Insights into the origin and evolution of intraplate magmatism in the Caribbean (initial stage of the Galápagos hotspot) and the South Atlantic (Discovery and Shona hotspot tracks)

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Antje Dürkefälden

Preface

The following dissertation is composed of five independent articles, which are either published or accepted for publication in an international peer-reviewed journal. I am the first author of the first three articles and co-author of the last two articles. The first article is accepted for publication in *Lithos*, the second article is accepted for publication in *Chemical Geology*, the third article is published in *Earth and Planetary Science Letters*, the forth article is published in *Geology* and the fifth article is published in *Earth and Planetary Science Letters*.

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Abstract

According to the classic mantle plume model, the evolution of a mantle plume comprises an initial plume head stage followed by a later plume tail stage. My thesis aims at deciphering the origin and evolution of submarine structures resulting from intraplate magmatism in two different areas: 1) the Caribbean Large Igneous Province (CLIP) formed during the plume head stage and 2) the Discovery Rise and adjacent structures in the South Atlantic representing the plume tail stage.

The CLIP is assumed to have formed during the plume head stage of the Galápagos plume. Whereas this initial stage typically leads to the generation of huge continental flood basalt provinces and oceanic plateaus, the CLIP does not form such a coherent plateau. Instead, it consists of numerous oceanic flood basalt fragments accreted by tectonic processes on land around the margins of the LIP. In addition, large parts of the Caribbean seafloor are likely to be covered by CLIP sequences. In contrast to the better accessible subaerial fragments, the submarine sequences are poorly explored. Thus, my thesis addresses the detailed geochemical and geochronological investigation of two large submarine structures in the Caribbean Sea, the Beata Ridge and the Lower Nicaraguan Rise (LNR), to get new insights into the origin and evolution of the CLIP.

My studies show for the first time that parts of the Beata Ridge formed during the main magmatic CLIP stage at ~89 Ma by widespread extrusive activity, contrasting previous assumptions that the ridge dominantly represents an intrusive complex formed during a later magmatic phase at ~76 Ma. My $^{40}Ar/^{39}Ar$ age dating yielded ages of ~92-77 Ma and thus cover both phases confirming long-term volcanism. Stratigraphically controlled sampling shows a high geochemical variability on a small scale (<100 km) with trace element and radiogenic isotope compositions ranging from depleted to enriched. These observations point to the preservation of enriched and depleted mantle source components and small-scale heterogeneities within the plume head. A rough trend to more depleted compositions from older to younger samples indicates that the depleted component may have become more pronounced with time.

All analyzed samples from the LNR are volcanic contradicting the suggestion of some authors that it belongs to the continental Chortís block in Central America. Instead, it is likely to be part of the CLIP. The majority of samples show strongly depleted

incompatible element and radiogenic isotope compositions, and only a few samples have more enriched compositions similar to those found throughout the CLIP region. Combined with previously published seismic data and ages of ~81 Ma for similar depleted rocks drilled on the Hess Escarpment bordering the LNR, these results suggest that the enriched rocks represent the main CLIP event, whereas the depleted rocks were generated by second-stage melting ~10 Ma after the main stage. Lithospheric thinning probably led to upwelling of still hot, residual plume head material.

The plume tail stage explored in my second study area in the South Atlantic typically leads to the formation of linear hotspot tracks. In contrast to the Tristan-Gough hotspot track, the other structures in this area do not form such linear seamount chains but are more irregular. As they are poorly investigated so far, I produced comprehensive geochemical and geochronological datasets for volcanic rocks from the Discovery Rise and from the Richardson Seamount, Agulhas Ridge and Meteor Rise in order to test if the structures are related to the Discovery and Shona hotspots, respectively. Thus far, these two plumes have largely been identified based on geochemical anomalies along the southern Mid-Atlantic Ridge (SMAR) indicating plume-ridge interaction.

My new $^{40}Ar/^{39}Ar$ age data for the Discovery Rise show an age progression in the direction of plate motion from 23-40 Ma supporting a mantle plume origin. The rise consists of two parallel seamount chains. These display differences in incompatible element and Sr-Nd-Hf-Pb radiogenic isotope data indicating a spatial geochemical zonation of the Discovery plume. The northern chain has compositions similar to those of the nearby Gough subtrack and characteristic for the enriched DUPAL anomaly, a large geochemical domain in the Southern Hemisphere. In contrast, the southern chain is compositionally more enriched representing an extreme DUPAL-like component. These differences in composition are reflected in lavas from the close-by SMAR pointing to a geochemical zonation of the plume for ~40 Ma. The Richardson Seamount, Agulhas Ridge and Meteor Rise show geochemical characteristics ranging from Gough-like compositions to compositions similar to those for the Shona geochemical anomaly along the SMAR. My new $^{40}Ar/^{39}Ar$ age data range from 83-72 Ma, and combined with published age data from the Meteor Rise and Shona Ridge, they indicate that the structures roughly become younger toward the SMAR. These results suggest that the structures represent the hotspot track of the Shona plume.

My new geochemical data additionally provide new insights into the origin of the DUPAL anomaly. They indicate that detached or delaminated subcontinental lithospheric mantle (SCLM) and/or lower continental crust recycled through the lower mantle could represent the source of the anomaly. Furthermore, the South Atlantic plumes are located above the margins of the African Large Low Shear Velocity Province (LLSVP), and the geochemical zonation of the Tristan-Gough plume has been attributed to sampling of material from the LLSVP (DUPAL-like Gough component) and the ambient lower mantle (Tristan component). Similar DUPAL-like compositions for the other South Atlantic plumes suggest that these plumes also sample material from the LLSVP. The occurrence of an additional extreme DUPAL-like component in the southern Discovery Rise samples, however, points to a third lower mantle reservoir besides the Gough-type reservoir and the ambient lower mantle. Thus, the distinct geochemical domains may alternatively be independent of the LLSVP.

Kurzfassung

Dem klassischen Mantelplumemodell zufolge umfasst die Entwicklung eines Mantelplumes ein initiales Plumekopfstadium gefolgt von einem Plumeschwanz- oder Plumeschlauchstadium. Meine Dissertation zielt darauf ab, neue Erkenntnisse über den Ursprung und die Entwicklung von submarinen, durch Intraplattenmagmatismus entstandene Strukturen in zwei unterschiedlichen Gebieten zu gewinnen: 1) die Karibische Flutbasaltprovinz (CLIP), die während des Plumekopfstadiums gebildet wurde, und 2) den Discovery Rise und benachbarte Strukturen im Südatlantik, die das Plumeschlauchstadium repräsentieren.

Es wird angenommen, dass die CLIP während des Plumekopfstadiums des Galápagos Plumes entstanden ist. Während diese Anfangsphase normalerweise zur Entstehung von riesigen kontinentalen Flutbasaltprovinzen und ozeanischen Plateaus führt, bildet die CLIP kein derart zusammenhängendes Plateau. Sie besteht stattdessen aus zahlreichen ozeanischen Flutbasaltfragmenten, die durch tektonische Prozesse rund um die LIP an Land akkretiert wurden. Außerdem sind wahrscheinlich große Teile des karibischen Meeresbodens von CLIP-Sequenzen bedeckt. Im Gegensatz zu den besser zugänglichen Fragmenten an Land sind die submarinen Sequenzen bislang kaum erforscht worden. Daher umfasst meine Dissertation die detaillierte geochemische und geochronologische Untersuchung von zwei submarinen Strukturen im Karibischen Meer, den Beata Rücken und Lower Nicaraguan Rise (LNR), um neue Erkenntnisse über die Entstehung und Entwicklung der CLIP zu gewinnen.

Meine Untersuchungen zeigen erstmals, dass Teile des Beata Rückens während des Hauptstadiums der CLIP vor ~89 Ma durch ausgedehnte effusive Aktivität entstanden. Dies steht im Gegensatz zu früheren Annahmen, dass der Rücken in erster Linie einen intrusiven, während einer späteren magmatischen Phase vor ~76 Ma gebildeten Komplex darstellt. Meine $^{40}Ar/^{39}Ar$-Altersdatierungen ergaben Alter von ~92-77 Ma und umfassen somit beide Phasen, sie eine magmatische Aktivität über lange Zeiträume aufzeigen. Die stratigraphisch kontrollierte Beprobung zeigt eine kleinräumige (<100 km), hohe geochemische Variabilität mit Spurenelement- und Isotopenzusammensetzungen, die von verarmt bis angereichert reichen. Diese Beobachtungen weisen auf den Erhalt von angereicherten und verarmten Komponenten und auf kleinskalige Heterogenitäten innerhalb des Plumekopfes hin. Ein leichter Trend zu stärker verarmten Zusammensetzungen von älteren zu jüngeren Proben deutet darauf hin, dass die verarmte Komponente mit der Zeit mehr zu dominieren scheint.

Alle analysierten Proben vom LNR sind vulkanischer Natur, was im Widerspruch zu der Annahme einiger Autoren steht, dass er zum kontinentalen Chortís Block in Zentralamerika gehört. Stattdessen ist er wahrscheinlich Teil der CLIP. Der Großteil der Proben zeigt eine stark verarmte Zusammensetzung der inkompatiblen Elemente und radiogenen Isotope, und nur wenige Proben haben eine angereicherte Signatur, die der ähnlich ist, die überall in der CLIP-Region zu finden ist. Diese Ergebnisse, kombiniert mit publizierten seismischen Daten und Altern von ~81 Ma für ähnlich verarmte Gesteine, die am den LNR begrenzenden Hess Escarpment erbohrt wurden, lassen vermuten, dass die angereicherten Gesteine die Hauptphase der CLIP repräsentieren, während die verarmten Gesteine durch spätere Schmelzvorgänge ~10 Ma nach der Hauptphase entstanden. Eine Ausdünnung der Lithosphäre führte wahrscheinlich zur Aufwölbung und zum Schmelzen von noch heißem residualen Plumekopfmaterial.

Das Plumeschlauchstadium, das Gegenstand meines zweiten Untersuchungsgebiets im Südatlantik ist, führt typischerweise zur Bildung von linearen Hotspotspuren. Im Gegensatz zu dem Tristan-Gough Hotspot bilden die übrigen Strukturen im Südatlantik keine derartigen linearen Seamountketten, sondern sind eher unregelmäßig. Da sie bis jetzt kaum erforscht wurden, habe ich einen umfassenden geochemischen und geochronologischen Datensatz für vulkanische Proben vom Discovery Rise sowie vom Richardson Seamount, Agulhas Ridge und Meteor Rise generiert, um zu überprüfen, ob die Strukturen im Zusammenhang mit dem Discovery beziehungsweise Shona Hotspot stehen. Bisher wurden die beiden Plumes weitgehend aufgrund von geochemischen Anomalien entlang des südlichen Mittelatlantischen Rückens (SMAR), die auf Plume-Rücken-Interaktion hinweisen, identifiziert.

Meine neuen $^{40}Ar/^{39}Ar$-Altersdaten für den Discovery Rise zeigen eine Altersprogression in Richtung der Plattenbewegung von 23-40 Ma und deuten somit auf einen Mantelplume als Urspung hin. Der Discovery Rise besteht aus zwei parallel angeordneten Seamountketten. Diese zeigen Unterschiede in inkompatiblen Element- und Sr-Nd-Hf-Pb-Isotopendaten, was auf eine räumliche geochemische Zonierung des Discovery Plumes hinweist. Die nördliche Seamountkette zeigt Zusammensetzungen, die denen der benachbarten Gough-Hotspotspur ähnlich und charakteristisch für die angereicherte DUPAL-Anomalie, ein weiträumiges geochemisches Gebiet in der südlichen Hemisphäre, sind. Die südliche Kette dagegen weist stärker angereicherte Zusammensetzungen auf und repräsentiert eine extreme DUPAL-artige Komponente. Da Laven vom nahegelegenen SMAR diese unterschiedlichen Signaturen widerspiegeln, deutet dies auf eine geochemische Zonierung des Plumes über eine Zeitspanne von etwa 40 Ma hin. Richardson Seamount, Agulhas Ridge und Meteor Rise zeigen geochemische Merkmale, die sich von Gough-ähnlichen Zusammensetzungen zu solchen, die denen der Shona-Anomalie entlang des SMAR ähneln, erstrecken. Meine neu gewonnen Altersdaten liegen zwischen 83 und 72 Ma, und kombiniert mit schon veröffentlichten Altersdaten vom Meteor Rise und Shona Ridge weisen sie darauf hin, dass die Strukturen zum SMAR hin jünger werden. Daher stellen sie wahrscheinlich die Hotspotspur des Shona Plumes dar.

Meine geochemischen Daten bringen außerdem neue Erkenntnisse über den Ursprung der DUPAL-Anomalie. Sie weisen darauf hin, dass abgeschuppter subkontinentaler lithosphärischer Mantel und/oder untere kontinentale Kruste, durch den unteren Mantel rezykliert, als Quelle der Anomalie dienen können. Darüber hinaus befinden sich die Plumes im Südatlantik über den Rändern der Afrikanischen Large Low Shear Velocity Province (LLSVP), und die geochemische Zonierung des Tristan-Gough Plumes wird durch inkorporiertes Material von der LLSVP (DUPAL-artige Gough-Komponente) und vom umgebenden unteren Mantel (Tristan-Komponente) erklärt. Ähnliche DUPAL-artige Zusammensetzungen für die übrigen Plumes lassen vermuten, dass dieses Plumematerial auch von der LLSVP stammt. Allerdings deutet das Vorkommen einer zusätzlichen Extrem-DUPAL-Komponente in den südlichen Discovery Seamounts auf ein drittes Reservoir im unteren Mantel neben dem Gough-Typ Reservoir und dem umgebenden unteren Mantel hin. Daher könnten die unterschiedlichen geochemischen Bereiche auch unabhängig von der LLSVP sein.

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Chapter 1

General Introduction

1.1 Mantle plumes and intraplate volcanism

Magmatism caused by mantle plumes is attributed to magmatic events, which are not associated with plate boundaries such as subduction zones or mid ocean ridges. Instead, the ascent of mantle plumes results in intraplate magmatism, although the plumes can also be randomly located beneath or nearby a mid-ocean ridge leading to plume-ridge interaction. Mantle plumes are generally thought to originate from deep in the mantle, presumably the core-mantle boundary (CMB), and to be more or less stationary (e.g., Wilson, 1963; Morgan, 1971). They consist of a large, mushroom-like, head being about 1000 km in diameter and a narrow tail (100-200 km; Griffiths and Campbell, 1990, 1991). When a plume rises and its head reaches the base of the lithosphere, the head spreads out laterally to form a broad disk with a diameter of ~2000-2500 km (Griffiths and Campbell, 1990; Campbell, 2007). This initial plume head stage is characterized by enormous outpourings of magma over relatively short geological timescales of often only a few million years leading to the formation of Large Igneous Provinces (LIPs; e.g., Coffin and Eldholm, 1994) such as continental flood basalt provinces (e.g., the Deccan and Siberian Traps) and oceanic plateaus (e.g., the Ontong-Java and Mahihiki Plateaus). The plume head stage is followed by the plume tail stage, and movement of the tectonic plate over the remaining long-lived tail results in the formation of a linear age-progressive volcanic chain, the so-called hotspot track. Thus, the sometimes observed association of flood basalt provinces and hotspot tracks such as the Paraná-Etendeka flood basalt province and the Tristan-Gough hotspot track can be explained by this plume head–plume tail model, which was initially introduced by Richards et al. (1989). A number of LIPs, however, are not associated with a hotspot track and there are many volcanic chains, which are not related to a LIP. Furthermore, some hotspot tracks are not well pronounced or irregular. Thus, there is some controversy about the mantle plume theory ("The Great Plume Debate") and alternative models explaining the origin of intraplate volcanism have been developed such as the plate model. It is based on plate tectonic processes and attributes the occurrence of intraplate volcanism for example to partial melting of geochemically heterogeneous upper mantle controlled by lithospheric stress or cracks and lateral temperature gradients in the upper mantle (e.g., Anderson, 2000; Foulger, 2002; Anderson, 2005).

1.2 Studied Areas

This dissertation comprises two distinct geographic areas and aims at investigating the different stages of mantle plumes according to the plume head–plume tail model. One area is located in the Caribbean Sea and is discussed in chapters 2 and 3. The chapters encompass the characterization of submarine magmatic samples from two different structures presumably belonging to the Caribbean Large Igneous Province (CLIP) in order to study the plume head stage and its different phases: the main plume head phase of the Galápagos plume in chapter 2 (Beata Ridge) and second-stage CLIP volcanism in chapter 3 (Lower Nicaraguan Rise). The second area is located in the South Atlantic and is discussed in chapters 4 and 5. Chapter 4 deals with the geochemical and geochronological investigation of the Discovery Rise, whereas chapter 5 comprises the investigation of parts of the Shona hotspot track. Both structures are assumed to be hotspot tracks representing the plume tail stage of two different mantle plumes. Whereas the Discovery Rise represents an example of a hotspot track, which cannot be related to a specific LIP, the Shona hotspot track could possibly be associated with the Karoo LIP in southern Africa. Chapter 6 addresses a more general discussion of the composition of mantle plumes and the deep mantle using geochemical data from the CLIP and the Ontong Java Plateau (OJP).

1.2.1 The Caribbean Large Igneous Province

The Caribbean Large Igneous Province (CLIP) is an oceanic flood basalt province formed during a major phase of oceanic plateau formation worldwide in the Cretaceous. It covers much of the submarine part of the Caribbean Plate, but also consists of accreted and tectonically uplifted terranes, which are exposed around the margins of the Caribbean Sea (Costa Rica, Panama, Jamaica, Hispaniola, Curaçao, Aruba) and in northwestern South America (Colombia, Ecuador, Gorgona Island; Fig. 1.1; e.g., Kerr et al., 1996; Sinton et al., 1998; Hauff et al., 2000a, 2000b; Hoernle et al., 2004; Loewen et al., 2013; Hastie et al., 2016). The CLIP is assumed to be formed during the initial stage of a mantle plume, presumably the Galápagos hotspot, and thus by large degrees of melting of the plume head. At least two stages of magmatic activity led to the generation of the CLIP, a main stage at ~89 Ma (95-83 Ma) and a less voluminous stage at ~76 Ma (81-71 Ma). Some younger magmatic activity at ~62-52 Ma occurred only locally.

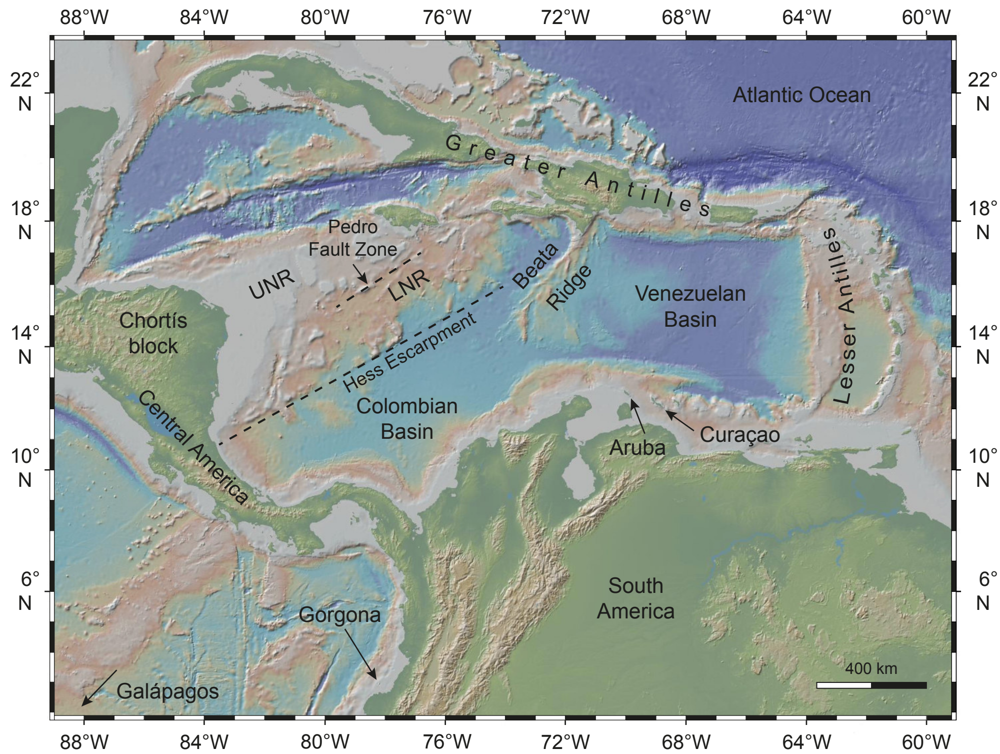

Fig. 1.1 Overview map of the Caribbean Region including Central and South America, the Greater and Lesser Antilles and the structural highs and basins of the Caribbean Sea. UNR = Upper Nicaraguan Rise, LNR = Lower Nicaraguan Rise.

Many of the CLIP rocks show uniform geochemical compositions, which are characteristic for oceanic LIPs with flat rare earth element (REE) patterns and slightly enriched radiogenic isotope compositions pointing to a relatively homogeneous mantle source and extensive homogenization of the melts in the plume head. Rocks with depleted and enriched trace element and isotopic compositions, however, are increasingly found showing that the mantle source region of the CLIP is heterogeneous containing enriched and depleted components.

Whereas the subaerially exposed fragments of the CLIP are extensively sampled, the submarine part is only poorly explored so far. Thus, two chapters of this thesis focus on two prominent submarine structures in the Caribbean Sea, the Beata Ridge and the Lower Nicaraguan Rise (LNR), and are described in more detail in the following sections 1.2.1.1 and 1.2.1.2.

1.2.1.1 The Beata Ridge

The Beata Ridge is a large bathymetric high in the central part of the Caribbean Sea bordered by Hispaniola in the north and trending in SSW direction for ~450 km (Fig. 1.1). It separates the Venezuelan Basin in the east from the Haiti sub-basin in the west, which forms the northern continuation of the Colombian Basin and is located between the Beata Ridge and the Lower Nicaraguan Rise. The Beata Ridge rises up to 2000 m above the surrounding basins and has steep scarps to the west but more gentle slope to the east (Mauffret et al., 2001).

The only detailed sampling of the ridge so far was conducted by submersible during the 1996 Nautica cruise and the geochemical results were published by Révillon et al. (2000). The samples comprise nearly exclusively gabbros and dolerites and only two basaltic rocks leading the authors to the conclusion that the Beata Ridge was mainly formed by an intrusive magmatic event. Whereas the intrusive samples show geochemical compositions typical for CLIP rocks with flat REE patterns, the basalts display enriched, ocean island basalt (OIB)-like compositions. $^{40}Ar/^{39}Ar$ age dating yielded ages of ~81-74 Ma and two remarkably younger ages of ~56 Ma and ~55 Ma (Révillon et al., 2000), and thus the ages mainly fall within the second CLIP phase but also show a minor late magmatic event. Additionally, the southern Beata Ridge was sampled by drilling at Site 151 (DSDP Leg 15; Donnelly et al., 1973) and a basaltic sample with an enriched geochemical composition was recovered.

In my thesis, I present geochemical and $^{40}Ar/^{39}Ar$ age data from samples recovered during three dives with the remotely operated vehicle (ROV) Kiel 6000 on the northern and central Beata Ridge and by dredging on the southern Beata Ridge. The aims are to evaluate if I can confirm the observations of Révillon et al. (2000) that the ridge was formed by a mainly intrusive magmatic event during the second CLIP phase or if there is evidence for earlier extrusive volcanic activity as originally expected for this structure. Furthermore, it is important to investigate if the sampled rocks also show largely uniform geochemical patterns or display geochemical variations at different locations on the ridge and/or with different ages pointing to source heterogeneities as observed for other areas belonging to the CLIP.

1.2.1.2 The Lower Nicaraguan Rise (LNR) and Hess Escarpment

The Nicaraguan Rise is located in the northwestern part of the Caribbean Plate and can be subdivided into the Upper Nicaraguan Rise (UNR) in the north and the Lower Nicaraguan Rise (LNR) in the south (Fig. 1.1). The UNR forms the continuation of the continental Chortís block in northern Central America and is flat and shallow. The LNR is separated from the UNR by the Pedro Fault Zone and is deeper than the UNR. It is bordered by the ~1000 km long Hess Escarpment in the southeast, which separates the LNR from the Colombian Basin. In contrast to the UNR, the LNR has a rough morphology (Mutti et al., 2005) and so far it is not clear whether it belongs to the Chortís block together with the UNR and thus is of continental origin (e.g., Dengo, 1985; Krawinkel and Seyfried, 1994; Hradecky, 2011) or whether it is composed of oceanic crust (e.g., Case et al., 1990; Holcombe et al., 1991; Mauffret and Leroy, 1997) and is possibly part of the CLIP.

Until now, the LNR was only sampled by drilling during ODP Leg 165 at Site 1001 and DSDP Leg 15 at Site 152 (Donnelly et al., 1973; Sigurdsson et al., 1997). Both drill sites are located directly on the Hess Escarpment and are only ~35 km apart from each other. The recovered lavas show depleted geochemical compositions (Sinton et al., 1998; Hauff et al., 2000b; Thompson et al., 2004; Kerr et al., 2009) and $^{40}Ar/^{39}Ar$ age dating of the Site 1001 basalts revealed an age of ~81 Ma.

In the framework of my thesis, I produced the first comprehensive geochemical dataset (major and trace element and Sr-Nd-Hf-Pb double spike isotope data) of the northeastern part of the LNR in order to investigate the geochemical characteristics and the origin of this structure, in particular to clarify if the LNR is of continental or oceanic origin and to discuss a possible connection to the CLIP.

1.2.2 South Atlantic hotspot tracks

In the South Atlantic Ocean, four distinct hotspot tracks are located between the African continent and the southern Mid-Atlantic Ridge (SMAR), namely the Tristan-Gough, Discovery, Shona and Bouvet hotspot tracks (Fig. 1.2). They are arranged roughly subparallel to each other extending from northeastern to southwestern direction but do not form classical long and narrow volcanic chains. Instead they are more irregular and can also be discontinuous. The northernmost track is the Tristan-Gough hotspot track consisting of the Walvis Ridge in the northeast, which is the oldest part, and the Tristan and Gough subtracks forming the continuation of the Walvis Ridge. The subtracks become progressively younger in southwestern direction and lead to the active islands of Tristan da Cunha and Gough, which are fed by the underlying Tristan-Gough mantle plume. The Discovery hotspot track is located south of the Tristan-Gough track and extends only over a relatively short distance. It is represented by the Discovery Rise, which is described in more detail in section 1.2.2.1. The Shona hotspot track, located in the southeast of the Discovery Rise, is long and irregular consisting of several volcanic and tectonic structures (Cape Rise Seamounts – Richardson Seamount – Agulhas Ridge – Meteor Rise – Shona Ridge) described in section 1.2.2.2. The Bouvet hotspot track is only very poorly defined. The associated mantle plume is assumed to be situated in the vicinity of the Bouvet triple junction and is largely detected by signs of plume-ridge interaction found in lavas from the southern Mid-Atlantic Ridge, Southwest Indian Ridge and American-Antarctic Ridge (Le Roex et al., 1987 and references therein).

Geochemical analyses of lavas associated with the four hotspots reveal that they have enriched compositions typical for the DUPAL anomaly. The DUPAL anomaly, named after Dupré and Allègre (Dupré and Allègre, 1983), is a large mantle domain in the Southern Hemisphere between the Equator and 60°S showing anomalous radiogenic isotopic compositions. $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$ are high relative to the Northern Hemisphere Reference Line (NHRL), and $^{87}Sr/^{86}Sr$ ratios are also elevated (Hart, 1984). In the South Atlantic, the anomaly is concentrated at about 40°S and is additionally characterized by elevated Ba/Nb ratios (Class and le Roex, 2011).

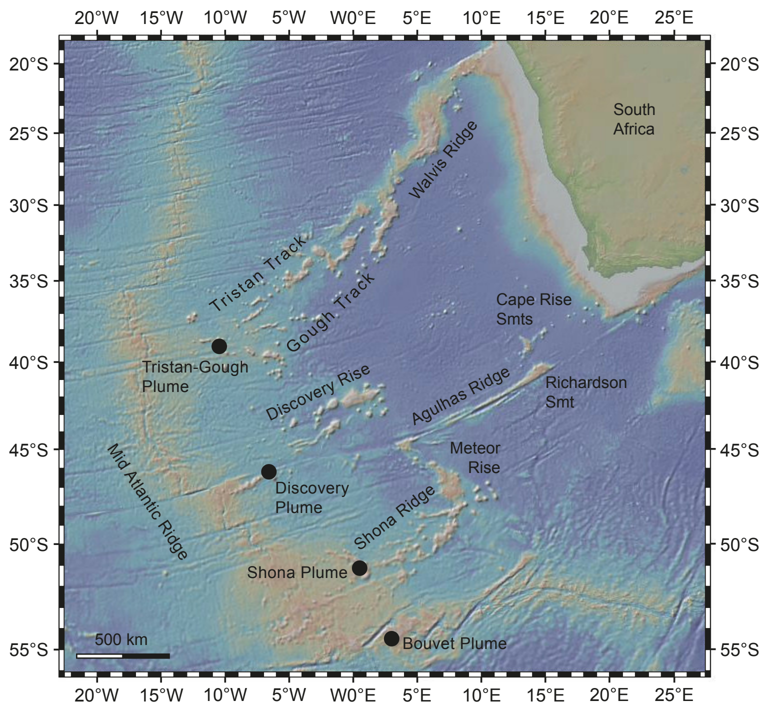

Fig. 1.2 Overview map of the South Atlantic Ocean showing the assumed locations of the Tristan-Gough, Discovery, Shona and Bouvet mantle plumes and their associated hotspot tracks.

The origin of the DUPAL anomaly, however, is still under debate. Some authors propose shallow processes and recycled continental lithosphere or recycled sediments subducted along with oceanic crust as the source for the anomalous composition (e.g., Douglass et al., 1999; Hanan et al., 2004; Geldmacher et al., 2008; Hoernle et al., 2011). Other authors assume a deep mantle origin and a possible relation to the African Large Low Shear Velocity Province (LLSVP), also called the African Superplume (e.g., Castillo, 1988; Class and le Roex, 2011; Rohde et al., 2013). LLSVPs are thermal or thermo-chemical regions, which are located at the base of the lower mantle and which seem to be stable and long-lived over hundreds of millions of years. A second superplume, the Pacific LLSVP, is situated in the Pacific Ocean. It has been proposed that the margins of the LLSVPs can be regarded as plume generation zones and that mantle plumes ascent from these zones (Burke et al., 2008; Steinberger and Torsvik, 2012). Furthermore, the boundaries of the LLSVPs are thought to give rise to spatially zoned mantle plumes in the Pacific and Atlantic Ocean, which possibly sample geochemically distinct material from both inside and outside of the LLSVPs. The four hotspots in the South Atlantic are roughly located above the margin of the African LLSVP, and spatial geochemical zonation has been demonstrated for the Tristan-Gough mantle plume so far (Rohde et al., 2013; Hoernle et al., 2015).

1.2.2.1 The Discovery Rise

The Discovery Rise is located about 1,600 km southwest of South Africa in the South Atlantic Ocean (Fig. 1.2). The rise comprises 12 large seamounts and several smaller bathymetric highs forming two northeast to southwest trending sub-parallel chains and covering an area of about 250 x 350 km. The seamounts rise up to ~4000 m above the surrounding abyssal plain and show a guyot-type morphology with steep flanks and flat tops indicating that they are former ocean island volcanoes, which were eroded to sea level and subsequently submerged.

Thus far, the structure has been only sparsely sampled, namely the huge Discovery Tablemount in the central part and four seamounts at the northeastern end. The published data comprise major and trace element analyses (Le Roux et al., 2002; Le Roex et al., 2010) for the sampled seamounts, but only a single basaltic rock from the Disovery Tablemount was analyzed for radiogenic isotope data (Sun, 1980; Andres et al., 2002; Le Roux et al., 2002). $^{40}Ar/^{39}Ar$ age dating from O'Connor et al. (2012) yielded ages between ~41 and 35 Ma for the northeastern end of the rise, whereas the basaltic sample from the Discovery Tablemount gave a K/Ar age of ~25 Ma (Kempe and Schilling, 1974). The Discovery Rise forms the older end of the Discovery hotspot track (Douglass et al., 1999; O'Connor et al., 2012) and is assumed to represent the surface expression of a mantle plume. Geochemical studies of basalts from the adjacent southern Mid-Atlantic Ridge (SMAR) between latitudes 45-49°S display signs of plume-ridge interaction, and since the isotopic composition of these basalts is similar to that of the Discovery Tablemount sample, this SMAR anomaly is associated with the Discovery hotspot (Douglass et al., 1999). The exact location of the mantle plume, however, is not clear, although it must be located in the southwest of the Discovery seamounts and east of the SMAR anomaly.

The published geochemical data from the Discovery seamounts display enriched, DUPAL-like compositions and the available isotopic data from the Discovery Tablemount sample are very similar to the isotopic compositions of samples from the Gough subtrack implying a common origin.

In my thesis, I present a comprehensive dataset including major and trace element analyses, Sr-Nd-Hf-Pb isotope ratios and $^{40}Ar/^{39}Ar$ age data from almost the entire Discovery Rise. The aims are 1) to evaluate if the age data show an age progression from southwest to northeast in the direction of plate motion, which then would support formation of the rise through passage of the lithosphere over a mantle plume; 2) to evaluate if the geochemical composition of the analyzed rocks is similar to that of the Discovery Tablemount sample and thus also shows an enriched DUPAL-like signature and overlaps with the Gough-type composition; 3) to get new insights into the origin of the DUPAL anomaly.

1.2.2.2 The Shona hotspot track

The Shona hotspot track is located in the South Atlantic Ocean southwest of South Africa and in the vicinity of the Discovery Rise. It consists of several structures forming an irregular, zigzag-shaped track probably due to displacement of parts of the track by tectonic processes (Hartnady and le Roex, 1985). These structures are from northeast (oldest part, closest to South Africa) to southwest (youngest part, near the SMAR) the Cape Rise Seamounts, Richardson Seamount, Agulhas Ridge, Meteor Rise and Shona Ridge (Fig. 1.2). The Cape Rise Seamounts comprise several large seamounts arranged linearly in NE-SW direction. South of the westernmost Cape Rise seamount, the Richardson Seamount rises more than 2,000 m above the surrounding seafloor. It has a guyot-like shape with a huge plateau extending over about 180 x 80 km, and numerous small volcanic cones are situated on the eastern part of the flat top, which are likely to have formed during late-stage volcanic activity. Such small cones are also present on the seafloor directly south of the plateau. The Richardson Seamount is located at the northeastern tip of the Agulhas Ridge, which extends along the Agulhas-Falkland Fracture Zone (AFFZ). The Agulhas Ridge consists of two parallel ridges extending in southwestern direction with narrow, up to 6,000 m deep, troughs in between. The ridges have steep flanks towards the troughs and more gentle slopes on the opposite side in direction to the abyssal plain. Several seamounts and small ridges are sitting directly on the two ridges possibly formed during reactivation of the AFFZ. At its southwestern tip, the Agulhas Ridge merges into the Meteor Rise with the Meteor guyot being located between the two structures. The Meteor Rise extends in southeastern direction for ~600 km and then merges into the Shona Ridge, which extends into the same direction as the Agulhas Ridge.

Major and trace element analyses have been published for samples from the Cape Rise Seamounts, Richardson Seamount, Meteor Rise and Shona Ridge (Le Roex et al., 2010) and show enriched, OIB-like, compositions for these structures. So far, radiogenic isotope data (Sr and Nd) have been published only for rocks recovered from ODP Leg 144 Site 703 on the Meteor Rise and display radiogenic compositions similar to those from the Gough subtrack (Mueller et al., 1992). Additionally, enriched compositions compared to N-MORB have been found in a section of the SMAR indicating plume-ridge interaction of the Shona mantle plume with the MAR (Le Roux et al., 2002). $^{40}Ar/^{39}Ar$ age dating from O'Connor et al. (2012) reveals ages of 74-72 Ma for the Cape Rise Seamounts, 81-74 Ma, 53 Ma and 26 Ma for the Richardson Seamount, 44-31 Ma for the Meteor Rise and 15 Ma and 3 Ma for the Shona Ridge indicating a rough age progression with ages becoming progressively younger to the southwest. The young age of 26 Ma for the Richardson Seamount possibly points to late stage volcanic activity.

Chapter 5 of my thesis comprises a new set of trace element, radiogenic isotope and $^{40}Ar/^{39}Ar$ age data from the Richardson Seamount, the Agulhas Ridge and the Meteor Rise to evaluate if these structures indeed are related to the Shona hotspot and to which extent large-scale tectonic processes influence the form of a hotspot track. The Agulhas Ridge has not been sampled before, and since it extends along the AFFZ, it is particularly important to investigate if the Agulhas Ridge is a solely tectonic feature related to the AFFZ or if it has been reactivated during formation of the Shona hotspot track leading to volcanic activity younger than the AFFZ. Then the geochemical signature would be expected to be similar to that of the remaining Shona hotspot track structures and the ages to fit into the age progression of the track.

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