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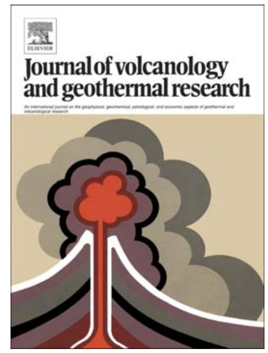

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The field and remote sensing analysis of the Kerguelen Archipelago structure, Indian Ocean

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Abstract

The Kerguelen Archipelago is part of an oceanic plateau with a complex history. Little work has been done on the tectonics of the onshore areas, even though the extensive outcrop renders the islands especially good for structural work. We present the results of three field campaigns and remote sensing analysis carried out in the main Kerguelen Island, around Val Travers valley and Mt Ross volcano (Central Plateau) and in the Rallier du Baty peninsula (SW part of the archipelago). We have mapped faults, fracture sets, and the location and geometry of intrusive bodies. We found that the plateau basalt lavas that make up most of the area are densely fractured, crossed by many veins, dykes and some small faults. This work provides a general framework for the structure of Kerguelen Archipelago that is dominated by 110°-striking faults and veins, dyke swarms and an alignment of recent central volcanoes, which have formed in N-S to NNW-SSE directed extensional stress field. The other structures are fractures, veins and dykes which strike 130°-150°, 000° and 030°-050°. They are likely related to transform faults of the Indian oceanic crust and to faults of the north Kerguelen Plateau (offshore basement of the archipelago). These buried structures were likely re-activated by a low magnitude stress field.

Keywords: Field Relationship, Remote Sensing, Tectonics, volcanology, Indian Ocean

1. Introduction

The Kerguelen Plateau is sometime described as an old Large Igneous Province (LIP) located on a young oceanic crust (Giret et al., 2003). From the onset of its formation during the lower Cretaceous until now, the Kerguelen hot spot has produced the second largest LIP on Earth (Giret et al., 2003). The rifting of the plateau along the SE Indian mid-oceanic Ridge (SEIR) followed by its break-up has formed NW-SE-striking normal faults in the plateau basalts (Rotstein et al., 2001).

The Kerguelen Archipelago is the largest onshore area of the Kerguelen Plateau (Fig. 1). Its linear structures, such as fractures and faults, and magma injections, such as dykes and intrusive complexes, may be shaped by structures inherited from the rifting phase and by active far-field (mid-oceanic ridge spreading) and near-field (ongoing magma activity) movements. This paper combines remote sensing and field observations to investigate the structure of the archipelago. The remote sensing data provide information about the strike and statistical occurrence of onshore lineaments, such as fractures and dykes. The field campaigns reveal the structures causing the lineaments (e.g. fractures and faults), enable a precise mapping of small-scale intrusions (mostly dykes) and mapping of the geometry of the largest intrusive complex of the archipelago on the SE part of Rallier du Baty peninsula (Fig. 2). These data allow us to define a model that attempts to explain the origin of the abundant fracturing on Kerguelen and provide a tectonic context for the deformation.

2. Geological setting

The Kerguelen plateau is a 2300 km long, NNW-SSE-elongated submarine plateau located on the Indian Ocean crust, south of the SEIR. The plateau is divided into several morphological units (e.g. Fig. 1).

The formation of the Kerguelen Plateau is closely linked to sea-floor spreading between Antarctica, Australia and India that initiated 132-136 Ma ago (Powell et al., 1988; Müller et al., 2000). The South Kerguelen Plateau (SKP), the Elan Bank, the Central Kerguelen Plateau (CKP) and Broken Ridge, the 90°E Ridge and the Skiff Bank, and, eventually, the North Kerguelen Plateau (NKP), formed successively since 120 Ma (Duncan, 2002; Coffin et al., 2002).

At 43 Ma, Australia and Antarctica spread apart on the NW-SE-striking and newly formed SEIR (Rotstein et al., 2001) that was located in the area now occupied by the Kerguelen Plateau. The SEIR is responsible for the separation of Broken Ridge and 90°E Ridge from the rest of the LIP. The break-up was preceded by rifting phases that formed NW-SE-, N-S- and E-W-trending structures in the plateau basalts. The NW-SE-striking structures are normal to the extension direction and correspond to ridges and normal faults, which sometimes delimit tilted blocks, formed between 88 Ma and 43 Ma (Coffin et al., 1986; Fritsch et al., 1992; Rotstein et al., 1992; Rotstein et al., 1991; Royer and Coffin, 1992; Könnecke and Coffin, 1994; Angoulvant-Coulon and Schlich, 1994; Munschy et al., 1993). Two N-S striking grabens named the 77°E and 75°E grabens are pull-apart related to sinistral strike-slip movements along the NW-SE structures (Munschy at al., 1993). The E-W direction corresponds to a rift zone in the Banzare bank (SKP, e.g. Fig. 1) and its origin is unknown (Angoulvant-Coulon and Schlich, 1994; Charvis et al., 1993).

From 43 Ma, the hot spot activity was increasingly confined in the Antarctic oceanic plate and the NKP (68–0 Ma) continued to form. By 25 Ma, Kerguelen magmatism was fully in an intra-plate position (Giret, 1990). The Kerguelen Archipelago formation initiated at this moment (from 30 Ma; Nicolaysen et al., 2000; Coffin et al., 2002). This 6500 km^2 set of islands is mainly made of plateau basalts (e.g. transitional-tholeiitic to alkaline basalts) that form 1-5 m thick lava flows dipping 2°-3° toward the SE (Nougier, 1970a). Several differentiated magma complexes are intruded in the plateau basalts. The largest magma intrusions are located in the Société de Géographie peninsula, in the western De l'Ouest Island and in Rallier du Baty peninsula (Fig. 2). There are also several recent central volcanoes located along an E-W line in the southern part of the main Kerguelen Island. The Mt Ross (1852 m) volcano for example, is 2-0.1 Ma old (Weis et al., 1998). Also, the active volcanoes of the western part of Rallier du Baty peninsula have erupted recent trachyte lava flows and pumice deposits, which cover the eroded intrusive complexes (Gagnevin et al., 2003).

3. Methodology

The Kerguelen Archipelago is part of the TAAF (Terres Australes et Antarctiques Françaises) and is isolated in the Indian Ocean. Its particular climate has formed high quality outcrops which are, however, accessible for short period of time during the summer scientific campaigns organized in November, December and January. For this reason, few people had the chance to map and sample the exposed rocks and the work presented in this paper, which grouped the observations of three field campaigns, is part of a work in progress. The field campaigns were carried in Val Travers valley (2006), around Mt Ross volcano (2007-2008) and in the SE part of Rallier du Baty peninsula (2009-2010) as part of the DyLiOKer 444 IPEV (Institut Polaire Paul-Emile Victor) program. The field data are combined with remote sensing observations in the first part of this paper, which group analysis of lineament orientations made on the SRTM (Shuttle Radar Topographic Mission) DEM (Digital Elevation Model) and on Landsat, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and SPOT (Satellite Pour l'Observation de la Terre) images.

The numbers given hereafter, such as 110° for example, refer to the strike of planes or to the trend of lines. The notation 090°/50°S refers to a 090°-striking plane dipping 50° toward the south.

4. Remote sensing analysis

a) Geology

Many of the intrusive complexes of the Kerguelen Archipelago are light-colored rocks intruded in dark-colored plateau basalts (Fig. 3-a). This color contrast is visible on satellite images and was exploited to map the intrusive rocks (syenite, and possibly also gabbro) of Loranchet and Rallier du Baty peninsulas (Fig. 4, 5).

The southern part of Rallier du Baty peninsula is mostly made of a well exposed and roughly circular in plan view intrusive complex named the Southern Centre (Lameyre et al., 1976). The Northern Centre mapped by Gagnevin et al. (2003) is mostly hidden by ice, with the exception of a couple of differentiated sills and dykes located on the eastern margin of the intrusive complex (Fig. 4). In Loranchet peninsula, the intrusive complex of Société de Géographie peninsula (Giret et al., 1981) is covered with ice and difficult to map with remote sensing data (Fig. 5). It is surrounded by numerous dykes striking 060°, 110° and 170° (n=137). Sills are well exposed in the north of the peninsula. Another cluster of dykes, sills and possibly saucer-shaped sills is observed in the Mt Ballons area (Fig. 5). The Loranchet peninsula cluster of intrusions may be roughly aligned along the 130°-140° direction. The mapped intrusions are however surrounded by erosion valleys and ice and their exact extent is hidden.

The dark-colored lava flows of the Mt Ross and Jeanne d'Arc-Ronarch peninsulas areas are also topped with light-colored rocks, which are mostly circular and less than 1 km in diameter (Fig. 6). Most of these structures correspond to differentiated extrusions or domes according to Nougier (1970b). Other dark-colored small-scaled hills distributed along a 100°-120°-striking line around Mt Ross volcano, correspond to the individual volcanic centers or monogenetic vents mapped by Lameyre et al. (1984).

b) Structures

The low resolution of the SRTM DEM (e.g. 90 m) highlights the valleys and the largest lineaments. These structures are concentrated in the flat topped plateau basalt located in the central part of the main island (Fig. 7). The 668 lineaments observed on the SRTM strike mostly 110°-150° and 060° (Fig. 7-a). The 000° and 090° directions are poorly represented. The Plateau Central lineaments, bays and valleys which surround Mt Ross, are parallel to the circular base of the volcano (Fig. 6).

The analysis of ASTER and SPOT images reveals that the Kerguelen Archipelago rocks contain a large amount of lineaments, which are again more abundant (or better preserved) in the flat topped plateau basalts. The general orientation of these structures is

150°-160° (n= 1606, Loranchet peninsula, Fig. 7-d), 120°-130° and 030°-040° (n= 837, Rallier du Baty peninsula, Fig. 7-c), 100°-120° and 065° (n= 4601, Central Plateau).

The lineaments have been measured in selected delimited circular areas free of erosion valleys, ice cap and bays to determine the relative abundance of individual strikes. These measurements were made exclusively in the plateau basalts. The 100°-120° direction is the best represented and found in the whole island. The 150° direction is also well represented in the Central Plateau (130°-150°, Fig. 7-e) and in the Loranchet peninsula (150°-160°, Fig. 7-b), where it dominates. The 030° (Rallier du Baty peninsula) and 080°-090° (Central Plateau) directions are poorly represented. Note that the 150° and 080°-090° striking lineaments are radial around Cook glacier. The 130°-150° striking lineaments of the Central Plateau are located east and west of Mt Ross volcano (Fig. 7-e).

5. Field data

5.1. Mapping of geological units

5.1.1. The plateau basalt lava flows

In the area visited in the field, the plateau basalts are a dark pile of long and continuous sub-horizontal layers. The lavas are generally aphyric but contain occasionally large amounts of feldspar phenocrysts. Conglomerates and river sands are intercalated in the lava pile in every visited area. The lava flows are mostly 1-5 m thick. Between the Courbet peninsula and the Plateau Central, thicker flows (10-50 m thick) located in the pile of thin lava flows are exposed. These thick flows may have been emitted by the Armor Base cluster of volcanic edifices, which were unfortunately too quickly crossed to be studied by the 2006-2010 field campaigns.

Individual lava flows of the Plateau Central are on average oriented 090° and dip 10°-20° toward the south (n=30). In the Rallier du Baty peninsula, the orientation of flows has been modified by the magma complex injections.

5.1.2 The southern Rallier du Baty intrusive complex

The Rallier du Baty peninsula contains 5 (Dosso et al., 1979 ; Giret, 1980) or 2 (Gagnevin et al., 2003) intrusive complexes (Fig. 2). This section focuses on the largest and southernmost complex, named the Southern Centre, which is a 12 km in diameter 15 to 7.6 Ma old cluster of magma intrusions (Lameyre et al., 1976; Dosso et al., 1979). It is made of quartz-rich and quartz-poor syenite and, to a lesser extent, gabbro and granite (Giret, 1980). These alkaline rocks are mantle derived and have mostly evolved by crystal fractionation (Nougier, 1970a; Marot and Zimine, 1976; Dosso et al., 1979; Giret, 1983; Lameyre et al., 1984). The Southern Centre is described as a ring complex (Lameyre et al., 1976) such as defined by Bonin and Giret (1990): cluster of intersecting ring dykes injected following the down-sagging of a crust block in a magma accumulation and overlay by a caldera at the surface. Each of the 7 to 12 ring dykes of the Southern Centre is a 100-2,000 m thick circular sheet-shaped intrusion with outward dipping margins. The ring dykes are surrounded by 4 smaller (2-3 km in diameter), older and less differentiated satellite intrusions (Giret, 1980). The ring dykes are progressively younger and more differentiated toward the centre of the complex, with the exception of the less differentiated central syenite. Each ring dyke possesses a chilled margin and may contain enclaves of older injections (Marot and Zimine, 1976).

The Southern Centre is intruded in 20-25 Ma old plateau basalts (Dosso et al., 1979). A 3.5-2.5 km uplift has tilted the basalts by 20° prior the injection of magma (Lameyre et al., 1981). The outer ring dyke dips steeply (70°-80°) outward. The syenite intrusion possesses a less than 10s of meters thick chilled margin at the discordant contact with the plateau basalt (Lameyre et al., 1981).

The aim of the field campaign is to clarify the geometry of the Southern Centre. The intrusion is 12 km (N-S) to at least 15 km long in the E-W direction (Fig. 8). The plateau basalts dip 20°-30° outward at the contact with the syenite intrusion to 10° outward 1 km away from the intrusion. The lava flows dip toward the south and the east, south and east of the complex, and toward the east for those located north of the complex. These last flows have been re-oriented by the injection of the more recent Northern Centre described by Gagnevin et al. (2003).

According to our measurements, the contact between the syenite and the plateau basalt is usually steep (80°-90°) and dips inward. The SW contact (Jérémine crest) dips 50° inward. This contact is either a plane or consists in a complex area of crushed plateau basalts injected by aplitic syenite. The syenite has intruded the surrounding lava flow pile in every measured area. These sill are 1 cm to tens of meters thick. Two large sills may form the main part of Mt Voltz hill and Longue Attente valley. Other sills hide the contact between the northern part of the Southern Centre and its host-rocks.

The northernmost area of the Fig. 8 map is a cluster of a few meters thick syenite sills usually discordant with the plateau basalt lava pile, whose exact morphology has not been determined due to a lack of time. This area corresponds to the eastern margin of the Northern Centre mapped by Gagnevin et al. (2003).

The 2 km in diameter rounded intrusion located in the SW part of Jérémine Crest (Fig. 8) is a gabbro (outer part) to syenite (central part) injection with steep margins and has been carefully described by Lameyre et al. (1981).

In the southern part of the Southern Centre, several closely spaced 0.5-2 m thick interbedded syenite and basic microcrystalline inclined sheets are observed (Fig. 3-b). The syenite-basic rock contact is either angular (enclaves of basic rock in the syenite) or is smooth (mingling structures). The contacts are injected by less than 0.5 m thick aplitic syenite and pegmatitic quartz-feldspar injections (Fig. 3-b). The Plage Jaune valley rocks have a different morphology: they are a hydraulic breccia of basic magma injected by syenite magma. These sheet-shaped rocks strike 110° (west, Vulcain lava flow area) to 070° (east, Mt Voltz) and dip 50° toward the south (Fig. 8). South of the Centre, at the southern extremity of Plage Jaune valley, a sill injection with a similar composition strikes about 080°-060° and dips 20°-50° toward the NW.

5.2. Structural data

5.2.1. Dykes

Small-scaled sub-vertical magma injections, or dykes, have been identified by the different teams in every visited area. Three days spent in the Loranchet peninsula enabled the identification of 130°-150° and 045° striking and 1-2 m thick dykes (n= 10) of, respectively, basic and alkaline composition. A few dykes striking 110° (n=3, 0.5-1 m thick) and 050° (n=1, 0.2 m thick) have been identified in the Central Plateau. The Val Travers valley contains hundreds of dykes, among which 53 were measured. The basaltic dykes are aphyric or contain feldspar-pyroxene phenocrysts, they are 1-2 m thick and strike mostly 100° (n= 40), and, to a lesser extent, 000° and 045°. Some 120° striking trachyte dykes were also measured. The plateau basalts of the Mt Ross volcano area contain few dykes, among which 66 were observed and measured (Fig. 9). Half of these 0.2-5 m thick injections of aphyric basalt dip steeply and strike 120°-100° and 70°-90° (Fig. 10-c). The other half strike 120°/70°NE and 100°/75°SW (Fig. 10-d).

The Southern Centre of Rallier du Baty is cut by basic dykes, which strike 100°-110° and dip 60° NE (n= 120, andesite dykes, Fig. 10-b) and 60°-90° NE (n= 60, basaltic dykes). The dykes located in the plateau basalt are mostly oriented 080°/70-80°NW (n= 117). However, the plateau basalts were rotated and occasionally baked by the Southern Centre formation and the initial orientation of the dykes they contain can not be determined with field data. The Southern Centre is also cut by 170°-010° (n= 77, basalt) and 170°-010°/60°W (n= 30, andesite) striking dykes. Its western part contains 030°-050° (n= 59) striking dykes parallel to the 045°-striking crest formed by the most recent volcanoes of Kerguelen Archipelago (Fig. 8).

5.2.2 Structures

The linear valleys observed with remote sensing data correspond to U-shaped valleys dug by glaciers. The lineaments of satellite images correspond to isolated fractures and closely-spaced parallel fractures which are 0.5-2 m thick crush zones. Most of these structures are exploited by erosion and form linear cm to tens of m deep trenches or canyons. These structures have been observed in every plateau basalt and syenite outcrop visited on the field.

Sub-vertical fractures, crush zones and veins have been systematically measured (n= 4620) in the plateau basalt of the Mt Ross volcano area (Fig. 10-e). The measured veins are related to hydrothermal circulation and are straight and discrete tension structures, that gives an indication of the stress orientation at the time of their formation. The networks of short and randomly distributed veins related to fractured or hydrothermally altered rocks infiltrated by a fluid have not been measured. In the Mt Ross area, the veins and fractures are mostly oriented 130°-150° (n= 1991) and 090°-110° (n= 1180). A small proportion of the structures strike 020°-030° (n= 274).

Despite a careful inspection, only 3 faults were identified in the plateau basalts underlying Mt Ross volcano: 1) 140°-striking and 2-5 m thick crush zone which may correspond to a fault plane (Radioleine valley); 2) 095°/60°NE oriented normal fault (Olsen Valley); 3) 105°/65°SW oriented dextral transtensional fault plane injected by dykes (south of Dante Plain).

6. Discussion

6.1. The Southern Center of Rallier du Baty peninsula

The map of the 12 ring dykes of the Southern Center of Rallier du Baty by Giret (1980) is based on the following analysis: 1) microscopic analysis of few samples; 2) identification of ring dyke chilled margins in valleys; 3) visual distinction between more or less yellow syenite and more or less grey rocks from afar. More careful analysis can not be undertaken in this remote part of the archipelago, and large amounts of samples are hard to move. A part of the chilled margin, whose orientation is not reported by Giret (1980), may have been mistaken with the abundant aplitic injections observed during our field study. The visual interpretations made from afar are open to some doubts, especially because a part of the rocks are altered and colored by hydrothermal fluid circulation (e.g. Fig. 8). According to our observations, we can not confirm that the Southern Center is a cluster of ring dykes. It may as well correspond to a slowly cooled and in-situ differentiated magma accumulation. It may also correspond to a cluster of sill injections with different ages and contrasting petrology, which have injected the contact between plateau basalt lava flows. Such a cluster of sill injections is named a laccolith and is similar to the laccolith intrusions described by Johnson and Pollard (1973). This last hypothesis is supported by the abundance of concordant sill injections observed in the lava pile at the outer margin of the Southern Centre. The sub-vertical margin of the Southern Center may correspond to the inflation of individual sill injections. Note that the abundant sills observed in the plateau basalt may indicate that the vertical load was small at the time of the Southern Centre formation and that it emplaced at shallow depth. This last hypothesis needs to be confirmed by petrological tools able to quantify the emplacement depth of the Southern Centre.

The E-W elongation of the Southern Centre may have two origins: 1) the magma chamber formed in an E-W extensional or N-S compressional stress field (e.g. analogue experiments of Holohan et al., 2005); or 2) the cluster of sill injections were fed by an E-W striking dyke swarm developed in a N-S extensional stress field. We favour the second hypothesis because we interpret the Southern Centre as a cluster of sill injections.

The circular intrusion located SW of the Jérémine Crest likely corresponds to an independent rising batch of magma, which is contemporaneous to the Southern Centre according to its age (Giret, 1980).

The band of basic magma and enclave-rich sheet injections in the southern part of the Southern Centre may correspond to a large plateau basalt enclave infiltrated and assimilated by the magma complex. This hypothesis implies that the plateau basalt enclave has melted or re-crystallised and has been rotated to its present day orientation (e.g. 070°-110°/50°S) by further sill injections and inflations. This hypothesis is however dismissed because the petrological analysis of Lameyre et al. (1981) indicates that the basic rocks have not re-crystallised. These rocks may also correspond to an early basic sill injected and dissected by later syenite sill injections, or to the injection of mingled basic and acid magma. More investigation is required to confirm this hypothesis.

6.2. Fractures and lineaments

The SRTM data indicates that the Kerguelen Archipelago contains many roughly NW-SE striking structures and that Mt Ross volcano is circled by curved bays and valleys. The statistical analysis of ASTER and SPOT images (e.g. analysis made in circles A to Q, Fig. 7) shows that the distribution of lineaments is similar E and W of Mt Ross. It did not indicate that the lineaments circle the volcano. The circle of valleys and bays is either an illusion created by the erosion of a limited amount of structures around the Mt Ross volcano relief or a subtle circle of deformation un-detected by remote sensing data.

The analysis of ASTER and SPOT images indicate that the 150°, 080°-090° and 130°-150° lineaments are radial around the Cook glacier. These lineaments were likely highlighted by glacial erosion. The abundant 100°-120° and rare 030°-striking lineaments are found in the whole archipelago and are the most likely to be related to a tectonic event.

The 2007-2008 field campaign (Mt Ross area) corroborates the abundance of 130°-150°, 090°-110° and 020°-030° striking lineaments, which correspond to fractures, veins, crush zones and rare faults. The normal faults and abundant veins indicate that the 100°-120° striking structures have likely developed normal to a NNE-SSW-trending least principal stress (sigma 3). The 130°-150° structures are also well represented. The 030° striking lineaments and fracture and the 045°-striking Val Travers valley are rare and may be related to erosion rather than tectonic movements. Note that the hypothetical circle of deformation around Mt Ross volcano is not detected by field data and that it may not exist.

6.3. Dyke injections

The relative abundance of dykes in individual parts of the Kerguelen Archipelago is difficult to determine. For example, the Central Plateau is morphologically characterised by several E-W-trending U-shaped valleys, which are usually studied in the field because easier to walk than plateau areas. Such valleys facilitate the measurement of N-S striking structures. As a consequence, few 110°-striking dykes were measured in the Central Plateau area. On the opposite, the 045°-trending Val Travers valley enables the observation of hundreds of 100°-striking dykes. Thus, the distribution of dyke intrusions can not be quantified with our field data.

Despite this problem, our data indicate that the plateau basalt basic dykes mostly strike 110°. The Southern Centre is not associated with cone sheet or radial dyke injections. The measured dykes were likely formed independently from the stress field generated by the intrusive complex and mostly strike 100°-110°. These intrusions have developed following a horizontal, NNE-SSW-trending least principal stress (sigma 3) related to an extensional state of stress. Note that the strike of dykes is similar to that of the 100°-120°-striking eruptive vents alignment of Mt Ross volcano.

In the Central Plateau area, less abundant dykes strike 080°, 000° and 045°. Some 170°-010°-striking dykes were also measured in the Southern Centre area. These intrusions may have used weak plans of the lava pile. The 030°-050°-striking dykes of Rallier du Baty peninsula are close and likely related to the 040° alignment of recent to active volcanic centres which form the western part of the peninsula.

6.4. A N-S to NNW-SSE directed state of stress?

The 110° direction is well represented by dykes, fractures, veins and by rare normal faults. It also corresponds to the strike of the lava flows layers of the Central Plateau. The Kerguelen Island central volcanoes are roughly distributed along an E-W band in the south of the main island and the Southern Centre syenite may have been fed by roughly E-W to ESE-WNW striking dykes. Finally, the Banzare bank structure (SKP) strikes E-W (Angoulvant-Coulon and Schlich, 1994; Charvis et al., 1993). These structures formed in a N-S to NNE-SSW-trending least principal stress. This extensional state of stress was active after 30 Ma (age of the oldest onshore plateau basalts; Nicolaysen et al., 2000; Coffin et al., 2002) and 15-7.6 Ma (age of the Southern Centre according to Lameyre et al., 1976; Dosso et al., 1979) and which may still be active today. Regionally, this stress field corresponds to the N-S spreading movements of the SWIR and to the northern directed drift of India (Rotstein et al., 2001).

6.5. The other structures

The Kerguelen Archipelago contains many 000°, 130°-150° and 030°-050° striking fractures and veins. The Loranchet peninsula intrusive complexes may be aligned in the 130°-150° direction. The 000° structures were abundantly infiltrated by dykes in the Rallier du Baty peninsula. The 030°-050°-striking structures were also infiltrated by dykes and may host the sub-volcanic complex of the active volcanoes of Rallier du Baty peninsula. Surprisingly, these structural directions are not associated with any observable faults.

The bulk of these structures corresponds to the following regional directions: 1) the SEIR (130°-150°) and rifting structures of the Kerguelen Plateau (000°, 130°-150°); 2) Indian Ocean transform faults (030°-050°). The transform faults may have been active since the formation of the 30 Ma old Kerguelen Islands (Nicolaysen et al., 2000; Coffin et al., 2002) and may have fractured the plateau basalt. The rifting associated with the SEIR formation ended 43 Ma ago (Rotstein et al., 2001), prior the formation of onshore rocks. The Kerguelen Archipelago 130°-150° and 000°-striking structures may be related to small movements of the rift faults of the NKP re-activated by low magnitude regional stresses. Such movements would be too small to extend the buried faults toward the surface and to produce discrete fault planes instead of the observed fractures and veins occasionally infiltrated by magma.

7. Conclusions

The remote sensing and field observations indicate that the Kerguelen Archipelago is structured as follow: 1) its northern part (Loranchet peninsula) is intruded by 130°-150° aligned magma complexes; 2) its southern part contains 110°-striking dyke swarms and active volcanoes; 3) the rocks, and especially the plateau basalt, are affected by fractures, crush zones, veins and rare faults; 4) the plateau basalts are tilted toward the south.

There are 3 minor and 1 predominant structural orientations in Kerguelen, which are, respectively, 130°-150°, 000°, 030°-050° and 110°. The 110° direction developed in a N-S to NNW-SSE directed least principal stress (sigma 3) related to an extensional stress field, which has controlled the orientation of most magma intrusions. This stress field is related to the northern directed drift of India and may still by active in the Kerguelen Archipelago area. The 130°-150°, 000° and 030°-050°-striking structures are parallel to Indian Ocean transform faults and SEIR related rift faults. They may correspond to NKP faults re-activated in the Kerguelen Archipelago area by low magnitude far-field movements.

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Figures caption

Fig. 1: The Kerguelen Plateau and the Indian Ocean spreading system. The sub-marine structures are drawn from the gravity map of Rotstein et al. (2001); SEIR: South East Indian Ridge, SWIR: South West Indian Ridge, SKP: South Kerguelen Plateau, CKP: Central Kerguelen Plateau, NKP: North Kerguelen Plateau; 1. Lineaments (probably transform faults) formed from 133 Ma with an initial NE-SW orientation, 2. Lineaments formed from 99-96 Ma with an initial N-S orientation, 3. Transform faults formed from 43 Ma, 4. Onshore lands, 5. Offshore Kerguelen Plateau.

Fig. 2: Kerguelen Archipelago and topographic features referred to in the text (after Lameyre et al., 1984; Gagnevin et al., 2003).

Fig. 3: a) Picture of Mt du Commandant Hill, view from the north and illustrating the color contrast between plateau basalt and syenite; b) Picture of basic microcrystalline rock, syenite and aplitic intrusions located north of Mt du Commandant hill (cf. Fig. 8 for location).

Fig. 4: Map of Rallier du Baty peninsula made with the analysis of Landsat, SPOT and ASTER images; 1. Light-colored areas, which may correspond to intrusive rocks; 2. Dark-colored areas, which likely correspond to plateau basalts; 3. Ice, river sediments, lake and sea; 4. lineaments.

Fig. 5: Map of Loranchet peninsula made with the analysis of Landsat, SPOT and ASTER images; 1. Light-colored areas, which may correspond to intrusive rocks; 2. Dark-colored areas, which likely correspond to plateau basalts; 3. Rocks covered with a thin layer of snow (un-mapped area); 4. Ice, lake and sea; 5. lineaments; 6. Circular features which may correspond to saucer-shaped intrusions, whose morphology is similar to that of intrusions described by Galland et al. (2009).

Fig. 6: Map of the Central Plateau and Jeanne d'Arc-Ronarch peninsulas made with the analysis of Landsat, SPOT and ASTER images. The map is display over a shaded relief map extracted form the SRTM DEM (sun elevation= 45°, azimuth= 045°); 1. Sea and lakes; 2. Circular light-colored rocks and dark hills, which likely correspond to differentiated intrusions, extrusions and individualized eruptive vents; 3. Circular distribution of valleys and lineaments around Mt Ross volcano.

Fig. 7: Analysis of lineaments observed on the SRTM DEM (e.g. map and histogram a) and on SPOT and ASTER images. The satellite image lineaments were mapped in areas I to III and in circular areas free of erosion valleys to study their statistical distribution (e.g. circles A to Q).

Fig. 8: Geological map of Rallier du Baty peninsula established after the 2010 field campaign.

Fig. 9: Map of Mt Ross volcano established after the 2007-2008 field campaign and remote sensing observations. 1. Eruptive vents (differentiated domes, phreatomagmatic vents and vulcanian vent); 2. Table-shaped lava interpreted as eroded lava lakes which formed in the crater of scoria cones; 3. Mt Ross volcano and its trachyte lava flows; 4. Plateau basalts; 5. Two 5-10 m thick welded ignimbrite horizons located in the plateau basalt at 150-180 m and 130-150 m elevations; 6. Basic dykes (dolerite); 7. Faults measured on the field; 8. Lineaments mapped on ASTER and SPOT images.

Fig. 10: Rose diagrams (a to d) and histogram (e) based on measurements made in the Rallier du baty peninsula (a-b) and around Mt Ross volcano (c-e); a) strike of sub-vertical basalt dykes (n= 56); b) orientation of 40°-70°-dipping andesite dykes (n= 103); c-d) strike of sub-vertical (c, n= 53) and 50°-80°-dipping basalt dykes (d, n= 39); e) strike of sub-vertical crush zones (black, n= 720) and veins (white, n=980). The rose diagrams are lower hemisphere projections.

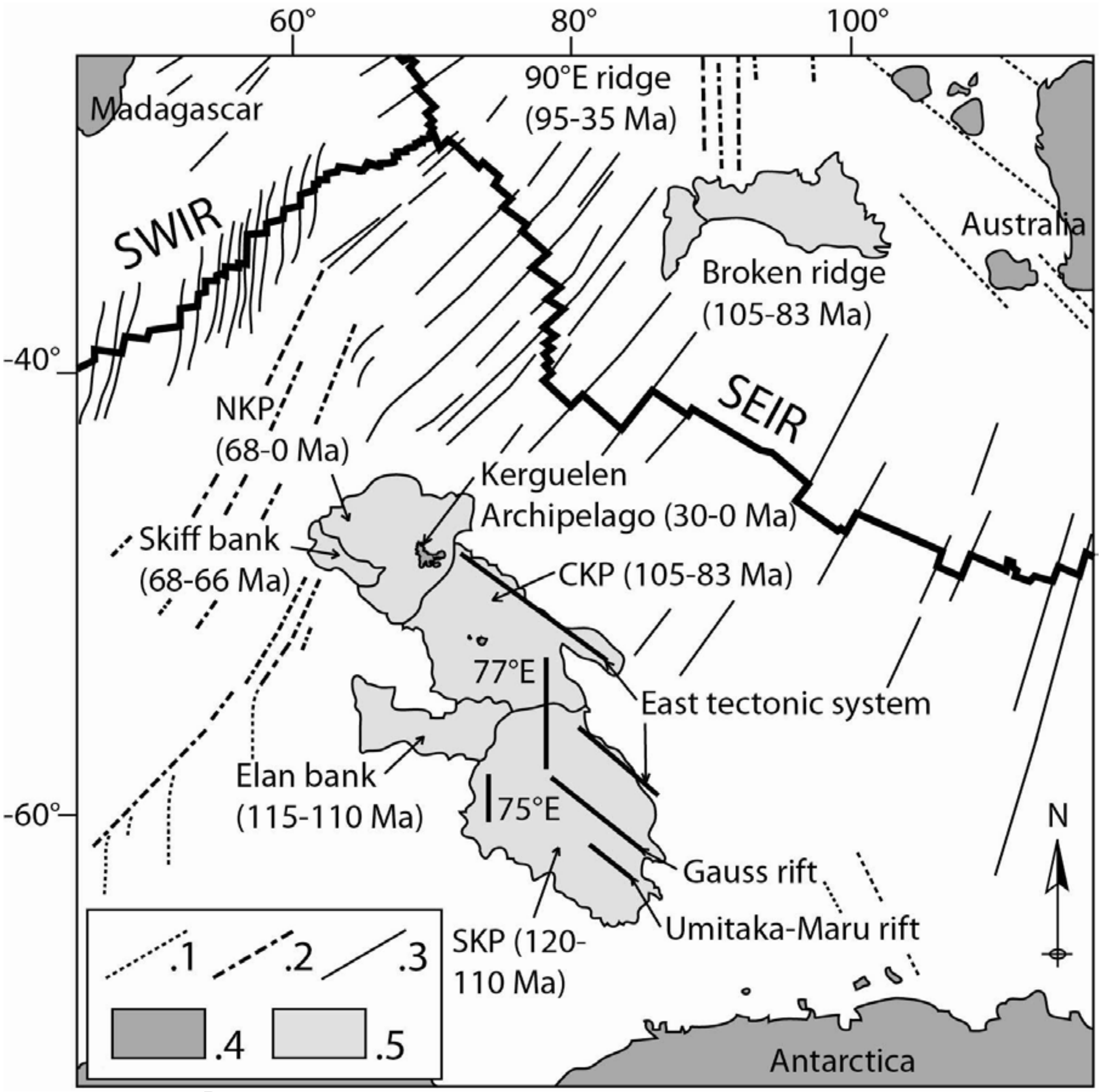
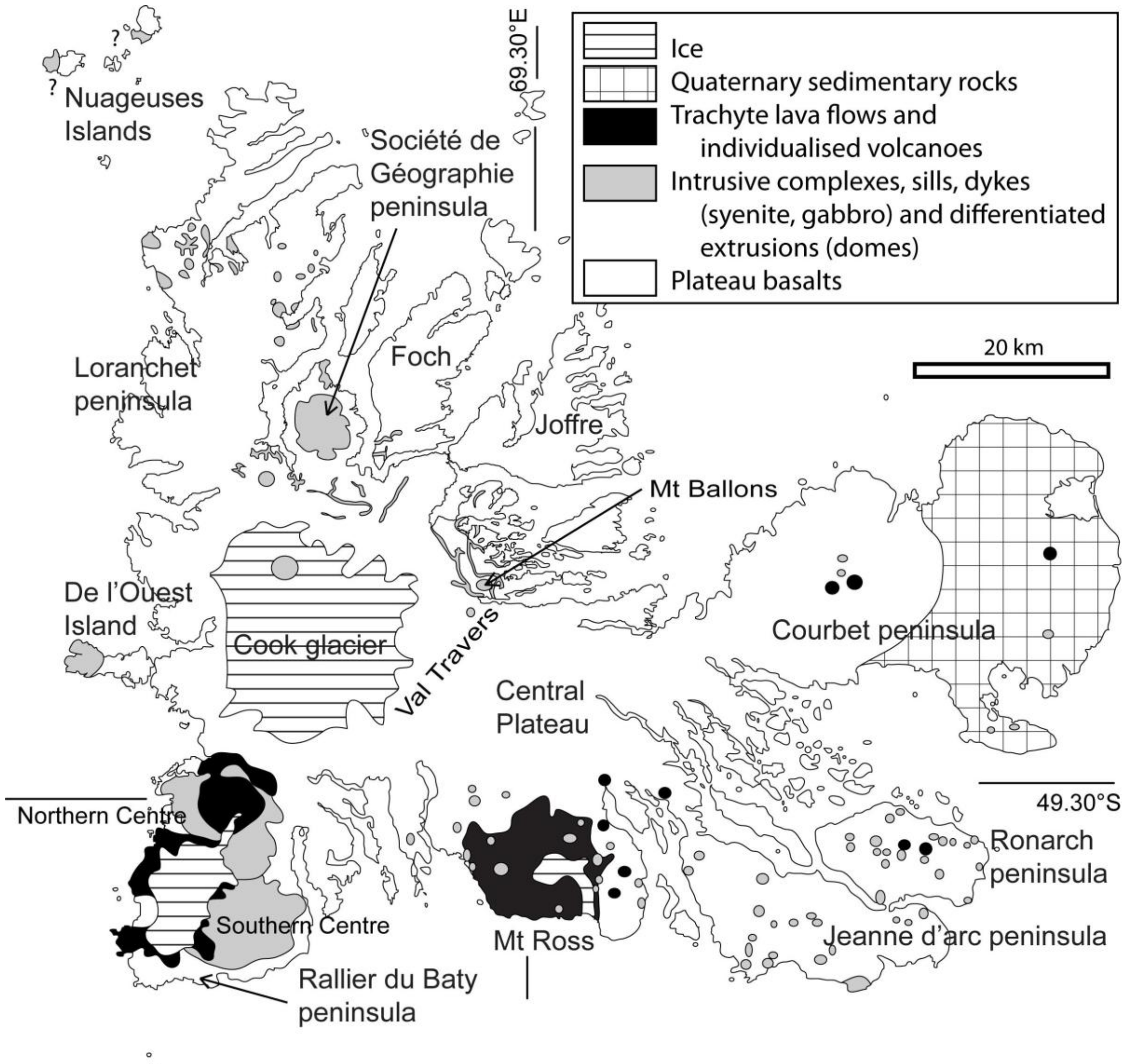

60°
80°
100°
-40°
-60°
Madagascar
90°E ridge
(95-35 Ma)
Australia
SWIR
Broken ridge
(105-83 Ma)
SEIR
NKP
(68-0 Ma)
Kerguelen
Archipelago (30-0 Ma)
Skiff bank
(68-66 Ma)
CKP (105-83 Ma)
77°E
East tectonic system
Elan bank
(115-110 Ma)
75°E
Gauss rift
Umitaka-Maru rift
SKP (120-
110 Ma)
N
.1
.2
.3
.4
.5
Antarctica

Figure 1



Ice
Quaternary sedimentary rocks
Trachyte lava flows and individualised volcanoes
Intrusive complexes, sills, dykes (syenite, gabbro) and differentiated extrusions (domes)
Plateau basalts
20 km
69.30°E
49.30°S
Nuageuses Islands
Société de Géographie peninsula
Foch
Loranchet peninsula
Joffre
Mt Ballons
De l'Ouest Island
Cook glacier
Val Travers
Courbet peninsula
Central Plateau
Northern Centre
Southern Centre
Mt Ross
Ronarch peninsula
Jeanne d'arc peninsula
Rallier du Baty peninsula

Figure 2

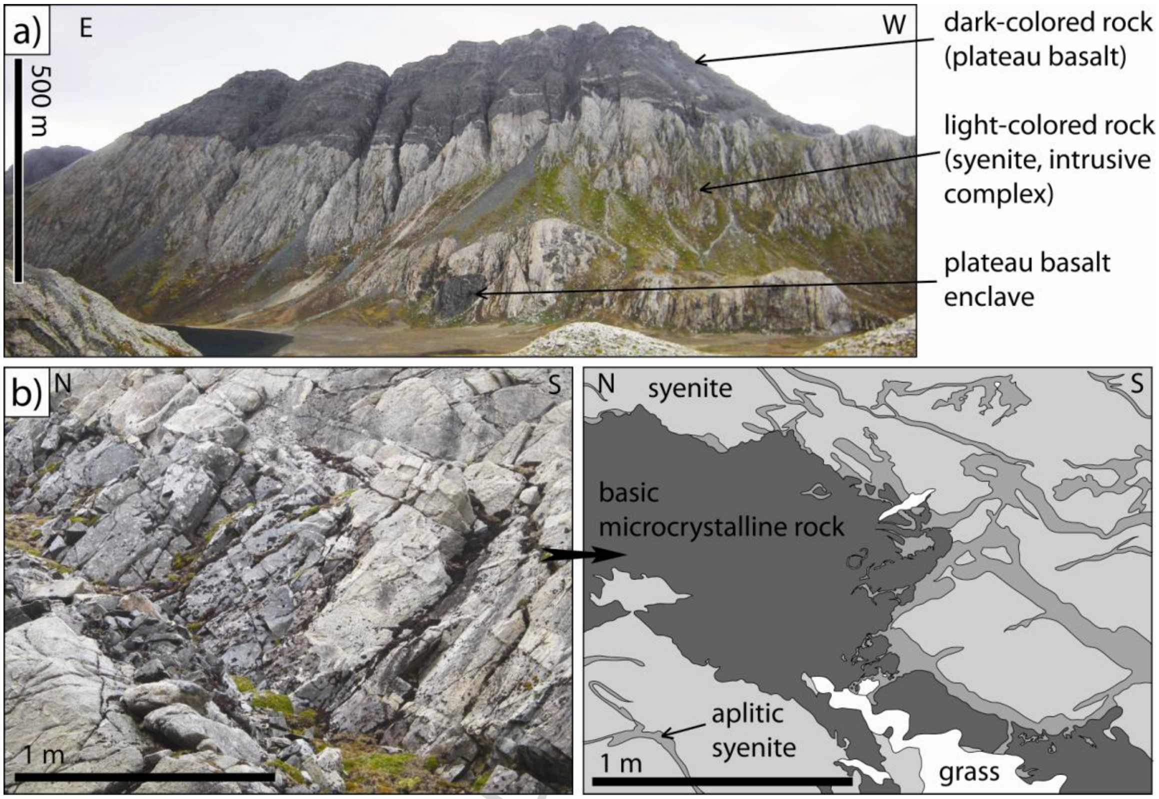

a)
E
W
500 m
dark-colored rock (plateau basalt)
light-colored rock (syenite, intrusive complex)
plateau basalt enclave
b)
N
S
1 m
N
syenite
S
basic microcrystalline rock
aplitic syenite
1 m
grass

Figure 3

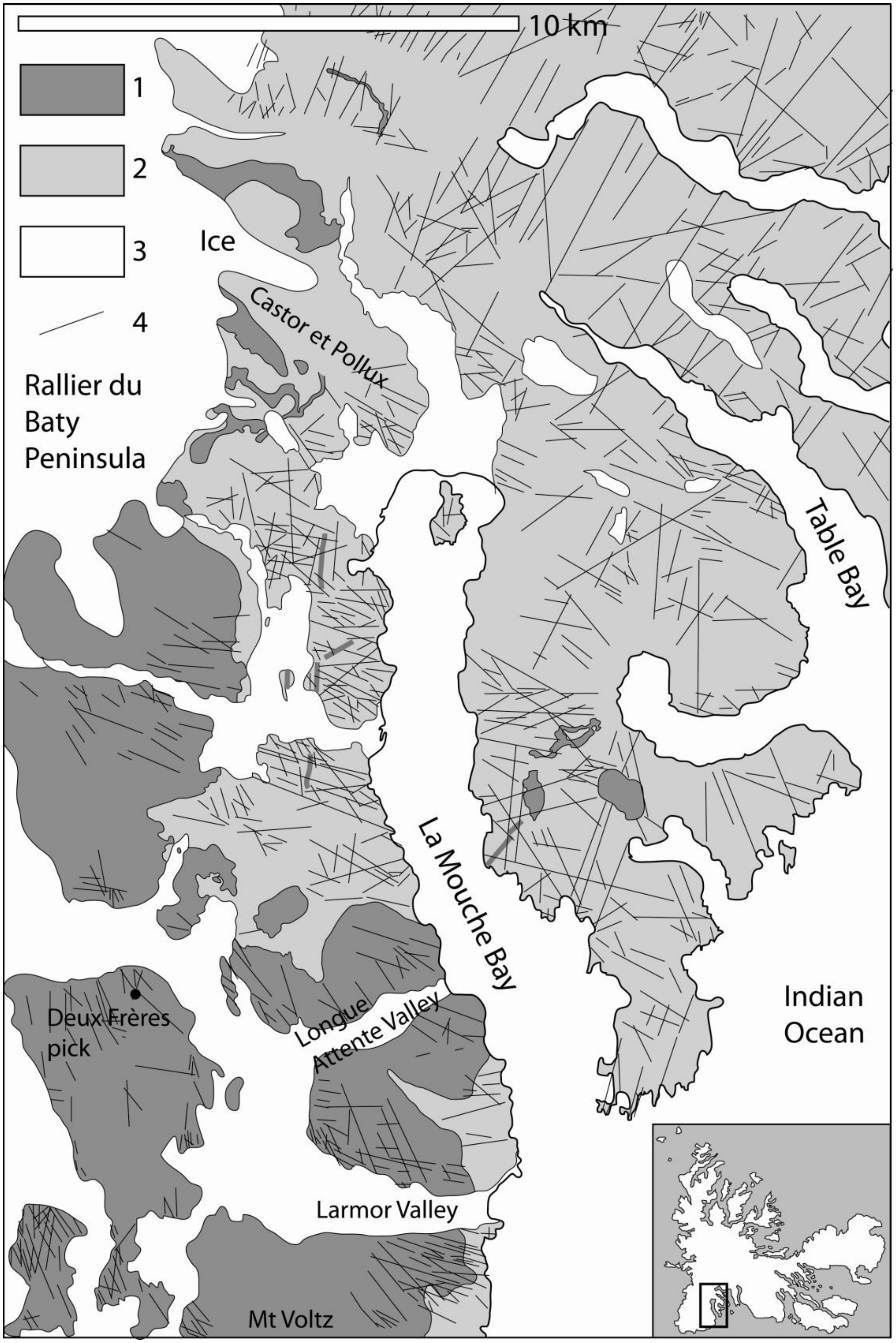

10 km
1
2
3
4
Ice
Castor et Pollux
Rallier du
Baty
Peninsula
Table Bay
La Mouche Bay
Indian
Ocean
Deux Frères
pick
Longue
Attente Valley
Larmor Valley
Mt Voltz

Figure 4

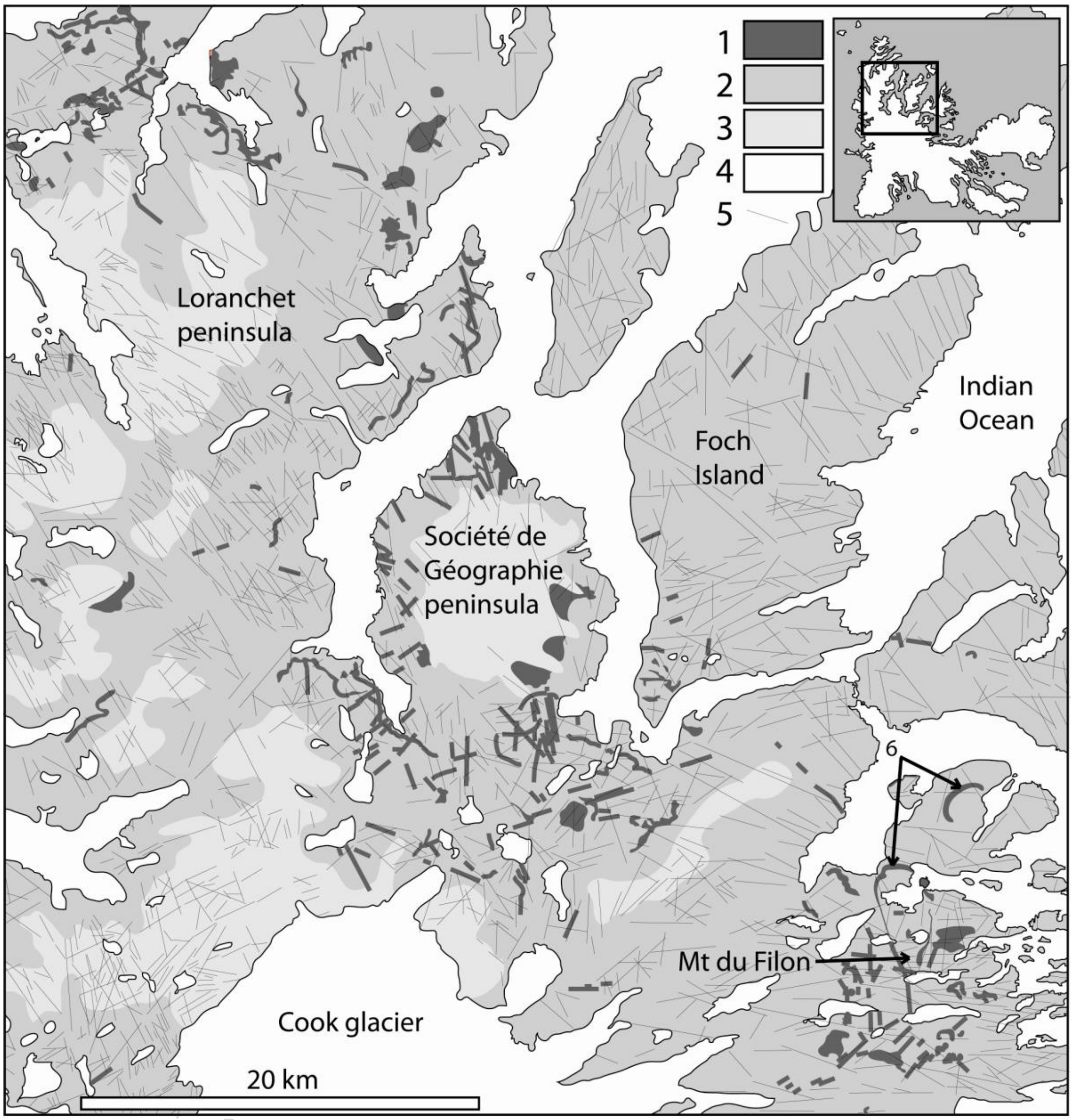

1
2
3
4
5
Loranchet
peninsula
Indian
Ocean
Foch
Island
Société de
Géographie
peninsula
6
Mt du Filon
Cook glacier
20 km

Figure 5

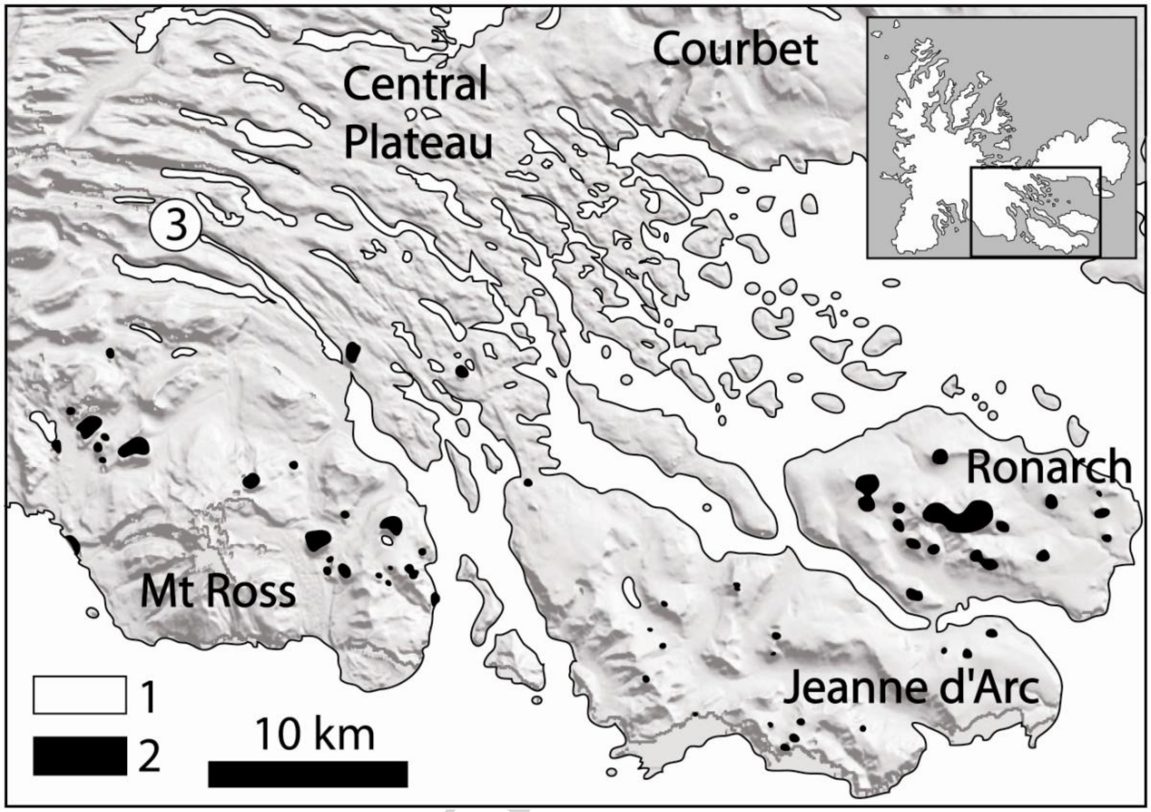

Courbet
Central
Plateau
3
Ronarch
Mt Ross
Jeanne d'Arc
1
2
10 km

Figure 6

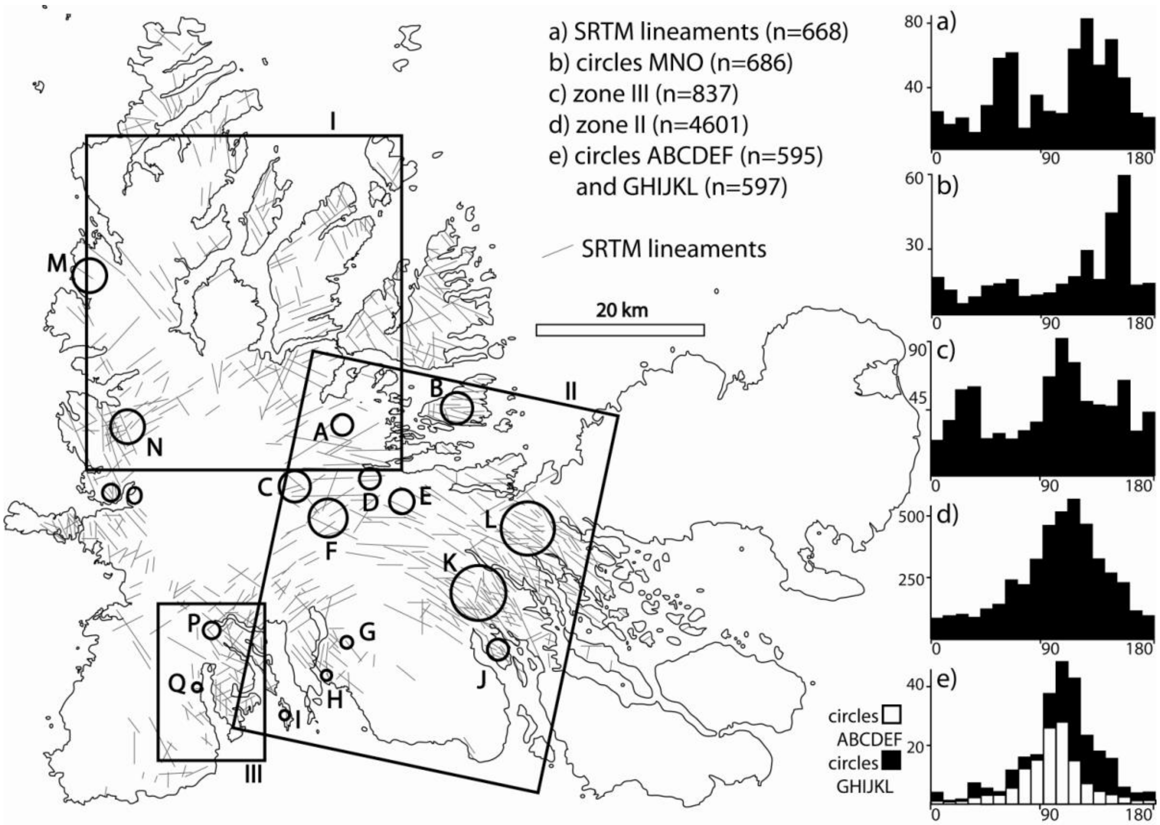

a) SRTM lineaments (n=668)
b) circles MNO (n=686)
c) zone III (n=837)
d) zone II (n=4601)
e) circles ABCDEF (n=595)
and GHIJKL (n=597)
SRTM lineaments
20 km
I
II
III
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
circles ABCDEF
circles GHIJKL

Figure 7

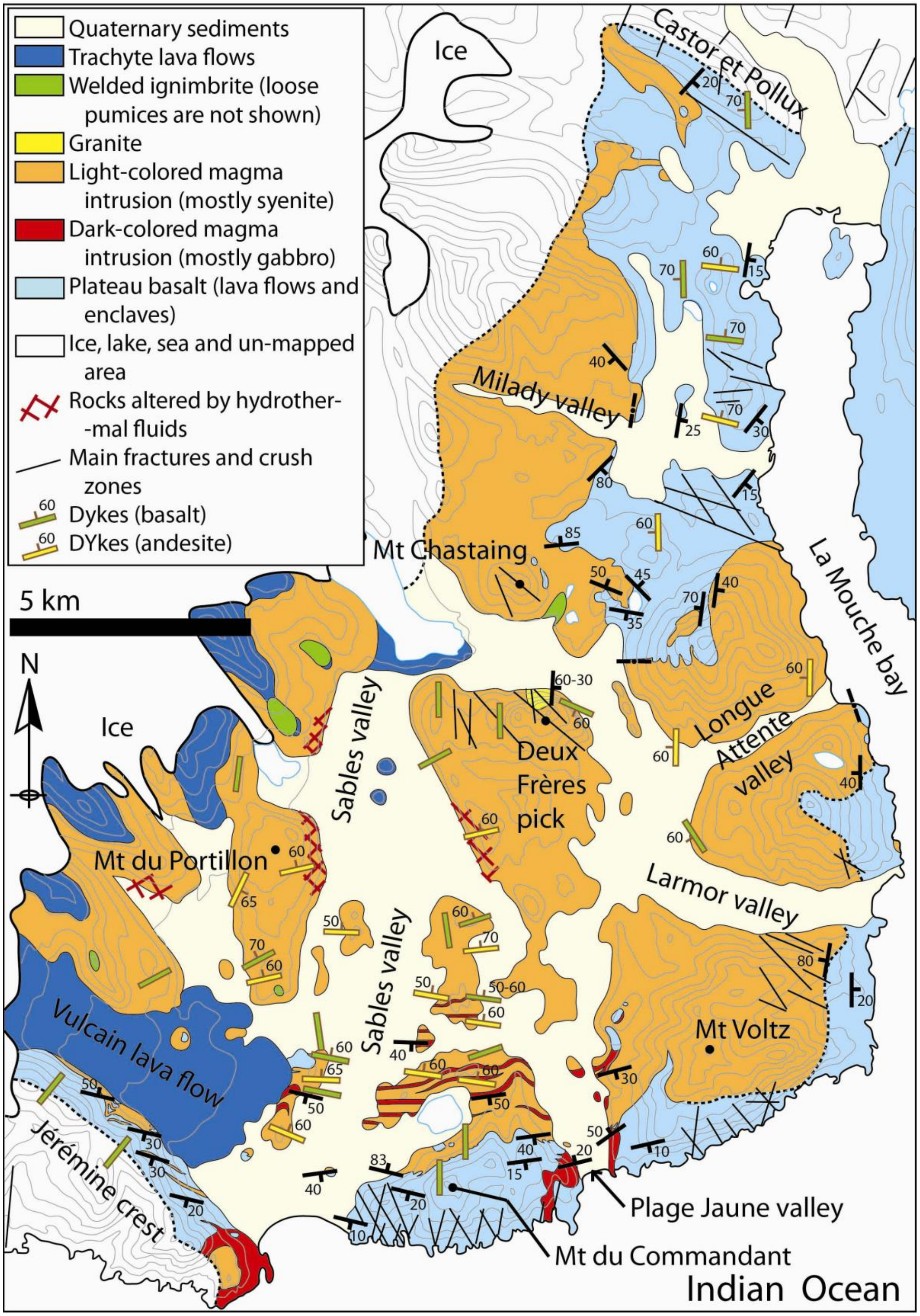
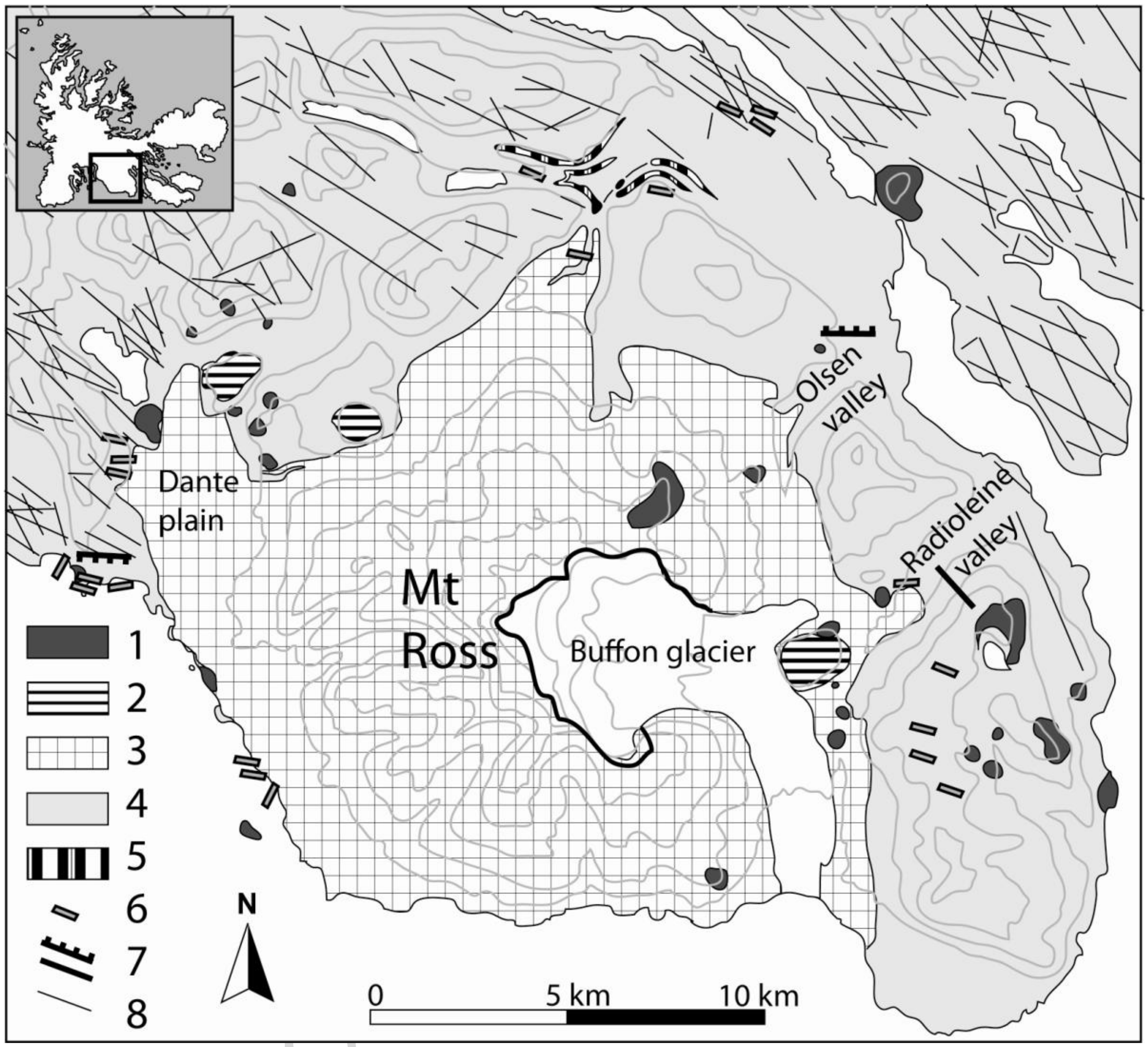

Quaternary sediments
Trachyte lava flows
Welded ignimbrite (loose pumices are not shown)
Granite
Light-colored magma intrusion (mostly syenite)
Dark-colored magma intrusion (mostly gabbro)
Plateau basalt (lava flows and enclaves)
Ice, lake, sea and un-mapped area
Rocks altered by hydrother--mal fluids
Main fractures and crush zones
Dykes (basalt)
DYkes (andesite)
5 km
N
Ice
Castor et Pollux
Milady valley
Mt Chastaing
La Mouche bay
Sables valley
Deux Frères pick
Longue Attente valley
Mt du Portillon
Larmor valley
Sables valley
Vulcain lava flow
Mt Voltz
Jérémine crest
Plage Jaune valley
Mt du Commandant
Indian Ocean

Figure 8



Olsen
valley
Dante
plain
Radioleine
valley
Mt
Ross
Buffon glacier
1
2
3
4
5
6
7
8
N
0
5 km
10 km

Figure 9

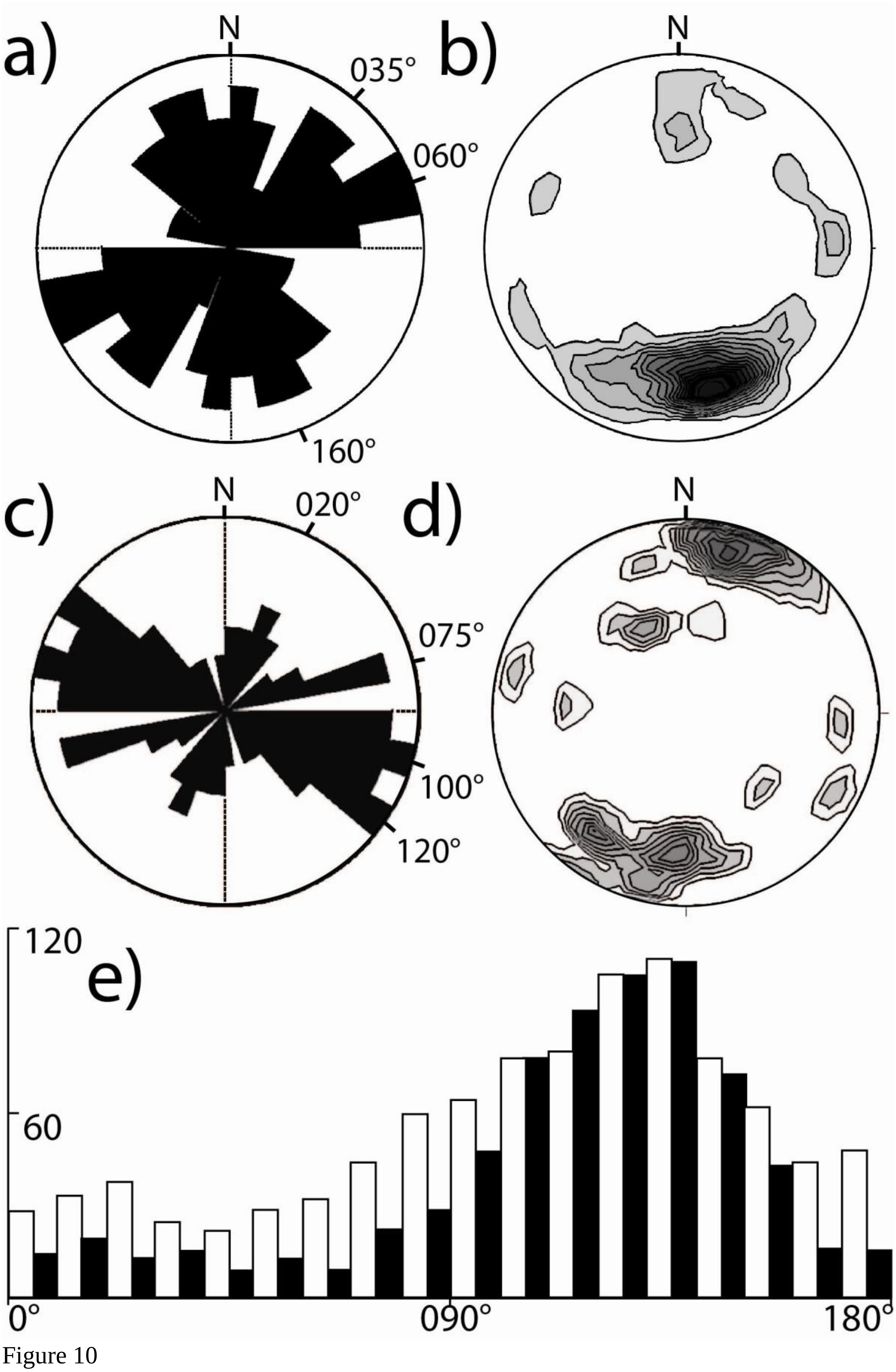


Figure 10

Research highlights

This paper focuses on the geology of the main Kerguelen Island, Indian Ocean. The flood basalt, intrusive complexes and volcanoes of this remote archipelago are succinctly presented. The manuscript focuses on the structure of the Archipelago. The structural data reported in the manuscript are fractures, faults, veins, dykes and lineaments measured in the field and on satellite images.
This study concludes that the main structural direction is E-W to NNW-SSE and corresponds to the strike of normal faults and dyke injections. These structures have developed in a N-S to NNE-SSW oriented extensional stress field. Regionally, this stress field corresponds to the N-S spreading movements of the SW-Indian mid-oceanic-ridge and to the northern directed drift of India.