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The Iceland Plateau – Jan Mayen Volcanic Breakup Margin: an Analogue for Axial Rift and Transfer Zones Onshore North Iceland

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ABSTRACT

Structural-, volcano-stratigraphic-, and igneous-province-mapping is a fundamental prerequisite for resource modelling and management, such as geothermal exploration or mining. Our tectonic-kinematic model of the Jan Mayen region was constructed utilizing gravity- and magnetic anomalies, multibeam bathymetric data, seismic reflection, and refraction data, borehole and seafloor samples. The Jan Mayen igneous complexes and the Iceland plateau rift portray the complexity of long-lived volcanic margins within an unstable rift-transfer tectonic setting from Eocene to Miocene times. Both regions are characterized by rift basins, en-echelon volcanic ridges, sill and dyke intrusive structures, and geothermal fluid venting structures such as chimneys, cutting through pre-existing crustal and sediment sections, commonly along re-activated fault planes. Using a dense seismic reflection dataset provides a unique opportunity to map intercalated igneous domains and rift zones of the Jan Mayen microcontinent in a three-dimensional space, enabling us to estimate the volcano-stratigraphic types, size, and extent of these rift and volcanic systems, as well as large-scale igneous features, such as deeper-seated intrusions, volcanic complexes, or rift valleys. The igneous Jan Mayen and Iceland Plateau regions represent a prime example of what is commonly referred to as Iceland type crust, i.e. the systematic build-up of thicker oceanic crust by rift-transfer processes, overlapping sub-aerial and sub-surface igneous activities in conjunction with localized microplates.

1. INTRODUCTION

Igneous complexes on the flanks of the Jan Mayen microcontinent (JMMC) and within the Iceland plateau (IP) constitute an analogue area for present day Iceland. Based on offshore potential field data and seismic reflection-refraction analysis (Blischke et al., 2017, 2019a,b) (Figure 1), we are able to construct a three-dimensional map of the JMMC-IP rift zones, including more detailed imaging of the type, size, and extent of individual rift and volcanic systems, as well as smaller scale igneous features, such as sill, dyke, or venting structures and their connection to deeper-seated intrusions that served as conduits for rising magmatic material and geothermal fluids. Our insight into Eocene-Miocene structures offshore may thus serve as analogues for present day processes within the volcanic rift zones of Iceland. Here we specifically address the complex volcanic and structural interaction represented in offshore seismic reflection data which generally present major challenges for on land geothermal field exploration.

2. DATA AND METHODS

Vintage and new JMMC-IP geological and geophysical datasets (1970´s-2017), including seismic reflection and refraction profiles, gravity and magnetic anomaly data, high-resolution multibeam bathymetric imagery, and borehole and seafloor sample information were used to build a comprehensive volcano-stratigraphic model (e.g. Vogt et al., 1970, 1986; Talwani and Eldholm, 1977; Åkermoen, 1989; Doré et al., 1999; Lundin et al., 2005; Gaina et al., 2009, 2014, 2017a,b; Gernigon et al., 2012, 2015, 2019; Hopper et al., 2014; Haase and Ebbing, 2014; Nasuti and Olesen, 2014; Funck et al., 2014, 2016, 2017; Haase et al., 2017; Blischke et al., 2017a,b; 2019a,b). Datasets were processed using the Petrel software tool © Schlumberger, an integrated interpretation software for 3D mapping of geophysical and geological datasets, here specifically seismic reflection, borehole, or multibeam bathymetric datasets. JMMC-IPR microplate reconstructions and projections were adapted from Blischke et al. (2017; 2019a,b) utilizing GPlates, an interactive fitting method (www.gplates.org; Müller et al., 2018; Gaina et al., 2017b). Newly acquired, high-resolution multibeam bathymetric maps (Hégadóttir, 2008; Hélgadóttir and Reynisson, 2010) were correlated with seismic reflection and potential field data, in order to constrain structural trends and igneous features, such as volcanic cones, axial ridges, or pockmarks. This combined with seismic reflection data enabled us to distinguish between normal and strike-slip faults, shallow volcanic activity, or slump fault systems that are still active along the steep JMMC escarpments. Volcano-stratigraphic seismic units were characterized by sedimentary and igneous stratigraphic units and seismic reflection characteristics in tie with available borehole and potential field data. Seaward dipping reflectors (SDR), volcanic ridges, igneous complexes, or extrusives, such as flood basalt domains were primary volcano-stratigraphic elements (Figures 1b; 2). Together this data formed the basis for establishing the three-dimensional stratigraphic framework of the JMMC-IP (Figure 3).

Gravity and magnetic anomaly mapping are effective methods to study areas where few seismic reflection profiles exist. A joint interpretation that combines seismic and potential field data thus produces a synergy that help to significantly improve and validate the geological and structural interpretations of potential prospects (Nasuti and Olesen, 2014). Gravity data are normally used to study the extent and depth of sedimentary basins, major tectonic features and to investigate variations in crustal thickness, segmentation and density across a region (Haase and Ebbing, 2014, 2016).

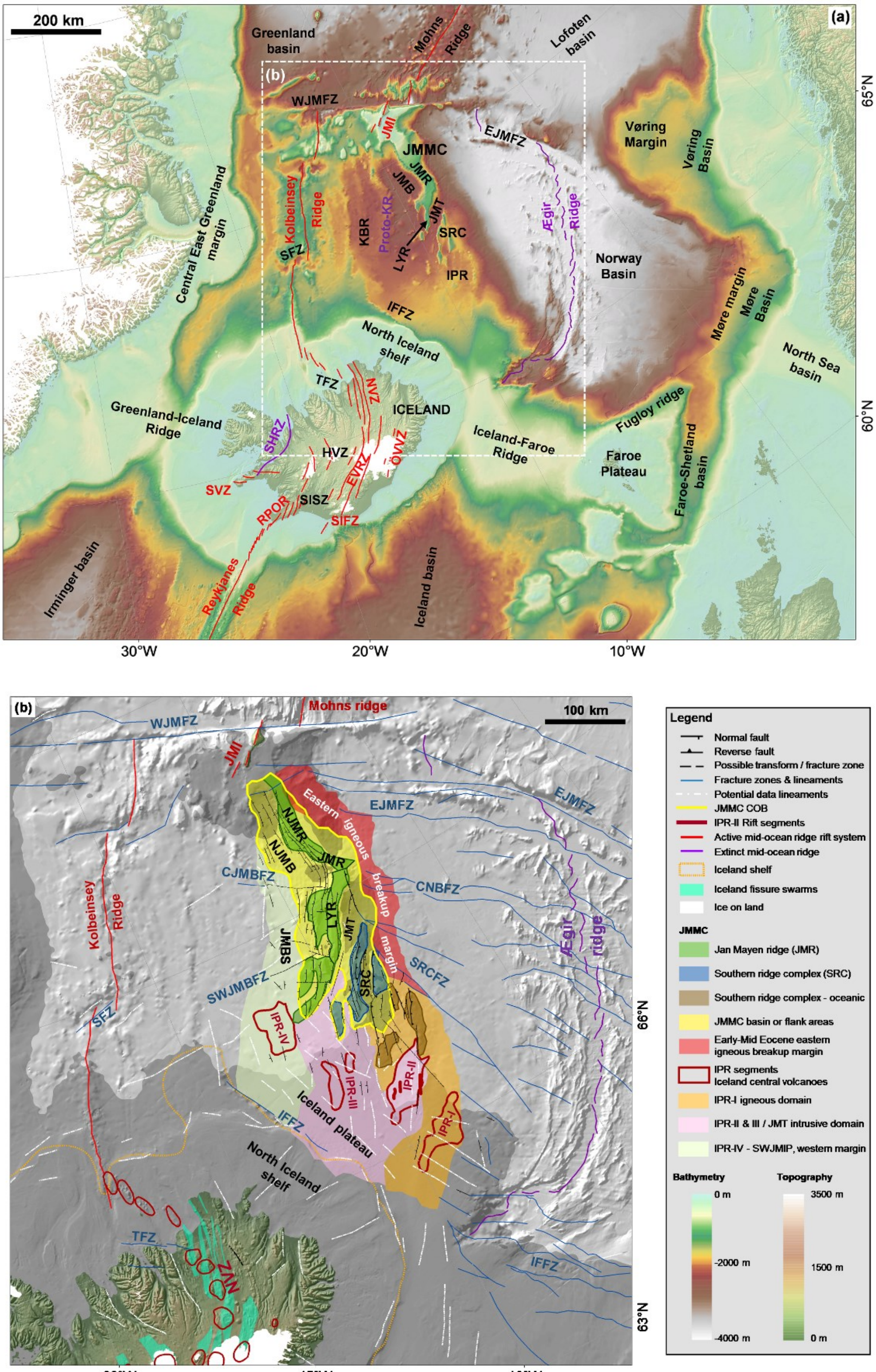

Figure 1: Central NE-Atlantic tectonic map showing faults, fractures zones and lineaments based on Einarsson and Sæmundsson (1987), Einarsson (2008), Hjartardóttir et al. (2013); Magnúsdóttir et al (2015); Blischke et al. (2017a, 2019a,b). The background is a hill shade bathymetry map (IBCAO 3.0; Jakobsson et al., 2012). Abbreviations: CJMBFZ – Central Jan Mayen Basin Fracture Zone; CNBFZ – Central Norway Basin Fracture Zone; EJMFZ – East Jan Mayen Fracture Zone; EVZ – Eastern Volcanic Zone; HVZ – Hofsjökull Volcanic Zone; IFFZ – Iceland-Faroe Fracture Zone; IPR – Iceland Plateau Rift; JMMC – Jan Mayen Microcontinent (JMB – Jan Mayen Basin; JMBS – Jan Mayen Basin south; JMI – Jan Mayen Island igneous complex; JMR – Jan Mayen Ridge; JMT – Jan Mayen Trough; LYR – Lyngvi Ridge; SRC – Southern Ridge Complex; SRCFZ – Southern Ridge Complex Fracture Zone; SWJMBFZ – Southwest Jan Mayen basin fracture zone; KRB – Kolbeinsey Ridge Basin; NVZ – Northern Volcanic Zone; ÖSVZ – Öræfajökull-Snæfell Volcanic Zone, proto-KR – proto Kolbeinsey Ridge, RPOR – Reykjanes Peninsula Oblique Rift; SISZ – South Iceland Seismic Zone; SHRZ – Snæfellsnes-Húnaflói Rift Zone; SVFZ – Snæfellsnes Volcanic Zone; TFZ – Tjörnes Fracture Zone; WJMFZ – Western Jan Mayen Fracture Zone; WVZ – Western Volcanic Zone.

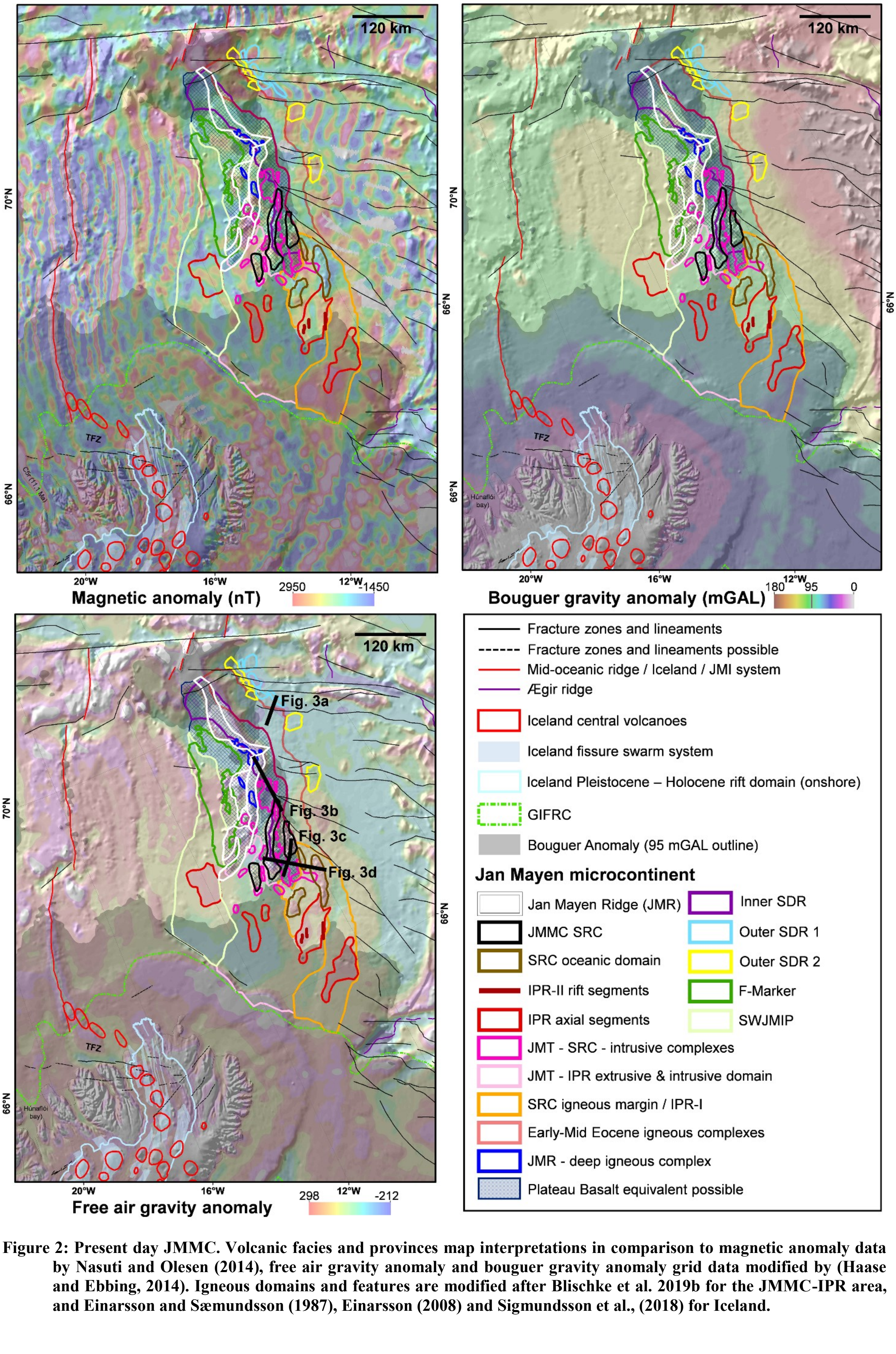

Figure 2: Present day JMMC. Volcanic facies and provinces map interpretations in comparison to magnetic anomaly data by Nasuti and Olesen (2014), free air gravity anomaly and bouguer gravity anomaly grid data modified by (Haase and Ebbing, 2014). Igneous domains and features are modified after Blischke et al. 2019b for the JMMC-IPR area, and Einarsson and Sæmundsson (1987), Einarsson (2008) and Sigmundsson et al., (2018) for Iceland.

Magnetic data are used to investigate subsurface geology based on anomalies in Earth´s magnetic field that effected and preserved the field´s orientation of the underlying rocks at its time of emplacement. Thus, providing a chronological mapping tool of magnetic anomalies across the ocean floor (Gaina, 2014). Magnetic data also provide information on hidden geological structures, especially in volcanic and metamorphic terrains and structures in non-magnetic sedimentary terrains (e.g. Gaina et al., 2017b; Blischke et al., 2019b). Several extrusive and intrusive features can be seen on gravity and magnetic maps (Figures 2-4).

3. GEOLOGICAL SETTING

Understanding the geological setting of an area is the basis for any exploration or development field work. The JMMC study was initially focused on the tectono-volcano-stratigraphic framework of the Lyngvi ridge and southern ridge complex (SRC), (Figure 3). To understand their formation, a comprehensive study the microcontinent and IPR region became necessary, in order to gain an understanding of the sub-areas and the forming of smaller scale volcano-stratigraphic features.

3.1 The Jan Mayen microcontinent (JMMC)

The JMMC and IPR area is defined as a 400-450 km long and 100-310 km wide domain located in the central NE Atlantic, between the extinct Ægir ridge to the east and the Kolbeinsey ridge to the west (Figure 1). The northern boundary comprises of the Jan Mayen fracture systems and the Jan Mayen island igneous complex, with leaky fracture zones, e.g. the eastern Jan Mayen Fracture Zone (EJMFZ) (Figure 4a). The region´s southern boundary is formed by the Iceland-Faroe fracture zone (IFFZ) and the NE Iceland insular shelf. The JMMC comprises a series of bathymetric ridges with water depth ranging between 200-2500 m (e.g. Vogt et al., 1970; Talwani et al., 1977). The microcontinent has been subdivided into the main Jan Mayen Ridge (JMR), the Lyngvi Ridge, the Jan Mayen Basin with a northern and southern segment, the Jan Mayen Trough, and the Southern Ridge Complex (SRC). The main northern JMR is a well-defined, continuous and flat-topped structural feature. The SRC is comprised of several smaller ridges, which become more indistinct towards the south, where the fan-shaped, oblique IPR-domain intersects the JMMC´s southern ridges (Figures 1-4).

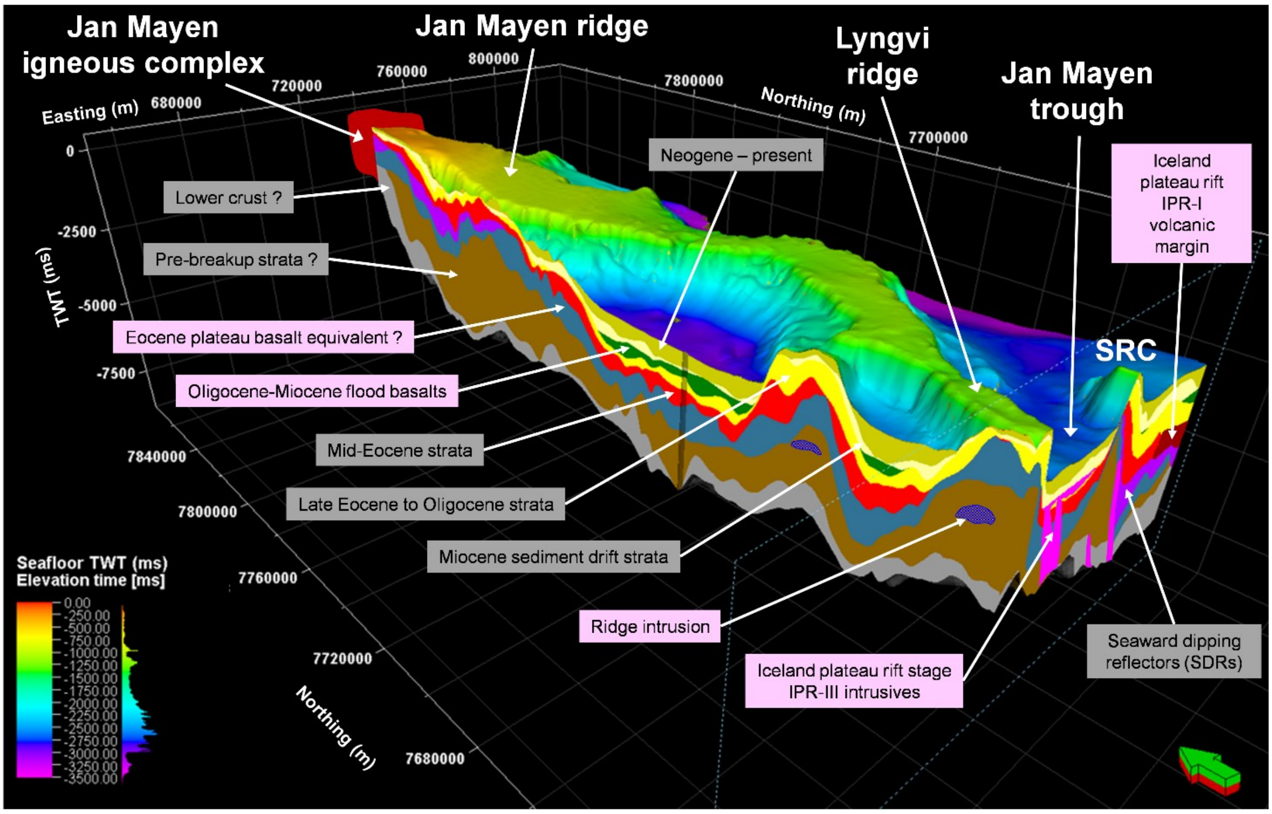

Figure 3: Present day three-dimensional JMMC primary volcano-stratigraphic framework after Blischke et al. 2019a,b. Abbreviations: SRC – Jan Mayen southern ridge complex.

These ridge structures resulted of microcontinent´s location within a dual-breakup scenario, first from the central Norwegian shelf and the Vøring-Møre margin, and finally from the central East Greenland margin (e.g. Talwani et al., 1977; Gaina et al., 2009; Gernigon et al., 2015, 2019). The reconstructed geo-chronology of the central NE Atlantic region and mapped igneous domains was updated and indicates sex major phases influencing the JMMC´s breakup history by Blischke et al. (2017, 2019a,b) (Figures 1a; 2):

(1) Early Paleogene: Possible pre-breakup magmatic intrusions underneath central East Greenland – JMMC (~63-55 Ma). Initial breakup phase and rupturing of the overlying lithosphere along SW-NE-striking, pre-existing fracture zones. During the initial rifting and breakup phase, overlapping igneous systems developed along the divergent plate boundary, with subaerial plateau basalt flows across the central NE Atlantic, including the JMMC region.

(2) Early Eocene: North-to-south development of an inner and first set of seaward-dipping reflectors along the eastern margin of JMMC. Another two sets of outer seaward-dipping reflectors overlapped the first and inner SDR set, as a precursor to the formation of the Ægir ridge (55-52 Ma).

(3) Early-Mid Eocene: Forming of JMMC´s eastern volcanic margin that continued into the IPR-I. IPR-II segment intersects the IPR-I segment and the southern extent of the SRC. Creation of an overlapping spreading system of the IPR segments with the southern Ægir ridge connecting into the northern extent of the Greenland-Iceland-Faroe Ridge Complex (GIFRC) (~52-40 Ma).

(4) Late Eocene-Oligocene: The formation of segment IPR-III and the Jan Mayen southern ridge complex, alongside extensions within the Jan Mayen trough and separation from the main Jan Mayen ridge (35-25 Ma).

(5) Late-Oligocene-Early Miocene: Forming of the western igneous margin of the JMMC, along the proto-Kolbeinsey ridge that initiated the final breakup of the JMMC from Greenland (25-21 Ma).

(6) Early Miocene: Spreading along the Kolbeinsey ridge with complete separation of the JMMC from the central East Greenland margin (since 21 Ma).

The JMMC-IPR area represents a unique area for research related to a dual breakup system of the two rifting complexes that created the Jan Mayen microcontinent, with a firm link of the oblique Iceland plateau rift system and the central East Greenland margin with respect to timing, geochemistry and tectono-magmatic processes, specifically in the Southern Ridge Complex and Jan Mayen Trough areas.

3.2 The Jan Mayen Southern Ridge Complex and Jan Mayen Trough

The Southern Ridge Complex (SRC) is a collection of several ridges that were formed during extension and rift transfer along the southern part of the microcontinent (Figures 1-4) (e.g. Talwani et al., 1977; Gaina et al., 2009; Peron-Pinvidic et al., 2012a; Gernigon et al., 2015; Blischke et al., 2017b). The SRC area initiated during the Ægir Ridge breakup phase by forming a wide igneous margin, which was broken into several smaller segments, forming several small basins with numerous post-breakup intrusives and vent structures along fault and fracture zones. The three northernmost SRC ridges appear similar in seismic characteristics to the eastern flank of the Jan Mayen ridge and are linked to the origin of the microcontinent. These blocks were not as much affected by post-breakup volcanism as the three southernmost SRC ridges, which are segments of the original Early-Eocene volcanic breakup margin, intersected by many intrusives (Figures 1a; 2; 3). Sill, dyke, and venting structures can be observed along fault- and fracture zones, nearly up to the seafloor, possibly indicating igneous activity over a longer duration (Figure 4c). The Jan Mayen Trough (JMT) separates the Lyngvi ridge from the SRC and widens towards the southwest with one segment of the SRC embedded within it (Figures 1b; 2). The entire JMT is covered by a flat-lying and almost opaque reflector on seismic reflection data and is chrono-stratigraphically placed within the Late-Oligocene flood basalts (Figures 2; 3; 4d). Even with the most recent, higher-resolution seismic reflection data, it is difficult to clearly define and map underlying deeper structures, though fault blocks can be seen that are separated by intrusives. These intrusives and fault blocks are correlated to the stratigraphic framework and to distinct changes in Bouguer gravity and magnetic anomaly values, indicating a potential grouping of these intrusive in order of emplacement in between the fault blocks (Figures 2-4).

3.3. Iceland Plateau Rift

The IPR formed an overlapping spreading system with the southernmost Ægir Ridge, tectonically compensating the southwards decrease in spreading rate along the Ægir ridge. Hyper-extended slivers of JMMC type crust were intersected by dyke and sill intrusions related to the Mid-Eocene to Late Oligocene formation of the IPR-I - IPR-IV volcanic ridges and flood basalts (Figures 2; 4c,d). The oblique IPR rifting domain, formed a fan-shaped intersection with the southern ridges of the JMMC, by crustal thinning and breaches where axial rift systems and volcanic ridges would develop (Blischke et al., 2019b). The total JMMC type crustal thickness varies between 7-12 km across the IPR segments based on seismic refraction data and gravity crustal thickness inversions (Haase and Ebbing, 2014; Brandsdóttir et al., 2015). The IPR, south and southeast of the SRC, is primarily of oceanic origin based on interpretation of seismic refraction velocity data (Talwani et al., 1977; Brandsdóttir et al., 2015), and detailed seismic reflection, magnetic and gravity data interpretations (Peron-Pinvidic et al., 2012a; Blischke et al., 2017b, 2019a,b) (Figures 1b, 2; 4c,d). The oblique IPR-I and II systems were linked to the Blosseville Kyst of central East Greenland during the Eocene (52 – 40 Ma). The separation of the JMMC from the central East Greenland margin during Oligocene to early Miocene (~35 Ma – 21 Ma) was accompanied by extension, the formation of a distinct S-N oriented volcanic ridges and final breakup margin along the southwestern and western extend of the JMMC. The southwestern-western margin including the emplacement of igneous complexes, such as the SW Jan Mayen igneous province. The Jan Mayen basin is possibly part of a buried western Late Oligocene breakup margin that covered the basin with regionally extensive flood basalt (Figures 1b; 2; 3). The JMMC - IPR transition portraits the complexity of long-lived, active volcanic margins within an unstable rift-transfer tectonic setting, exhibiting both lateral and vertical crustal accretion throughout its formation in Eocene through Miocene times. Thus, accounting for some of the for oceanic type domain´s anomalously thick crust due to overlapping systems and repeated reactivations that was accompanied by deep and shallow intrusive formations that preceded the present-day NE Iceland rift transfer system.

4. IGNEOUS AND STRUCUTRAL FEATURES OF THE JMMC AND IPR

This section briefly summarizes the JMMC and SRC-IPR areas focusing on volcanic and structural examples from seismic reflection data tied with potential field data (Figure 4), such as volcanic ridges – SRC-JMT igneous complexes, and structural examples of the Southern Ridge Complex fracture zone (SRCFZ) (Figure 5). The integrated data analysis was specifically applied to the JMFZ, SRC and IPR areas, focusing on volcanic ridges and other visible structures south, southeast and within the SRC and JMT, represented by up-doming structures of volcanic material within the seismic records. Up-doming structures, visible on some of the seismic reflection data (Figure 4b-d), are described in the literature as a crustal breach and passage followed by magma in a volcanic system (Decker and Decker, 2005). These structures are clearly identified for the rifting of the IPR-II and IPR-III systems inferred by Brandsdóttir et al. (2015); and described by Blischke et al. (2017a,b, 2019a,b); or Erlendsson and Blischke (2019) (Figure 4b-d). The volcanic ridges appear both as decentralized structures or along large faults or fault blocks that serve as conduits of rising magma along the fault zones that leads to deformation and uplift of the fault block. Often, an increase of intrusion events within sedimentary strata is associated with these conduits, lateral to and/or above the conduit structure.

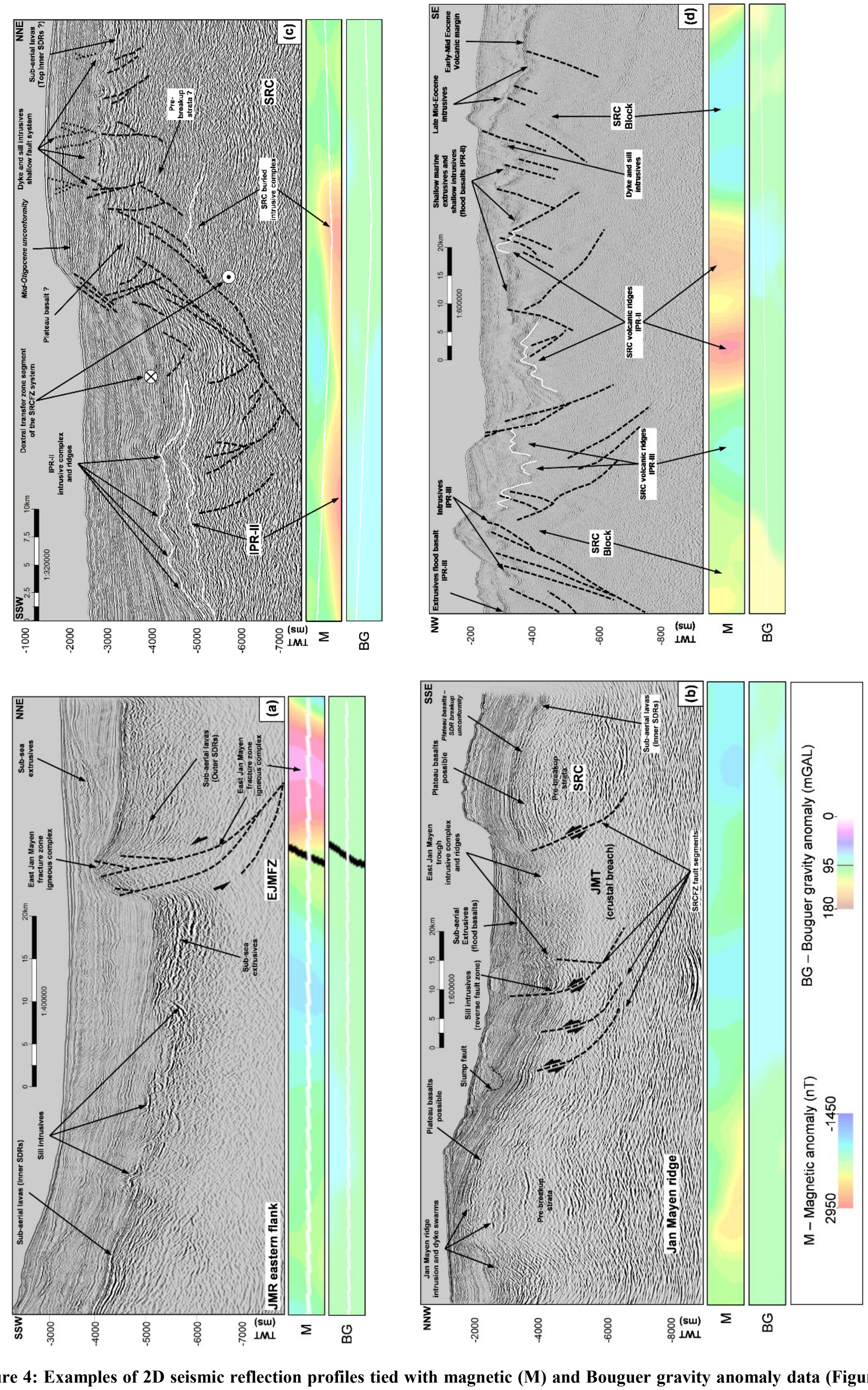

Figure 4: Examples of 2D seismic reflection profiles tied with magnetic (M) and Bouguer gravity anomaly data (Figure 2), outlining major fault and fracture zones in relationship to structural and igneous domain elements. For profile locations, see Figure 2 on the free air gravity map.

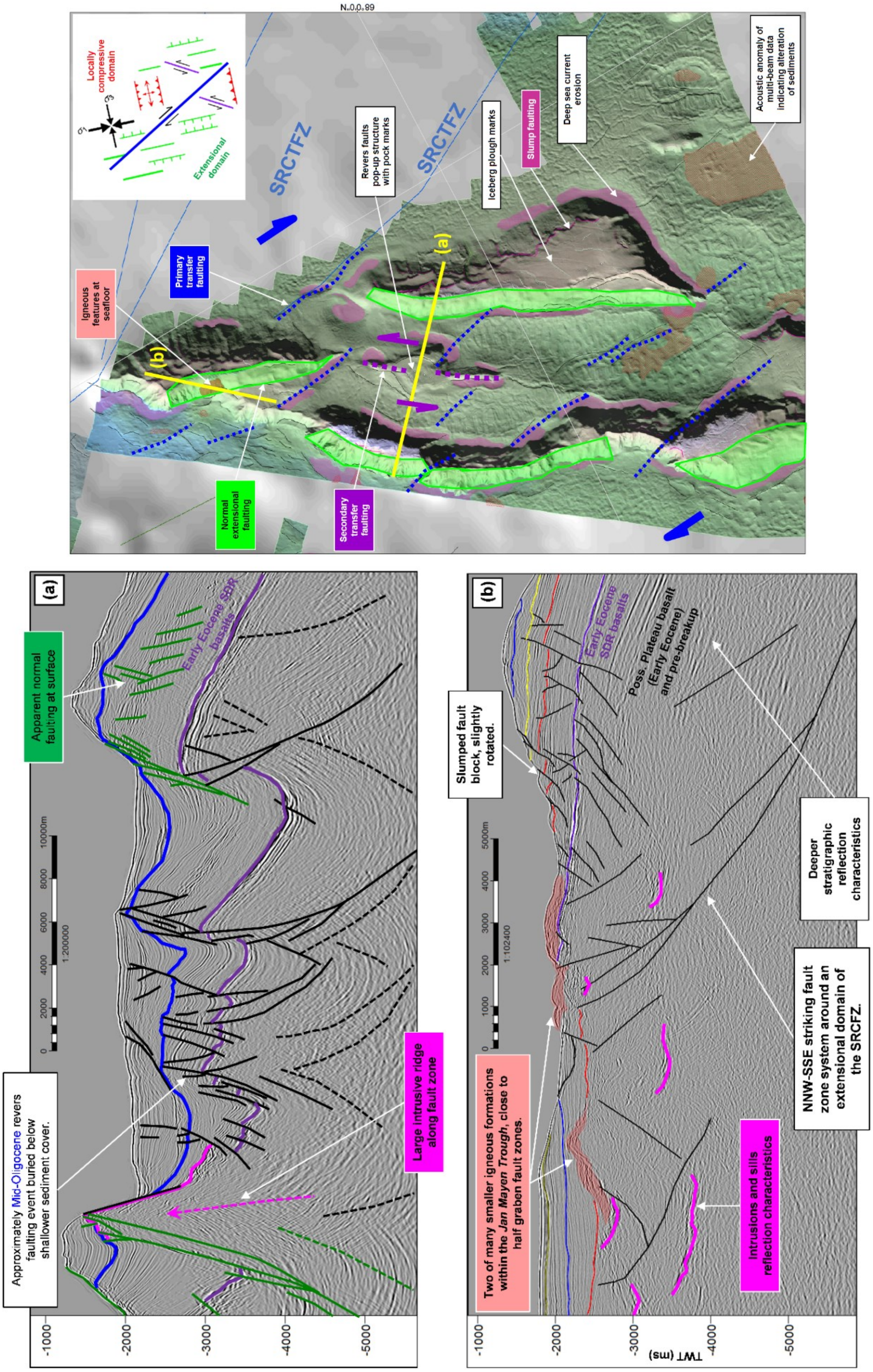

Figure 5: Detailed multibeam bathymetric map with structural features map of the JMMC, within the extensional domain of the Southern Ridge Complex Transfer Zone (SRCFZ), defining fault types, local fault patterns within a transfer system, and stress-field location that served as pathways for igneous features, such as intrusive dykes, sills or volcanic ridges, and seafloor extrusive lavas or build-ups. Viewing the depth dimension by seismic reflection profiles: (a) reverse fault structures within a transfer system, and (b) extensional fault patterns and intrusions crossing a transfer system modified after Blischke et al. (2017). Simplified stress field related fault type sketch modified after Lacazette, A. (2009).

The SRC is a collection of several ridges that were formed during extension and rift transfer along the southern part of the microcontinent in association with igneous activity along the IPR and the Southern Ridge Complex transfer zone (SRCFZ) (Figures 1b-5). The SRC area was created during the Ægir ridge breakup phase by the formation of a wide igneous margin, which was subsequently broken into several smaller segments, forming several small basins. The basins were heavily intruded by post-Eocene breakup sill and dyke intrusions, and vent structures along fault and fracture zones (Figure 4b-d).

Fracture zone segments of a dextral strike slip system and associated igneous intrusive complex are clearly visible within the Jan Mayen trough (JMT) and the northwesternmost segment of the SRCFZ (Figures 3; 4b). Structural elements, such as smaller scale fault system and fault-parallel sill and dyke complexes, enabled us to differentiate strike-slip from normal fault systems and slump faulting along the steep escarpments of the microcontinent's ridges (Figure 5a,b). The normal extensional fault system of the SRC blocks are aligned to the SRCFZ within an obliquely opening region. Parallel extensional and compression structural domains were formed by oblique WSW-ENE opening of the SRC along the SRCFZ trend. Mapped seafloor and subsurface fault types fit these systems and are linked with the minimum horizontal stress orientation of 75-80 deg. in an ENE direction that governs the direction of opening of the extensional fault system. Secondary sinistral strike-slip fault zones compensate the fault block rotation within the oblique opening along the SRCFZ, represented by pop-up structures within the center graben of the SRC (Figure 5). Our data underlines the study by Cianfara and Salvini (2015), which identified large regional scale lineament structures and segmentation in relationship to regional strike-slip corridors. Here, a comparison with the Tjörnes Fracture Zone system is highly interesting, which together with the connected Iceland oblique Northern Volcanic Rift Zone presents a striking similarity to the SRC – IPR area.

5. THE NORTHERN VOLCANIC RIFT ZONE OF ICELAND (NVZ) AND TJÖRNES FRACTURE ZONE (TFZ)

The Northern Volcanic Zone in northeast Iceland is a ~200-175 km long and ~50-100 km wide subaerial segment of the Mid-Atlantic ridge and located 200-300 km southwest of the JMMC-IPR domain (Figure 1). The NVZ is one segment of the onshore Iceland plate boundary that continues southwards into the Iceland hotspot, located beneath the Vatnajökull icecap and into the southward propagating Eastern Volcanic Zone. The offshore-onland Tjörnes Fracture Zone links the NVZ with the Kolbeinsey mid-oceanic ridge. The TFZ consists of the Dalvík seismic zone (DSZ), Húsavík-Flatey transfer zone (HFF), and the Grímsey oblique rift system (GOR) (Sæmundsson, 1974, 1978; Einarsson and Sæmundsson, 1987; Brandsdóttir and Menke, 2008; Einarsson, 2008; Thordarson and Höskuldsson, 2008; Magnúsdóttir et al., 2015; Brandsdóttir et al., 2015; Hjartardóttir et al., 2013, 2016, 2017; Drouin et al., 2017; or Sigmundsson et al., 2018). The NVZ is believed to have started to develop 6-7 million years ago following an eastward rift jump of the divergent plate boundary, towards the center of the Iceland hotspot (Sæmundsson 1978). The divergent NVZ is make up of 5-6 volcanic systems, consisting of central volcanoes with transecting fissure swarms, which form overlapping en-echelon domains up to 100 km in length and approximately 20 km in width. They have been subdivided and are monitored by seismicity activity, surface structural, geological and geothermal expressions (Björnsson et al. 1977; Sigurðsson and Sparks 1978; Einarsson 1991). Differences in fissure swarm width and elevation are believed to have been influenced by increased magma supply from the Iceland hotspot, which has a center below the western part of Vatnajökull glacier (Vogt 1971; Wolfe et al. 1997; Gaherty 2001). The hotspot can be seen as magnetic and gravity anomalies (Figure 2), and as low P- and S- seismic velocities (Wolfe et al., 1997).

Rifted depressions, as seen on the Mid-Atlantic ridges, characterize slow spreading (<3.5 cm/yr) divergent plate boundaries, while elevated volcanic edifices characterize fast spreading (>5 cm/yr) divergent plate boundaries (Mutter and Karson 1992). The structure of the divergent plate boundary across Iceland is in that sense more similar to fast spreading, rather than slow spreading divergent plate boundaries. Here reflected as well by the highly fractured and faulted fissure swarms and their episodic intrusives (Hjartardóttir et al., 2017). These indicate episodic deformation processes along fissure swarm zones and primarily along the central volcanoes that are the deep crustal links, which can be seen as localized magnetic and gravity anomalies (Jonsson et al., 1991). During rifting episodes, when magma is intruded into the fissure swarms as dike intrusions, the structural patterns changes abruptly, as intensive earthquake activity is felt and measured directly both within the central volcanoes, as well as in distinct parts of the linked fissure swarm (e.g. Brandsdóttir and Einarsson 1979; Einarsson and Brandsdóttir 1980; Buck et al. 2006). Thus, causing subsidence along grabens and accompanying fracture movements within the fissure swarms (Hjartardóttir et al., 2016, Sigurdsson, 1980). Detailed mapping is ongoing to increase the understanding of fissure swarms, rift zones, exact locations of eruptive centers, orientation of stress fields at eruption times, and their interaction with transform zones (e.g. Hjartardóttir et al. 2013, 2016, 2017; Magnúsdóttir et al., 2015; or Drouin et al., 2017). Here specifically transfer zones are complex structural systems that form complex sets of normal and reverse faulting, which are associated to strike-slip fault systems and challenging to resolve with surface data alone (Khodayar and Einarsson 2004; Guðmundsson et al. 2008). As detailed mapping works well for the present-day active parts of the NVZ, is it challenging to locate and map dormant or old inactive volcanic systems, fissure swarms, and fracture zone systems. Thus mapping, delineating, and timing those dormant volcanic systems and related structures with potential field and offshore seismic reflection data become useful.

5.1 Potential field data observations

As potential field data had been crucial for delineating the JMMC domain, magnetic anomalies may be used to define major anomalies on land Iceland as well (Figure 2), (Jonsson et al., 1991). The Pleistocene-Holocene boundary (2,6 Ma) correlates with a low negative magnetic anomaly domain onshore along its western limit (Figure 2a). However, this low magnetic anomaly domain appears much broader along the eastern Pleistocene-Holocene boundary that is based on surface geological exposures. The main positive magnetic anomaly that reflect the main breakup zone and plate boundary within the Pleistocene-Holocene time domain, appear to be segmented and subdivide by large scale, deeply buried transfer elements, as there are not clear at surface or seismicity data (Figure 2). Small positive magnetic anomaly segments can be observed, straddling the main positive anomaly within the 2,6 Ma negative magnetic anomaly domain. These small-scale anomalies possibly reflect blocks of older segments that are in-bedded within the Pleistocene time domain, or alternatively relate to present-day small-scale flank rift systems that are part of the Holocene and active fissure swarm within the NVZ. An apparent structural lineament trend appears across Iceland southwest to northeast that can be seen on magnetic and gravity anomalies data (Figure 2). This lineament is not seen on surface but appears to be deeply buried and offsets anomalies and aligns with Bouguer gravity trends. Interestingly does this trend align to the pre-breakup ridge trend that was present between central East Greenland and the Fugloy ridge area, which kept dominating the opening history of the

Greenland-Iceland-Faroe ridge complex from Early Eocene onwards (Blischke et al., 2019b). Another well recognizable positive magnetic anomaly trend correlate to chron C5r (11,1 Ma; Gaina et al., 2014) (Figure 2a). This anomaly aligns with the northern extend of the Snæfellsnes-Húnaflói rift zone that is estimated to have been active between ~15 Ma to ~7 Ma (Harðarson et al., 1997, 2008). Simultaneously magmatic activity reactivated in central East Greenland and the Kolbeinsey ridge had fully established as a mid-oceanic ridge system. East of the C5r anomaly that abruptly terminates in the Húnaflói bay, small scale NW-SE striking positive anomalies can be observed (Figure 2a) these appear to be linked by W-E trending anomaly signatures that align parallel to the present day active TFZ. A zone and trend that is even dominant on Bouguer gravity anomaly data (Figure 2b). As such, these observations might prompt to revisit the northern shelf area that has very limited seismic reflection or refraction data to be tied into potential field data or onshore geological field records.

6. REGIONAL COMPARISON

Apparent similarities between the JMMC-IPR region and the Northern Volcanic Zone are apparent, both containing oblique rift systems. Potential field data show good correlations to igneous centers and axial rift segments, structural offset of large-scale transfer and fracture zones, and the forming of micro-plates in between rift zones. Both regions have proven strike-slip zone structures that often are buried and difficult to assess. Many volcanic domains have been mapped across Iceland, such as axial and oblique rift systems, pre-Pleistocene-Holocene flexure zones, regional unconformities, tectonostratigraphic ties of local areas across Iceland indicating micro-plate and transfer zone formation. These are all features that also can be seen across the JMMC-IPR study area with observed opening fabric and mechanism based on mapped data compositions that clearly delineate the JMMC, such as: (1) clear north-south asymmetric SDR formation along the eastern JMMC breakup margin and the Ægir rift system that formed preferably linked to variations in the pre-rift lithospheric structure and very likely above a thermal mantle anomaly; (2) establishing a firm link of the oblique Iceland plateau rift system to offset margins in timing, geochemistry and tectono-magmatic connection; (3) reasonable explanation for the initiation of the fanned-out appearance of the oblique IPR rifting domain that inter-fingers with the southern ridges of the JMMC due to crustal thinning and breaching that allowed the formation of several axial rift systems and volcanic ridges; (4) the presence of a pre-breakup complex breakup margin along the JMMC southwestern to western flank, with emplacement of igneous complexes that precede the formation of the Kolbeinsey ridge system; (5) presence of dual breakup system of two opposed rifting complexes that created the JMMC; and (6) concentration of igneous centers, volcanic ridges, or flood basalts close to transfer zones that are linked to a complex fabric of strike-slip and normal fault structures.

High-temperature geothermal areas appear to be confined to active central volcanoes along the divergent plate boundary of Iceland, and most likely sustained by replenishment of shallow crustal magma chambers or intrusions, in form of sills, dykes, and venting structures. As these central volcanoes are also closely located to rift transfer systems, a comprehensive volcano-seismic stratigraphic mapping and sub-surface modelling approach would be highly important. This would increase the understanding of the internal rift graben settings of an area, their major structural elements, such as transfer zones and igneous complex structures that are accompanied by series of dykes and sills intruded at different time stages. As this is a challenging task onshore Iceland with limited seismic reflection data functionalities, would the focus lie in future 2D multi-channel deep seismic reflection data acquisitions close to Iceland´s coast and across the Iceland shelf, where deep subsurface imaging is feasible.

Specifically, for low temperature areas in Iceland, knowing how an area was placed within a rift setting and how often it was impacted by consecutive volcanic activity is a crucial task for understanding geothermal systems and what fault fracture trends are most likely active. The understanding of the sub-division of Iceland in time with future $^{40}Ar/^{39}Ar$ age data analysis of pre-Pleistocene strata is of essence, in order to resolve tectono-stratigraphic reconstructions of onshore Iceland. Holocene tephrachronology can be used to chronologically stratify the youngest areas, however age analysis of younger igneous systems, e.g. Pleistocene - Pliocene are challenging, whereas would sequential stratigraphic analysis tied to subsurface structural segmentation and build-up be one approach for subsurface structural modelling. This includes the subsurface delineation of structural domains based on detailed seismic refraction, gravity and magnetic data acquisitions, which are feasibly option to improve subsurface imaging onshore Iceland.

7. CONCLUSION

The JMMC-IPR study portraits a none-uniform formation of tectono-magmatic rifted margins and domains that are in process comparison not dissimilar to Iceland. Igneous and structural domains, such as the north-south asymmetric and segmented SDRs formation along the eastern JMMC breakup margin, or the firm link of the oblique Iceland plateau rift system to the central East Greenland. A reasonable explanation was demonstrated for the initiation of the fanned-out appearance of the oblique IPR rifting domain that inter-fingers with the southern ridges of the JMMC due to several axial rift systems and volcanic ridge formation along over-stretched and breached crustal weak zones. The existence of a dual breakup scenario and the associated with a series of volcanic zones (fissure swarms and their central volcanoes) that are linked to transfer system has been imaged, as well as the full opening of the Jan Mayen basin as an igneous domain with massive dyke and sill intrusive activities and the regionally extensive flood basalt before final its final breakup. These observed processes are seen onshore Iceland, and are easier imaged within the active NVZ, but challenging for dormant volcanic systems and their fault and fracture trends. Thus, the applied methods and data compilations could improve the understanding of the Iceland onshore and shelf regions by focusing on: (1) primary use of all potential field data to better outline the underlying deep intrusive systems, thus aiding detailed tectonostratigraphic reconstruction of the central NE Atlantic region; (2) enables to differentiate between older structural trends vs. dominating known present-day trends, which is information that only becomes apparent by structural reconstructing an area; (3) focus on areas with direct volcanic rift influence vs. oblique rift system, such as the NVZ vs. TFZ domains; and (4) use nearby offshore areas to acquire seismic reflection and refraction data to more accurately map in detail subsurface structures that have much high resolution then commonly used methods onshore.

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