Petrology of the basalts of the Central Indian Ridge and regional variations of MORBs along the eastern part of the Southwest Indian Ridge

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Abstract

中央海嶺で生成される中央海嶺玄武岩（MORB）は部分溶融程度、結晶分化の程度、またはソースマントルの不均一性などの要因により様々な組成を示す。超低速拡大海嶺である南西インド洋海嶺（SWIR）は海嶺軸に沿った玄武岩組成の不均質が指摘されている一方で、中速であるインド洋中央海嶺（CIR）のロドリゲス三重会合点（RTJ）近傍での研究はほとんどない。本研究では CIR、SWIR から得られた試料を元に海嶺軸に沿った MORB の組成変化をセグメントスケール、さらに広域な範囲で検討を行った。

YK05-16 Leg.1 航海では CIR セグメント 2（CIR-S2）とセグメント 3（CIR-S3）において海嶺軸の横断方向にしんかい 6500 によるサンプリングを行った。CIR-S2 は海嶺軸内に円錐形の小海丘（コニカルコーン）が見られるが、CIR-S3 は海嶺軸谷と平行な地形的高まりが存在する。CIR-S2 の neo-volcanic zone (NVZ)ではコニカルコーンの斜面で枕状溶岩が観察され、頂上はシートフローで覆われていた。CIR-S2 の断層崖（AVW)の下部はドレライト、上部は枕状溶岩で構成されている。また、シート状岩脈群がこの下部で発見されている。コニカルコーンで採取された玄武岩はほとんどが無斑晶質玄武岩だが、AVW の玄武岩・ドレライトはすべて斜長石の斑晶を持つ。CIR-S3 は NVZ、old-volcanic zone (OVZ)、AVW のそれぞれのサンプリングが行われ玄武岩が採取された。OVZ から採取された玄武岩のみ 1-1.4%の斜長石斑晶を持つ。また AVW から得られた玄武岩は 1-3.4%の発泡孔を持つ。このように得られたサンプルはそれぞれのセグメントの内部でも採取場所により異なった記載岩石学的特徴を持つ。

CIR-S2、CIR-S3 から得られた玄武岩・ドレライトの全岩化学組成は CIR-S2 のコニカルコーン、AVW と CIR-S3 でそれぞれ異なる特徴を示す。コニカルコーンから得られた玄武岩は非常に均質な組成を示し、またマントルかんらん岩のかんらん石と平衡な Mg#を示す。一方で CIR-S3 の AVW と CIR-S3 から得られた玄武岩・ドレライトの組成はコニカルコーンよりは分化した値を示し、それぞれの結晶分化トレンドを示す。また高い K_2O や揮発性成分やインコンパチブル元素含有量から CIR-S3 の玄武岩は T-MORB の特徴を示す。コニカルコーンの玄武岩組成を未分化メルトと仮定し、低圧（1kbar）と高圧（5kbar）で結晶分別をする計算を行った結果、CIR-S2 AVW の玄武岩は高圧の、CIR-S3 の玄武岩は低圧の結晶分別を被っていることが明らかになった。このような違いは海嶺下でのマグマシステムの違いによると推測される。CIR-S2 の海嶺下ではマントルの伝導的冷却が効果的に起こり、メルトはマントル内（高圧）での結晶分別を被り、貫入岩としてマントル内で固結するため、生成される地殻は薄くなる（CIR-S2 AVW）。また、そのような高圧の結晶分別を被ることなく噴出した未分化な玄武岩も存在する（コニカルコーン）。一方 CIR-S3 ではマントルポテンシャル温度が高かった、または T-MORB 成分のためマントルがより深くから溶け始めたと考えられる。従って形成

される地殻は厚く、噴出する玄武岩は分化する。このように隣り合ったセグメント同士でも異なるマグマシステムを持つことが明らかになった。

次に、SWIR に沿った玄武岩組成変化を検討した。先行研究を元に、本研究ではロドリゲス三重会合点 (70°E)から Gallieni FZ (52°20′E)の間を東から西に向かって Area I から Area IV の 4 地域に分け、これらの組成の関係を検討した。玄武岩の主要元素・微量元素組成で Area I、III、IV は一連の結晶分化トレンドを示すのに対して、Area II の玄武岩組成は Al_2O_3、Na_2O が高く、TiO_2、FeO*、CaO が低く、他の 3 地域とは違う傾きのトレンドを持つ。また Area II の REE パターンは HREE では Area I 同じ組成範囲示すが、LREE は Area I よりも高い特徴を示す。同じマントルを仮定してメルティングと結晶分別の計算を行うと Area III と IV の玄武岩は Area I よりも低い部分溶融程度のメルトからの結晶分別で説明することができる。また Area III 玄武岩のインコンパチブル元素含有量がわずかに Area IV よりも高いことから Area III の玄武岩のほうがより低い部分溶融程度のメルトが起源であることが示唆される。このように Area I、III、IV の玄武岩組成の違いは同一のソースからの異なる部分熔融度の違いで説明できたのに対し、Area II の玄武岩組成を説明することはできない。従って、Area II の玄武岩組成は異なるソースに由来していることが推測される。

このように本研究ではセグメントスケールからより広い範囲で玄武岩組成が異なることが明らかになった。それはソースマントルの部分溶融程度の違いや結晶分化作用の程度、あるいは海嶺下のマグマシステムの違いで説明することができる。また SWIR にはマントル組成の不均質があることが明らかになった。

Compositions of mid-ocean ridge basalts vary depending on the degree of partial melting, extent of fractional crystallization and source mantle etc. Near the Rodriguez triple junction RTJ (70°E), the regional variations of MORB compositions along the SWIR, ultra-slow spreading ridge, have been reported and shown a heterogeneity of the MORB compositions, but few studies have been done along the CIR, intermediate spreading ridge. In this study, using basaltic samples from the CIR and the SWIR, compositional variations of the MORB along ridges are investigated.

During YK-05-16 Leg.1, 2 dives have been done at the segment center of the segment 2 of the CIR (CIR-S2) and the segment 3 (CIR-S3). A number of conical cones (CC) are observed in a neo-volcanic zone (NVZ) within the CIR-S2. Pillow lavas appear at the slope, while the top of the CC are covered by a sheet flow. The dike swarm occurs at the foot of the axial valley wall (AVZ). Several small-scale ridges parallel to the rift valley are present within CIR-S3. Basalts from the CC are mainly aphyric basalts with a glassy rim. Dolerites are recovered from the lower part, and basalts are obtained from the upper part of the AVW. Within CIR-S3, basalts from the NVZ and the AVW are aphyric, and only basalts from the AVW are vesicular. Basalts from the old volcanic zone (OVZ) have plagioclase phenocrysts.

Basalts from the CC show primitive and quite homogeneous composition and those from the AVW are more evolved. Basalt compositions from CIR-S3 show also more evolved features, but they are distinct from the crystallization trend of the AVW in CIR-S2. Trace element concentrations of basalts from CIR-S2 show N-MORB signatures and those from CIR-S3 have T-MORB signatures. Different crystallization trends between the AVW of CIR-S2 and CIR-S3 can be accounted by different fractionation pressures. Under the CIR-S2, efficient conductive cooling causes crystallization of melts in the mantle, therefore, basalts have undergone high pressure crystallization. In addition, primitive melts which have not undergone crystallization are also erupted (CC). In contrast, high mantle potential temperature or the T-MORB component in the CIR-S3 result in melting at deeper depth, and basalts which undergone low pressure fractionation are

erupted within CIR-S3. It is clear that there are different magma processes between adjacent segments.

The SWIR are divided into 4 areas from RTJ to Gallieni FZ, Area I to Area IV (east to west). Basalt compositions of Area I, Area III, and Area IV are interpreted by differences in melting degrees from a same source. Basalts from Area III and IV are formed from the melts of lower melting degree than those from Area I. Moreover, incompatible element concentrations of Area III basalts are slightly higher than those of Area IV basalts, thus, Area III basalts are derived from melts with lower melting degree than those of Area IV basalts. On the contrary, Area II basalts show high Na_2O and Al_2O_3, and low TiO_2, FeO* and CaO. Furthermore, REE patterns of Area II basalts show similar concentrations of HREE, but higher LREE than those of Area I. These compositional features of Area II can not be explained by different melting degrees. It suggests that basalts from Area II are derived from abnormal mantle source.

Using incompatible elements, and major element compositions of basalts from the CIR to the SWIR, including CIR-S1 and the RTJ area, these basalts (expect Area II basalts) can be produced by different melting degrees, extent of crystallization or pressures of fractional crystallization. Basalts from CIR-S2 and Area I are derived from higher melting degrees than other areas. Basalts from Area I (most primitive in SWIR) are more evolved than CC of CIR-S2 and those from RTJ are further more evolved. Basalts of Area III and Area IV are produced from lower degree of melting, and formed basalts which have wide range from primitive to evolved.

MORB compositions along the CIR and the SWIR near the RTJ show various features caused by differences degree of partial melting, extent of crystallization and magma system beneath the ridge. And it is clear that there is heterogeneity of mantle composition under the SWIR.

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1 Introduction

1.1 The general discussions of MORB

Mid-ocean ridges extend over 60,000 km and 2000 to 4000 m difference in elevation at seafloor, and magmas which were produced there occupy a large amount of igneous activities in the globe (Figure 1-1). Therefore, oceanic crust account for 60 % igneous activity on the world surface (Cogley, 1984).

Figure 1-1. Volume of igneous activity after Davidson et al. (2002) (Figure4.16).

There are mid-ocean ridges of varied spreading rates, and these show different topographic features and compositions of MORBs, respectively. Fast-spreading ridge (90 to 180 mm/yr: full spreading rate) such as the East Pacific Rise (EPR), and intermediate-spreading ridge (50 to 90 mm), such as the Juan de Fuca and the Central Indian Ridge (CIR), show tens of km for wavelength and tens to hundreds of meters for amplitude in axial-depth profiles (Figure 1-2). A topology of fast-spreading ridge generally exhibit rolling small undulation and there is no rift valley (Figure 1-3). Ultraslow- to slow-spreading ridges (less than 50mm/yr), such as the Mid Atlantic ridge (MAR), the Southwest Indian Ridge (SWIR) and the Gakkel ridge, show short wavelength and large amplitude (Figure 1-2) and have a wide and deep rift valley (Figure 1-3).

Figure 1-2. Axial depth profiles of mid-ocean rides (after Macdonald et al., 1991 and Macdonald, 1998). A: slow-spreading ridge B: fast-spreading ridge C: ultra-fast apreading ridge

Figure 1-3. Axial depth profiles of mid-ocean rides (after Juteau and Maury, 1997). As decrease of spreading rate, ranges of the active volcanic zone (AVZ) and the active tectonic zone (ATZ) became wide.

It is suggested that the stratigraphy of oceanic crust also shows different features depend on the spreading rates (Karson, 1998; Miyashita and Maeda, 2003). Figure 1-4 shows columnar sections of oceanic crust at fast- and slow-spreading ridges. The oceanic crusts which are produced at fast- to intermediate-spreading ridges have an ophiolite sequence. On the other hand, oceanic crust at slow-spreading rates have a heterogenous constitution that is

Figure 1-4. Stratigraphy of oceanic crust at fast- and slow spreading ridge. after Miyashita and Maeda (2003).

Figure 1-5. Sampling point of MORBs at mid-ocean ridge. Data from PetDB, sorted by spreading center of Pacific, Indian, Atlantic and Antarctic. Bathymetric map is made by GMT (Wessel and Smith, 1998). Global bathymetric data from Becker et al. (2009).

shown by a lack of sheeted dike complex and complicated association of gabbros and serpentinites (Figure 1-4). At fast-spreading ridges, sheeted dike complex develops due to presence of a melt-lens in long period which results in thick gabbro layers. The formation of thick gabbro layers as extracted cumulates brings about evolved extrusive rocks at fast-spreading ridges. At-slow spreading ridges, it is thought that there is a lack of melt-lens or temporal small one, so that gabbros consist of many intrusive bodies, and extrusive rocks are comparatively primitive (Miyashita and Maeda, 2003).

Figure 1-6. Comparison of MORB compositions from the Pacific, the Atlantic and the Indian ocean after Sato et al. (2008). Gray areas mean basalts composition ranges from Pacific ocean.

Compared with other tectonic setting, the Mid-ocean ridge basalt (MORB) have narrow compositional ranges, however, variations of the MORB have been considered associating with spreading rates, degree of partial melting, mantle

potential temperatures and source mantle. Huge quantities of MORBs collected from the mid-ocean ridges from the world (Figure 1-5). There are enormous numbers of studies about MORBs covering from a segment scale to global scale, and comparisons of compositions of MORBs from Pacific, Atlantic and Indian Ocean are reported using major and trace elements (Klein, 2003, Sato et al., 2008). Compositional ranges of Pacific MORBs are the largest, those of Indian MORBs are the smallest and those of Atlantis MORBs are intermediate (Figure 1-6).

MORB compositions from the Indian Ocean are characterized by low FeO and high Na_2O contents in comparison with those from the Pacific and the Atlantic Ocean, that is explained due to difference in spreading rates. Na_2O behaves as a compatible element in a basaltic melt, thus melts which is lower degree of melting have high Na_2O contents. Therefore Na_2O contents of MORBs from slow-spreading ridges show higher values. In addition, FeO contents are dependent on the melting depth (Langmuir et al., 1992), therefore, the melts which are derived from deeper depth have higher FeO contents.

Basalts compositions change with fractional crystallization. To eliminate the effect by fractional crystallization, $Na_{8.0}$ and $Fe_{8.0}$ etc. are used, which were calculated from Na_2O and FeO etc. analyses normalizing at MgO = 8.0 (Klein and Langmuir, 1987; Langmuir et al., 1992). Generally, the variation of $Na_{8.0}$ is negatively correlated to the degree of melting; higher $Na_{8.0}$ corresponds to a lower degree of melting. While, the variation of $Fe_{8.0}$ is positively correlated with a depth of melting; higher $Fe_{8.0}$ implies a deeper partial melting. Therefore, there is a negative correlation between $Na_{8.0}$ and $Fe_{8.0}$ for MORBs which are regionally averaged for world-wide ridge systems, and this trend is called as "global trend" (Klein and Langmuir, 1987) (Figure 1-7). Compositions from the Atlantis II FZ ("AII FZ" in the Figure 1-7) basalts from ultra-slow spreading ridge (14 mm/yr) show high $Na_{8.0}$ and low $Fe_{8.0}$. Compositions from slow-spreading ridges show also an orthogonal trend to the global trend, and it is called as "local trend" (Klein and Langmuir, 1989).

Figure 1-7. Compositional relation between Fe8.0 and Na8.0. Shaded area show average compositions from individual area. a: Samples from "normal" ridge segments. b: Samples from hot spot influenced ridge segments. After Langmuir et al. (1992) (Fig.21).

Melts are generated by a partial melting of a mantle due to mantle upwelling. It has been recognized that a model of melting regime changes depending on the mantle potential temperatures (Figure 1-8). Low mantle potential temperatures bring about a small melting column, shallow depth of melting and low degree of melting, therefore thin oceanic crusts are produced. On the other hand, hot mantle potential temperatures under the mid-ocean ridges, result in a thicker melting column and deeper depth for melting. Therefore, more thick oceanic crusts are formed at such circumstances.

Figure 1-8. Models of magma process after Langmuir et al. (1992). Under the influence of the cold manlte, melting regime are smaller and degrees of partial melting are lower than those of the hot manle. Therfore, oceanic crusts which formed by influence of the cold mantle are thinner than those of the hot manlte.

In this study, the compositional variations of the MORB along ridges are investigated using basaltic samples obtained from the CIR and the SWIR, and discuss the genesis of those variations.

1.2 Compositional variations of MORBs around RTJ

Central Indian Ridge (CIR) extends from the Rodriguez Triple Junction (RTJ) which assembles CIR, Southwest Indian Ridge (SWIR) and Southeast Indian Ridge (SEIR), to north and continues to Carlsberg ridge. Figure 4-1 shows a bathymetric map of this study area. From the RTJ to north, ridge segments are distinguished as the segment 1 of CIR (CIR-S1), CIR-S2 and CIR-S3. The study area is southern part of CIR, and corresponds to CIR-S2 and CIR-S3. The boundary between CIR-S2 and CIR-S3 is a non-transform discontinuity, where a

Figure 1-9. Bathymetric map around Rodriguez Triple Junction (RTJ). Dashed line squares show segment 1 to 3. Blue circle for Dive #926 site and red circle for Dive #927 site. 2 hydrothermal fields are also shown as star symbols. Bathymetry was compiled from YK05-16, YK01-15, KR00-05, KH-93-3 and the previous french cruises.

notable triangular shape mound mentioned as Knorr-Seamount by Van Dover et al. (2001) is present. In the southern part of CIR, 2 hydrothermal fields, Kairei hydrothermal field and Edmond hydrothermal field, are found (Van Dover et al., 2001). The Kairei hydrothermal field is characterized by a high hydrogen concentration (Van Dover et al., 2001) and locates on the western side of ridge segments at CIR-S1. On the other hand, the Edmond field locating at north of CIR-S3 is a normal hydrothermal type.

CIR-S2 is located in 25°S10′E to 24°S40′E and has an axial valley about 7 km wide. Numerous round-shaped mounds (conical cones) are observed within the axial valley (Figure 4-2a). CIR-S3 is located in 24°S20′E to 23°S53′E and has the axial valley with similar width. The full spreading rate of this segment is 46 mm/yr, thus it is classified as an intermediate-spreading ridge. However, the topography of CIR-S3 is slow-spreading-like feature. Several small-scale ridges parallel to the rift valley are present within a median rift valley (Figure 4-3a).

Geophysical data, such as mantle bouguer anomaly (MBA) and residual mantle bouguer gravity anomaly (RMBA), are obtained in CIR-S1 to CIR-S3 (Figure 1-9). MBA datum for CIR-S2 are higher than those of CIR-S3, suggesting that the igneous activity within CIR-S2 is less active than those of CIR-S3 and cold mantle underlies under CIR-S2 (Wakabayashi, 2003). Thus, it has been recognized that these 2 segments have different topographical and geophysical features.

Within the narrow area of southern end of CIR, basaltic samples were obtained and the major and trace element compositions were reported by Price et al. (1986) and Fujii et al. (1995). These basalts have similar compositions with N-MORBs from the Atlantic and Pacific Ocean.

a
69°50'
69°51'
69°52'
69°53'
69°54'
69°55'
69°56'
69°57'
69°58'
69°59'
70°00'
−24°47'
−24°48'
−24°49'
−24°50'
−24°51'
−24°52'
−24°53'
−24°54'
1 km
−2000
−3000
−4000
−5000

Figure 1-10a.

b
69°35'
69°36'
69°37'
69°38'
69°39'
69°40'
69°41'
69°42'
69°43'
69°44'
69°45'
−24°05'
−24°06'
−24°07'
−24°08'
−24°09'
−24°10'
−24°11'
−24°12'
1 km
−2000
−3000
−4000
−5000

Figure 1-10b.

During the YK05-16 Leg.1, 10 dives were done at CIR-S2 and CIR-S3, and at also around hydrothermal fields and an oceanic core complex (Kumagai et al., 2008). Furthermore, fine rock sampling was also carried out within CIR-S2 and CIR-S3., and 2 dives of them were done at the segment centers of CIR-S1 and CIR-S2, respectively. Using these results, it becomes to be possible to investigate magma processes along the CIR.

Details of observations at each dive and descriptions of samples are shown in a next chapter (Chapter 2.1).

Figure 1-10. Broad bathymetric map of ridge axis in (a) CIR-S2 and (b) CIR-S3. Bathymetry was compiled from YK05-16, YK01-15, KR00-05, KH-93-3 and the previous french cruises. Dive track (gray circles) and sampling point (red circles) are plotted. Red square is range of expanded map, Figure 2-1a and Figure 2-2a, respectively.

Figure 1-11. Along-axis profiles of deph of sea floor, mantle bouguer anomaly (MBA) and residual mantle bouguer gravity anomaly (RMBA) (after Wakabayashi, 2003).

1.3 Heterogeneity of MORB compositions at eastern Southwest Indian Ridge

The Southwest Indian Ridge (SWIR) is an ultraslow-spreading ridge (15mm/yr; Patriat et al., 1997), extending from the Rodriguez Triple Junction (RTJ) of the eastern edge to the Bouvet Triple Junction of the western edge. Relatively

successive samplings have been done along the eastern SWIR. The compositional variations of MORBs are indicated along the SWIR (Natland, 1991; Robinson et al., 1996; Meyzen et al., 2004; Nakamura et al., 2007. etc.). However, these studies used fragmentary points.

Figure 1-11. Distributions and compositions of Type 1 to 3 basalts in the Indian Ocean after Natland, (1991). Open circles for Type 1, filled circles for Type 2 and Xs for Type 3 basalts.

Based on Na_2O and TiO_2 contents, Natland (1991) distinguished basalts from Indian Ocean into Type 1 to 3 (Figure 1-11). Type 3 basalts distribute in the RTJ to the Atlantis II FZ along the SWIR. Type 2 basalts are obtained from the CIR and the SEIR. Type 1 basalts are recovered from Eocene-Cretaceous Deep Sea Drilling Project (DSDP) site. Type 1 basalts have the lowest Na_2O and TiO_2 contents, Type 3 basalts show the highest contents, and Type 2 basalts show intermediate values at given MgO contents.

Meyzen et al. (2003) studied glass compositions of basalts along the eastern SWIR (Figure 1-12). They divided the eastern SWIR into 2 zones; Zone A is eastern side and Zone B is western side of the Melville FZ (60°45′E). They indicate

that glass compositions from the Zone A have higher Na_2O and Al_2O_3 contents, and lower TiO_2 and HREE contents than those of the Zone B. They interpreted that the Zone A basalts are derived from mixing of harzburgite and fertile peridotite.

As described above, despite of different areas in preceding studies, it is certain that there is a large compositional heterogeneity of MORBs at the eastern SWIR. It is necessary to study the variation of MORB compositions using continual data along the SWIR. Therefore, using 2 surveys samples and other data from the PetDB, compositional variation of MORB are reconsidered in this study.

On the basis of magnetic and gravity studies, the SWIR ridge near the RTJ was opened by tectonic movement without magmatic activity (Honsho et al., 1996). Therefore, basalts from this area would be formed at past CIR or SEIR, but not at present SWIR. Fujii et al. (1995) showed that the compositions of basalts from near the RTJ are similar to those from the CIR and the SEIR which are produced at near the RTJ.

Figure1-12. Classification of Zone A and Zone B basalts along the SWIR, and glass compositions (after Meyzen et al., 2003). They distinguished basalts obtained along the SWIR to Zone A(eastern of the Melville FZ) and Zone B (western of the Melville FZ). Variations of major element compositions from Zone A and B basalts are shown right side. Variation diagrams of Na8.0 versus Fe8.0 and CaO/Al2O3 versus Ti8.0 show that compositions of Zone A basalts plot in out of N-MORB range.

2 Petrography

2.1 Basalts and dolerite from CIR-S2 and CIR-S3

Observations of Dive 926 and 927 sites

During the YK05-16 Leg.1, 2 dives were done as crossing a rift valley of ridge at CIR-S2 (Dive #926) and CIR-S3 (Dive #927). Both Dive #926 and #927 were carried out from a neo-volcanic zone to the Axial Valley Wall (AVW). 23 Basaltic rocks were obtained from a neo-volcanic zone and wall of axial rift valley for each during the 2 dives. Figures 2-1 and 2-2 show topographic maps and traces of Dive #926 and #927. The sample locations and representative mode of occurrences are also shown.

Figure 2-1. Bathymetry of CIR-S2 and photographs of outcrops. a: Bathymetric map of around the Dive #926 site. Bathymetry was compiled from YK05-16, YK01-15, KR00-05, KH-93-3 and the previous french cruises. Dive track, sampling points and lithology for sampled rocks are also plotted. b: Pillow lava at 3380 m water depth in slope of the conical cone. c: Sheet flow at the top of the conical cone. d: Dike swarm at 3303 m water depth in slope pf the AVW. e: Broken pillow lavas in slope of the AVW.

Figure 2-2. Bathymetry of CIR-S3 and photographs of outcrops. a: Bathymetric map of around the Dive #927 site. Bathymetry was compiled from YK05-16, YK01-15, KR00-05, KH-93-3 and the previous french cruises Dive track, sampling points and lithology for sampled rocks are also plotted. b: Pillow lava at 3490 m water deph in the slope of the NVZ. c: Broken pillow lavas in the slope of the OVZ between the NVZ and the AVW. d: Massive basalts in the AVW. e: The cooling joint at 3467 m water depth in the AVW.

Figure 2-1. (continued next page)

06/01/22 12:30:41 03°
-47° -23° 2000 F177
070° 3380m 2m
b

c

d
22 2:37PM

e
22 3:02PM

Figure 2-2. (continued next page)

06/01/23 12:01:15 00°
-90° -36° 2000 F254
258° 3490m 4m
b

c
23 1:00PM

d
23 3:26PM

06/01/23 15:34:16 03°
-24° -28° 2000 F000
233° 3467m 5m
e

Dive #926 started from a foot of conical cone (3545 m) within a neo-volcanic zone (NVZ) and moved up along the slope of conical cone (Figure 2-1a). Sea floor near the start place is covered by rubbles with a glassy rim. It seems to be broken pieces of pillow lavas. Unbroken pillow lavas were discovered at 3435m depth, and continued until near the crest (Figure 2-1b). The top of the conical cone about 3365m depth is a large flat plane and covered by a massive sheet flow (Figure 2-1c). 8 basalts (broken pillow lavas, non-broken pillow lavas, and sheet flow) were recovered from the conical cone. Almost rocks from the NVZ lack a manganese coating and have a glassy rim. The last half of Dive #926 observed an steep axial valley wall (AVW) from -3506 to -3024 m depth. Dolerites occur at the lower part of the wall. Apparent joints are well observed at 3444m depth and dike swarm is found at 3303m depth (Figure 2-1d). Then, broken pillow lavas were sporadically exposed at the upper part of the wall (Figure 2-1e). At the top of the wall, non-broken pillow lavas covered with sediments were observed. 3 dolerites and 2 basalts were sampled from the AVW. These samples have 3-10 mm manganese coating and 2 dolerites have a weathered rim. The pillow lavas are fragile and have thicker manganese coating than those of the NVZ.

Dive #927 site is located approximately 87 km north of Dive #926 site. As well as Dive #926, this dive also started from a knoll of the NVZ and went toward the AVW (Figure 2-2a). Sea floor of the NVZ (3551 m) is also covered by rubbles which consist of deformed pillow lava. Climbing up along the slope of the NVZ, spectacular pillow lavas occur immediately (Figure 2-2b). A top of the NVZ is also underlain by pillow lavas. All 4 basalts from this NVZ are non-manganese coating and have a glassy rim. Next surveyed area is a seamount located between the NVZ and the AVW (Figure 2-2a). The slope of this seamount is mainly underlain by basaltic rubbles and broken pillow lavas (Figure 2-2c). Undeformed pillow lava with a thin sediment cover occurs at a gentle slope (3725 m depth). The upper slope is covered by rubbles and pillow lavas were found again at 3580m depth near the top of the seamount. 3 basalts were obtained from the pillow lava outcrops and they have a filmy manganese coating and a grassy rim. These facts suggest that the basalts from this seamount were older than those of the NVZ. Thus, we call this seamount old volcanic zone (OVZ). The foot of the western AVW, from 3636m depth to 3580m depth is covered by sediment and scattering rubbles.

As climbing up the slope, rubbles become larger and increase in volume. The lower part of the western AVW consists of repeated gentle slopes covered with sediments and steep slopes underlain by outcrops consisting of massive basalts (Figure 2-2d). Around 3483m, intrusive sills with a cooling joint are sometimes observed (Figure 2-2e: no sampling). 3 basalts collected at the steep slope (3549m and 3430m depth) have a weathered rim and characterized by vesiculation.

Amount of sediments, degree of weathering and thickness of manganese coating were increased from the neo-volcanic zone to the wall of axial valley at both of Dive #926 and #927. Basaltic rocks recovered from both of the NVZ are extremely fresh and have a glassy rim (Table 2-1).

Sample descriptions

The basaltic rocks obtained during Dive #926 (CIR-S2) show different petrographic features due to the location. Aphyric basalts are predominant at the conical cone (Figure 2-3a). A small amount of plagioclase phenocryst less than 1 modal % is only contained in most samples from the conical cone. Whereas, the basalts and dolerites from the axial valley have more abundant phenocrysts of plagioclase and olivine than the conical cone (Figure 2-3b). The maximum modal contents of plagioclase phenocrysts attain 13% and the modal amount of phenocrysts ranges from 1.4 to 13.5%. All 3 dolerites which were sampled from the lower part of the AVW have 1.0-7.3 modal% of plagioclase phenocrysts (Figures 2-3b, c and d). 1 dolerite (926-10) has 2.2 modal% of olivine phenocrysts (Figure 2-3b). The plagioclase phenocrysts are mostly euhedral and attain up to 4 mm in diameters. Except 1 dolerite, all other basaltic rocks are non-vesicular (<1% vesicles).

The basalts from Dive #927 (CIR-S2) mainly consist of aphyric basalts (Figures 4-3e and f). Only 2 basalts recovered from the OVZ have 1.0-1.4 modal% of plagioclase phenocrysts (Figure 4-3g). The basalts from the NVZ and the OVZ are none vesicular, but basalts from the AVW are sparsely vesicular and have 1.0-3.4 modal% vesicles (Figure 4-3h). The plagioclase phenocrysts attain 4 mm in long-axis and are euhedral.

Figure 2-3. continued next page.

e

f

927-03 Aphyric basalt

g

927-05 Sparsely plagioclase phyric basalt

h

927-08 Aphyric basalt

Figure 2-3. (continued).

As mentioned above, basalts from Dive #926 are poorly vesiclulated, suggesting that there are difference in volatile content between the magmas CIR-S2 and CIR-S3.

Figure2-3. Photographs of rocks and thin sections.

a, f, h: Photographs of thin sections. b, d, g: Photographs of thin sections (cross nicol). White and black bars in photos of thin sections are scales for 5 mm. a: glass rim is obserbed at left side (pale bwon zone).

c, e: Onboard photographs of rock samples. c: Samples of 926-11 with weathered rim obtained from the AVW within CIR-S2. e: Piece of the pillow lava (927-03) with fresh grassy rim recovered from the NVZ within CIR-S3.

Sample No.	Latitude	Lontitude	Depth (m)	Lithology	phenocryst		microphenocryst		vesicule (%)	rim		
					PL (%)	OL (%)	PL (%)	OL (%)		Mn (mm)	glass rim	weathered rim
926-01	24°52.5005'S	69°57.9102'E	3545	Aphyric basalt	0.7		4.1	1.4			○	
926-02	24°52.5005'S	69°57.9102'E	3545	Aphyric basalt			2.9	0.6	0.3		○	
926-03	24°52.4944'S	69°57.9874'E	3433	Aphyric basalt	0.2		0.9	0.8	0.5		○	
926-04	24°52.4944'S	69°57.9874'E	3433	Sparsely plagioclase phyric basalt	1.2		1.7	0.9	0.1	filmy		
926-05	24°52.4799'S	69°58.0021'E	3408	Aphyric basalt	0.5		2.4	0.3	0.3	filmy		
926-06	24°52.4799'S	69°58.0021'E	3408	Aphyric basalt	0.6		1.8	0.5			○	
926-07	24°52.4799'S	69°58.0021'E	3408	Aphyric basalt	0.3		2.7	0.6	0.5		○	
926-08	24°52.4637'S	69°58.0864'E	3369	Aphyric basalt			3.1	0.9	0.5	0-1	○	
926-09	24°51.5503'S	69°59.3329'E	3434	Sparsely plagioclase phyric dolerite	1	0.4	1.4	0.3		5		○
926-10	24°51.5503'S	69°59.3329'E	3434	Moderately plagioclase olivine phyric dolerite	7.3	2.2	11.1	1.7		10		
926-11	24°51.5095'S	69°59.4627'E	3303	Sparsely plagioclase phyric dolerite	2.2		3.1		1.2	10		○
926-12	24°51.459'S	69°59.5273'E	3177	Sparsely plagioclase phyric basalt	1.8		1.2	0.9		3	○	
926-13	24°51.3965'S	69°59.6417'E	3063	Highly plagioclase phyric basalt	13.0	0.5	1.1	1.1		3	○	
927-01	24°8.056'S	69°39.0203'E	3592	Aphyric basalt			0.3	0.4			○	
927-02	24°8.056'S	69°39.0203'E	3592	Aphyric basalt	0.4		0.8	0.3			○	
927-03	24°8.0668'S	69°38.9195'E	3484	Aphyric basalt			2.4	1.6	0.1		○	
927-04	24°8.0668'S	69°38.9195'E	3484	Aphyric basalt			1.3	2.1	0.2		○	
927-05	24°8.8563'S	69°38.4622'E	3706	Sparsely plagioclase phyric basalt	1		1.3	0.4	0.1	filmy	○	
927-06	24°8.8563'S	69°38.4622'E	3706	Aphyric basalt	0.3		0.4		0.4	filmy	○	
927-07	24°8.9127'S	69°38.3921'E	3579	Sparsely plagioclase phyric basalt	1.4		0.1		0.1		○	
927-08	24°9.4046'S	69°37.8521'E	3549	Aphyric basalt			0.5	0.2	2.1	filmy		○
927-09	24°9.427'S	69°37.7561'E	3430	Aphyric basalt			0.7	0.1	3.4	0.5		○
927-10	24°9.427'S	69°37.7561'E	3430	Aphyric basalt	0.3	0.2	0.1		1.0	0.1	○	○

Table2-1. Lithology of basalts and dolerites from Dive #926 and Dive #927. Depth mean water depth. Rock names are determined depend on amount of phenocryst less than 1% as aphyric, 1 to 5% as sparsley phyric, 5-10% as moderately phyric and more than 10% as highly phyric.

2.1 Overview and petrography of samples

Dive 463・464 (R/V Yokosuka/Shinkai 6500 MODE'98 Leg4)

5 basalts were collected from Dive #463 site, the east of the Atlantis II FZ and south of RTI (Ridge-Transform Intersection) where the Atlantis II FZ insects ridge during Yokosuka/Shinkai 6500 MODE'98 Leg4 (Kinoshita et al., 1998). Basalts from this dive were plagioclase-olivine basalt and plagioclase basalt, and they are characterized by large phenocrysts of plagioclase (6 mm).

Dive #464 samples were collected from transform volcano south of Dive463. Olivine basalts, plagioclase basalts and aphyric basalts were collected and they are also characterized by large phenocrysts of plagioclase (5 mm).

Dive 171 (R/V KAIREI/KAIKO KR00-06)

Dive 10K#171 was conducted at 61°E non-transform discontinuity located east of the Melville FZ during KAIREI/KAIKO KR00-06 (Arai et al., 2000). This area is defined as Area II in this study (It is examined further in the chapter 5-5.1). Plagioclase-olivine basalts, plagioclase basalts and olivine basalts (olivines are pseudomorph) were collected. Plagioclase basalts constitute for most of samples and have large plagioclase phenocryst (maximum 15mm).

Major and trace element compositions of 3 basalts from Dive #463 site, 6 basalts from Dive #464 site and 6 basalts from Dive #10K171 site are analyzed and described in the chapter 3-3.2.

3 Analytical method and data

3.1 Bulk rock compositions of basalts and dolerites from Central Indian Ridge (Dive #926 and 927)

Bulk rock compositions of 8 samples from Dive #926 and 6 samples from Dive #927 were analyzed. Major element contents (SiO_2, TiO_2, Al_2O_3, FeO*, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5) were analyzed by X-ray fluorescence analysis (XRF) (Rigaku RIX 3000) at Niigata University following the analytical method of Takahashi and Shuto (1997). JB-1b of GSJ (Geological Survey of Japan) geostandard samples as also analyzed and measured values are shown Table 3-1. Loss on ignition (LOI) for basalts and dolerite are -0.32 to 0.34 from Dive #926, and -0.28 to -0.01 from Dive #927. These results show that collected basalts and dolerites from the study areas are very fresh concordant with descriptions (Chapter 2-2.1).

	JB-1b	
	This study	Reference value
SiO_2	52.15	51.11
TiO_2	1.25	1.26
Al_2O_3	14.51	14.38
FeO*	8.26	8.12
MnO	0.15	0.147
MgO	8.33	8.14
CaO	9.81	9.6
Na_2O	2.72	2.63
K_2O	1.33	1.32
P_2O_5	0.26	0.256
Total	98.76	96.96
Trace elemets		
V	212	214
Cr	400	439
Ni	138	148

Table 3-1. Major elements and trace elements compositions of JB-1b by XRF analysis. Reference values referred from Imai et al. (1995).

Elements	W-2 (ppm)		Relative error
	This study	Reference Value	(%)
Sc	37.4	36.2	3.3
Co	46.2	46	0.5
Zn	82.9	77	7.7
Ga	18.0	17.4	3.4
Rb	21.0	20.1	4.4
Sr	201	192	4.8
Y	23.6	22.8	3.6
Zr	95.0	92.0	3.3
Nb	8.00	7.76	3.2
Cs	0.94	0.92	2.6
Ba	176	171	2.9
La	11.1	10.6	4.7
Ce	24.1	23.1	4.4
Pr	3.12	3.03	3.2
Nd	13.3	13.0	2.7
Sm	3.43	3.31	3.7
Eu	1.14	1.09	4.2
Gd	3.87	3.69	4.8
Tb	0.64	0.62	3.4
Dy	3.87	3.79	2.1
Ho	0.84	0.80	5.6
Er	2.27	2.26	0.3
Yb	2.07	2.03	2.2
Lu	0.31	0.30	4.9
Hf	2.30	2.30	-0.2
Ta	0.50	0.48	2.9
Pb	11.6	7.81	48.3
Th	2.38	2.21	7.7
U	0.52	0.50	4.2

Table 3-2. Accuracy of trace element compositions analysis by ICP-MS. Compare to the geostandard sample of W-2 from Eggins et al. (1997).

V, Cr and Ni contents were also analyzed by XRF. The another 29 trace element concentrations were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) at Niigata University and calibrated using the reference values for BHVO-1 (U.S. Geological Survey [USGS]) of Eggins et al. (1997). USGS Geochemical Reference Standard W-2a was analyzed to check the analytical accuracy for trace elements (Table 3-2). Calculated relative error values between this study values and reference values (Eggins et al., 1997) are also indicated in

Table 3. Except Ho and Th, the relative error values of trace elements are less than 5 %.

Basalt compositions from Dive #926 and #927 are show in Table 3-3.

3.2 Bulk rock compositions of basalts from the SWIR

Major and trace element compositions of 3 basalts from the Dive #463, 6 basalts from the Dive #464 at the eastern side of the Atlantis II FZ and 6 basalts from the Dive 10K#171 at the eastern side of the Melville FZ are analyzed. Analytical method and results are reported in Neo (2005) and Adachi (2003). Here, these 15 basalts compositions are shown in Table 3-4.

Basalts from the Dive #463 and #464 are very fresh and LOI (wt%) of these basalts are very low (Dive #463: 0.4 to -0.26. Dive #464: -0.08 to -0.36). Mg# (100Mg/(Mg + Fe)) ranges from 52 to 57 for Dive #463 and from 58 to 62 for Dive #464. Plagioclase-olivine basalts and plagioclase basalts that are less weathered and altered were selected for analysis. These basalts show slightly high LOI (1.09 to 1.97).

	CIR-S1							
	926-02	926-04	926-07	926-08	926-10	926-11	926-12	926-13
SiO_2	50.79	50.31	50.60	50.51	49.49	50.09	50.27	50.29
TiO_2	0.966	0.957	0.964	0.954	0.822	1.126	1.078	1.01
Al_2O_3	15.7	15.7	15.7	15.6	17.9	16.8	16.8	16.9
FeO*	8.24	8.15	8.19	8.15	7.14	8.07	8.29	8.12
MnO	0.153	0.151	0.151	0.149	0.121	0.14	0.148	0.146
MgO	9.49	9.35	9.44	9.28	8.12	7.74	7.22	7.23
CaO	12.4	12.3	12.3	12.4	12.4	11.7	12.2	12.3
Na_2O	2.18	2.20	2.17	2.23	2.61	3.02	2.76	2.64
K_2O	0.133	0.135	0.133	0.132	0.069	0.133	0.115	0.079
P_2O_5	0.087	0.083	0.088	0.085	0.059	0.097	0.083	0.077
Total	100.14	99.41	99.72	99.50	98.70	98.89	98.95	98.83
LOI	-0.25	-0.28	-0.14	-0.23	0.24	0.34	-0.16	-0.32
Mg#	70.5	70.4	70.5	70.2	70.1	66.4	64.4	64.9
Sc	35.44	35.66	35.87	35.13	28.17	32.79	33.95	34.30
V*	240	231	234	234	177	213	241	220
Cr*	384	375	382	396	335	294	283	298
Co	43.27	42.86	43.62	43.02	62.91	53.89	77.36	107.73
Ni*	156	155	156	150	212	121	93.5	96.4
Zn	67.03	66.19	66.08	64.78	57.90	67.97	66.68	66.70
Ga	14.27	14.28	13.94	14.37	13.86	14.99	14.90	15.15
Rb	0.721	0.679	0.651	0.629	0.739	1.608	0.922	0.503
Sr	88.25	89.52	90.03	85.70	102	139	110	114
Y	26.77	26.84	26.69	26.98	21.08	26.82	28.00	26.80
Zr	57.92	57.51	55.24	57.82	43.74	78.22	66.74	65.67
Nb	1.279	1.268	1.206	1.183	0.370	2.564	1.034	0.947
Cs	0.00793	0.00912	0.01005	0.00932	0.05758	0.02895	0.01822	0.00773
Ba	9.291	8.796	8.944	8.133	1.864	18.97	5.804	5.611
La	1.996	2.035	2.019	2.008	1.329	3.199	2.132	2.035
Ce	6.182	6.392	6.229	6.093	4.939	9.074	7.117	6.720
Pr	1.072	1.118	1.101	1.133	0.878	1.616	1.306	1.274
Nd	5.964	6.187	6.026	6.159	5.279	8.326	7.311	6.963
Sm	2.155	2.206	2.209	2.298	2.070	2.783	2.590	2.589
Eu	0.873	0.869	0.825	0.846	0.822	1.064	1.019	0.915
Gd	3.343	3.207	3.216	3.297	2.796	3.693	3.696	3.553
Tb	0.613	0.628	0.627	0.620	0.533	0.682	0.676	0.643
Dy	4.029	4.155	4.049	4.224	3.365	4.205	4.431	4.232
Ho	0.905	0.943	0.928	0.946	0.791	0.954	1.002	0.963
Er	2.640	2.752	2.609	2.791	2.129	2.661	2.658	2.628
Yb	2.474	2.573	2.442	2.596	1.970	2.417	2.581	2.495
Lu	0.377	0.374	0.369	0.393	0.294	0.371	0.398	0.386
Hf	1.596	1.533	1.492	1.552	1.198	1.806	1.716	1.659
Ta	0.083	0.085	0.079	0.082	0.055	0.220	0.144	0.194
Pb	0.325	0.315	0.315	0.350	0.379	1.053	0.580	0.506
Th	0.105	0.100	0.106	0.098	0.036	0.213	0.078	0.068
U	0.041	0.030	0.053	0.042	0.073	0.083	0.039	0.028

Table 3-3. Major and Trace element compositions of basalts and dolerite from CIR-S2 and CIR-S3. FeO*: total iron as FeO. LOI: loss on ignition. Mg#: 100*Mg/(Mg+Fe^{2+}).

	CIR-S2					
	927-02	927-03	927-05	927-07	927-08	927-10
SiO_2	50.03	51.50	51.09	50.93	51.34	51.31
TiO_2	1.657	1.833	1.288	1.339	1.914	1.838
Al_2O_3	13.9	14.5	15.7	15.8	14.6	14.7
FeO*	9.96	10.29	8.53	9.07	9.81	9.68
MnO	0.185	0.184	0.157	0.161	0.18	0.179
MgO	6.84	7.05	7.96	7.67	6.32	6.51
CaO	10.1	10.0	11.4	11.3	10.2	10.4
Na_2O	2.96	3.22	2.69	2.72	3.22	3.09
K_2O	0.24	0.272	0.213	0.204	0.528	0.483
P_2O_5	0.172	0.176	0.133	0.127	0.224	0.212
Total	96.04	99.09	99.15	99.33	98.30	98.37
LOI	-0.11	-0.28	-0.11	-0.12	-0.01	-0.05
Mg#	58.7	58.7	65.9	63.7	57.2	58.2
Sc	37.96	37.22	35.37	34.64	38.93	39.01
V*	317	316	256	256	319	313
Cr*	160	141	308	266	179	185
Co	41.92	85.36	39.59	74.95	38.42	39.64
Ni*	87.4	78.5	136	117	74.8	80.4
Zn	88.44	88.38	73.06	75.70	89.11	86.71
Ga	17.27	17.42	15.26	15.68	16.78	17.07
Rb	2.248	3.756	1.877	2.595	4.959	4.273
Sr	114	123	107	111	146	149
Y	42.47	45.16	33.03	34.35	43.39	42.40
Zr	129.90	150.17	97.11	101.92	144.91	140.75
Nb	3.791	5.814	3.519	3.729	7.259	6.680
Cs	0.02683	0.03863	0.02887	0.02511	0.04944	0.04808
Ba	22.09	33.80	22.33	23.44	50.65	46.48
La	4.857	6.327	4.034	4.194	7.126	6.833
Ce	14.141	17.831	11.524	12.042	19.670	18.324
Pr	2.370	2.723	1.877	1.994	3.101	2.904
Nd	12.336	14.159	9.584	10.016	15.000	14.312
Sm	4.181	4.823	3.239	3.388	4.630	4.551
Eu	1.421	1.530	1.109	1.191	1.586	1.556
Gd	5.751	6.141	4.276	4.535	6.031	5.664
Tb	1.034	1.071	0.783	0.828	1.103	1.069
Dy	6.716	7.109	5.175	5.458	6.906	6.687
Ho	1.485	1.539	1.147	1.166	1.537	1.479
Er	4.443	4.300	3.284	3.454	4.388	4.258
Yb	3.966	4.063	3.079	3.171	3.997	3.834
Lu	0.594	0.644	0.450	0.484	0.590	0.570
Hf	3.177	3.509	2.453	2.601	3.539	3.394
Ta	0.244	0.441	0.209	0.314	0.449	0.401
Pb	0.641	0.916	0.513	0.756	1.020	0.780
Th	0.304	0.511	0.297	0.317	0.623	0.564
U	0.096	0.147	0.094	0.098	0.185	0.436

Table 3-3.

	Atlanis II FZ (Area III)							
	463-03	463-04	463-05	464-01	464-02	464-03	464-04	464-05
SiO_2	49.82	50.15	50.31	49.89	48.92	49.81	49.95	49.88
TiO_2	1.702	1.822	2.08718832	1.517	1.716	1.734	1.736	1.643
Al_2O_3	15.8	16.6	15.4	16.8	15.1	15.5	15.4	15.6
FeO*	9.64	9.23	10.11	8.72	9.33	9.33	9.43	9.30
MnO	0.178	0.162	0.181	0.16	0.173	0.173	0.172	0.169
MgO	7.31	6.37	6.11	6.89	7.87	7.75	8.16	7.75
CaO	10.5	10.4	10.2	11.2	10.4	10.7	10.6	10.8
Na_2O	3.28	3.56	3.40	3.09	3.14	3.26	3.11	3.18
K_2O	0.281	0.363	0.573	0.352	0.305	0.366	0.326	0.296
P_2O_5	0.213	0.199	0.254	0.191	0.201	0.207	0.205	0.179
Total	98.76	98.84	98.58	98.81	97.14	98.81	99.04	98.81
LOI	-0.26	-0.13	0.04	-0.08	-0.19	-0.13	-0.22	-0.25
Mg#	57.48	55.16	51.87	58.47	60.05	59.66	60.66	59.74
Sc	33.59	33.01	36.78	32.23	36.56	35.93	36.13	35.70
V	249	248	290	229	264	259	251	255
Cr	219	207	266		278	283	285	266
Co	41.59	42.04	41.22	38.88	43.04	42.40	40.85	41.22
Ni								
Zn	84.81	91.82	97.47	78.07	80.52	80.08	75.93	76.02
Ga	17.70	18.35	18.83	16.94	16.76	16.52	16.08	16.30
Rb	1.456	5.100	2.656	2.976	1.529	2.470	1.526	1.948
Sr	158.86	207.30	173.92	165.75	184	184	179	171
Y	43.60	40.39	50.52	39.22	38.97	38.37	37.87	37.54
Zr	175.86	151.74	197.39	154.66	151.41	147.51	145.33	138.25
Nb	3.769	3.435	4.038	3.009	4.095	4.025	3.900	3.151
Cs	0.01418	0.16296	0.07373	0.08051	0.01748	0.08704	0.02106	0.06664
Ba	13.26	15.53	14.43	9.84	15.05	14.72	13.87	11.57
La	5.927	5.188	6.675	5.305	5.418	5.460	5.274	4.893
Ce	18.367	15.761	20.766	16.025	16.540	16.195	15.593	14.544
Pr	3.060	2.744	3.522	2.693	2.718	2.663	2.547	2.494
Nd	15.543	14.245	18.313	13.758	13.744	13.974	12.948	13.282
Sm	5.133	4.562	5.847	4.339	4.429	4.256	4.216	4.144
Eu	1.697	1.692	2.012	1.503	1.520	1.565	1.448	1.490
Gd	6.293	5.776	7.393	5.668	5.513	5.549	5.255	5.190
Tb	1.133	1.043	1.306	1.006	0.984	0.995	0.930	0.951
Dy	7.051	6.333	8.304	6.263	6.170	6.242	5.731	6.036
Ho	1.506	1.389	1.761	1.371	1.324	1.335	1.254	1.306
Er	4.228	3.960	5.035	3.788	3.847	3.835	3.656	3.690
Yb	3.946	3.546	4.639	3.590	3.431	3.475	3.246	3.397
Lu	0.590	0.538	0.698	0.532	0.522	0.530	0.493	0.519
Hf	3.932	3.399	4.689	3.564	3.323	3.298	3.161	3.101
Ta	0.240	0.220	0.286	0.204	0.259	0.270	0.254	0.207
Pb	1.180	0.775	1.211	0.737	0.810	0.740	0.889	0.751
Th	0.258	0.201	0.250	0.205	0.242	0.233	0.239	0.206
U	0.098	0.167	0.188	0.218	0.104	0.168	0.123	0.096

Table 3-4. Major and Trace element compositions of basalts from eastern Atlantis FZ and eastern Melville FZ. FeO*: total iron as FeO. LOI: loss on ignition. Mg#: 100*Mg/(Mg+Fe).

	Atlanis II FZ (Area III)	Melville FZ (Area II)					
	464-06	171-3	171-6	171-12	171-14	171-16	171-22
SiO_2	49.56	49.47	50.24	48.66	48.65	49.36	49.52
TiO_2	1.388	1.468	1.380	1.355	1.216	1.464	1.303
Al_2O_3	16.8	17.2	16.2	17.3	16.7	16.8	17.2
FeO*	8.44	7.87	7.72	7.97	8.22	8.49	7.62
MnO	0.156	0.120	0.121	0.128	0.148	0.149	0.197
MgO	7.85	5.88	6.93	6.02	7.79	6.26	5.43
CaO	11.4	10.5	9.6	10.6	9.9	10.1	10.9
Na_2O	2.92	3.46	3.70	3.18	2.95	3.29	3.41
K_2O	0.216	0.129	0.106	0.132	0.203	0.238	0.235
P_2O_5	0.153	0.173	0.169	0.146	0.136	0.168	0.140
Total	98.82	96.35	96.14	95.49	95.96	96.34	96.00
LOI	-0.36	1.47	1.97	1.40	1.83	1.58	1.09
Mg#	62.37	57.12	61.50	57.38	62.82	56.78	55.94
Sc	31.53	33.29	33.29	30.83	32.02	33.27	35.15
V	223	196	192	189	173	202	186
Cr	274	283	318	300	334	277	295
Co	39.69	36.89	41.77	42.05	43.27	34.54	47.07
Ni		130.5	145.1	116.4	137	97	67.1
Zn	72.98	108.48	64.12	61.42	56.60	76.95	64.38
Ga	15.84	15.91	14.01	15.54	14.30	15.68	15.37
Rb	0.968	0.554	0.454	0.865	2.665	3.856	1.791
Sr	162	197	176	187	199	194	182
Y	32.96	33.11	31.45	30.39	27.51	32.14	30.09
Zr	118.67	136.78	121.82	123.46	113.44	135.22	116.01
Nb	2.640	2.798	2.732	2.336	2.533	2.769	2.338
Cs	0.01011	0.0146	0.01170	0.05106	0.21439	0.23494	0.12068
Ba	9.09	7.45	4.06	11.26	13.77	9.08	9.37
La	4.063	5.332	5.005	4.425	4.440	5.114	4.202
Ce	12.612	15.479	14.572	13.742	13.169	15.102	12.687
Pr	2.083	2.510	2.397	2.306	2.129	2.474	2.079
Nd	10.794	12.253	11.515	11.403	10.141	11.833	10.348
Sm	3.687	3.706	3.559	3.565	3.143	3.835	3.379
Eu	1.302	1.320	1.236	1.278	1.146	1.322	1.215
Gd	4.675	4.622	4.488	4.327	3.899	4.584	4.192
Tb	0.832	0.813	0.773	0.753	0.673	0.798	0.732
Dy	5.193	5.065	4.805	4.812	4.372	5.081	4.711
Ho	1.133	1.105	1.058	1.046	0.941	1.083	1.015
Er	3.196	3.200	3.108	3.074	2.862	3.238	3.038
Yb	2.985	2.966	2.860	2.751	2.567	2.944	2.750
Lu	0.449	0.441	0.420	0.413	0.377	0.428	0.405
Hf	2.770	2.883	2.674	2.661	2.383	2.846	2.560
Ta	0.183	0.204	0.203	0.175	0.174	0.192	0.186
Pb	0.705	0.828	0.567	0.766	0.577	0.793	0.562
Th	0.174	0.203	0.193	0.162	0.173	0.192	0.163
U	0.074	0.163	0.162	0.116	0.077	0.127	0.117

Table 3-4.

3.1 Mineral chemistry

Major element compositions of olivine, plagioclase and spinel of basalts and dolerite from CIR-S2 and CIR-S3 were analyzed using by an electron probe micro-analyzer (JEOL JXA-8600SX) at Niigata University. Conditions of measurement are as bellow, acceleration voltage 15 kV, beam current 1.30×10^{-8} A, beam diameter 1μm and corrected by Oxide ZAF. Compositions of these minerals are shown in Table 3-5.

Mineral compositions of basalts and dolerites from CIR-S2

Forsterite % (Fo %) of olivine micro phenocrysts of basalts from the Dive #926 conical cone show 88.0 to 89.2 and those of basalts and dolerite from the AVW show 86.2 to 87.8. Olivine phenocrysts of basalts and dolerite from the AVW have Fo % 88.1 to 90.3. Dolerite (926-10; Moderately plagioclase olivine phyric dolerite) that obtained from the lower part of the AVW have highest value of Fo % 90.3. Basalt of 926-04 from the conical cone during the Dive # 926 has phenocrysts of only plagioclase. Plagioclase phenocryst of euhedral type has anorthite % (An %) 81.4 and corrosion type has An % 76. Micro-phenocrysts of basalts from the conical cone have An % 80.4 to 86.1. An % of plagioclase phenocrysts of basalts and dolerite from the AVW show 75.2 to 88.8. Plagioclase micro-phenocrysts of basalts and dolerites show 68.9 to 84.8. Cr# (Cr# = Cr/(Cr+Al)) values of spinel range from of basalts from the AVW 0.330 to 0.439.

Mineral compositions of basalts from CIR-S3

Fo % of olivine micro phenocrysts of basalts from the Dive #927 show 84.0 to 86.1. Plagioclase phenocrysts of basalts have An % 84.0 to 86.8 and micro-phenocrysts have An % 66.8 to 68.7. Spinel Cr# of basalt is 0.426.

Olivine

Sample No.	926-04					926-10					
Point No.	1	5	19	21	25	78	81	82	83	86	93
Type	micro	micro	micro	micro	micro	phenocryst	micro	micro	micro	phenocryst	phenocryst
SiO2	40.03	39.70	39.73	39.78	39.81	40.07	39.96	39.87	39.42	39.91	39.64
TiO2	0	0	0	0.004	0.029	0.089	0.083	0.067	0.093	0.078	0
Al2O3	0.075	0.029	0.016	0.017	0.068	0.033	0.021	0.016	0.029	0.031	0.041
Cr2O3	0.067	0.051	0.031	0.035	0.039	0.094	0.058	0.105	0.062	0.074	0.105
FeO	11.37	10.36	11.21	10.51	11.71	9.49	11.10	11.19	10.89	10.94	11.58
MnO	0.126	0.136	0.114	0.223	0.003	0.058	0.119	0.08	0.036	0.061	0.216
MgO	48.75	48.18	47.45	47.84	48.15	49.73	48.76	48.84	48.13	48.70	48.31
CaO	0.286	0.308	0.31	0.334	0.318	0.273	0.298	0.298	0.292	0.289	0.276
NiO	0.293	0.263	0.296	0.273	0.239	0.242	0.252	0.262	0.193	0.252	0.082
Total	101.0	99.1	99.2	99.0	100.4	100.1	100.7	100.8	99.2	100.4	100.3
Fo%	88.4	89.2	88.3	89.0	88.0	90.3	88.7	88.6	88.7	88.8	88.1

Sample No.	926-12				926-13			927-05		
Point No.	56	64	65	66	40	41	48	33	34	35
Type	phenocryst	micro	micro	micro	micro	micro	micro	micro	micro	micro
SiO2	39.55	39.63	39.85	39.23	39.71	40.05	39.88	39.48	38.98	39.45
TiO2	0.075	0.069	0.073	0.084	0.079	0.056	0.034	0.052	0.073	0.068
Al2O3	0.041	0.043	0.026	0.023	0.052	0.038	0.031	0.055	0.062	0.033
Cr2O3	0.089	0.062	0.07	0.023	0.046	0.093	0.108	0.069	0.111	0.077
FeO	11.26	11.99	11.97	13.47	13.42	12.53	12.58	13.50	15.41	14.42
MnO	0.03	0.091	0.075	0.077	0.141	0.044	0.116	0.077	0.149	0.157
MgO	48.47	48.21	48.01	47.03	47.61	48.21	47.94	47.00	45.41	45.73
CaO	0.277	0.313	0.29	0.297	0.306	0.338	0.33	0.285	0.343	0.336
NiO	0.249	0.18	0.208	0.221	0.208	0.201	0.257	0.216	0.185	0.223
Total	100.0	100.7	100.6	100.6	101.6	101.6	101.3	100.8	100.8	100.5
Fo%	88.5	87.8	87.7	86.2	86.3	87.3	87.2	86.1	84.0	85.0

Plagioclase

Sample No.	926-04									
Type	phenocryst				phenocryst				micro	micro
	core	core	rim	rim	core	core	rim	rim	core	core
Point No.	7	9	8	10	11	16	12	15	17	23
SiO2	47.81	47.52	46.89	49.63	48.79	49.25	48.86	48.66	47.48	45.79
TiO2	0	0	0	0	0.042	0	0.054	0	0.011	0.057
Al2O3	32.293	32.461	32.834	30.746	31.081	31.454	31.633	31.555	32.607	33.679
FeO	0.311	0.33	0.308	0.536	0.403	0.379	0.346	0.433	0.338	0.293
MnO	0.01	0.03	0.02	0.02	0.07	0.02	0.02	0.03	0.06	0.06
MgO	0.314	0.314	0.293	0.374	0.269	0.274	0.319	0.307	0.303	0.249
CaO	16.23	16.35	16.65	15.10	15.03	15.15	15.37	15.66	16.26	17.41
Na2O	2.102	2.062	1.894	2.762	2.789	2.639	2.494	2.389	2.179	1.548
K2O	0	0.007	0.009	0.004	0.01	0	0	0.002	0.015	0.003
Total	99.1	99.1	99.1	99.3	98.6	99.2	99.2	99.1	99.4	99.3
An%	81.0	81.4	82.9	75.1	74.8	76.0	77.3	78.4	80.4	86.1

Table 3-5. Olivine, plagioclase and spinel compositions of basalts and dolerites from CIR-S2 and CIR-S3.

Sample No.	926-10									
Type	phenocryst			phenocryst		phenocryst		phenocryst		micro
	core	core	rim	core	rim	core	rim	core	rim	core
Point No.	75	76	77	89	91	95	96	97	98	84
SiO2	47.99	48.89	49.22	46.36	49.26	46.22	50.84	46.67	49.41	46.27
TiO2	0.057	0	0.022	0.026	0.026	0.017	0.08	0.003	0.025	0
Al2O3	31.75	31.20	31.02	33.23	31.03	33.44	29.30	32.84	31.07	33.20
FeO	0.306	0.339	0.37	0.319	0.416	0.287	0.559	0.298	0.33	0.288
MnO	0	0.036	0.02	0.031	0.034	0.053	0.034	0.022	0.034	0
MgO	0.205	0.231	0.28	0.216	0.276	0.173	0.327	0.198	0.244	0.205
CaO	15.65	14.95	14.70	16.73	14.93	16.95	13.31	16.63	14.92	17.04
Na2O	2.442	2.716	2.779	1.804	3.025	1.716	3.852	1.953	2.966	1.682
K2O	0.016	0.013	0.011	0.012	0.01	0	0.007	0.004	0	0
Total	98.5	98.4	98.5	98.9	99.2	99.0	98.3	98.7	99.0	98.8
An%	77.9	75.2	74.5	83.6	73.1	84.5	65.6	82.5	73.5	84.8

Sample No.	926-12						
Type	phenocryst		phenocryst		phenocryst		micro
	core	rim	core	rim	core	rim	core
Point No.	60	61	62	63	68	70	67
SiO2	48.32	45.52	46.54	45.98	45.69	46.29	48.54
TiO2	0.021	0	0.031	0.017	0.029	0.055	0.061
Al2O3	31.73	33.51	32.89	32.92	33.21	33.36	31.60
FeO	0.29	0.32	0.277	0.212	0.379	0.309	0.355
MnO	0.028	0.031	0.034	0.062	0.028	0.042	0.028
MgO	0.297	0.214	0.249	0.231	0.205	0.198	0.235
CaO	15.8	17.484	16.907	16.939	17.424	16.694	15.087
Na2O	2.422	1.414	1.779	1.623	1.501	1.656	2.724
K2O	0.008	0	0	0.002	0.047	0.023	0.02
Total	98.9	98.5	98.7	98.0	98.5	98.7	98.6
An%	78.2	87.2	84.0	85.2	86.3	84.7	75.3

Sample No.	926-13							
Type	phenocryst		phenocryst		phenocryst		micro	micro
	core	rim	core	rim	core	rim	core	core
Point No.	42	44	45	47	49	51	38	39
SiO2	47.23	49.58	45.177	49.214	47.833	46.021	50.73	49.90
TiO2	0.076	0.047	0.051	0.048	0.066	0.042	0.063	0.07
Al2O3	32.79	31.25	34.20	31.47	32.38	33.59	30.33	30.74
FeO	0.433	0.384	0.379	0.535	0.328	0.365	0.362	0.409
MnO	0.01	0.00	0.059	0.02	0	0	0.00	0.02
MgO	0.243	0.25	0.192	0.274	0.259	0.21	0.273	0.275
CaO	16.50	14.82	17.848	14.903	16	17.148	13.83	14.25
Na2O	2.134	2.988	1.217	3.018	2.377	1.636	3.455	3.429
K2O	0.046	0	0.042	0.035	0	0	0	0.044
Total	99.5	99.3	99.4	99.6	99.3	99.0	99.0	99.2
An%	80.8	73.3	88.8	73.0	78.8	85.3	68.9	69.5

Table 3-5.

Sample No.	927-05					927-07	
	phenocryst			micro	micro	phenocryst	
Type	core	core	rim	core	core	core	rim
Point No.	27	30	29	36	37	99	104
SiO2	46.09	45.84	50.51	51.22	50.40	46.37	45.92
TiO2	0.04	0.031	0.114	0.09	0.085	0	0.05
Al2O3	33.38	33.83	30.12	29.95	30.06	32.90	33.74
FeO	0.298	0.26	0.599	0.571	0.564	0.255	0.29
MnO	0.01	0.00	0.04	0.00	0.03	0.048	0.014
MgO	0.254	0.231	0.309	0.254	0.268	0.258	0.219
CaO	17.28	17.66	13.82	13.54	14.06	16.836	17.14
Na2O	1.796	1.481	3.593	3.678	3.482	1.775	1.392
K2O	0	0	0.063	0.067	0.089	0	0.001
Total	99.2	99.3	99.3	99.4	99.1	98.6	98.8
An%	84.2	86.8	67.8	66.8	68.7	84.0	87.2

Spinel

Sample No.	926-10			926-12	927-07
SiO2	0.133	0.08	0.123	0.097	0.084
TiO2	0.253	0.41	0.495	0.419	0.363
Al2O3	39.43	31.32	29.54	30.37	31.71
Cr2O3	28.97	34.33	37.15	35.45	35.10
FeO	12.56	16.52	16.90	17.14	17.96
MnO	0.062	0.289	0.103	0.167	0.183
MgO	19.14	16.88	16.51	16.36	15.82
CaO	0.022	0.016	0.032	0.022	0.022
NiO	0.186	0.195	0.146	0.121	0.178
Total	100.84	100.10	101.06	100.16	101.47
Mg#	0.442	0.424	0.419	0.418	0.406
Cr#	0.330	0.424	0.458	0.439	0.426

Table 3-5.

3.2 Data from PetDB

The PetDB (http://www.petdb.org/) is database which provides data for bulk rock compositions and isotope ratio of oceanic rocks from the world. In this study, major and trace element compositions of MORBs were also obtained from this database. MORB data from the CIR and the SWIR satisfying conditions for the sample location from spreading center and fresh basalt were selected. All major elements data were recalculated as total Fe as FeO and adjusted to 100 % on anhydrous basis.

In addition, there are 2 type data of basalt compositions from the database, "whole rock analyses" and "glass analyses", which are distinctively shown in this paper. The presence of a glass in basalt is usually used to indicate a freshness of the basalt. In general, the glass composition is regarded to show the melt composition than the bulk rock composition, therefore, many scientists use only glass compositions of basalts for discussion. However, as comparing bulk rock compositions and glass compositions of basalts from study area, there are no significant differences. Consequently, both of whole rock and glass data are used in this study.

4 Bulk rock compositions of MORBs near the Rodriguez Triple Junction in the Central Indian Ridge

4.1 Bulk rock compositions of basalts and dolerite

Major and trace elements features

Compositions of Dive #926 basalts and #927 basalts show a broad range covering over all range of those from the CIR, though they were collected from narrow restricted areas within the CIR (Figure 4-1). It is important to note that both the most primitive and the most evolved basalt are obtained from this study area.

Basaltic rocks from Dive #926 are divided into a high-MgO (wt%) group (MgO = 9.3 to 9.4 wt%) (926-02, 04, 07 and 08) and comparatively low-MgO (wt%) group (MgO = 7.2-8.2 wt%) (926-10, 11, 12 and 13). High-MgO group shows primitive compositions (Mg#: $100 \times Mg/(Mg + Fe^{2+})$ = 70.2 to 70.5) and low-MgO (except 926-10) group has less evolved values (Mg#: 64.4 to 66.4). 926-10 (moderately plagioclase-olivine-phyric dolerite) has MgO (wt%) = 8.23 but the FeO* content (7.25 wt%) is lower than others of the low-MgO group, therefore it has high Mg# (70.1). Bulk rock compositions of the high-MgO group (4 samples) are surprisingly homogeneous, on the other hand, those of low-MgO group exhibit a some compositional range possibly due to a fractional crystallization. These two groups are obtained from different situations, respectively. The high-MgO basalts are collected from the conical cone within a neo-volcanic zone while the low-MgO basalts are obtained from the axial valley wall.

Basalts from the Dive #927 have MgO ranging from 6.4 to 8.0 wt% showing more evolved features of the Dive #927 basalts than those of the Dive #926 basalts. These basalts from the Dive #927 show also an unique compositional feature at each sampling point. The most primitive rocks occur at the OVZ (Mg#: 63.7 to 65.9), most evolved rocks at the AVW (Mg#: 57.2 to 58.2) and intermediate

Figure 4-1. Major element compositions of basalts and dolerites from Dive #926 and Dive #927. Gray triangles show MORB compositions from the CIR. The Dive #926 was carried out within the CIR-S2, and the Dive #927 was carried out within the CIR-S3.

Figure 4-1.

basalts at the NVZ (Mg#: 58.7), respectively. Although the basalts from the Dive #927 have unique compositions at each locality, they have a tight correlation in MgO-variation diagrams (Figure 4-1). With decreasing MgO, SiO_2, TiO_2, FeO*, Na_2O, K_2O and P_2O_5 contents of basalts increase, while Al_2O_3 and CaO decrease (Figure 4-1).

Trace element compositions of basaltic rocks from this study show also similar behaviors to those of major elements compositions. Trace elements compositions of basalts from the conical cone (Dive #926) are also very homogeneous. In contrast, trace element compositions of basalts from the AVW (Dive #926) and the Dive #927 have considerable compositional ranges, respectively, which are derived from magmatic differentiation. Figure 4-2 shows a variation of trace

926-10
(Moderately plagioclase phyric olivine phyric dolerite)
CIR
Dive #926 (conical cone)
Dive #926 (AVW)
Dive #927
Cr (ppm)
Ni (ppm)
Rb (ppm)
Sr (ppm)
Zr (ppm)
Nb (ppm)
Yb (ppm)
Hf (ppm)
MgO (wt%)
MgO (wt%)

Figure 4-2. MgO variation diagrams of trace elements of basalts and dolerites from the CIR-S2 and CIR-S3. Gray triangles for compositions of CIR basalts from PetDB.

element compositions versus MgO contents. It is apparent that negative correlation is observed for incompatible trace elements and MgO contents while positive correlation is obvious for compatible trace elements. The samples of 926-10 has higher Ni content than those from the AVW (Dive #926) samples, due to a presence of olivine phenocrysts attaining 2.2 modal %.

Basalts from the AVW (Dive #927-08 and 927-10) exhibit high Rb and Sr contents, consistent with high volatile components suggested from a high vesiculation in those basalts.

Figure 4-3 is trace elements spider diagrams. Concentrations of basalts from the Dive #926 conical cone show similar patterns to the N-MORB from the Mid Atlantic Ridge (MAR) (Klein 2003). However, they have higher Cs, Rb and Ba contents than the N-MORB. Although basalts and dolerites from the Dive #926 AVW have patterns close to the N-MORB, trace element compositions of 926-10 exhibit lower contents than the N-MORB, and those of 926-11 show higher content up to intermediate concentrations between the N-MORB and the T-MORB, in particular in high-incompatibility elements. On the other hand, trace element compositions from the Dive #927 basalts are higher concentrations than those of the Dive #926 basalts and dolerites, and exhibit the T-MORB pattern. Furthermore, the trace element contents from the Dive #927 AVW (927-08 and 927-10) and the NVZ (927-03) are higher than the T-MORB.

REE patterns of the conical cone (Dive #926) basalts are similar to the N-MORB pattern (Figure 4-4). REE patterns of the Dive #927 basalts are distinct from the N-MORB patterns in respect to much higher concentrations in LREE, but cross those of the E-MORB pattern. They are similar to the T-MORB pattern. Thus, trace element compositions from the Dive #926 indicate that these basaltic rocks have the N-type MORB (N-MORB) signatures. While, basaltic compositions of the Dive #927 show the T-MORB signatures.

Figure 4-3. Continued next page.

Figure 4-3. (continued). Multi elements spider diagram. Values are normalized to primitive mantle (Sun and McDonough, 1989). MAR N-MORB, T-MORB and E-MORB values after Klein (2003). Toward to left, imcompatibility becomes higher.

Figure 4-4.(next page) REE patterns of basalts and dolerite from Dive #926 and 927. REE concentrations are normalized by the chondrite (Sun and McDonough, 1989). Compositions of MAR N-MORB, MAR T-MORB and MAR E-MORB from Klein (2003), and these data show from La to Yb. REE concentrations of 4 basalts from the conical cone show extremely homogeneous feature in this graph.

100
10
1
Sample/chondrite
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Yb
Lu
926(CC)
926-12
MAR N-MORB
926-10
926-13
MAR T-MORB
926-11
MAR E-MORB

100
10
1
Sample/chondrite
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Yb
Lu
927-02
927-07
MAR N-MORB
927-03
927-08
MAR T-MORB
927-05
927-10
MAR E-MORB

Using the Zr-Nb-Y discrimination diagram (Meschede, 1986), all basalts and dolerites from this study area are plotted within N-MORB field (Figure 4-5). REE concentrations from the conical cone (Dive #926) basalts are also quite homogeneous. The 926-10 dolerite has most depleted REE contents, and those of the 926-11 dolerite show LREE-enriched pattern (Figure 4-4). All REE patterns from Dive #927 have a negative Eu anomaly. Within range of REE concentrations for Dive #927 basalts, those of the NVZ and the AVW are higher than those of the OVZ.

Figure 4-5. The discrimination diagram for basalts (after Meschede, 1986). Border lines of the diagram are followed by Meschede (1986).

Compared to the bulk rock composition of basalt from the AVW (Dive #926), those of the Dive #927 are slightly evolved and some major elements contents (SiO_2, TiO_2, FeO*, K_2O and P_2O_5) are higher than those from the AVW of the Dive #926. However, it is noted that the Na_2O content of basalts from both sites shows

similar compositions. Almost incompatible elements contents of the Dive #927 basalts are higher than those of the AVW (Dive #926) (Figure 4-1). However, Sr, Ni and Cr contents of both areas show similar values each other at given MgO contents (Figure 4-2).

4.2 Discussion

High K/Ti signatures of basalts and dolerite

As described above, trace element compositions of basalts from the Dive #927 have T-MORB signatures, and show high Rb and Sr contents. The T-MORB is defined as having a compositional feature between the N-MORB and the E-MORB which show high incompatible elements concentrations. Detrick et al. (2002) define K/Ti ratio < 0.09 as N-MORB, 0.09 < K/Ti < 0.15 as T-MORB and K/Ti > 0.15. Reynolds et al. (1992) also define T-MORB as Ba/TiO_2 > 10 or K_2O/TiO_2 > 0.09.

Figure 4-6. K/Ti and Ba/TiO2 ratios of basalts and dolerites.

Using major element contents, K/Ti ratios of the Dive #926 have 0.11-0.2, and those of the Dive #927 have 0.20-0.38. Ba/TiO_2 ratios of basalts and dolerite from the Dive #926 are lower than 10 (except 926-11), and those from the Dive #927 are higher than 10 (Figure 4-6). These high K/Ti signatures of the Dive #926 basalts and dolerites are reflected in low TiO_2 contents rather than the N-MORB.

Magma system under CIR-S2

Major and trace element compositions of basalts and dolerites from the CIR-S2 and the CIR-S3 show a wide range covering whole the CIR basalts compositions (Figures 4-1 and 4-2). Basalts from the conical cone within the CIR-S2 have the most primitive feature, and those of the AVW within the CIR-S3 are most evolved in the compiled the CIR basalts. Basalts compositions from this study area show distinct characteristics depending on their locations and segments, despite of only 87 km distance between the CIR-S2 and the CIR-S3.

Basalts from the conical cone within the CIR-S2 have primitive compositions (Mg#: 70.2 to 70.5) which is in equilibrium with Fo 88.7 to 88.8 olivine assuming $K_D = 0.3$ (Roeder and Emslie, 1970) which are comparable with olivine compositions of a mantle peridotite. In addition, olivine microphenocrysts of aphyric basalt from the conical cone also have high Fo contents (88 to 89). The lherzolite from the Atlantis Bank in the SWIR have Fo 90 olivine (Warren and Shimizu, 2010). These suggest that basalts from the conical cone are nearly primitive and derived from the mantle without fractional crystallization. Furthermore, a dolerite from the AVW within the CIR-S2 have also the primitive olivine phenocryst (Fo = 90.3), supporting that the primitive melts are frequently extruded without fractional crystallization. Configuration of the conical cone indicates that the conduit of basaltic magmas from the mantle is focused (pipe-like) and the eruptions occur at time intervals on a sea floor. Thus, several monogenetic volcanoes are probably produced by a small amount of local intermittent igneous activity within the CIR-S2.

It is indicated that the melt which have not undergone fractionation erupt at slow-spreading ridges. Both of primitive basalts which have not fractionated

gabbros and evolved basalts which have fractionated gabbros are erupted at the Atlantis Bank in the SWIR with a ultra-slow spreading rate (Neo, 2005). Furthermore, primitive gabbros and evolved gabbros were also obtained, it is represented that exclusive magma system under the slow-spreading ridge.

Different crystallization system of basalts from Dive #926 and #927

The AVW from the CIR-S2 exhibits a crustal section from 3545 to 3024m water depth and sheeted dike complex are observed at the lower part of the AVW (3303m). Wide compositional ranges and occurrence of evolved basalts and dolerites compositions from the AVW within the CIR-S2 indicate that considerable fractional crystallization occurred to form the crustal section. The variations of major element compositions from the AVW (Dive #926) basalts and dolerites are mainly controlled by clinopyroxene fractionation (Figure 4-7). However, this result does not account for the relation between compositions of the conical cone and those of the AVW within the CIR-S2. It suggests that basaltic compositions underlie the CIR-S2 had changed for a short time due to changes of a melting degree, pressure or a mantle source.

Basaltic compositions from the CIR-S3 show a single trend. This compositional trend of the CIR-S3 basalts can be controlled by olivine - plagioclase - clinopyroxene fractionation (Figure 4-7). However, within Dive #927 basalts, the most primitive basalts (Mg# 66) show slightly evolved composition. Additionally, it seems that major and trace element compositions of #926 (CC) fall on primitive end member of those of #927 basalts trend.

Figure 4-7. MgO-variation diagram of major elements. Blue and red arrows are subtraction trends followed by Cox et al. (1979) using the clinopyroxene composition of gabbro from the Atlantis bank (Neo, 2005) for basalts and dolerites compositions from the AVW in Dive #926. For basalts from Dive #927, using compositions of olivine, plagioclase and clinopyroxene of gabbro (Ol: 10%, Pl: 35% and Cpx: 55%) from the Atlantis bank (Neo, 2005).

Using major element compositions of the conical cone basalt (926-07) which had not undergone significant fractional crystallization, as a starting material, the residual liquid compositions at 1 kbar (within a crustal section) and 5 kbar (within an upper mantle condition) are calculated by MELTS (Ghiorso and Sack, 1995)(Figure 4-8). H_2O content in the starting material is hypothecated as 0.25 % which is water content of most fresh MORB. Major element contents of basalts fractionated by different styles of fraction, fractional crystallization and equilibrium crystallization, are also calculated at each pressure.

Figure 4-8. Comparison of basalt compositions from Dive #926 and 927 with calculations of crystallizations by MELTS (Ghiorso and Sack, 1995). Starting material is basalt (926-07) from the conical cone of the segment 2. Results of fractional and equilibrium crystallizations at 1 kbar and 5 kbar are also shown.

Calculated values of SiO_2, TiO_2, FeO, K_2O and P_2O_5 contents at 1 kbar are higher than those values at 5 kbar, and Al_2O_3 content is low. In range of basalts MgO contents from 926AVW and 927 (6.43 to 8.23), MnO contents at 1 kbar slightly higher and CaO contents at 1 kbar lower than those values at 5 kbar.

Na_2O contents do not show a large difference at 1 kbar and 5 kbar. In addition, it shows that difference of fractionation style is not effective than different compositions for differing pressures.

Major element compositions from the Dive #927 basalts are consistent with the liquid line of decent (LLD) at 1 kbar and those of Dive #926 AVW basalts and dolerites are consistent with the LLD at 5 kbar. These results suggest that basalts from Dive #927 had undergone low pressure fractional crystallization within a crustal level. On the other hand, basalts and dolerites from Dive #926 AVW had undergone high pressure fractional crystallization at upper mantle conditions. Therefore, it is apparent that there is a significant difference in crystallization pressures between the CIR-S2 and the CIR-S3. This may be interpreted by the thermal difference between the two segments.

Based on the MELTS calculation, olivine is fractionated first at 1 kbar and 1220°C, then, olivine + clinopyroxene + feldspar are fractionated at 1200°C. While, clinopyroxene is fractionated first at 5 kbar and 1275°C, then clinopyroxene + feldspar are fractionated at 1235°C. This result is consistent with the subtraction calculation for Dive #926 and #927, respectively.

Assuming that conductive cooling of a mantle had efficiently occurred under the CIR-S2, ascending melts in the upper mantle must be partly crystallized in the mantle. Therefore, melts were partly solidified within the mantle as intrusive rocks, and thin oceanic crust was formed. Thus, basalts and dolerites from the AVW within the CIR-S2 were derived from evolved melts which underwent high-pressure fractional crystallization. On the other hand, basaltic melts which were free from the high pressure fractional crystallization erupted at the conical cone.

Under the CIR-S3, on the other hand, the melts ascend across the Moho without crystallization within the mantle due to high mantle potential temperatures. Consequently, thicker oceanic crust was formed, and melt has undergone fractionation at low pressure and comparatively evolved basalts have erupted due to the fractionation of thicker lower crust.

It is also possible that composition of the T-MORB signatures of the itself CIR-S3 cause thicker oceanic crust. Because, enrichment in LIL component of T-MORB may lead to the mantle melting at deeper depth. Therefore, larger amounts of melts are produced, and thicker oceanic crust is formed.

Figure 4-9. Models of magma system beneath the CIR-S2 and the CIR-S3 modified from Langmuir et al. (1992). Under influenced of low mantle potential temperature, prtial melting of the mantle have terminated and gabbros are fromed within upper mantle (left-side). High mantle potential temperatures result in larger melting colum and thicker oceanic crust than those of cold mantle conditions (right-side).

Figure 4-9 is models of the ridge systems beneath the CIR-S2 and the CIR-S3. Low mantle potential temperature under the CIR-S2 causes stopping partial melting of the mantle at deeper depths, and a part of melts may solidify and form a gabbro within the upper mantle. For this reason, the melts which are supplied beyond the Moho have undergone high pressure fractionation and result in thin oceanic crust. On the other hand, mantle potential temperatures are high under the CIR-S3, almost melts are supplied beyond the Moho and form thick oceanic crust. Therefore, the melts undergone low pressure fractionation and evolved basalts erupted. These are consistent with geophysical observations which indicate thick oceanic crust and high mantle temperature for the CIR-S3 based on a mantle burger anomaly (Wakabayashi, 2003).

As mentioned above, it is clear that different compositions of parental material and variant fractional crystallizations occur at between adjacent segments. Therefore, erupted basalts show different compositional trends for major and trace elements. Furthermore, delicate sampling and analysis of basalts traversing the ridge axis revealed that basalts compositions have been changed in time within same segment.

Comparison of CIR basalts

During KH93-3, 2 dredges (DR1 and DR3) have been done within the CIR-S1, and compositions of a glass of basalts are reported (Fujii et al., 1995) (Figure4-10). Dredge site of DR1 is located at the segment center of the CIR-S1, and DR3 is located at the northern segment end of the CIR-S1 near the CIR-S2. Major elements variations of the CIR-S1 basalts are shown in Figure 4-11. MgO contents of DR1 and DR3 basalts show a narrow range from 7.82 to 8.24 wt%, and not show crystallization trends, like a trend of basalts from the Dive #927. Major element contents of basalts from DR1 are similar to those from DR3. However, K_2O contents of DR1 basalts are higher than those from DR3. Comparing to the basalts compositions from the CIR-1 with those from the CIR-2 and the CIR-3, those of the CIR-1 plotted at the higher MgO end of the the CIR-3 trend.

Trace element concentrations of the CIR-S1 basalts show different signatures between DR1 and DR3. Basalts compositions from DR1 are similar to those of the CIR-S3 (i.e., T-MORB) (Figure 4-12), and those of DR-3 show CIR-S2 signatures (N-MORB) which have low concentrations of high incompatibility elements, respectively. As DR-3 site is located near the CIR-S2, it seems that basalt compositions from DR-3 resemble to those from the CIR-S2.

Figure 4-10. (next page) Bathymetoric map of RTJ after Fujii et al., 1995. Dredge sites and rock core sites are polotted during KH93-3. Basalts data from DR1 and DR3 within the CIR-S1, and DR4 and DR9 within the RTJ area are used in this study.

69° 50'
70° 00'
70° 10'
-25° 20'
-25° 30'
-25° 40'
-25° 50'
DR3
RC5
RC4
DR1
RC1
DR4
RC6
DR5
DR27
DR9
DR15
DR8
DR2
DR16
DR25
DR26
DR17
RC10
RC9
DR7
RC7
RC8
RC2
RC3
RC11
DR6
RC12
DR20
RC13

Figure 4-10.

Dive #926 (conical cone)
Dive #926 (AVW)
Dive #927
CIR-S1(DR1)
CIR-S2(DR3)
SiO₂ (wt%)
TiO₂ (wt%)
Al₂O₃ (wt%)
FeO* (wt%)
MnO (wt%)
CaO (wt%)
Na₂O (wt%)
K₂O (wt%)

100
10
1
0.1
Sample/primitive mantle
Cs Rb Ba Th U Ta Nb La Ce Pb Sr P Nd Zr Sm Eu Ti Dy Y Er Yb
DR1-A1
DR1-B2
DR3-A1
DR3-B1
MAR N-MORB
MAR T-MORB
MAR E-MORB

100
10
1
0.1
Sample/primitive mantle
Cs Rb Ba Th U Ta Nb La Ce Pb Sr P Nd Zr Sm Eu Ti Dy Y Er Yb
DR1-A1
DR1-B2
DR3-A1
DR3-B1
MAR N-MORB
MAR T-MORB
MAR E-MORB

Figure 4-11.

Figure 4-11. (previous 2 pages) Glass compositions of basalts from the CIR-S1 on MgO variation diagram. Basalts and dolerite from the CIR-S2 and the CIR-S3 are also plotted. Gray triangles show basalts compositions from the CIR. DR1 site is located at the segment center of the CIR-S1, and DR3 is located at the segment end of CIR-S1. Major element compositions of DR1 and DR3 basalts by Fujii et al. (1995).

Figure 4-12. (previous page) Trace element concentrations of basalt glass from the CIR-S1. Trace element contents of 4 samples from the PetDB. P contents of CIR-S1 basalts are not reported. DR1-A1: HAK9303-001-A1, DR1-B2: HAK9303-001-B2, DR3-A1: HAK9303-003-A1, DR3-B2: HAK9303-003-B2. In upper graph, light blue lines show trace element concentrations of the CIR-S2 basalts and dorelites, in lower graph, light green lines show those of the CIR-S3.

5 Regional compositional variations of MORB along the Southwest Indian Ridge

5.1 Compositions of MORBs along the SWIR

New classification: Area I to Area IV

Based on precedent studies, we considered compositional variations of MORBs along the eastern SWIR. In this study, bulk rock compositions from Dive #463, #464 and Dive 10K#171 are used. Basalt compositions from Pet DB are also used, to discuss regional variations of basalt compositions along the SWIR.

Figure 5-1. Distributions of Area I to IV basalts along the eastern SWIR from the Gallieni FZ to the RTJ. Red circles are sampling positions of basalts which are used in this study.

4 areas are defined from the Rodriguez Triple Junction (RTJ) to the Gallieni FZ (52°20′E) based on the characteristics of basalts compositions; Area I: RTJ (70°E)-69°E, Area II: (69°E)-Melville FZ (60°45′E), Area III: Melville FZ - Atlantis II FZ (57°E) and Area IV: Atlantis II FZ –Gallieni FZ (52°20′E) (Figure 5-1). The boundary between Area I and Area II is not a fracture zone, but there is a compositional gap between the 2 areas (to be described next). Area I and II correspond to Type 3 by Natland (1991) and Zone A by Meyzen et al., (2003), Area III: Type 3 by Natland (1991) and Zone B by Meyzen et al. (2003), Area IV: Type 2 by Natland (1991) and Zone B by Meyzen et al. (2003), respectively. Compositions of Dive #463 and 464 basalts are defined as Area III, and those of Dive 10K#171 as Area II.

Bulk rock compositions

Along axis variations of basalt composition are shown in Figure 5-2. TiO_2 contents of basalt increase from the RTJ to the Atlantis II FZ (Area I to Area III), then decrease from the Atlantis II FZ to the Gallieni FZ (Area III to Area IV). Along axis variation of Na_2O contents exhibits a peculiar behavior. There is a big gap between Area I and Area II, and 2.2 to 3.6 wt% at Area I while 3.1 to 4.5 wt% at Area II. On the other hand, the Na_2O contents in the Area III and IV tend to decrease toward the Atlantis II FZ which divides the Area III and IV. Al_2O_3 contents increase from the RTJ to the Melville FZ (Area I to Area II), and rapidly decrease beyond the Melville FZ, then slightly decrease until the Atlantis II FZ in the Area III, and show constant values from the Atlantis II FZ to the Gallieni FZ (Area III to Area IV). FeO* contents in Area I and II are relatively lower than those of Area III and IV. Mg# values from Area I (58-69) basalts show slightly higher than Area II (53-68) and Mg# values from Area III (49-63) and Area IV (52-62) show more evolved values. Therefore, Mg# values decrease from Area I to Area IV. F (wt%) which indicates a degree of partial melting is also shown Figure 5-2. F (wt%) of Area I basalts are the highest, and drastically decrease in Area II, and increase from Area II to Area III.

Bulk rock compositions of basalts from each area (Area I to IV) show different features, respectively (Figure 5-3). MgO contents of study area range from 7.3 to

Figure 5-2. Along axis compositional variations of MORBs from 70°E to 52°20′E.

10 wt% for Area I, 5.7 to 9.5 wt% for Area II, 6 to 8.5 wt% for Area III and 6.8 to 8.5 wt% for Area IV, showing that MgO contents of Area I are the highest and those of other area are similar ranges. SiO_2 contents increase roughly with decreasing MgO as a whole, but different trends are recognized for each area. In particular, SiO_2 contents of Area I basalt show higher, while those of Area IV

Figure 5-3. Along axis compositional variations of MORBs from 70°E to 52°20′E.

show lower at given same MgO contents. TiO_2 and FeO* contents show also a negative correlation with MgO contents. However, we can distinguish considerable difference for TiO_2-, FeO*-MgO relation. Those of Area II show lower TiO_2 and FeO, while Area III and IV show higher TiO_2 and FeO* at given MgO contents. It is noted that these of Area IV have slightly higher TiO_2 and FeO contents than Area III. Al_2O_3 and CaO contents of Area I, III and IV basalts show similar positive correlations with MgO contents. However, Area II basalts have higher Al_2O_3 contents and lower CaO contents than the other areas at given MgO contents, and show a flat pattern oblique to the positive trends of other areas. Na_2O contents show a negative correlation with MgO contents as a whole. Area II basalts are characterized by especially higher Na_2O contents than other areas. K_2O contents of Area III show the highest values, and those of Area II show slightly low, and those from Area I and IV have intermediate and similar ranges at given MgO.

In summary, basalts from Area II have distinct compositions different from basalts of other areas. For major elements, basalts of Area II show higher Na_2O and Al_2O_3, lower FeO*, CaO and TiO_2 than other areas at given MgO contents. These features were mentioned also by Meyzen et al. (2003). Basalts from Area III and IV have similar bulk compositions except for K_2O contents. Although basalts of Area I show similar trends on MgO variation diagram with Area III and IV, MgO contents of the Area I basalts are higher than the Area III and IV. Therefore, the Area I basalts are regarded to be less evolved than Area III and IV basalts.

Trace element compositions of basalt from Area I to IV are shown in Figure 5-4. Compatible element (Ni) concentrations from in this area show a tight positive correlation with MgO. Ni contents of Area I basalts are the highest, and those of Area II and III show lower concentrations. As Rb and Sr concentrations of basalts from this study area exhibit scattering distribution, it seem that they have affected by alteration. Regarding high field-strength elements (HFSE; Zr, Nb, Ce, Sm, Yb, Hf, Ta and etc.) which are not affected by alteration, basalts of Area I show lower concentrations than the other areas, and those of Area III and IV have similar concentrations at given MgO contents. The HFSE contents of

Figure 5-4. Trace element compositions of MORB from Area I to IV.

Figure 5-4.

Area I, III and IV basalts show a negative correlation with MgO contents (Figure 5-4). While, the HFSE concentrations (Ce, Sm and Hf) of Area II basalts have intermediate values between Areas I and III. Yb concentrations of Area II basalts have low as much as Area I basalts.

REE patterns of MORBs from Area I to IV are shown in Figure 5-5. REE concentrations from Area I exhibit the N-MORB pattern. REE patterns of Area II MORB have similar to Area I for heavy rare earth elements (HREEs), however these show higher light rare earth elements (LREEs) concentrations than those of Area I. REE contents of MORBs from Area III and IV show similar pattern and both of them have higher concentrations than those from Area I.

Figure 5-5. REE concentrations from Area I to IV. Gray area shows REE patterns from Area I. Green lines indicate N-MORB (Sun and McDonough, 1989). All of values are normalized chondrite value (Sun and McDonough, 1989).

Figure 5-6. La/Sm and Zr/Y ratios versus MgO diagram.

Zr/Y and La/Sm ratios of basalts from Area I to Area IV show nearly flat pattern as shown in Figure 5-6. This indicates that the Zr/Y and La/Sm ratios are not significantly varied during a fractional crystallization. The Zr/Y and La/Sm ratios of Area II basalts are highest, those of Area I are lowest, and those of Area III show intermediate ratios at given MgO contents. Although trace elements data of Area IV basalts are few, these ratios of Area IV basalts are similar to Area III basalts.

$Na_{8.0}$, $Fe_{8.0}$

In this study, $Na_{8.0}$ and $Fe_{8.0}$ etc. were calculated for each area (Figure 5-7). Furthermore, the degrees of melting (F wt.%) were also calculated by using $Na_{8.0}$, $Al_{8.0}$ and $Ca_{8.0}$ based on algorithm by Niu and Batiza, (1991)(Figure 5-2).

Area II basalts show the highest $Na_{8.0}$ in this study area, and basalts of Area I show lower $Na_{8.0}$ than the other areas. Basalts of Area III and IV show intermediate $Na_{8.0}$, and basalts of Area IV have higher $Na_{8.0}$ than those of Area III. On the other hand, Area II basalts show the lowest $Fe_{8.0}$, and Area IV basalts show the highest $Fe_{8.0}$. Basalts of Area I and III are intermediate in $Fe_{8.0}$, and basalts of Area I show lower $Fe_{8.0}$ than Area III basalts.

Figure 5-7. Na8.0 and Fe8.0 variation of MORB from Area I to IV. Calculations of Na8.0 and Fe8.0 are shown on a text. Global trend range refers to Asimow (1999).

5.2 Discussion

Degree of the melting

Chemical features of basalts from each area mentioned above suggest that basalts of Area II are derived from the lowest degree of melting at the shallowest depth. Calculated degrees of melting (F wt.%) were 11 to 20% for Area I, 6 to 13% for Area II, 10 to 15% for Area III and 12 to 17% for Area IV, respectively.

It has been already argued that the $Na_{8.0}$ of basalts from Indian Ocean Ridge tends to be higher than those from Pacific and Atlantic Ocean Ridges (Langmuir et al., 1992). Therefore, assuming the same mantle source, Indian Ocean MORBs may be derived from lower degree of partial melting than Pacific and Atlantic Ocean Ridges. Low degree of melting at Indian Ocean can be explained by the slower spreading rate (intermediate to ultraslow) than the Pacific and Atlantic Ocean ridges. $Na_{8.0}$ of basalts for this study area (except Area I) are higher than a global trend, and Area II basalt have particularly the highest $Na_{8.0}$ in this areas.

As mentioned above, major and trace element compositions of Area II basalts are distinct from those of the other areas and the compositions of Area II basalts can not be explained by fractional crystallization. Such unusual compositions of Area II basalts might be effected by different in degree of partial melting or mantle heterogeneity under SWIR.

We will examine for Area II basalts that are derived from different degree of melting or not. Using incompatible elements, melting and fractional crystallization trajectories were calculated and shown in Figure 5-8. Depleted mantle (Salters and Stracke, 2004) was used as starting material in this melting model, and fractional crystallization was launched from the melt of 10 % equilibrium melting.

Basalts of Area II data are considerably deviated to the left from the calculated melting trajectory (Figure 5-8). This suggests that Area II basalts are not likely derived from different degrees of melting of the same source with other areas. In the same way, relations of basalts from the Area I, III, and IV are also examined.

In $(La/Sm)_n$-$(Yb)_n$ diagram (Figure 5-8), basalts of Area I, III and IV are plotted along with this calculated fractional crystallization trajectory. In $(Ce)_n$-$(Yb)_n$ diagram (Figure 5-8), it is noted that the Area III and IV basalts and the Area I basalts plot along two parallel trends with the crystallization trajectory. This fact suggests that basalts from the Area III and IV are derived

Figure 5-8. Calculations of a melting and a fractionation. Using depleted mantle (Salters and Stracke, 2004) as starting material, imcompatible element concentrations of the melt are calculated. The equilibrium melting and the fractional melting, and the equilibrium crystallization and the fractional crystallization are also show.

from the source mantle with lower degree of melting than those of Area I basalts. Furthermore, basalts of the Area III and IV are more evolved than basalts of Area I in both of $(La/Sm)_n$-$(Yb)_n$ and $(Ce)_n$-$(Yb)_n$ diagrams, in consistent with higher of Mg# values of basalts from the Area III and IV than the Area I basalts.

On the contrary, it seems that the basalt compositions of Area II and Area III and IV follow the same fractional crystallization trend in $(Ce)_n$-$(Yb)_n$ diagram in Figure 5-8. However, variations of major elements of these areas are not explained by the same fractional crystallization as shown in Figure 5-8. Thus, it is concluded that basalts of Area II and Area III and IV were not produced from a same mantle source.

As mentioned above, basalt compositions of the Area III and IV have similar features for trace elements ratios, suggesting that they are derived from a similar source. According to those of major and trace elements concentration, it is suggests that the Area III have lower degree of partial melting than basalts of the Area IV. Basalts of the Area I, III and IV were produced from the same mantle source, the Area I basalts derived from highest degree of melting melt, the Area III basalts derived from lower degree of melting melt, and the Area IV basalts derived from lowest degree of melting in this 3 areas. On the other hand, basalts of the Area II were produced from different mantle source of other 3 areas.

Origin of Area II basalts: E-MORB

Although the compositional variations of basalts from Area I, III and IV were interpreted by the difference of melting degrees in a common source mantle, basalts from Area II were not produced in this way. As comparing basalt compositions of Area II with those of Area I, the values of $(La/Sm)_n$ and $(Ce)_n$ from Area II are higher than Area I at given $(Yb)_n$ (figure 5-8). Trace elements enrichment of MORB is usually interpreted by an involvement of E-MORB component. However, REE concentrations of Area II basalts show neither E-MORB nor N-MORB pattern (figure 5-5). Furthermore, Area II basalts have similar HREE contents, but higher contents in middle to light REE than those of Area I basalts. That is, REE patterns of both areas are oblique, indicating that

the source mantle of Area II is different from Area I and enriched in middle to LREE.

5.3 Regional variations of MORB compositions from CIR to SWIR

Basalt compositions from the CIR-S1, the CIR-S2, the CIR-S3, RTJ area, Area I and Area II are compared in Figure 5-9. RTJ area is indicated in the southern CIR-S1 (Figure4-10). Major and trace element contents of the CIR-S1 basalts plot between those of Area I and those of the CIR-S3. Basaltic compositions of Area I, the CIR-S1, the CIR-S3 and RTJ area show the same fractional crystallization trend. The trend of basalt compositions for the CIR-S3 are interpreted by low-pressure fractional crystallization from primitive basalt obtained from the conical cone in the CIR-S2. Therefore, it is appeared that basalts from Area I, CIR-S1, CIR-S3 and RTJ area are affected by the same process as the CIR-S3. SiO_2, Al_2O_3, FeO and HREE contents from Area II basalts show similar behavior to the AVW of the CIR-S2 which are affected by high pressure fractionation, but TiO_2, CaO, Na_2O and other trace element contents are not similar.

Figure 5-10 shows trace element concentrations of basalts. $(Ce)_n$ concentrations of the CIR-S2 (both of the conical cone and the AVW) are similar to those of Area I. Those of the CIR-S3 basalts show same trend of Area III and Area IV basalts. Basalts from the CIR-S1 (DR1) have higher $(Ce)_n$ concentrations than those of the CIR-S1 (DR3). It is suggested that basalts from the CIR-S1 (DR1) were formed with lower melting degree than those from the CIR-S1 (DR3). In general, it is expect that the melt at segment center shows higher degree of melting, however, opposite phenomenon are observed within the CIR-S1.

Regional variations of MORB compositions along axis from CIR-S3 at the CIR to Area IV at the SWIR show heterogeneous features (Figure 5-11). The most primitive basalts obtained from the conical cone within the CIR-S2 and part of the Area I, basalts from the CIR-S3, CIR-S1, RTJ area, Area I, Area III and Area IV underwent low pressure fractional crystallization, and basalts and dolerites from the AVW of CIR-S2 underwent high pressure fractional crystallization from

Area I WR
Area I GL
Area II WR
Area II GL
CIR-S2(CC)
CIR-S2
CIR-S3
CIR-S1(DR1)
CIR-S1(DR3)
RTJ
SiO2
TiO2
Al2O3
FeO*
CaO
Na2O
Yb
Zr
MgO
MgO

Figure 5-9.

Figure5-9. MgO variation diagrams of major elements. Comparisons of basalts compositions from Area I, Area II within the SWIR, and CIR-S1, CIR-S2, CIR-S3 and RTJ area.

Figure 5-10. Trace element variation of basalts from the SWIR and the CIR. Concentrations of Ce and Yb are normalized by chondrite (Sun and McDonough, 1989). Caluculated melting line and LLD are also shown (detail of calcurations in Figure 5-8).

the same mantle source. The conical cone melt show highest melting degree, and Area I, CIR-S1 (DR3) and RTJ area basalts were evolved from the conical cone melt. Area III, Area IV and CIR-S1 (DR1) were formed from the melt with lower melting degree than the conical cone melt. CIR-S3 basalts show lower degree of melting due to high concentration of REEs, however, this enrichment are derived from T-MORB. It is estimated to original of CIR-S3 is generated from lower degree of melting melt.

Figure 5-11. Relationship of magma system from the CIR to the SWIR. Basalts from this study area, except Area II basalts, are drived from same mantle source. The degree of fractional crystallization is refered from Mg# of bulk rock data and the degree of melting is refered from the Ce concentration. The partial melting degree of basalts from CIR-S3 is comparatively low value, but it is caused by addition of T-MORB component.

6 Conclusion

Petrological studies on basaltic rocks from the Central Indian Ridge (CIR) and the eastern Southwest Indian Ridge (SWIR) were performed to reveal geochemical variation in the source mantle around slow-spreading ridges triple junction, Rodriguez Triple Junction (RTJ). The rock samples from the CIR were obtained in the segment 2 (CIR-S2) and 3 (CIR-S3) during YK05-16 Leg.1. Those from the SWIR were obtained from the Atlantis II FZ and Melville FZ by Dives #463 and #464 of R/V Yokosuka/Shinkai 6500 MODE'98 Leg4 and Dive #171 by R/V KAIREI/KAIKO KR00-06.

A number of conical cones exist in the axial valley of the CIR-S2. The conical cone consists of pillow lavas, and the flat crest is overlain by massive sheet flow. The lower part of the AVW consists of dolerite and dike swarm, and the upper part of the AVW in the CIR-S2 consists of broken pillow lavas. At 3303m water depth dike swarm was discovered. Basalts and dolerites from the AVW have phenocrysts of olivine or plagioclase, or both of them.

Several small-scale ridges parallel to the rift valley are present in the CIR-S3. Slope of the NVZ consists of pillow lavas, those of the OVZ mainly consists of basaltic rubbles and broken pillow lavas, and those of the AVW mainly consists of sediments and massive basalts. Basalts from the NVZ are aphyric basalts and have a glassy rim. Only basalts obtained from the OVZ have plagioclase phenocrysts. Basalts from the AVW are vesiculated aphyric basalts, and have weathered rim.

Bulk rock compositions of basalts and dolerites from the CIR-S2 and the CIR-S3 show different features among the conical cone (CIR-S2), the AVW (CIR-S2) and the CIR-S3. Major and trace elements of the conical cone basalts are extremely homogeneous and primitive. Those of the AVW (CIR-S2) and the CIR-S3 show crystallization trends, respectively. Basalts from the CIR-S3 have high concentration of incompatible and volatile elements, suggesting that these basalts were originated from the source affected by the T-MORB. Crystallization

trends of the AVW (CIR-S2) and the CIR-S3 are explained by different pressure conditions for fractionation. Using the basalt composition of the conical cone as starting material, it is suggested that basalts and dolerites from the CIR-S2 underwent high pressure fractional crystallization, and those of the CIR-S3 underwent low pressure one. These differences are explained as follows. Beneath the CIR-S2, ascending melts are partly crystallized in the mantle, because conductive cooling in the mantle occurred efficiently (Wakabayashi, 2003). On the other hand, under the CIR-S3, the partial melting of upper mantle occurs at deeper depth due to high mantle potential temperatures. T-MORB features of the CIR-S3 may accrue this process. Therefore, oceanic crust of the CIR-S2 become thin, meanwhile, these of CIR-S3 became thick.

Eastern SWIR are subdivided into 4 areas, from the RTJ (70°E) to 69°E (Area I), from 69°E to Melville FZ (60°45′E) (Area II), from Melville FZ to Atlantis II FZ (57°E) (Area III), from Atlantis II FZ to Gallieni FZ (52°20′E) (Area IV). Compositions of Area I, Area III and Area IV basalts are explained by the different partial melting degree of the same mantle sources. It is suggested that Area III and IV basalts are derived from lower degree of melting than those of Area I. Furthermore, Area III basalts are derived from the melts with lower melting degree than those of Area IV. On the other hand, compositions of Area II basalts are characterized by higher Al_2O_3 and Na_2O contents, and lower TiO_2, FeO* and CaO contents than the other 3 areas. Basalts from Area II are expected to be formed in a peculiar mantle source.

Compositional variations of basalts along the CIR (CIR-S3) and the SWIR (Area IV), expect Area II basalts, were produced by different melting degrees from the same mantle source, extent of crystallization and involvement of the T-MORB component.

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