moreover, the succession is devoid of limestone. Very similar blocks of limestone containing the same types of archaeocyaths have been found in the Dwyka tillites, and all are thought to have originated in what is now the Transantarctic Mountains. The original limestone beds were eroded by glaciers during the widespread Carboniferous to Permian glaciation of Gondwana, with erratics carried onto those regions which, after fragmentation of the supercontinent, became South Africa and the Falkland Islands.

Research into the origin and significance of the Fitzroy Tillite Formation also benefitted, unexpectedly, from a series of onshore boreholes that formed part of an extensive mineral exploration programme, to be discussed in more detail in the next section of this review. The core recovered from several of the boreholes sampled the top of the tillite formation and the immediately overlying strata, a succession that recorded the deglaciation history of the Falklands region of Gondwana during the Early Permian. Through the generosity of the exploration company, Falklands Gold and Minerals Ltd., and collaboration between the British Geological Survey, the British Antarctic Survey and the FIG Mineral Resources Department, a significant amount of the relevant core was recovered to UK for further study (Stone 2011). It is lodged with the BGS Geoscience Data Centre in Keyworth, Nottingham, and was the subject of a University of Cambridge MSc project by Kate Horan, with the main results subsequently published (Horan 2015; Stone & Horan 2016). Analysis of the core showed that the lithologies and sedimentary fabrics recorded a switch from deposition of the Fitzroy Tillite Formation under a grounded ice sheet to glacio-lacustrine/marine deposition at the base of the Port Sussex Formation during a period of overall ice sheet retreat punctuated by short-lived episodes of ice readvance. Periodicity in the data matched the frequencies expected from Earth's orbital cyclicities and suggested that the deglaciation timescale was of the order of 1.2 million years.

Surprisingly, in view of the abundant evidence for its glacial origin, the Fitzroy Tillite Formation has been recently reinterpreted as a deposit of smashed and ejected debris created by the Early Permian impact (to the west of the Falklands in present-day terms) of a huge meteorite (Rocca & Presser 2015). The suggestion has not received much support, with the geophysical features interpreted in terms of an impact crater more generally thought to arise from an offshore basin containing Permian strata akin to the Lafonia Group (e.g. Richards *et al*. 1996).

Onshore mineral exploration and the Mesozoic dyke swarms

In the late 1990s, there was an upsurge in commercial interest in the offshore hydrocarbon potential around the Falkland Islands, but interest in the possible economic potential of Falklands' geology was not restricted to offshore areas. An onshore exploration programme with gold mineralisation as the principal target, culminated between 2005 and 2007 in an extensive borehole campaign, as indicated above with reference to the Fitzroy Tillite Formation. As part of the pre-drilling data acquisition, aeromagnetic surveys were flown over most of East and West Falkland and the results precipitated a radical reinterpretation of the Falkland Islands dolerite dyke swarms. A much-improved discrimination of the principal swarms was possible, which was then augmented by radiometric dates and geochemical analyses of representative specimens. Of most importance was the identification of a previously unsuspected dyke swarm that spanned West and East Falkland, and the offshore area to the south-east. It proved to be of Early Cretaceous age with radiometric dates in the range 121-135 Ma (Stone *et al*. 2008; Richards *et al*. 2013). This was significantly younger than the previously defined, Early Jurassic swarms which had been dated to about 184-178 Ma. The different dyke swarms, whilst all being broadly doleritic, are petrographically and geochemically distinct with, in particular, the Cretaceous dykes having a much higher iron content than the Jurassic dykes.

The new data have allowed some possible correlations between the onshore dyke swarms and evidence for magmatism in the offshore Falkland Plateau Basin (Richards *et al*. 2013). The onshore Jurassic dykes, and possibly correlative dolerite forming seismic basement in the Falkland Plateau Basin, are associated with the regional magmatism linked to the initial break-up of Gondwana (the Karoo and

Ferrar igneous provinces, Figure 5). The Early Cretaceous onshore magmatism has the same age as that assigned from seismic interpretation to probable lava flows within the Falkland Plateau Basin succession. The onshore and offshore Early Cretaceous magmatism is all associated with the extension of the Falklands Plateau and rifting of the North Falklands Basin during the initiation of the South Atlantic Ocean.

An assessment of the asymmetry of the linear aeromagnetic anomalies associated with individual dykes (Stone *et al*. 2009) supported the rotational model of a Falklands microplate. There is a contrast between the anomalies associated with the Jurassic dykes and those associated with the Cretaceous dykes that is best explained by the former having experienced a pre-Cretaceous, clockwise rotation of about 120º. However, that interpretation had previously been questioned. As part of his PhD study based at the University of Birmingham, Hodgkinson (2002) had unsuccessfully attempted to replicate the palaeomagnetic results previously reported from the dykes. He thought the failure to be the result of reorientation of critical minerals during tectonic deformation of the dykes as they were emplaced, reducing their reliability as palaeomagnetic indicators.

It is worth noting that during their comprehensive geological survey, Aldiss and Edwards (1999) had identified six separate dyke swarms on the basis of composition and orientation. None of these corresponded to the recently discovered Early Cretaceous swarm, and three occurred only in the western part of West Falkland, largely beyond the limit of the aeromagnetic survey, centred on Cape Orford, New Island and Saunders Island. The history and relationship of the various intrusive dyke swarms remains one of the least well-known aspects of Falkland Islands geology.

A Cenozoic forest?

As the only possible Cenozoic deposit in the Falkland Islands, the origin of the West Point Forest Bed has been much debated. It is a clay layer packed with tree debris and found beneath solifluction deposits close to sea level on West Point Island, West Falkland (Figure 2). Halle (1911) thought it to be the remains of an *in situ*, pre-glacial tree cover, whereas Baker (1924) concluded that it was simply a buried accumulation of driftwood. Recently, a very detailed study of pollen grains by Macphail & Cantrill (2006) has supported Halle's interpretation and shown that the bed derives from a wet, temperate rainforest dominated by species of southern beech (*Nothofagus*). It is likely that at the time of its growth, about 6 or 7 million years ago, this forest community covered much of the Falkland Islands.

Offshore exploration

Seismic refraction profiles had been shot across the Falklands area as early as the late 1950s, as part of an academic research project based at the Lamont-Doherty Geological Observatory (now Earth Observatory) of Columbia University in the City of New York. These were followed by more seismic research studies focussed not on hydrocarbon potential but on the fundamental nature of the Falkland Plateau. This phase of activity culminated in 1974 in the drilling of three boreholes on the Maurice Ewing Bank, several hundred kilometres to the east of the Falkland Islands, during Leg 36 of the international Deep Sea Drilling Project. One of the boreholes (DSDP 330) proved a basement of crystalline metamorphic rocks similar to some of the lithologies seen in the Cape Meredith Complex; also proved was the existence of a potential oil source rock. The latter discovery encouraged more commercial interest and in the 1977-78 austral summer two speculative, regional seismic surveys were shot around the Falkland Islands. Data from these surveys remained proprietary and were not made publically available.

Given the state of knowledge in 1982, it seems unlikely that offshore hydrocarbons potential figured very highly in the calculations of either the Argentine or British governments when, in that year, the Falkland Islands were invaded and temporarily occupied by an Argentine military force. Thereafter, it was not until the early 1990s, and with the British Geological Survey having been appointed by the Falkland Islands government to help manage and promote hydrocarbon activity, that renewed interest in the offshore potential led to the acquisition of more speculative seismic data to both the north and south of the archipelago. In 1996 the first Production Licenses were awarded for acreage to the north, in the North Falkland Basin, and initiated the more focussed exploration programmes that continue today. The location of the sedimentary basins under investigation is shown in Figure 1; their geology was reviewed by Richards *et al.* (1996). Since then they have been the subject of extensive seismic surveys and exploration wells have been drilled, mostly in the North Falkland Basin. Some have proved the presence of oil and/or gas. With only a few exceptions, the data collected is held on a confidential basis by the companies concerned and is commercially sensitive. Nevertheless, the general configuration of the sedimentary basin network surrounding the Falkland Islands has been confirmed and recently reviewed by Stone (2016). They all contain a Jurassic and younger sedimentary succession that lies either on strata equivalent to the onshore West Falkland and Lafonia groups, or on possible Jurassic volcanic rocks.

North Falkland Basin

To the north of the Falklands archipelago, the North Falkland Basin is a classic example of a failed-rift basin with two main structural components. An elongate area of subsidence controlled by extensional faults running approximately north-south (the North Falkland Graben) is from 30 to 50 km wide, widening northwards, and about 250 km long with the southern margin only some 35 km north of the islands. To the south-west of the graben is another area of subsidence controlled partly by north-south extensional faults and partly by NW-SE extensional faults thought to be influenced by the reactivation of structures that originated as compressional thrusts in the underlying Palaeozoic rocks. Reactivation of this sort has been described from the West Falkland Group at the onshore northern margins of East and West Falklands.

There have now been three drilling campaigns in the North Falkland Basin, the first in 1998 with six wells, the second in 2010-2011 with 16 wells, and the third in 2015-2016 with five wells. Of these, at least six have made potentially commercial hydrocarbon discoveries and a thematic set of papers devoted to the petroleum geology of the highly promising Sea Lion Field has been published recently in *Petroleum Geoscience* (2015, **21** (2-3), 83-209). As a result of the drilling campaigns, and with the additional data generated by detailed seismic surveys, the structure and stratigraphy of the basin are becoming clearer. Subsidence probably began with east-west extension, commencing in the Triassic and continuing through the Jurassic and into the earliest Cretaceous, during the initial break-up of Gondwana. In some parts of the basin subsidence gave way to localised uplift during the Late Cretaceous, a process that was most probably driven by the initial uplift of the North Scotia Ridge farther to the south.

The earliest phase of basin subsidence appears to have produced a rift trending NW-SE and now preserved in the SW of the North Falkland Basin. Superimposed on this structure and extending northwards from it is the main north-south rift (Figure 6a) that is the principal focus of hydrocarbons exploration. Therein, the sedimentary deposits may be as much as 10 km thick and are dominantly lacustrine clay, mudstone and sandstone in the lower part of the succession and fluvial sandstones in the upper part. Some of the mudstones are highly organic and are the source rocks for the basin's hydrocarbons. The Jurassic and earliest Cretaceous sedimentation took place in fluvial plains, associated alluvial fans and ephemeral lakes. Thereafter, through much of the Early Cretaceous, a large and permanent lake system occupied the central part of the basin and most probably reached depths of over 500 metres in places; analogies have been drawn with Lake Malawi in the present-day East African Rift (Richards & Hillier 2000). From the north, the basin was filled by a large sandy delta. Smaller deltas extended from other parts of the basin margins but elsewhere these merged laterally with swampy alluvial plains (Richards *et al*. 2006). From the Late Cretaceous onwards, the succession becomes progressively more marine in character.

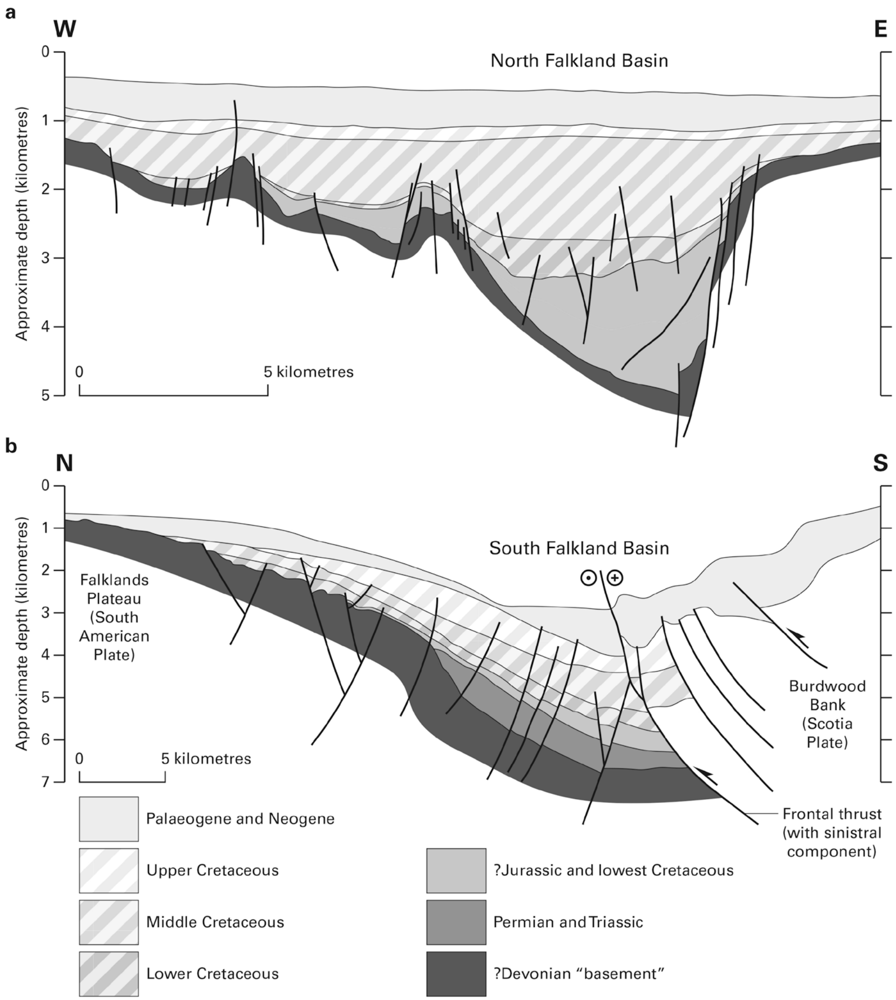

Figure 6. Representative cross-sections for two of the Mesozoic to Palaeogene sedimentary basins in the Falkland Islands offshore zone.

a. *The northern part of the North Falkland Basin, developed from Richards* et al. *(1996) and Richards & Hillier (2000).*
b. *The South Falkland Basin, after Richards* et al. *(1996) and Bry* et al. *(2004).*

The southern basins

To the south of the Falklands three separate basins are structurally linked along their southern margins by interaction with the major structural boundary between the Falklands Plateau and the Scotia plate to the south (the North Scotia Ridge transform fault, Figure 1). Despite this common feature the structure of each basin has unique elements, and they all differ markedly from the 'failed-rift' structural configuration seen in the North Falklans Basin.

South-east of the Falklands archipelago, the **Falkland Plateau Basin** is a passive margin-type basin on the south-western flank of the Falkland Plateau. The basin contains a succession of Late Jurassic to Cretaceous strata, up to about 15 km thick, which has so far been examined by only four commercial wells. At its eastern extremity, the basinal strata extend onto the Maurice Ewing Bank where the DSDP boreholes showed them to lie unconformably on Proterozoic crystalline rocks. Elsewhere in the basin, seismic evidence has been interpreted as showing that the Jurassic to Cretaceous sedimentary succession overlies rocks akin to those of the onshore West Falkland and Lafonia groups. However, one of the commercial wells penetrated dolerite beneath the Jurassic strata, and it may be that igneous rocks of that type form at least part of the 'seismic basement'. The composition of the dolerite is similar to that of one of the onshore, Early Jurassic swarms seen in the southern part of West Falkland. Another possible onshore-offshore correlation lies higher in the basin succession where seismic evidence has been interpreted to show igneous rock, either as sills or lava flows, within the Early Cretaceous part of the succession (Richards *et al*. 2013).

At its south-western extremity, the Falkland Plateau Basin runs into a narrower zone of subsidence adjacent to the northern edge of the Scotia plate. There, the major fault complex separating the Scotia plate and Burdwood Bank to the south, from the Falklands Plateau to the north, is a complicated plexus of extensional, compressional and strike-slip components. Together, these effects, with the compressional elements involving north-directed thrusting have created a foredeep and a foreland basin on the north side of the fault zone (Figure 6b). This is the **South Falkland Basin**, where two wells were drilled in 2012; one in the fold-and-thrust belt itself and one in the foreland basin. Most of the succession comprises a relatively thick series of Mesozoic, probably marine sandstones and mudstones, overlain by a thinner Cenozoic accumulation of similar lithologies; together they make up about 5 km of strata. To the west, and to the south-west of the Falklands archipelago, the basin opens out into a broader zone of subsidence, mostly in Argentine waters, known as the **Malvinas Basin**.

Did the Falklands rotate?

This remains the most controversial question in Falklands' geology, with different answers being supported by different datasets, as reviewed by Stone (2016). From the perspective of the onshore geology, regional Gondwana relationships are best reconciled by rotation of a Falklands microplate away from an original position adjacent to what is now the south-east coast of South Africa. Such rotation has been independently supported by palaeomagnetic work on the Falkland Islands dyke swarms although the reliability of the results has been challenged. No data in support of rotation has been reported from the offshore explorations. Instead, they are entirely compatible with a Gondwana break-up history in which the archipelago and Falkland Plateau formed a promontory from the South American margin, albeit one that has undergone much extension. In this context, if rotation did occur it must have been a relatively rapid, mid-Jurassic event that was followed by the prolonged east-west extension that led to formation of the South Atlantic Ocean. The question seems unlikely to be resolved without new and unequivocal palaeomagnetic results from the Falkland Islands dykes.

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