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Mesozoic dyke swarms of the Falkland Islands (South Atlantic)

Geology and Regional Geophysics Programme

Internal Report OR/13/026

BRITISH GEOLOGICAL SURVEY

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INTERNAL REPORT OR/13/026

Mesozoic dyke swarms of the Falkland Islands (South Atlantic)

P Stone

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Front cover

An Early Cretaceous dyke cutting quartzite of the Port Stanley Formation, West Falkland Group, as exposed (in 2007) on the north face of Pony's Pass Quarry, near Stanley, East Falkland. BGS image number P696274.

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Foreword

This report arises from onshore geological investigations in the Falkland Islands, South Atlantic Ocean, carried out by the British Geological Survey on behalf of the Department of Mineral Resources, Falkland Islands Government. It provides background information on the Jurassic and Cretaceous dyke swarms that was collected as part of a geological consultancy programme, led by Dr Phil Richards, supporting onshore mineral prospecting and offshore hydrocarbon exploration.

Acknowledgements

Field support for the author was provided by the Department of Mineral Resources, Falkland Islands Government. Falkland Gold and Minerals Ltd generously made available data from the 2004 aeromagnetic survey and samples from the Peat Banks and Old House Rocks boreholes; in particular, the assistance of Derek Reeves, the project manager, is acknowledged. Ar-Ar dating of dolerite samples was carried out at the New Mexico Geochronological Research Laboratory by W. C. McIntosh (Teal Creek and Peat Banks) and R. P. Esser (Pony’s Pass and Port Sussex). Thanks go to Geoff Kimbell and Sandy Henderson for assistance in the preparation of figures. The report is published by permission of the Falkland Islands Government and the Executive Director, British Geological Survey (NERC).

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Figure 4

Bartholomew Sulivan's sketches illustrating dolerite dykes seen in West Falkland in 1844 or 1845. After Burkhardt and Smith (1987, p. 118):

a. The effect of thermal metamorphism altering and hardening the host sandstone (most probably from the Port Stephens Formation). Sulivan wrote:

"[W]here the vein [dyke] had fallen out the two sides or walls of the crevice stuck up in this manner and were very much harder than the rest of the sandstone but only for two or three inches".

b. A dyke cutting obliquely across sandstone beds (most probably from the Port Stephens Formation) as seen in a small island off West Falkland. Sulivan wrote: "the appearance of the island is like this the height of the cliff being about 100 feet and the vein [dyke] about 6 feet thick".

Figure 5

Sketch map of the Teal Creek area showing the dyke pattern established by field mapping as a follow-up to the aeromagnetic survey. Sample localities are identified.

Figure 6

Ar-Ar spectra for dolerite samples from the onshore, N-S dyke swarm in East Falkland. After Richards and others (2013).

a. Results from plagioclase (p) separate, Teal Creek South (PS 711).

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c. Plagioclase (p) and whole rock (wr) results from Teal Creek North (PS 712).

d. Plagioclase (p) and whole rock (wr) results from Peat Banks (PS 713).

Figure 7

Element variation plots for dolerite samples from the Falkland Islands onshore dyke swarms. New data are superimposed on plots modified from Mitchell and others (1999, figure 3).

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Table 1. Whole-rock geochemical analyses (XRF) for East Falkland dolerite dykes.

Summary

An aeromagnetic survey that allowed an improved discrimination of the principal dyke swarms of the Falkland Islands has been augmented by additional radiometric dates and geochemical analyses of representative specimens. Most of the dykes previously described as forming a “north-south” swarm of Jurassic age are associated with a set of NE-SW linear magnetic anomalies that are entirely separate from another set of N-S to NNW-SSE anomalies, The NE-SW Jurassic dyke swarm occurs mostly in West Falkland but extends sparsely into East Falkland; a separate E-W dyke swarm, also of Jurassic age, is restricted to the southern part of West Falkland. The newly discovered N-S swarm spans West and East Falkland, and the offshore area to the south-east and has proved to be Early Cretaceous in age. The different dyke swarms are petrographically and geochemically distinct with, in particular, the Cretaceous dykes having a much higher Fe content than the Jurassic dykes. Ar-Ar age dating of East Falkland dykes has confirmed an Early Jurassic, ca 184-178 Ma, age for the NE-SW swarm, and has provided an Early Cretaceous age range for the N-S orientated dyke swarm of ca 135 Ma (Valanginian-Hauterivian) to ca 121 Ma (Aptian); although it is apparently robust, on regional grounds the validity of the Aptian age may be questionable. The onshore Jurassic dykes, and a possible correlative dolerite body forming seismic basement in the offshore Falkland Plateau Basin, are associated with the regional Karoo-Ferrar magmatism, linked to the initial break-up of Gondwana. The Early Cretaceous onshore magmatism has the same age as that assigned from seismic interpretation to sills and/or lavas within the Falkland Plateau Basin sedimentary succession. Both the onshore and offshore Early Cretaceous magmatism is likely to be associated with the later extension phases of the Falklands Plateau and rifting of the North Falklands Basin as the South Atlantic Ocean initially opened.

1 Introduction

The Falkland Islands lie in the South Atlantic Ocean, about 650 km east of the Strait of Magellen, at the western end of the Falkland Plateau, a rectilinear, relatively shallow water (<2500 m approximately) bathymetric feature that extends eastwards from the South American continental shelf (Figure 1a). Mesozoic sedimentary basins to the north (North Falklands Basin) and the south-east (Falkland Plateau Basin) of the archipelago are currently the focus of offshore hydrocarbons exploration within the designated Falkland Islands Exploration Area. Onshore, a clastic sedimentary sequence ranging in age from Siluro-Devonian to Permian makes up most of the Falkland Islands. The sedimentary rocks are cut by numerous dolerite dykes that until recently were known principally from West Falkland and regarded as exclusively Jurassic (e.g. Mussett and Taylor 1994), but which are now known to be both Jurassic and Cretaceous in age (Stone and others 2008; Richards and others 2013). Palaeomagnetic results from the Jurassic dykes (Taylor and Shaw 1989) have been taken to support the proposition that the Falkland Islands form part of a microplate that during the break-up of Gondwana was rotated through 180o from an original position adjacent to the east coast of South Africa (Adie 1952; Mitchell and others 1986; Marshall 1994; Storey and others 1999). Despite proximity to South America, the geological association of the Falklands with the Cape Province of South Africa has long been recognized: the general similarities were appreciated by Halle (1911) and Baker (1924), and were discussed in terms of continental drift by Du Toit (1927, 1937).

Key features of Falkland Islands geology are shown in Figure 1b. At the southern extremity of West Falkland, a small outcrop of Proterozoic crystalline basement –Cape Meredith Complex – has been dated at approximately 1100 -1000 Ma (Jacobs and others 1999). The Proterozoic rocks are uncomformably overlain by a Siluro-Devonian to Carboniferous succession of fluvial to neritic, clastic strata predominantly comprising quartzite, sandstone and mudstone. This succession is known as the West Falkland Group; it crops out over most of the western of the two main islands (West Falkland) and is left unshaded in figure 1b. In the eastern of the two main islands (East Falkland) the West Falkland Group crops out in the north, whereas the south of East Falkland and its smaller peripheral islands are underlain by the tillite, mudstone and sandstone of the Carboniferous to Permian Lafonia Group, which is shaded grey in figure 1b. Pre-Devonian, mafic dykes cut the Cape Meredith Complex (Thistlewood and others 1997) with widespread, polyphase swarms of mafic, Jurassic and Cretaceous dykes (discussed below) cutting the basement and all of the overlying sedimentary succession. The geology of the Falkland Islands is more fully described by Aldiss and Edwards (1999) and Stone and others (2005).

This report summarises recently acquired geochronological and geochemical data pertaining to the dyke swarms and discusses the regional implications that arise. The main focus is on the dykes of East Falkland and, in particular, on the Early Cretaceous swarm that was identified following a commercial aeromagnetic survey flown in 2004. Numerous linear anomalies showed the presence of many more dykes than had previously been appreciated (Figures 1c, 2 and 3).

2 Discovery and distribution of the dyke swarms

Dolerite dykes are particularly numerous in West Falkland. As early as 1834, during the famous surveying voyage of HMS Beagle a piece of black, highly vesicular basalt was found on the beach near Cape Meredith by Assistant Surgeon William Kent and passed to Charles Darwin. This specimen was assimilated by Darwin into his ‘Beagle’ collection (as specimen number 1891) though he made no further mention of it and so probably regarded it as having an exotic origin, perhaps as an ice-rafted erratic similar to those he had seen in Patagonia (Darwin 1842). The specimen is now held by the Sedgwick Museum, Cambridge (with the number 112292). The Sedgwick Museum register describes it (following Darwin’s original notes) as ‘scoriae, picked up on beach’. A comment added to the Sedgwick Museum label by Professor Alfred Harker suggests that the rock fragment may have ‘floated-in’ from a volcanic Antarctic island but whilst pumice is common on Falkland Islands shores, specimen 1891 is very fresh and seems a little too dense to float very far. Although it is possible that the specimen in question was derived from one of the many dolerite dykes now known from the south of West Falkland, very few of these are vesicular, and none are as fresh-looking as Darwin’s specimen 1891.

The first definitive observations of dykes from West Falkland were made, most probably in 1844, by Captain (later Admiral Sir) Bartholomew Sulivan during a survey voyage by HMS Philomel (Stone and Rushton 2013). Sulivan had previously served on HMS Beagle, had become firm friends with Darwin during that voyage, and wrote to Darwin from HMS Philomel reporting his new geological discoveries. The dyke descriptions are contained in a letter dated 13th January to 12th February 1845 (Darwin Correspondence Number 730, Burkhardt and Smith 1987), firstly with specific reference to dykes cutting the quartzose sandstones of New Island and Weddell Island (though Sulivan referred to Weddell by its original name of Swan Island). However, Sulivan noted that he had been observing the features more widely for some time, but had only recently become convinced of their intrusive origin. He wrote as follows, with an accurate description of the effects of thermal metamorphism on the host sandstone beds:

“One reason that made me doubtful before about the dykes being Igneous was, that the rock on each side was so little altered (though for some inches it was decidedly so) and where the vein had fallen out the two sides or walls of the crevice stuck up in this manner [see sketch reproduced in Figure 4a] and were very much harder than the rest of the sandstone but only for two or three inches.”

Sulivan then went on to record “[n]umerous dykes running perpendicular in a North and South direction” and also included in the letter a sketch showing a dyke cutting obliquely across the strata exposed in the cliffs of a small island (Figure 4b), to which he dispatched a boat so that a specimen of the dyke could be recovered. Later in the letter he commented that “there are hundreds of these dykes running miles in length . . . . and some are twenty feet wide, and all sizes from that down to two inches”. He also described the characteristic spheroidal weathering style of the dolerite, likening the appearance of the spreads of rounded boulders to “a pile of shot”. It is likely that Sulivan sent specimens of the dykes back to Darwin, but it is unclear whether or not Darwin saw them or even if they reached him. However, Sulivan’s letter was clearly received in time for a footnote – “Captain Sulivan observed on the western island numerous basaltic dykes” – to be added to Darwin’s 1846 paper “On the geology of the Falkland Islands”, which had been presented at a meeting of the Geological society of London on March 25th of that year.

With only Darwin’s rather vague, 1846 footnote as a published guide, the full extent of the West Falkland dyke swarm remained unappreciated and did not become apparent until more detailed geological investigations in the early to middle twentieth century by Andersson (1907), Halle

(1911) and Baker (1924), the last of whom reported dyke trends as varying from NNE-SSW around to WNW-ESE and suggested that they all shared a radial disposition emanating from a point somewhere to the east of Cape Meredith, the southern extremity of West Falkland (Figure 1b). This proposal was negated by the photo-interpretation of Greenway (1972) when she identified up to 400 individual dykes on West Falkland, separated into two distinct but intersecting swarms: NNE-SSW dykes occurred mostly in the north and centre of the island whereas WNW-ESE dykes were confined to the south and the southwestern outlying islands. More recent work appeared to broadly affirm the validity of Greenway's two trends which usually, if erroneously, became condensed as north-south and east-west dyke swarms, with the more variable pattern in the extreme southwest (noted by Greenway as an area of overlap) separated out as the distinct Cape Orford swarm (Figure 1c) (Taylor and Shaw 1989; Mussett and Taylor 1994; Mitchell and others 1999). Aldiss and Edwards (1999) mapped and described the West Falkland dykes in terms of 6 swarms defined on the basis of orientation, distribution and field characteristics. Three were of relatively restricted extent, in the far west of west Falkland beyond the limits of the aeromagnetic survey, whilst the Cape Orford swarm showed greater compositional variation than had been previously appreciated, but the dominant, regional pattern of dyke orientation established by Aldiss and Edwards was not fundamentally at odds with the previously established trends.

In contrast to the plethora of dykes in West Falkland, relatively few have been reported from East Falkland. In view of this it is perhaps paradoxical that the first petrographical description of a dolerite dyke, by Reynard (1889), utilised a specimen collected by the Challenger Expedition (1872-1876) at Port Sussex, on the west coast of East Falkland (Figure 1c). This dyke was subsequently rediscovered and extended by Baker (1924) but not detected by Greenway in her 1972 photo-interpretation, though she did locate a single East Falkland dyke trending NE-SW across Lively Island (Figures 1b and 3) and noted that "there are probably many more dykes which are invisible on aerial photographs." The more recent geological survey by Aldiss and Edwards (1999) led to the discovery of several more East Falkland dykes. Thereafter, a commercial aeromagnetic survey flown in 2004 detected more dykes in East Falkland and suggested an additional sub-division of the swarms. Across West Falkland the aeromagnetic survey allowed the so-called "north-south" dykes to be resolved into two discrete and intersecting swarms, on the basis that dolerite dykes were the cause of the sharp, linear anomalies seen: one of the swarms is closely N-S whilst the other trends uniformly NE-SW (Figures 2 and 3). All of the pre-existing data from "north-south" dykes proved to have been obtained from the NE-SW swarm, only a few members of which were present in East Falkland, whilst the aeromagnetic results demonstrated that the N-S swarm comprised about 40 dykes spaced equally (albeit exposed only very rarely) across both East and West Falkland. In East Falkland the dykes of the N-S swarm swing into a more NNW-SSE orientation as they are traced northwards on the basis of their linear anomalies.

The linear aeromagnetic anomalies that have no known coincidence with exposures of dolerite are nevertheless regarded as indicating the presence of dykes. However, there are a few known dolerite outcrops in the northern part of West Falkland that do not appear to lie on linear anomalies. The explanation for this apparent mismatch probably lies in the distribution and orientation of the airborne survey's flight lines which, across much of West Falkland, ran north-south and had a spacing of 500 m. However, in a 10 km-wide strip in the north-east of the island, technical problems resulted in a line spacing of 1 km. The 'missing' anomalies lie within this zone, and would more easily have been missed if they extended parallel to the north-south flight lines. Indeed, the parallelism of the N-S dykes and the flight lines creates a common issue of poor anomaly resolution.

3 The ages of the dyke swarms

A Jurassic age for West Falkland dykes was established by radiometric dating. Dykes from the vicinity of Cape Meredith have given K-Ar dates of 192±10 Ma (Cingolani and Varela 1976), and 176±7 Ma and 162±6 Ma (Thistlewood and others 1997); the latter two from NE-SW trending dykes. More precise Ar-Ar dates were reported by Mussett and Taylor (1994): a dyke from the Cape Orford swarm gave 190±4 Ma, an E-W dyke gave 188±2 Ma, and a NE-SW dyke gave a maximum age of 193±4 Ma (Fig. 3). These three Ar-Ar dates were regarded as indistinguishable within error, and were taken to show intrusion of all of the West Falklands dykes at about 190 Ma. An Ar-Ar date of 178.6±4.9 Ma was obtained by Stone and others (2008) from the NE-SW dyke at Port Sussex in East Falkland. This age is compatible with the Ar-Ar maximum age of c. 193 Ma reported by Mussett and Taylor (1994) from a NE-SW dyke in West Falkland, but is more closely aligned with the K-Ar date of c. 177 Ma reported by Thistlewood and others (1997) from Cape Meredith.

The recent discovery of Cretaceous dykes in the Falkland Islands, the N-S swarm identified in the aeromagnetic survey, has been described by Stone and others (2008 and 2009). One dolerite dyke from the N-S swarm in East Falkland, coincident with a reversed magnetic anomaly, was temporarily exposed in Pony's Pass Quarry, near Stanley (Front cover picture and Figure 3) and Ar-Ar dating reported by Stone and others (2008) gave an age of 121.3±1.2 Ma (Aptian) from this locality. A second dolerite dyke coincident with a linear N-S aeromagnetic anomaly was first reported by Aldiss and Edwards (1999), who noted dolerite east of Burntside House and near Teal Creek Pond (Figure 5). These localities lie on a north-south, reversed magnetic anomaly (Teal Creek: Figure 3), although resolution was poor because this trend runs parallel to the direction of the flight lines of the aeromagnetic survey. Subsequent ground investigations proved dolerite outcrop along a 5 km, north-south linear zone extending south from Burntside, crossing Teal Creek and extending to the coast at Choiseul Sound (Figure 5). Mineral exploration drilling of the "Teal Creek N-S anomaly" has proved a likely extension of the Teal Creek dyke about 5 km to the north of Burntside. At Teal Creek, a dolerite dyke is 15 m across and is separated from a second, adjacent but much narrower dyke by a narrow screen of country rock; at the coast of Choiseul Sound a single dyke is about 10 m across. Radiometric Ar-Ar ages from two dyke localities at Teal Creek were reported by Richards and others (2013). spectra were obtained from both plagioclase separates and groundmass, but in all cases are somewhat disturbed (Figure 6). However, the plagioclase spectrum from one sample (PS 711: Figure 6a) has a flat central portion that does meet plateau criteria and this gives a weighted mean age of 131±4 Ma (MSWD = 1.70). The integrated whole-rock ages for this sample is 133±4 Ma (Figure 6b) whilst the integrated whole-rock age for a second Teal Creek sample (PS 712) is 137±4 Ma (Figure 6c).

Mineral exploration drilling elsewhere in East Falkland has proved dolerite coincident with a N-S linear anomaly showing normal polarity at Peat Banks, Lafonia (Figures 1c and 3). The dyke at Peat Banks is at least 12 m wide; from the borehole core recovered Richards and others (2013) reported an Ar-Ar integrated whole-rock age of 138±4 Ma (Figure 6d). Stone and others (2009) interpreted the Peat Banks dyke as the local, shallow expression of a much deeper, N-S intrusive feature, the dyke having risen close to the intersection between its deeper source and a NE-SW fracture that had previously accommodated a dyke of early Jurassic-age.

Although individually the results reported by Richards and others lack precision, all four agree within analytical error, which provides some level of confidence. Taken together they suggest dyke intrusion at around 135 Ma, during the Valanginian or Hauterivian stages of the Early Cretaceous. This is significantly earlier than the Aptian age of intrusion given by the Pony's Pass dyke. The Aptian age of 121.3±1.2 Ma (MSWD = 0.8) would appear to be of a better precision and quality than the Valanginian/Hauterivian ages but, as will be shown, is less compatible with the regional setting than the younger ages. One question that might arise is the homogeneity of the Cretaceous dyke swarm.

One other feature of the Cretaceous dykes that impacts on their relative ages is the variation in palaeomagnetic polarity. Across the whole swarm, the eastern dykes show reversed magnetic polarity but the majority of those further to the west have normal polarity. Of the dated, ca 135 Ma dykes, the one at Teal Creek is reversed whilst the one at Peat Banks is normal. The overlapping ages of these dykes suggests that magmatism lasted long enough to span a magnetic reversal, of which there were several at around that time. The dated dyke at Pony's Pass Quarry has reversed polarity, though the 121 Ma age places it within the early part of the normal polarity Cretaceous super-chron, the so-called Cretaceous quiet zone. Whilst it is possible that the Pony's Pass dyke is part of a separate eastern East Falkland swarm, intruded later than the dykes to the west, the close compositional similarity between all of the analysed N-S dykes in East Falkland (discussed below) argues against any such division. The significance of the Pony's Pass date seems likely to remain unclear until more data is available.

4 Compositions of the different dyke swarms

All of the Cretaceous dykes, whether from Pony's Pass, Teal Creek or Peat Banks are petrographically very similar; they are dolerites with a distinctive glassy groundmass. They are distinct from the Jurassic dykes, which mostly fall into two categories: those forming the E-W swarm are plagioclase-clinopyroxene-olivine dolerites, whereas the NE-SW dykes are plagioclase-clinopyroxene-orthopyroxene dolerites lacking the glassy matrix characteristic of the Cretaceous dykes. The Cretaceous dykes are also markedly Fe-rich relative to all of the Jurassic examples (Mitchell and others 1999; Stone and others 2008). The geochemical similarities and contrasts are illustrated in Figure 7 as a series of variation diagrams for selected major and trace elements plotted against MgO. Data for the dated East Falkland dykes (Table 1) are superimposed on fields derived for the West Falkland, Jurassic dykes by Mitchell and others (1999); also included are results from the NE-SW-trending and low-Fe (and so presumed Jurassic) Lively Island dyke (Figure 3), an unusual occurrence from which the similarity of results demonstrates the compatibility of the two datasets.

The possibility that Jurassic dykes of different orientation formed parts of a conjugate set (Mussett and Taylor 1994) can now be discounted in view of their markedly different compositions. The results from Mitchell and others (1999) clearly demonstrate that there are systematic differences between the Jurassic NW-SE and E-W dyke swarms of West Falkland (Figure 7). Analyses of the NE-SW-trending Jurassic (c. 178 Ma) dyke from Port Sussex, East Falkland (Stone and others 2008) cluster within the Jurassic NE-SW field from West Falkland, as would be expected. The East Falkland Cretaceous dykes (Pony's Pass, Teal Creek and Peat Banks) form a distinct cluster in a range of element ratios with no overlap into the Jurassic fields. Despite the apparent variation in their ages, there are no significant compositional differences between the Pony's Pass dyke and those at Teal Creek and Peat Banks.

One peripheral feature of Figure 7 is the compositional outlier formed by two dykes from Mitchell and others' 'N-S' swarm (now redefined as NE-SW). These two dykes (Mitchell and others' "Evolved Group") have some compositional similarities to the Cretaceous dykes from East Falkland, including a relatively high Fe content, and it is possible that they are in fact part of the Cretaceous swarm. Against that interpretation is the absence of any linear, N-S aeromagnetic anomaly coincident with their reported position, although it may have been swamped by the E-W signature that is dominant in that area. As suggested by Aldiss and Edwards (1999), it seems likely that the dyke swarms in West Falkland are more complex than currently appreciated.

Representative specimens from the dolerite dykes in East Falkland that have been dated and analysed have been lodged in the rock collection of the British Geological Survey, Keyworth, Nottingham. Details follow:

LX 1079 (Falkland Islands Survey Number PS 504).

Port Sussex, north side [51° 41° S 58° 48° W]. See Figures 1c and 3.

Early Jurassic dyke dated at 178.6 ± 4.9 Ma (Ar-Ar). Associated with a NE-SW linear aeromagnetic anomaly.

LX 1080 (Falkland Islands Survey Number PS 853)

Hope Place, Saladero [51° 43° S 59° 03° W]

Early Jurassic dyke. Lies on the same NE-SW linear aeromagnetic anomaly as LX 1079.

LX 1081 (Falkland Islands Survey Number PS 505)

Pony's Pass Quarry, Stanley, north face in 2007 [51° 43° S 57° 58° W]. See Figures 1c and 3.

Early Cretaceous dyke dated at 121.3 ± 1.2 Ma (Ar-Ar). Associated with a N-S linear aeromagnetic anomaly.

LX 1082 (Falkland Islands Survey Number PS 501)

Burntside [51° 47° S 58° 56° W]. See Figure 5.

Early Cretaceous dyke. Lies on the 'Teal Creek' N-S linear aeromagnetic anomaly.

LX 1083 (Falkland Islands Survey Number PS 502/712)

Teal Creek, north side [51° 49° S 58° 55° W]. See Figures 1c, 3 and 5.

Early Cretaceous dyke dated at 137 ± 4 Ma (Ar-Ar, Figure 6c). Lies on the 'Teal Creek' N-S linear aeromagnetic anomaly.

LX 1084 (Falkland Islands Survey Number PS 503/711)

Teal Creek, south side [51° 49° S 58° 55° W]. See Figures 1c, 3 and 5.

Early Cretaceous dyke dated at 131 ± 4 Ma and 133 ± 4 Ma (both Ar-Ar, Figure 6, a and b). Lies on the 'Teal Creek' N-S linear aeromagnetic anomaly.

LX 1085

Teal Creek Pond, west side [51° 50° S 58° 55° W]. See Figure 5.

Early Cretaceous dyke. Lies on the 'Teal Creek' N-S linear aeromagnetic anomaly.

LX 1086

Choiseul Sound, north coast [51° 51° S 58° 56° W]. See Figures 5.

Early Cretaceous dyke. Lies on the 'Teal Creek' N-S linear aeromagnetic anomaly.

LX 1087 (Borehole Number DD 041)

Peat Banks, Lafonia [52° 02° S 59° 23° W]. See Figure 1c and 3.

Early Cretaceous dyke dated at 138 ± 4 Ma (Ar-Ar, Figure 6d). Lies on a N-S linear aeromagnetic anomaly.

5 The dyke swarms in a regional context

The regional association of the Early Jurassic dykes from the Falkland Islands, dated ca 178-184 Ma, with the Karoo-Ferrar magmatism in South Africa and Antarctica, which peaked at ca 180-183 Ma is widely accepted (references listed in Richards and others 2013). There is general agreement that this regional phase of early Jurassic magmatism, spanning the South African and Antarctic segments of Gondwana, marked the beginning of the break-up of that supercontinent. More specifically, Mitchell at al. (1999) considered that the Falklands Jurassic dykes marked an overlap between the Karoo and Ferrar provinces, with the “east-west” swarm of Karoo-type dolerite and the “north-south” swarm (i.e. NE-SW in current terms) showing more affinity to Ferrar-type dolerite. The Early Cretaceous dykes from the Falkland Islands, with ages in the range 135 Ma to 121 Ma, were related by Richards and others (2013 and references therein) to the early stages of Atlantic Ocean rifting rather than to the initial break-up of Gondwana. Comparisons were made with the ca 134 to 129 Ma Paraná-Etendeka flood basalts and associated dykes, which are now preserved much further north on opposite sides of the South Atlantic (Brazil and Angola/Namibia), and to the ca 131 Ma dyke swarm that occurs in the Cape Peninsula - False Bay area of SW South Africa.

Richards and others (2013) also linked the onshore Mesozoic dykes to features of the offshore sedimentary basins, currently the focus of hydrocarbon exploration in the Falkland Islands Exploration Area (Figure 1a). In the Falkland Plateau Basin, to the east of the Falkland Islands, seismic basement had been sampled in 2010 by a commercial borehole that terminated at 2476 m below sea level in aphyric, plagioclase-clinopyroxene-olivine dolerite of similar petrographic character to the E-W, Early Jurassic dykes onshore. Elsewhere in the Falklands Plateau Basin, Richards and others (1996) had identified a relatively thick (ca 2 km) succession of Jurassic to earliest Cretaceous rocks, which they dated by tying seismically back to DSDP boreholes on the Maurice Ewing Bank, some 600 km east of the archipelago. Within this Falkland Plateau succession, a series of high amplitude seismic reflectors are interpreted as sills and/or lava flows and ascribed a probable Early Cretaceous age. This age interpretation was made despite the evidence then available suggesting that only dykes of Early Jurassic age were present onshore in the Falkland Islands. The interpretation was based on the offshore sills being intruded into Jurassic rocks and so of necessity being younger than their hosts. Richards and others (1996) extended their argument to suggest that, conceivably, some of the onshore dykes may also prove to be of Early Cretaceous rather than Early Jurassic age, and so genetically linked to the opening of the South Atlantic. This inference has been justified by the subsequent discovery of Early Cretaceous dykes onshore, as documented in sections 2 and 3 of this report. It is likely that these onshore dykes are related to regional stresses associated with South Atlantic opening rather Gondwana fragmentation, and it seems logical that lava extrusion and/or sill intrusion offshore during the Early Creatceous would be related to the same regional stress field. The same regional stress system led to oceanic development to the north of the Falkland Plateau, and to east-west directed extension in the North Falkland Basin (Richards and Hillier 2000; Stone and others 2009).

6 Conclusions

Recently acquired aeromagnetic data for the Falkland Island has shown that previous interpretations of the West Falkland dolerite dyke swarms are inadequate. In particular, most of the dykes previously described as forming a “north-south” swarm of Jurassic age are associated with a set of NE-SW linear magnetic anomalies that are entirely separate from another set of more closely north-south anomalies, which spans West and East Falkland, and the offshore area to the south-east. The NE-SW dyke swarm extends sparsely into East Falkland, but a separate E-W dyke swarm is restricted to the southern part of East Falkland. All of the dyke swarms are petrographically and geochemically distinct. Ar-Ar age dating has confirmed the Early Jurassic, ca 180 Ma, age of the NE-SW dykes but has established Early Cretaceous, ca. 135 Ma and ca 121 Ma, ages for the recently-recognised N-S dyke swarm. It should be noted that whereas the ca 135 Ma dates fit well with the regional context, the ca 121 Ma date seems suspiciously isolated. The Cretaceous, N-S dykes are reversely magnetised in the east of the Falklands archipelago, but show both normal and reversed polarities in the west, suggesting that intrusion spanned a magnetic reversal

The onshore Jurassic dykes, and a possible correlative dolerite body forming seismic basement in the offshore Falkland Plateau Basin, are associated with the regional Karoo-Ferrar magmatism, linked to the initial break-up of Gondwana. The Early Cretaceous magmatism, both onshore and offshore is more likely to be associated with the later extension phases of the Falklands Plateau and rifting of the North Falklands Basin as the South Atlantic Ocean initially opened. The ca 135 Ma ages obtained for the onshore dykes add credence to the Valangian-Hauterivian age deduced for likely lava flows detected on seismic lines from the Falkland Plateau Basin.

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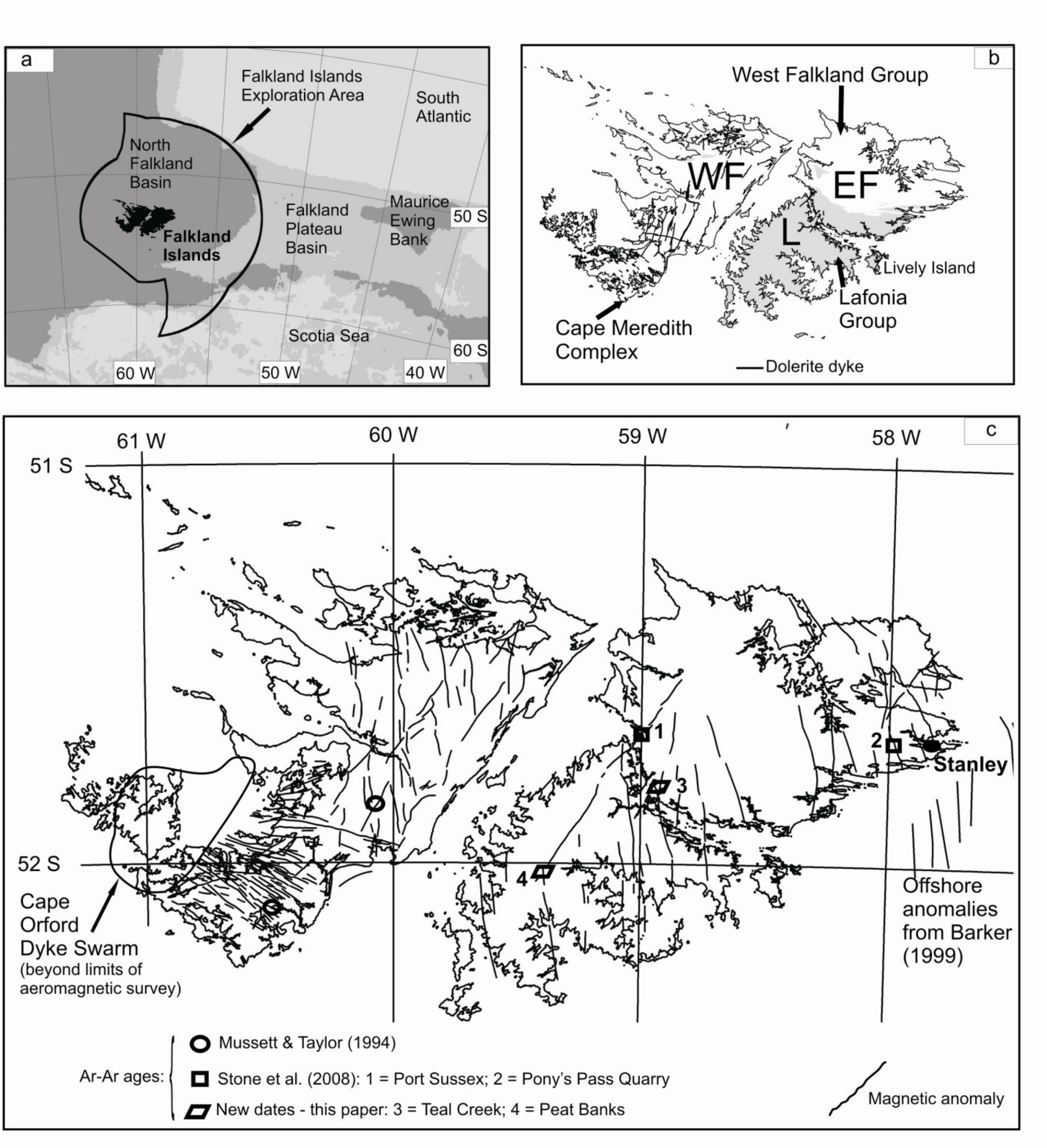

Figure 1. Location maps and outline geology for the Falkland Islands. After Richards and others (2013).

a. The regional setting at the western end of the Falkland Plateau, South Atlantic Ocean, with bathymetry represented by the grey scale from darkest = shallowest water (< 1500 m approximately) to palest = deepest water (>2500 m approximately).

b. Outline onshore geology for the Falkland Islands (WF = West Falkland, EF = East Falkland, L = Lafonia) with dykes at outcrop taken from Aldiss and Edwards (1999).

c. Linear aeromagnetic anomalies interpreted as dolerite dykes following the 2004 airborne survey, showing the locations of the analysed and dated samples – note that the aeromagnetic survey covered only the two main islands and extended neither to the western promontories of West Falkland nor to the smaller offshore islands. For survey boundaries and identification of normal or reversed anomaly characters see Figures 2 and 3.

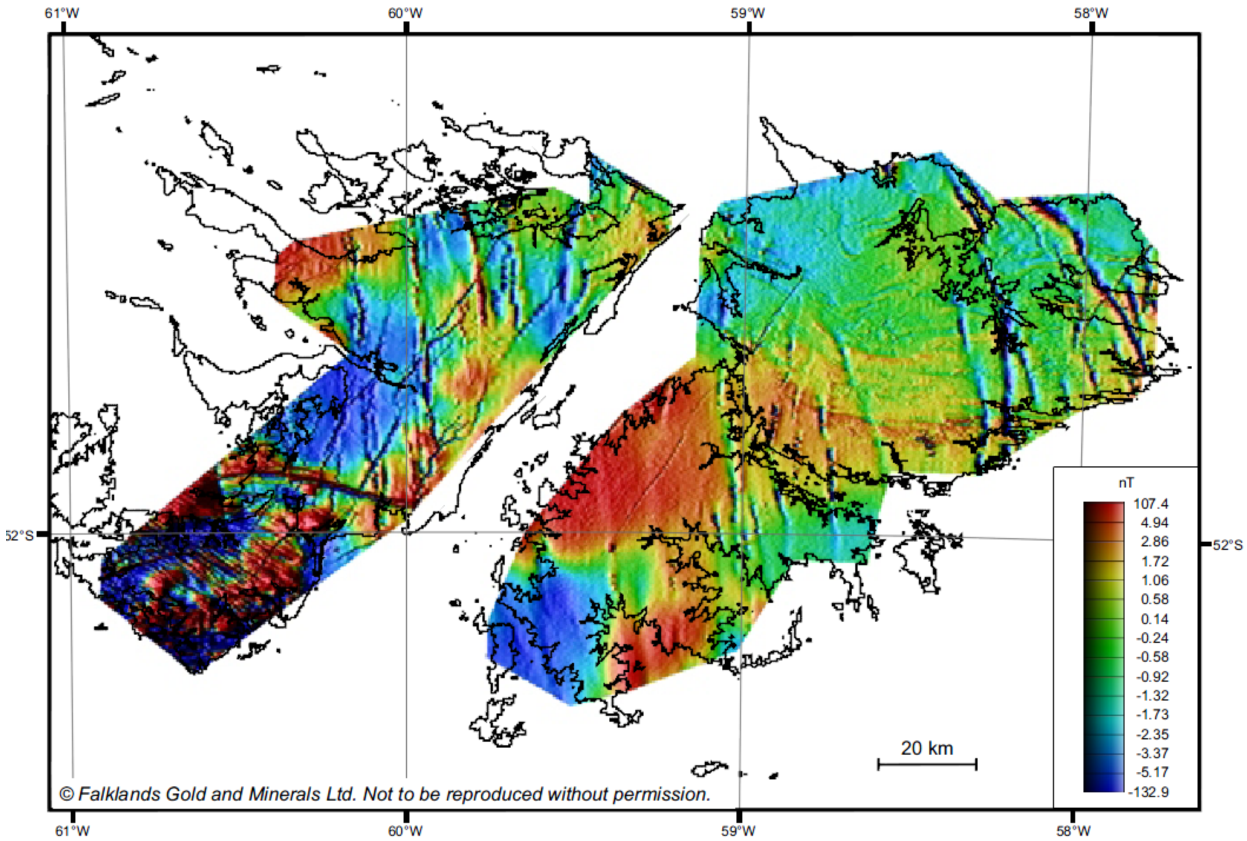

Figure 2: An aeromagnetic image derived from the 2004 airborne survey of the Falkland Islands, based on a residual field calculated by subtracting a 0.5 km upward continuation from the total magnetic field. Colour shaded-relief image with equal colour area and illumination from the west. The survey comprised north-south flight lines at a typical spacing of 0.5 km and east-west tie lines at a spacing of 5 km; the flying height was 120 m above ground surface. After Stone and others (2009)

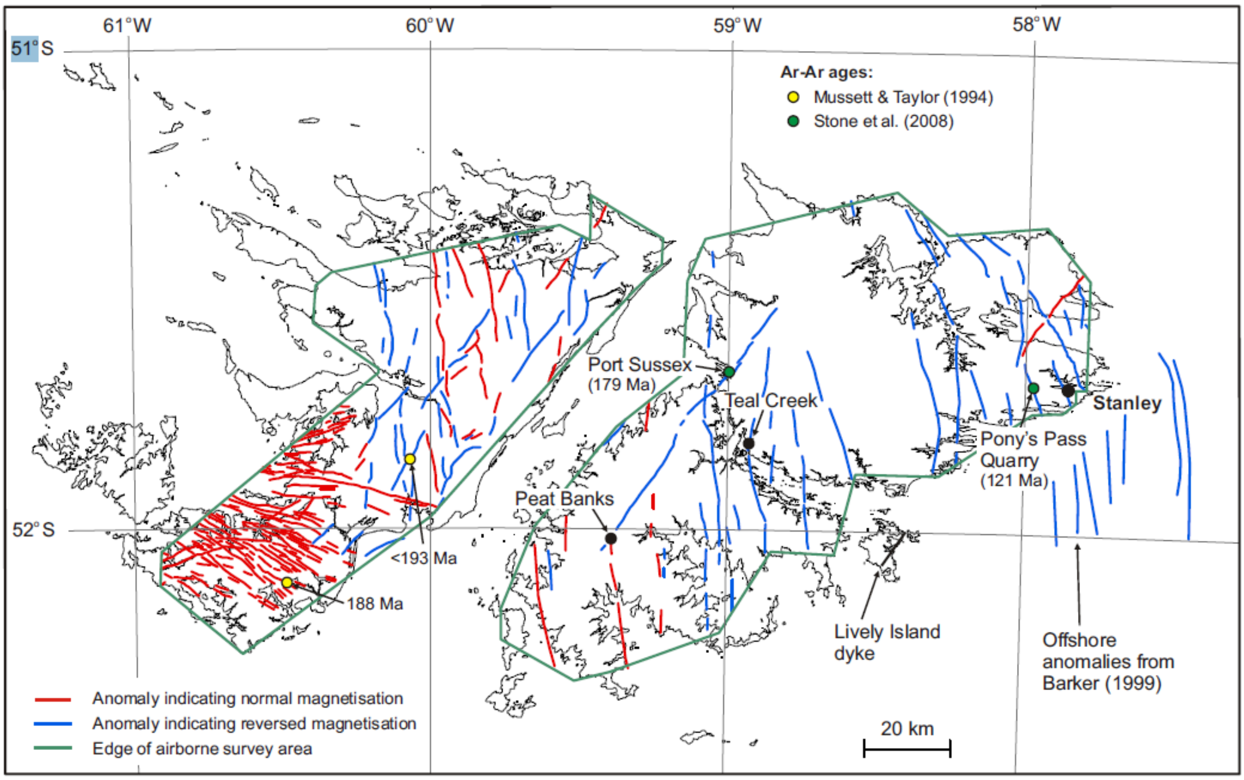

Figure 3: Linear anomalies from Figure 2 colour-coded to show normal (blue) or reversed (red) magnetization. After Stone and others (2009).

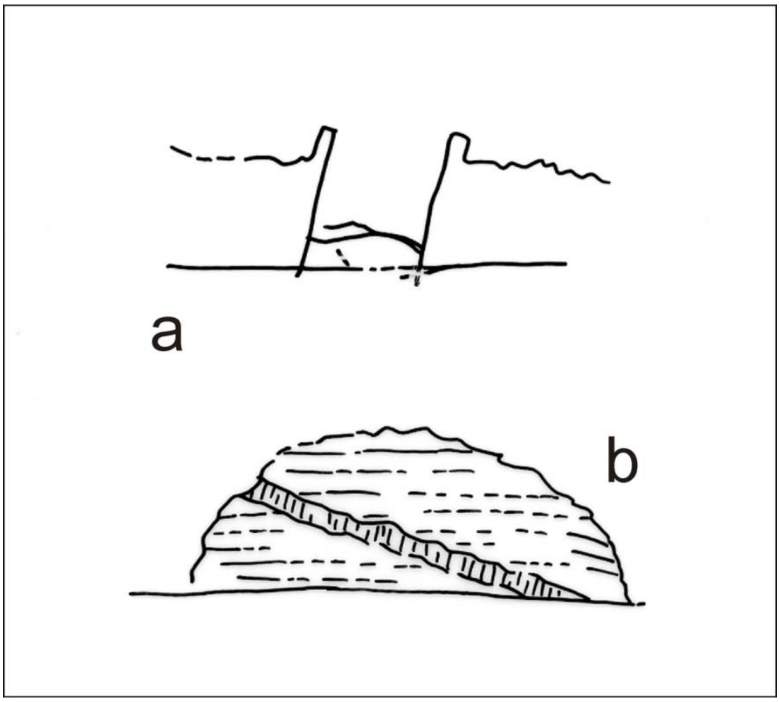

Figure 4: Bartholomew Sulivan's sketches illustrating dolerite dykes seen in West Falkland in 1844 or 1845. After Burkhardt and Smith (1987, p. 118):

a. The effect of thermal metamorphism altering and hardening the host sandstone (most probably from the Port Stephens Formation). Sulivan wrote:

"[W]here the vein [dyke] had fallen out the two sides or walls of the crevice stuck up in this manner and were very much harder than the rest of the sandstone but only for two or three inches".

b. A dyke cutting obliquely across sandstone beds (most probably from the Port Stephens Formation) as seen in a small island off West Falkland. Sulivan wrote: "the appearance of the island is like this the height of the cliff being about 100 feet and the vein [dyke] about 6 feet thick".

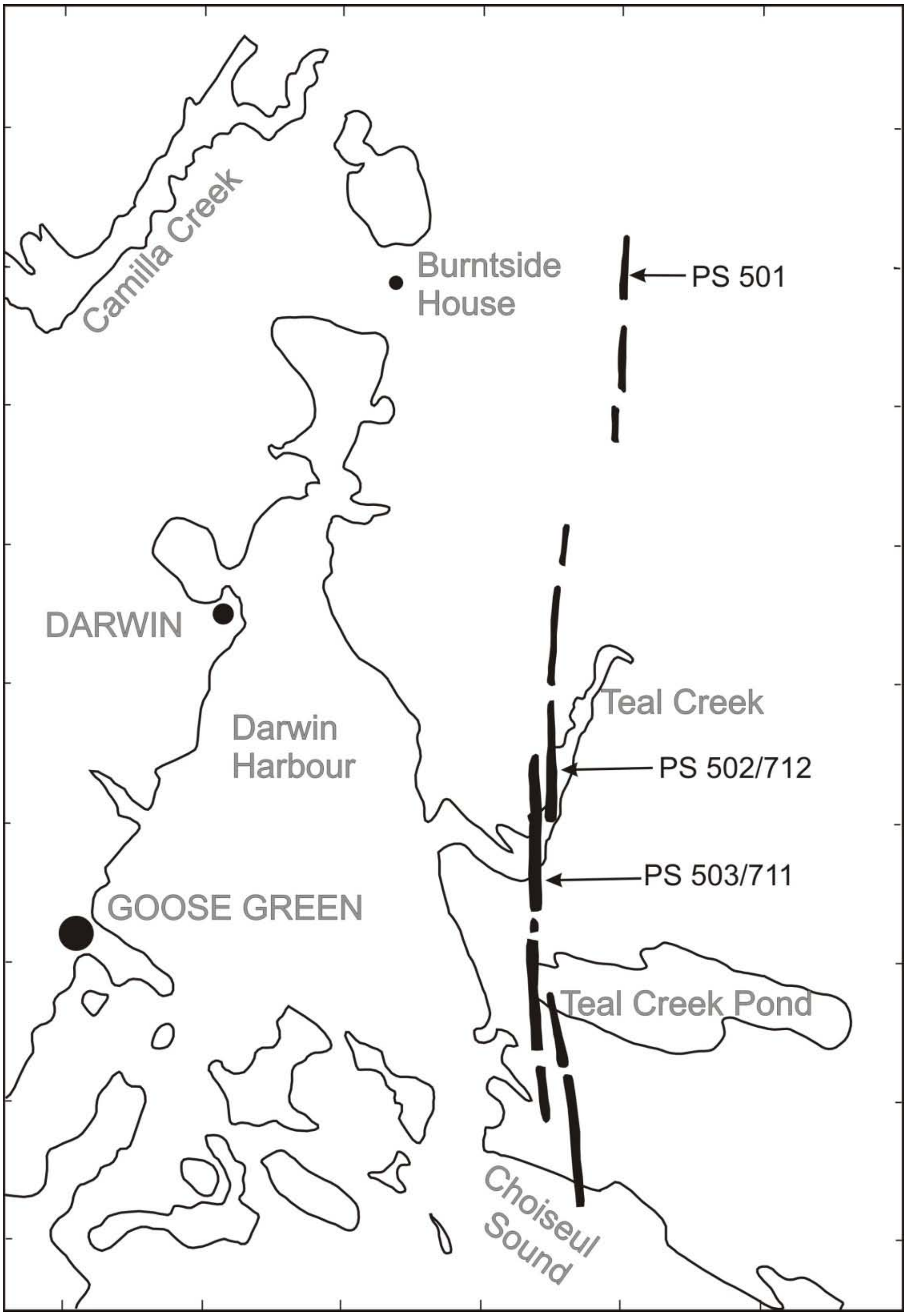

Figure 5. Sketch map of the Teal Creek area showing the dyke pattern established by field mapping as a follow-up to the aeromagnetic survey. Sample localities are identified.

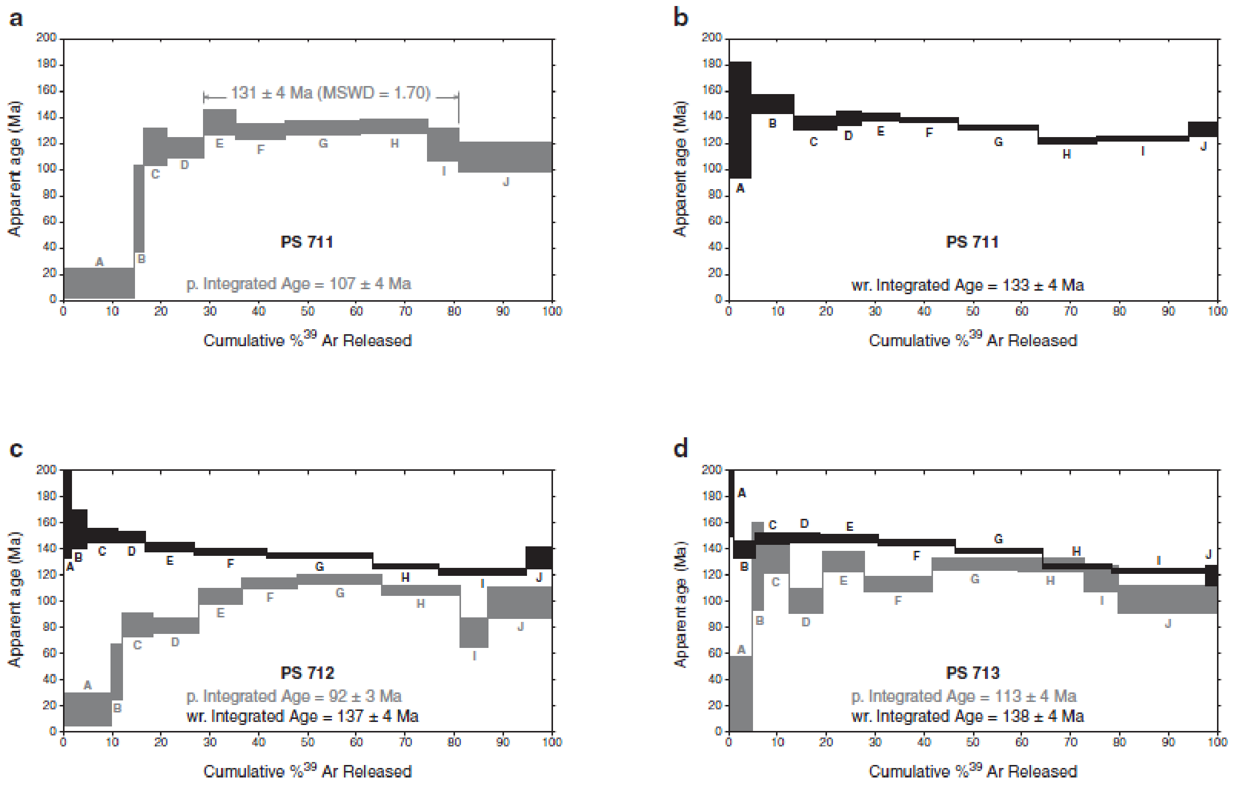

Figure 6: Ar-Ar spectra for dolerite samples from the onshore, N-S dyke swarm in East Falkland. After Richards and others (2013).

a. Results from plagioclase (p) separate, Teal Creek South (PS 711).

b. Whole rock (wr) results from Teal Creek South (PS 711).

c. Plagioclase (p) and whole rock (wr) results from Teal Creek North (PS 712).

d. Plagioclase (p) and whole rock (wr) results from Peat Banks (PS 713).

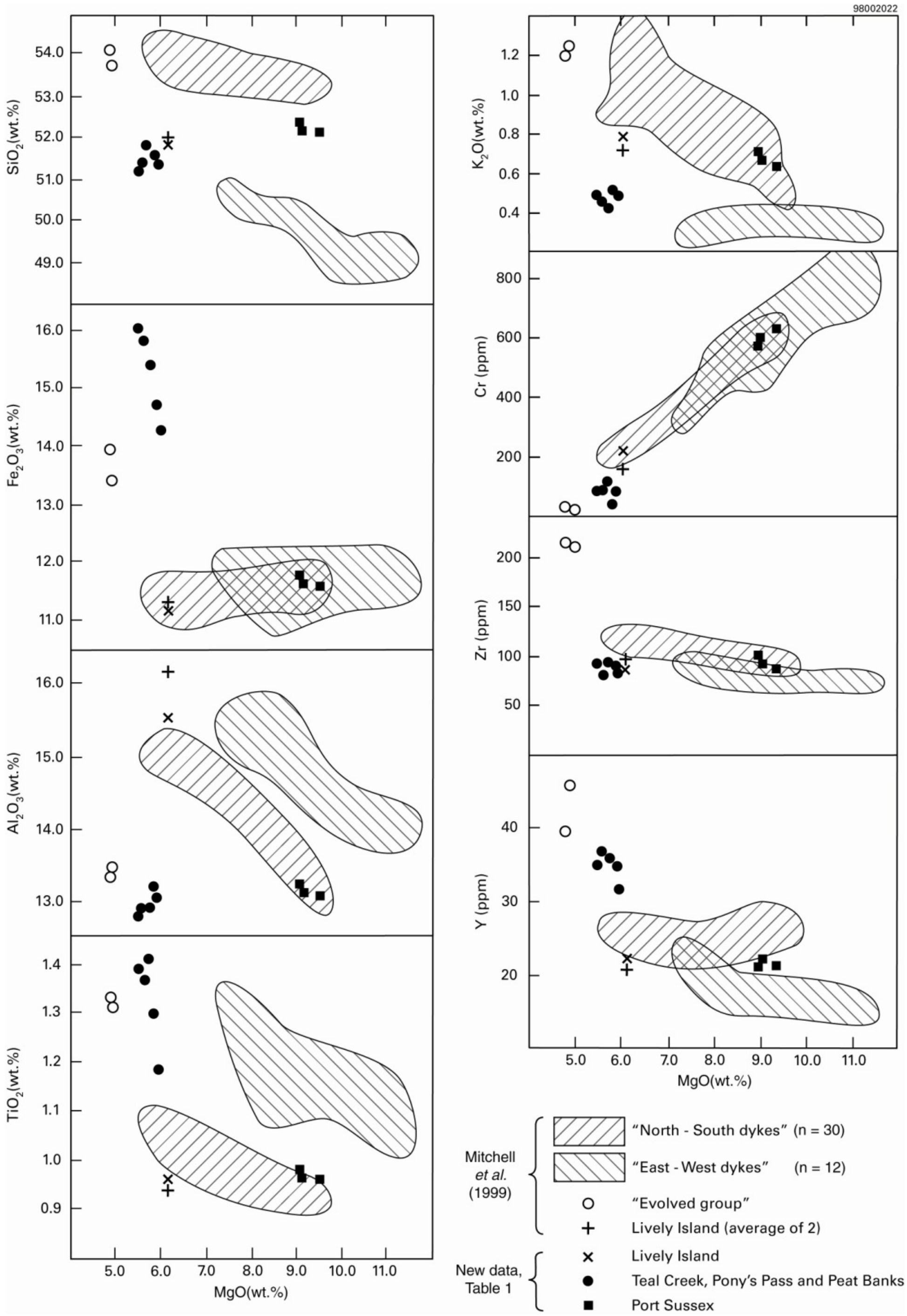

Figure 7. Element variation plots for dolerite samples from the Falkland Islands onshore dyke swarms. New data are superimposed on plots modified from Mitchell and others (1999, figure 3).

Sample name & number	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3t**	**Mn_3O_4**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**LOI**		**Total**
	%	%	%	%	%	%	%	%	%	%	%		%
PS 501 Burntside	51.14	1.39	12.65	16.01	0.26	5.48	9.60	2.26	0.48	0.13	0.14		99.61
PS 502/712 Teal Creek North	51.82	1.41	12.87	15.48	0.25	5.70	9.95	2.31	0.42	0.13	-0.13		100.28
PS 503/711 Teal Creek South	51.16	1.36	12.80	15.80	0.23	5.54	9.59	2.28	0.45	0.13	0.52		99.94
PS 504A Port Sussex	52.45	0.92	13.03	11.81	0.20	9.06	8.52	2.12	0.71	0.12	0.77		100.00
PS 504B Port Sussex	52.22	0.92	13.07	11.81	0.22	9.03	8.28	2.15	0.67	0.12	0.67		99.34
PS 504C Port Sussex	52.20	0.90	12.91	11.76	0.22	9.46	8.17	2.10	0.64	0.12	0.72		99.38
PS 505 Pony's Pass Quarry	51.38	1.29	13.26	14.75	0.32	5.81	9.78	2.41	0.50	0.14	0.55		100.28
PS 713 Peat Banks	51.34	1.18	13.17	14.21	0.23	5.93	10.53	2.29	0.50	0.12	0.11		99.69
PS 108 Lively Island North	51.79	0.84	15.50	11.18	0.19	6.09	10.37	2.34	0.77	0.16	0.21		99.52
	Sc	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
PS 501 Burntside	43	445	70	45	51	253	115	15	99	34	95	4	125
PS 502/712 Teal Creek North	45	456	82	52	55	279	118	12	103	36	94	6	118
PS 503/711 Teal Creek South	44	443	81	46	53	250	113	14	105	37	92	4	141
PS 504A Port Sussex	25	242	571	53	166	93	99	18	190	22	90	4	368
PS 504B Port Sussex	25	245	569	52	165	89	92	17	190	21	93	3	368
PS 504C Port Sussex	25	240	628	54	180	96	94	17	186	21	88	3	344
PS 505 Pony's Pass Quarry	41	396	47	64	69	205	293	15	126	35	94	5	189
PS 713 Peat Banks	44	370	78	44	56	192	102	16	200	31	92	5	118
PS 108 Lively Island North	34	207	213	39	64	63	97	18	207	22	90	9	212

Table 1. Whole-rock geochemical analyses (XRF) for East Falkland dolerite dykes.