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REPORT
ON
THE MINERAL EXPLORATION
IN
THE ORANGE AND KALKFELD AREAS, THE REPUBLIC OF NAMIBIA

SUMMARY

MARCH, 1995

JAPAN INTERNATIONAL COOPERATION AGENCY
METAL MINING AGENCY OF JAPAN

PREFACE

In response to the request of the Government of the Republic of Namibia, the Japanese Government decided to conduct Mineral Exploration in the Orange and Kalkfeld Areas and entrusted the survey to the Japan International Cooperation Agency (JICA) and the Metal Mining Agency of Japan (MMAJ), since this was a professional survey programme of mineral exploration.

The survey was conducted from 20 October, 1993 to 20 February, 1995, and completed as scheduled with the cooperation of the Government of the Republic of Namibia, particularly the Geological Survey of Namibia, which is a department of the Ministry of Mines and Energy.

This report describes the summary of the results of the all programmes of the Orange and Kalkfeld Areas.

We hope that this report will serve towards the development of the Project and contribute to the promotion of friendly relations between our two countries.

We wish to express our deep appreciation to the officials concerned in the Government of the Republic of Namibia for their close cooperation extended to the team.

February 1995

Kimio FUJITA
President
Japan International Cooperation Agency

Takashi ISHIKAWA
President
Metal Mining Agency of Japan

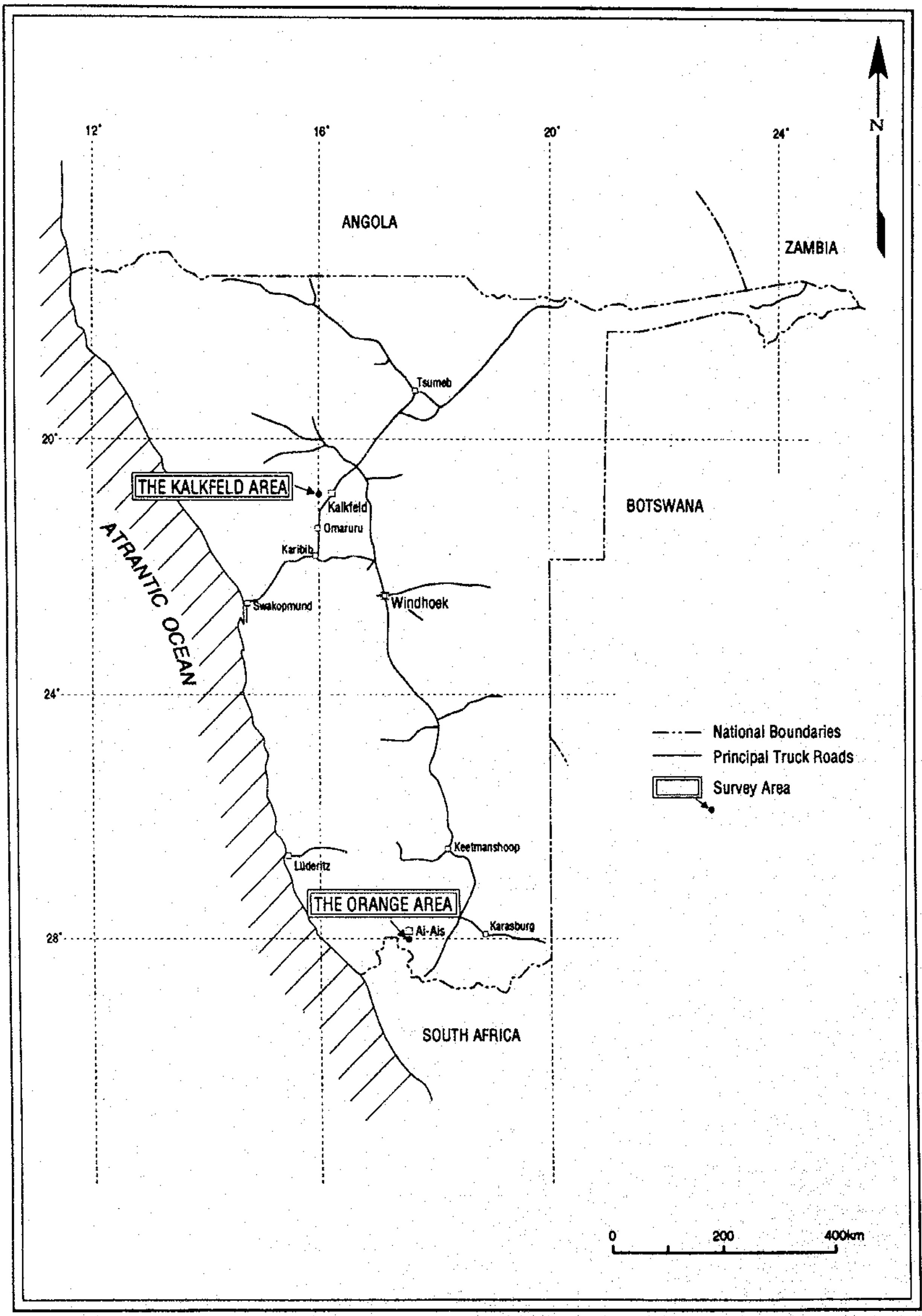

Fig.I-1-1 Location Map of the Survey Areas

Summary

This survey was carried out to clarify the geology and related mineralization, and to explore for new ore deposits in the Orange and Kalkfeld areas, the Republic of Namibia.

In 1993, the Phase I Survey, based on the literature research and geochemical survey, was conducted and revealed zones of high potential for mineralization. In 1994, the Phase II Survey, based on the geochemical and drilling survey, was conducted in the central and northeast beforsite bodies in the Orange area, which were located by the Phase I Survey.

The results by these surveys in the Orange and Kalkfeld areas are summarized as follows;

Orange Area

The Orange area is underlain by the Namaqua Metamorphic Complex of Precambrian age and the Nama Sequence of Cambrian age. These basement rocks are intruded by a carbonatite complex called the Marinkas Quelle Carbonatite Complex (MQC).

The Namaqua Metamorphic Complex is composed of gneiss, whereas the Nama Sequence is composed of slate, quartzite and arkose. The MQC has four main intrusive bodies. a syenite body, a sovite – syenite body, a central beforsite body and a northeast beforsite body, intruded in this order.

The major minerals of the carbonatite are calcite, dolomite and ankerite. Subordinate minerals are strontianite, apatite, barite, magnetite, sphalerite, galena, bastnaesite, monazite, synchysite and pyrochlore. The latter four minerals contain La, Ce, Nd and Nb.

The geochemical survey indicates the concentration of La, Ce, Nd, Nb and P in the MQC. In particular, light rare-earth elements (La, Ce and Nd) are concentrated in the outer zones of the two isolated beforsite bodies. Nb is concentrated in the inner zones of the two beforsites. P is concentrated in the northeast beforiste body.

The drilling survey showed that geochemical elements are concentrated underground as on the surface. But these elements have no tendency to increase underground.

Both beforistes contain 0.1% of rare-earth oxides, and 0.1% of Nb. The northeast beforsite contains 1.0% of P. In comparison to the carbonatite complex in the Klakfeld area, Nb and P are dominant in the MQC in the Orange area.

Kalkfeld Area

The Kalkfeld area is underlain by the Damara Sequence of Precambrian age. Granitoids and the Osongombo carbonatite Complex (OC) of Cambrian age intrude this basement rocks. The Damara Sequence is composed mainly of marble. The OC is composed mainly of volcanic breccia, beforsite, and iron ore, which intruded in this order.

Major minerals of carbonatite are dolomite and ankerite. Subordinate minerals are

manganocalcite, calcite, strontianite, apatite, goethite, hematite, galena and pyrochlore.

The geochemical survey revealed the concentrations of La, Ce, Nd, Th, Mn, Sr, and Fe in the OC. In particular, the beforsite body shows concentrations of La, Ce, Nd, and Nb. The iron ore shows concentrations of Th, Mn, Fe, and Sr. But the iron ore occupies a small part of the OC.

The beforiste contains 0.28% of rare-earth oxides, 0.04% of Th, 1.37% of Mn, and 10.86% of Fe. In comparison with the MQC in the Orange area, The OC shows a predominance of middle rare-earth elements (Sm, Eu and Tb), Th, Mn, Sr and Fe.

Recommendations for the Future

Current carbonatite mines have rare-earth oxides contents of 5 to 13%. Compared with these, the MQC and the OC have no high contents of rare-earth oxides.

As compared with other prospected carbonatite in Namibia, the Ondurakorume carbonatite contains 0.28% of rare-earth oxides, 0.24% of Nb_2O_5, and 7% of P_2O_5. This carbonatite is manifest as a plutonic plug and has an intermediate exposed area. Erosion level is intermediate, since erosion indicates a shallow-plutonic type.

The Kalkfeld carbonatite contains 0.2 to 0.8% of Ce, 0.05 to 0.5% of La, 0.1 to 0.25% of Nd, and 7 to 8% of P_2O_5. This carbonatite is manifest as a concentric ring in shape and has a large exposed area. Erosion level is deep, since erosion indicate a deep-plutonic type.

The MQC in the Orange area has an intermediate exposed area which is a characteristic of mid- level of a shallow plutonic plug. The underground concentration of the rare-earth elements is similar to the Kalkfeld carbonatite, based on the above-mentioned formation and the drilling survey, which shows no indication of the increase in rare-earth elements at depth.

The OC in the Kalkfeld area has a small exposed area, which is a characteristic of shallow erosion level of a diatreme. The contents of rare-earth elements is expected to increase, because the underground conditions are similar to the Ondurakorume from the above-mentioned formation type of carbonatite. But the area of the OC is small.

Therefore, further exploration in the Orange and Kalkfeld areas should be done, following an increase in economic demand for these elements, to evaluate the ore reserves by more a detailed drilling survey.

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Part I General Remarks

Part I General Remarks

Chapter 1 Introduction

1-1 Areas and Purpose of the Survey

Fig.I-1-1 and Appendix A-1 show the survey areas called the Orange and Kalkfeld areas. These areas are located in the southern and northern part of Namibia, respectively .

The Orange and Kalkfeld areas have high a potential for rare-earth elements related to carbonatites. More detailed survey and discovery of new deposits are urgently and strongly expected in these area.

Therefore, the Government of the Republic of Namibia sent a request to the Government of Japan for technical cooperation in mineral exploration. The Government of Japan accepted the request and conducted a literature research, geological surveys, geochemical surveys and a drilling survey. Following these surveys, survey teams were engaged to carry out a basic survey in order to assess the potential for ore deposits.

1-2 Method and Specification of the Survey

The survey was conducted as shown in the progress flow charts, Fig.I-1-2. Fig. II-1-3 shows the flow chart for selection of potential areas. Table I-1-1 shows the outline of the survey.

1-3 Terms and Members of the Survey

Table I-1-2 shows survey duration and members

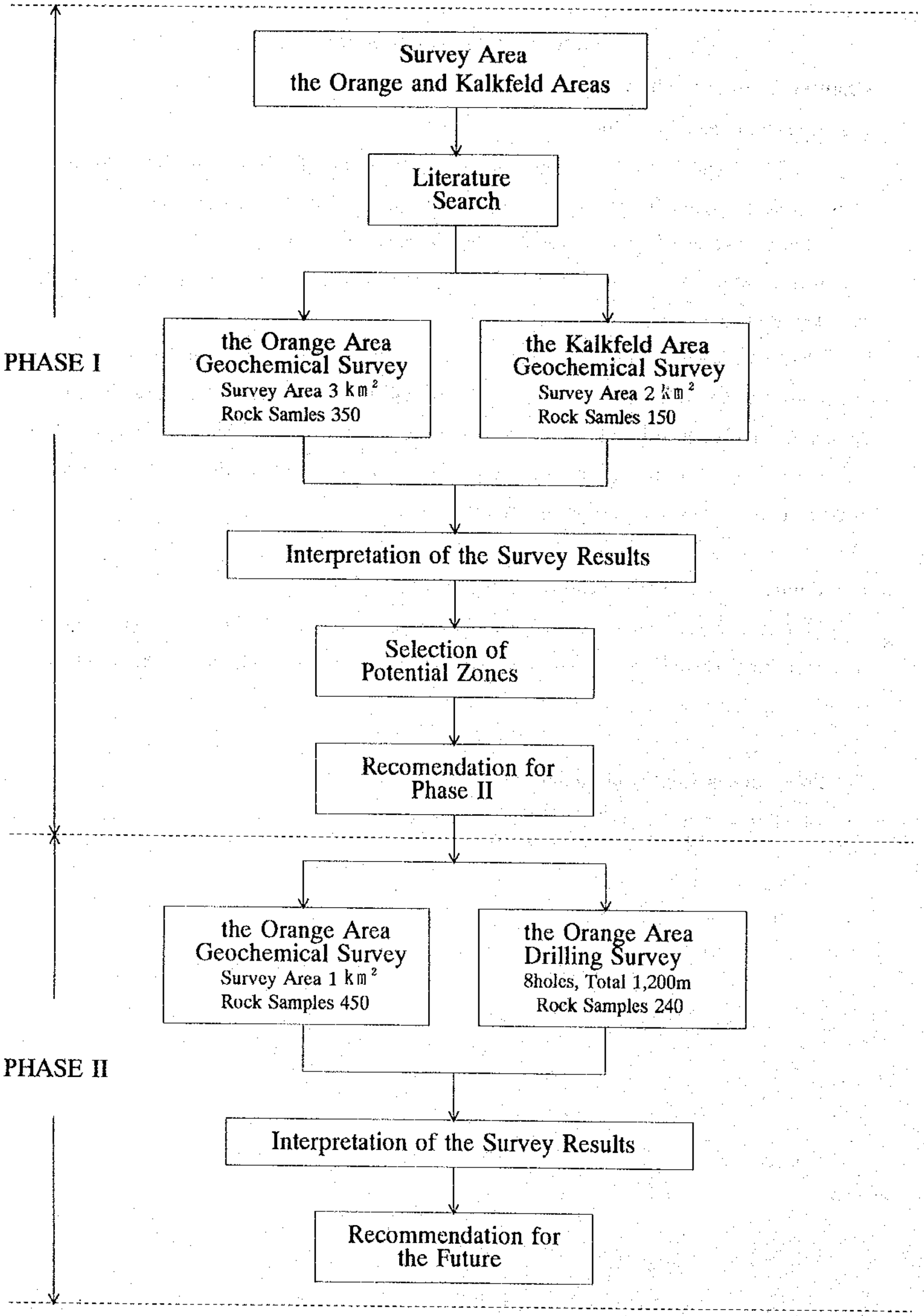

Fig.I-1-2 Progress Flow of the Survey

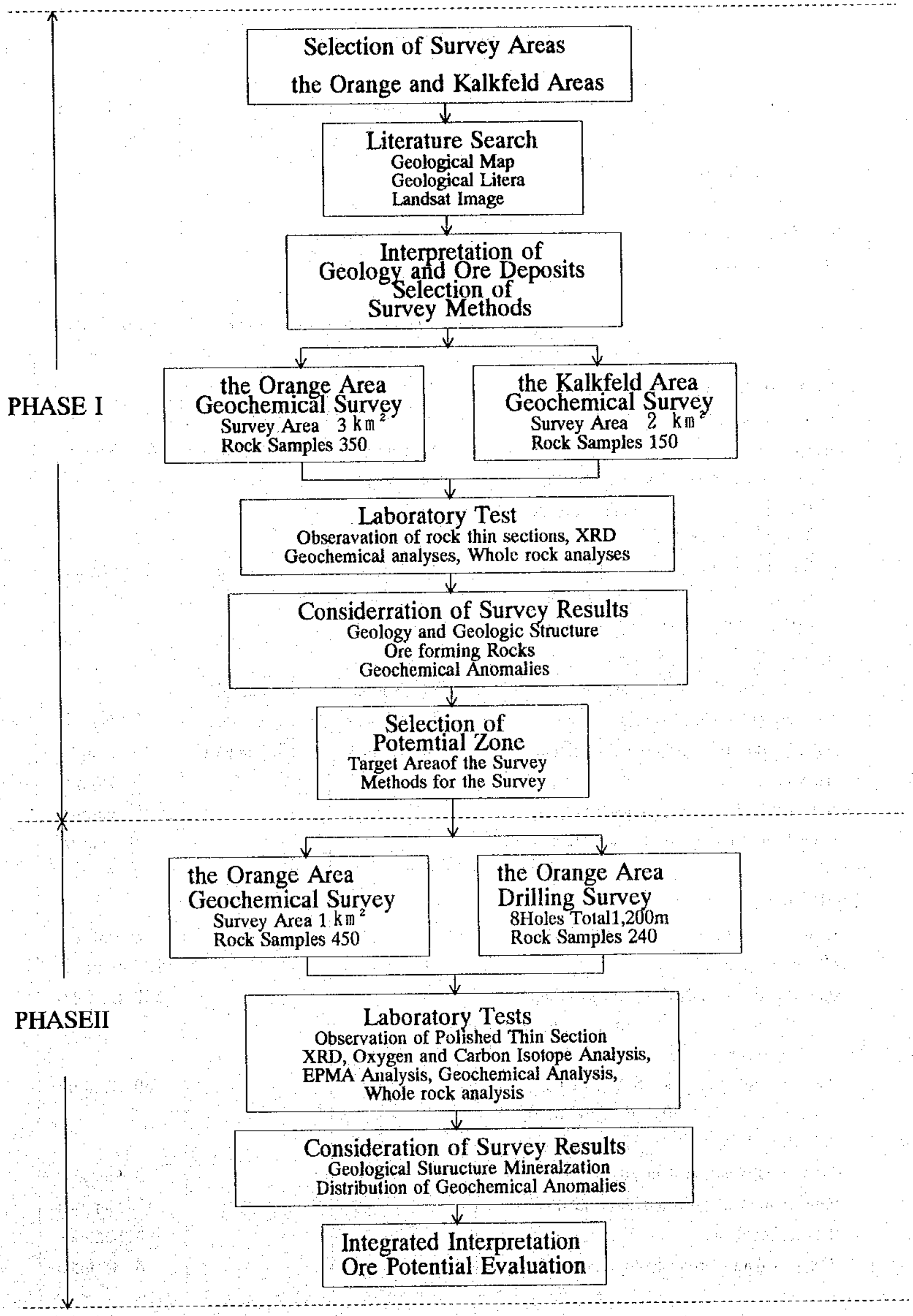

Fig.I-1-3 Flow Chart for Selection of Potential Areas

Table I-1-1 Outline of the Survey

Survey Methods	1994 Fiscal Year		1995 F.Y.
Literature Search			
•Geological Map	2 maps		
•Geological Literature	10 sets		
•Landsat Image	1 set		
	the Orange Area	the Kalkfeld Area	the Orange Area
Geochemical Survey			
•Survey Area	3 km^2	2 km^2	1 km^2
•Rock Samples	350 Samples	150 Samples	450 Samples
•Geochemical Analysis (La,Ce,Nd,Sm,Eu, Tb, Yb,Lu,Sc,Y,U,Th,Nb,Ta,Zr,Fe,Mn, Sr,P:19 elements)	350 Samples	150 Samples	450 Samples
•Whole Rock Analysis (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, CaO, Na_2O, MgO, K_2O, P_2O_5, LOI: 12 elements)	30 Samples	10 Samples	100 Samples
•Observation of Thin Section			
•Observation of Polished Section	30 Samples	5 Samples	
•X-Ray Diffraction Analysis	25 Samples	10 Samples	5 Samples
•Observation of Polished Thin Section	20 Samples	10 Samples	10 Samples
•EPMA Analysis			5 Samples
•Oxygen and Carbon Isotope Analysis			10 Samples
•Age Determination by Pb-Pb Method			1 Sample
Drilling Survey			
•Number of Holes			8 Holes
•Total Depth			1,200 m
•Geochemical Analysis (La,Ce,Nd,Sm,Eu, Tb, Yb,Lu,Sc,Y,U,Th,Nb,Ta,Zr,Fe,Mn, Sr,P:19 elements)			240 Samples
•Whole Rock Analysis (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, CaO, Na_2O, MgO, K_2O, P_2O_5, LOI: 12 elements)			60 Samples
•X-Ray Diffraction Analysis			5 Samples
•Observation of Polished Thin Section			10 Samples
•EPMA Analysis			5 Samples
•Oxygen And Carbon Isotope Analysis			8 Samples

Table I-1-2 Terms and Members of the Survey

Fiscal Year	1994	1995
Planning and Managing	Planning Metal Mining Agency of Japan Mr. Takahisa Yamamoto Ministry of Foreign Affairs Mr. Naofumi Hashimoto Ministry of International Trade and Indutry Mr.Yoichi Iida Japan International Cooperation Agency Mr.Koh Naito Metal Mining Agency of Japan Mr. Satoshi Shiokawa Mr.Yoichi Okuizumi Field Supervisor Metal Mining Agency of Japan Mr.Takafumi Tsujimoto	Field Supervisor Japan International Cooperation Agency Mr.Kenichi Takahashi Metal Mining Agency of Japan Mr.Haruhisa Morozumi Mr.Youichi Okuizumi
	Ministry of Mines and Energy Mr.Josephat Vatanavi Mazeingo Geological Survey of Namibia Dr.Brian G. Hoal Dr.Gabriele I.C. Schneider	Geological Survey of Namibia Dr.Brian G. Hoal Mr.Gabriele I.C. Schneider
Term	10 October,1993 to 25 January, 1994	13 August,1994 to 20 January, 1995
Field Survey	Dowa Engineering Co.,Ltd. Mr.Yukuo Kinryu Mr.HIrohide Konno Mr.Hiroyuku Okamura Geological Survey of Namibia Dr.Gabriele I.C. Schneider Mr.Herbert Roesener	Dowa Engineering Co.,Ltd. Mr.Yukuo Kinryu Mr.Hirohide Konno Mr.Keiichi Ikeda Geological Survey of Namibia Dr.Gabriele I.C. Schneider

Chapter 2 Previous Works

Verwoerd(1965,1967), Dendle(1971), Heath(1973), Schommarz(1988), and Smith(1990) have done reconnaissance for base metals, rare metals and radioactive elements related to carbonatite and alkaline intrusive in and around the survey areas. Several areas of Pb–Ag mineralization related to alkaline intrusive were confirmed by Rio Tinto Exploration Ltd.(1973), Blignault (1979) and Smithies (1990), but No large–scale mines are operating around the area.

Chapter 3 General Geology

Fig.I-3-1 shows Geological Map of Namibia after Geological Survey of Namibia (Miller and Schhalk, 1980). Regional stratigraphy is contributed by the Geological Survey of Namibia(Miller and Schalk, 1980) and the Geological Survey of South Africa(compiled by Kent, 1980). According to these literatures, five main periods of lithogenic activity have occurred. These as follows:

Tertiary to Recent (<65 Ma)
Carboniferous to lower Cretaceous (345 to 120 Ma)
Namibian (1,000 to 570 Ma)
upper Mokolian (1,800 to 1,000 Ma)
Vaalian to lower Mokolian (2,100 to 1,800 Ma)

The Vaalian to lower Mokolian sequences (>2,100 to 1,800 Ma) are composed of Precambrian metamorphic and plutonic rocks of the Khoabendus and Haib Groups and of the Kunene Anorthosite Complex. The Sequences underlie the northwestern and southern parts of Namibia.

The Upper Mokolian sequence (1,800 to 1,000 Ma) is composed of metamorphic rocks and pyroclastic rocks of the Namaqua Metamorphic Complex and the Sinclair & Rehoboth Sequences. The Sequence underlies the southern part of Namibia.

The Namibian sequence (1000 to 570 Ma) is composed of sedimentary rocks and granitoids of the Richard Granite / syenite complex, the Damara Sequence, the Gariep complex, the Damaran granite, the Nama Group and the Salem Granite. This period marks the Damaran orogenic phase.

The Carboniferous to lower Cretaceous (345 to 120 Ma) is composed of sedimentary rocks and pyroclastic rocks of the Karoo Sequence and the Post-Karoo Sequence. These rocks underlie the central and northern parts of Namibia. Alkaline complexes, which accompany some carbonatites, trend northeast to southwest along the tectonic line. The carbonatite complexes of this period are significant resources of rare-earth elements.

The Tertiary to Recent sequences (<65 Ma) are composed of unconsolidated sediments, which cover the major parts of Kalahari and Namib desert areas.

The regional geological map around the Orange area, after Blignault and Kroner (1974) is shown in Fig.I-3-2. Carbonatite complexes in the area belong to the group of alkaline intrusive which are arranged in the NE-SW direction of the Kuboos-Bremen tectonic line (Kroner and Blignault, 1976). The group of the alkaline intrusive intrudes in the Namaqua metamorphic complex, the Gariep group and the Nama sequence. The Rb-Sr age of the

Marinkas Quelle syenite ranges 505.88±18.68 Ma (Smithies, 1990).

The Marinkas Quelle carbonatite complex (MQC) was described initially by Blignault (1971), and a detailed geological map was made by Schommartz (1988).

The regional geological map around the Kalkfeld area after the Geological Survey of Namibia is shown in Fig.I-3-3. There are four carbonatite complexes, called the Osongombo, the Kalkfeld, the Ondurakorume, the Okorusu, which are closely related in distribution and genesis. They are distributed along a line in order of location from southwest to northeast , and the distance between the former three complexes is approximately 15 km.

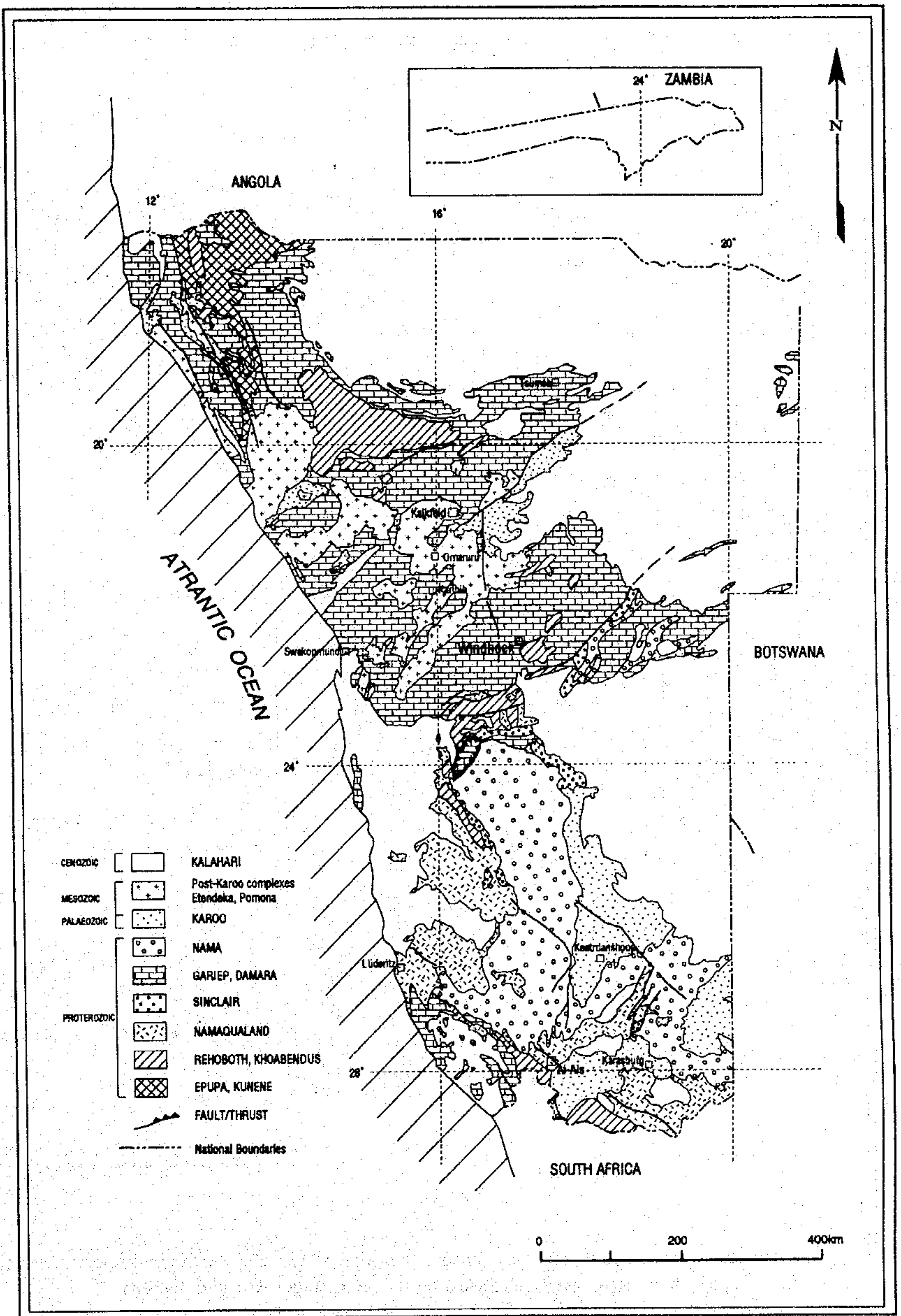

Fig.I-3-1 Geological Map of Namibia

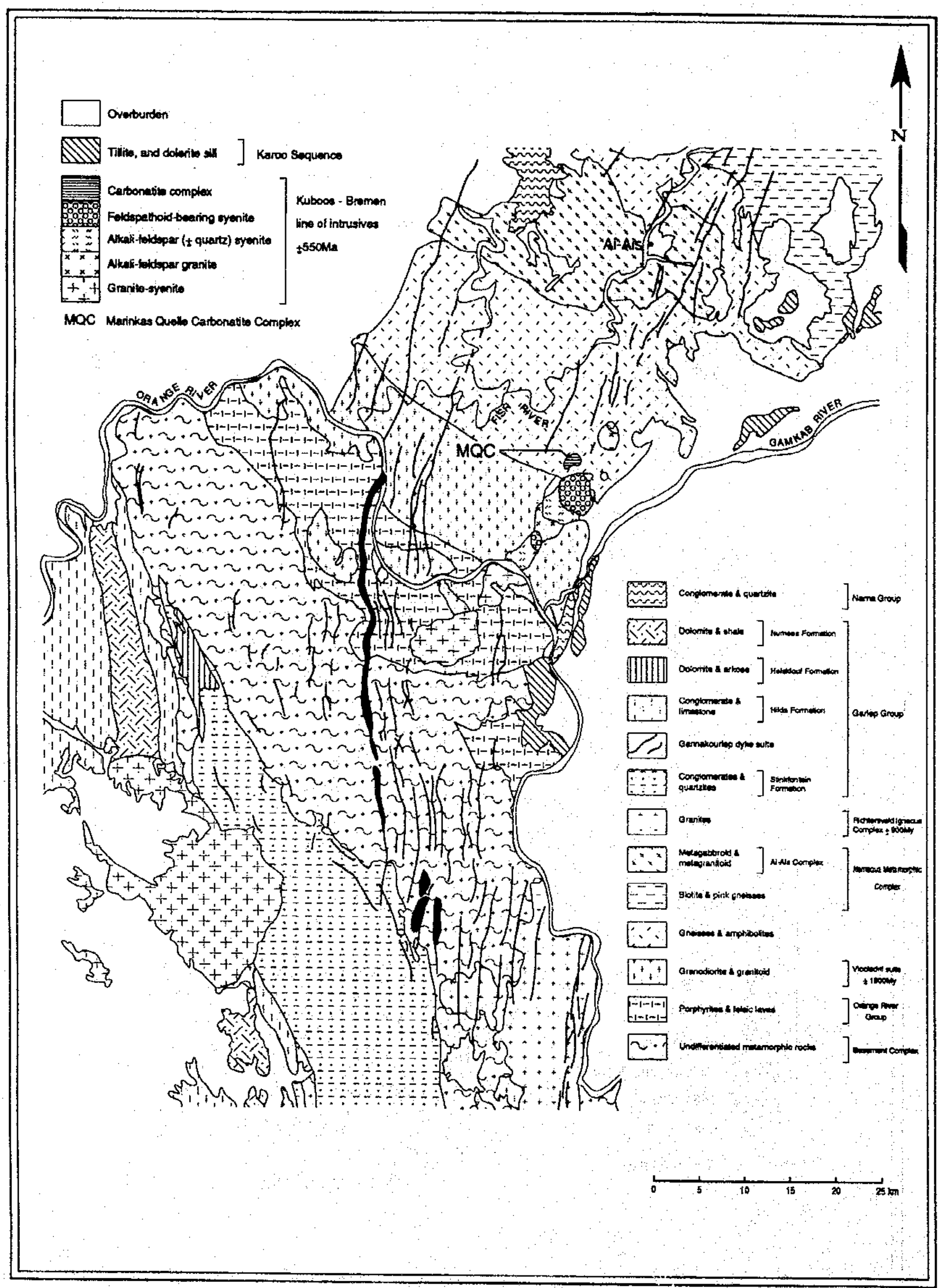

Fig.I-3-2 Regional Geological Map of the Orange Area and Vicinity

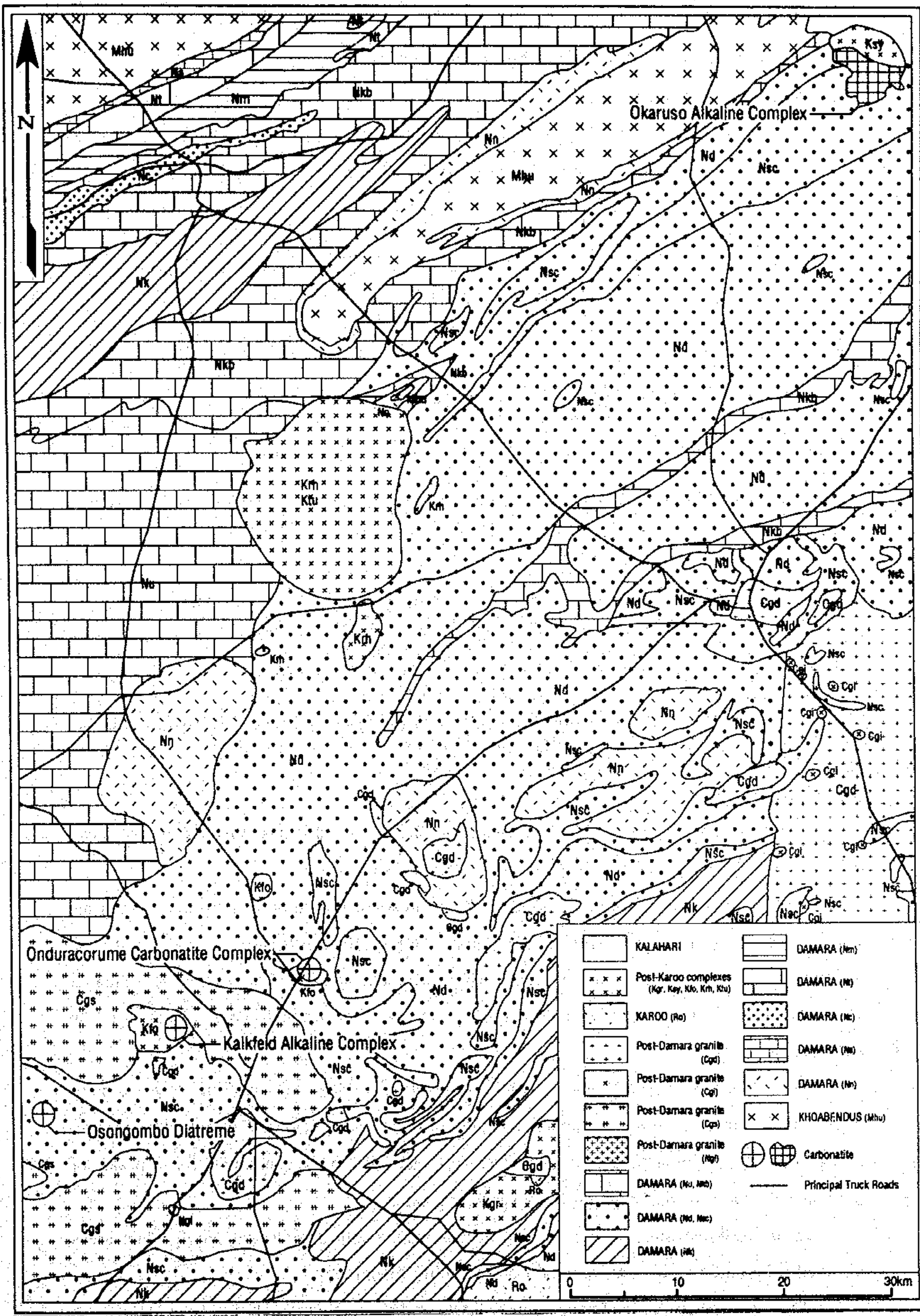

Fig.I-3-3 Regional Geological Map of the Kalkfeld Area and Vicinity

Chapter 4 Physical Features of the Survey Areas

4-1 Location and Transportation

The Orange Area is situated in Karasburg state, in the southern part of Namibia. Access from Windhoek, the capital of Namibia, by vehicle is as follows:

Windhoek	—	679 km (Route B1) 7 hours	—	64 km (Route C10) 1 hour	—	base camp site Ai-Ais	—	36 km (unpaved road) 40 min.
—	Kanabium Farm	—	20 km (unpaved road) 40 min.	—	the Orangre area			

The Kalkfeld area is situated in Omaruru state, in the northern part of Namibia. Access from Windhoek by vehicle is as follows:

Windhoek	—	64 km (Route B1) 45 min.	-	100 km (Route B2) 1 hour	—	61 km (Route C33) 40 min.	—	base camp site (Omaruru)
—	71 km (Route C33) 40 min.	—	Kalkfeld	—	20 km (gravel road) 20 min.	—	Osongombo	— 2.5 km (Gravel road) 10 min. — Kalkfeld Area

4-2 Environments

Namibia covers an area of 820,000 square kilometres. Namibia has twice the area of Japan and is bordered by Angola, Zambia, South Africa and Botswana.

The topography of Namibia is divided into a forest zone in north, a savannah zone in the inland plateau, and a desert zone along the Atlantic Ocean. The forest zone and the desert zone are flat in topography. The inland plateau is hilly to mountainous. The Orange area is situated on the boundary between the savannah and the desert zone. The Kalkfeld area is situated in the savannah zone.

The topography of the Orange area reflects its lithology. The parts underlain by basement metamorphic rocks shows steep mountainous landform. The parts underlain by intrusive granitic rocks show gentle mountainous shape. The parts intruded by carbonatites form peaks of mountains because of the relatively low weathering rate.

In the Kalkfeld area, areas underlain by basement marbles show flat relief, while areas intruded by granitic rocks and carbonatites show hilly topography.

The river systems in the Orange and Kalkfeld areas are not large. During the rainy season river water flows, but during the dry season the rivers dry up.

The climate of the survey area is semi-arid to subtropical.

The temperatures are highest in January and February, ranging from 17 to 31 °C, and lowest in July, ranging from 6 to 18 °C.

Capital Windhoek experiences 13 °C on the average in July and 23 °C on the average in December. Annual rainfall is 600 mm/year in the forest zone, 20 mm/year in the desert zone, and 350 mm/year in the inland plateau on the average. Rainfall is highest in summer, October to April, few in winter.

Vegetation is variable. The forest zone is mainly covered with broad-leafed trees. The inland plateau is pasture with stunted acacia and Welwitschia trees. The desert zone is sparsely covered by lichen and scrub.

Chapter 5 Conclusions and Recommendations for the Future

5-1 Conclusions

This survey was carried out to clarify the geology and related mineralization, and to explore for new ore deposits in the Orange and Kalkfeld areas, the Republic of Namibia.

In 1993, the Phase I Survey, based on the literature research and geochemical surveys, was conducted and revealed zones of high potential for mineralization. In 1994, the Phase II Survey, based on the geochemical and drilling survey, was conducted in the central and northeast beforsite bodies in the Orange area, which were located by the Phase I Survey.

The results of the surveys in the Orange and Kalkfeld areas are summarized as follows:

Orange Area

The Orange area is underlain by the Namaqua Metamorphic Complex of Precambrian age and the Nama Group of Cambrian age. These basement rocks are intruded by a carbonatite complex called the Marinkas Quelle carbonatite complex (MQC).

The MQC is located along the Kuboos-Bremen tectonic line which trends northeast to southwest and is also found at the intersection of the Kuboos-Bremen tectonic line and post-Karoo faults.

The MQC is manifest as in plutonic plug from it modes of intrusion. The erosion level is shallow to intermediate, since the MQC exposed through erosion indicates a shallow plutonic type. Therefore the MQC continues at depth in comparison with other carbonatite complexes.

The MQC has four main intrusive bodies, a syenite body, a sovite-syenite body, a central beforsite body and a northeast beforsite, intruded in this order. $\delta^{13}C$ and $\delta^{18}O$ also increase in this intrusion order.

The major minerals of the carbonatite are calcite, dolomite and ankerite. Subordinate minerals are strontianite, apatite, barite, magnetite, sphalerite, galena, bastnaesite, monazite, synchysite and pyrochlore. The latter four minerals contain La, Ce, Nd and Nb.

The geochemical survey indicated the concentrations of La, Ce, Nd, Nb and P in the MQC. In particular light rare-earth elements (La, Ce and Nd) are concentrated in the outer zones of the two isolated beforsite bodies. Nb is concentrated in the inner zones of the two beforsites. P is concentrated in northeast beforsite body.

The drilling survey showed that geochemical elemennts are concentrated underground as on the surface. But these elements have no tendency to increase underground.

Both beforsites contain 0.1 % of rare-earth oxides, 0.1 % of Nb. The northeast beforsite contains 1.0 % of P. In comparison to the carbonatite complex in the Klakfeld area, Nb and P are dominant in the MQC in the Orange area.

Kalkfeld Area

The Kalkfeld area is underlain by the Damara Sequence of Precambrian age. Granitoids and the Osongombo carbonatite complex (OC) of Cambrian age intrude these basement rocks. The Damara Sequence is composed mainly of marble. The OC is composed mainly of volcanic breccia, beforsite, and iron ore, which intruded in this order.

There are four carbonatite complexes, the Osongombo, Kalkfeld, Ondurakorume, and Okorusu, which are closely related in distribution and genesis to the Damarand Alkaline Province in the Damara Sequence. They are distributed along a line in order of location from southwest to northeast, and the distance between the former three complexes is approximately 15 km.

Major minerals of the carbonatite are dolomite and ankerite. Subordinate minerals are manganocalcite, calcite, strontianite, apatite, geothite, hematite, galena, pyrochlore.

The geochemical survey revealed the concentrations of La, Ce, Nd, Th, Mn, Sr and Fe in the OC. In particular, the beforsite body shows concentrations of La, Ce, Nd and Nb. The iron ore shows concentrations of Th, Mn, Fe and Sr. But the iron ore occupies a small part of the OC.

The Beforiste contains 0.28 % of rare-earth oxides, 0.04 % of Th, 1.37 % of Mn, and 10.86 % of Fe. In comparison with the MQC in the Orange area, The Oc shows a predominance of middle rare-earth elements (Sm, Eu and Tb), Th, Mn, Sr and Fe.

5-2 Recommendations

This survey is the first fundamental attempt to study to the Namibian carbonatites by geochemical and drilling surveys. This survey revealed the outline of the distribution of such valuable elements as lanthanides.

The Orange and Kalkfeld areas are underlain by carbonatite complexes which contain lanthanides, Nb and P as valuable elements. In particular, beforsite of the carbonatite complex, which is rich in dolomitic carboantite, concentrates these elements and is common in the carbonatite complex. Therefore beforsite is a target for exploration.

The central and northeast beforistes in the Orange area contain 0.1 % of rare-earth oxides and 0.1 % of Nb. The northeast beforsite contains 1 % of P. The beforsite in the Kalkfeld area contains 0.28 % of rare-earth oxides, 0.04 % of Th, 1.37 % of Mn and 10.86 % Fe.

On the other hand, current carbonatite mines have rare-earth oxides contents of 5 to 13%. Compared with these, the MQC and the OC have no high contents of rare-earth oxides.

As compared with other prospected carbonatites in Namibia, the Ondurakorume carbonatite contains 0.28 % of rare-earth oxides, 0.24 % of Nb_2O_5, and 7% of P_2O_5. This carbonatite is manifest as a plutonic plug and has an intermediate exposed area. Erosion level is intermediate, since erosion indicates a shallow-plutonic body.

The Kalkfeld carbonatite contains 0.2 to 0.8 % of Ce, 0.05 to 0.5 % of La, 0.1 to 0.25 % of Nd, and 7 to 8 % of P_2O_5. This carbonatite is manifest as a concentric ring and has a large exposed area. Erosion level is deep, since erosion indicate a deep-plutonic body.

The MQC in the Orange area has an intermediate exposed area, which is a characteristic of mid-level of a shallow plutonic plug. The underground concentration of the rare-earth elements is similar to the Kalkfeld carbonatite, based on the above-mentioned formation and the drilling survey which shows no indication of increase in rare-earth elements at depth.

The OC in the Kalkfeld area has a small exposed area which is a characteristic of shallow erosion level of a diatreme. The content of rare-earth elements is expected to increase, because the underground conditions are similar to the Ondurakorume from the above-mentioned formation type of carbonatite. But the area of the OC is small.

Therefore, further exploration in the Orange and Kalkfeld areas should be done, following an increase in economic demand for these elements, to evaluate the ore reserves by more a detailed drilling survey.

Part II Surveys Details

Part II Details of Surveys

Chapter 1 Research of Previous Works

1-1 Survey Method

The literature and documents concerning geology, geophysics, geochemistry and mineralization which are kept in the Geological Survey of Namibia, Ministry of Mines and Energy (GSN) were studied and analyzed.

Two regional geological maps, one Landsat imagery map, four aeromagnetic maps, 20 geological survey and mineral exploration papers, and 3 mining and mining regulation papers were researched. The characteristics of geology and mineralization based on these data were summarized and compiled in geologic maps at a scale of 1:2,500.

1-2 Survey Results

The survey areas are underlain by carbonatites, which are anticipated enrich with rare earth elements (REEs), niobium, phosphorus and so on.

Verwoerd(1967) divided the carbonatites of Namibia into three types as follows;

subvolcanic carbonatite complex: Okoruru, Ondurakorume, Kalkfeld, Osongombo,
volcanic carbonatite complex: Burukkaros, and
possible carbonatite: Garub, Graniteberg,

and classified the formation ages as follows;

middle Precambrian,
late Precambrian, and
lower Jurassic.

The characteristics of carbonatites in southern Africa are summarized by Verwoerd (1967) as follows:

1) Carbonatites are distributed with a spatial relationship to the subduction zone which is presently overlain by limestone.
2) Carbonatites are related to intense igneous activity.
3) Carbonatites form pluton 1 mile in diameter which show concentric zoning.
4) Carbonatites become rich in magnesium and iron due to crystal differentiation.
5) Carbonatites are rich in strontium.

The Marinkas Quelle Carbonatite Complex (MQC) in the Orange area was firstly discovered in early 1970. The mineral exploration in the form of gridding, soil and rock chip sampling, and geological mapping was subsequently performed by Rio Tinto Exploration (PTY) Ltd. (Heath, 1973), and soil samples were assayed for nickel, copper, lead, zinc, and cobalt. Recently, Schommarz (1988) mapped a detailed geology of the MQC, and recommended the whole rock geochemical survey for possible REEs concentrations.

The investigation of all suspected carbonatite occurrences was started in 1955 and completed in 1964 on behalf of the South African Atomic Energy Board. Geological mapping and radiometric assay of the Osongombo Diatreme in the Kalkfeld area were carried out during the term (Verwoerd, 1967).

Chapter 2 Orange area

This area was surveyed in 1993 and 1994. This area is situated on state land 25 km south of Ai-Ais resort, which was the base camp site of this survey.

2-1 Survey Method

In the 1993 phase I survey, a base map used for the field survey and geological mapping were enlarged versions of the published topographic maps from the scale of 1 to 50,000 to that of 1 to 2,500.

Geochemical rock sampling was done based on this map. Geology was checked simultaneously along the geochemical survey lines and compared with the previous geological map. Laboratory tests carried out were geochemical analysis, whole rock chemical analysis, X-ray diffraction analysis (XRD) and observation of rock thin sections.

In the 1994 phase II survey, geochemical and drilling surveys were conducted in the central and northeast beforsites which were determined to contain concentrations of rare-earth elements and other valuable elements in the phase I survey in 1993. Fig.II-2-1 shows the geochemical survey zones and drilling sites. Laboratory tests carried out were observation of rock polished thin sections (Appendix A-2), whole rock chemical analysis and norm analysis (Appendix B-1 and 2), geochemical analysis (Appendix B-1 and 3), XRD, EPMA, oxygen and carbon isotopic analysis (Table II-2-1) and age determination by Pb-Pb method.

2-2 Geological Survey

2-2-1 Outline of Geology

Fig.II-2-2 shows a geological map based on the field survey and after Schommarz (1988). Fig.II-2-3 shows the lithostratigraphy of the Orange area.

This area is underlain by the Namaqua Metamorphic Complex, the Gariep Group, the Nama Sequence, the Marinkas Quelle Carbonatite Complex (MQC) and syn- to post- Karoo Intursions.

2-2-2 Details of Geology

1. Namaqua Metamorphic Complex (Ngn)

This complex is a host rock of the MQC, and widely extends outside the area. It mainly consist of quartz-feldspar gneiss. Structural trend of foliation strikes NW-SE in direction and dips to south. Brecciated structure is commonly observed at the contact zone with the MQC. Fractures and surroundings of fragments in the brecciated zone are filled up by dark green to bluish-green amphibole, aegirine, aegirine-augite, phlogopite, carbonate minerals and apatite. Brown carbonatite veins also fulfill interstitially in the brecciated zone. The contact zone with the MQC is fenitized, and replaced by alkaline feldspars and carbonate minerals.

A large quantity of alkaline feldspars formed by fenitization and alkaline metasomatism are identified by the microscopic observation and through XRD analyses. The identified minerals is quartz, albitized plagioclase and potassium feldspar as the predominant components, aegirine–augite, gedrite, hornblende, riebeckite, biotite and phlogopite as subordinate minerals. Garnet, sphene, zircon, apatite, calcite, fluorite and opaque minerals are associated as accessory minerals. Cancrinites is identified in part of northern contact zone with the MQC.

2. Gariep Group (Gdd)

It consists of dolerite of the Gannakouriep dyke intruding in the Namaqua Metamorphic Complex. The dolerite is situated in the southwest of the area, and is intruded by the carbonatite dyke (Mcd).

3. Nama Sequence (Nsh)

It is situated in the eastern margin of the MQC and occasionally found in the northeastern part of the MQC as xenoliths. It consists of black shale, quartzite, grit and arkose. Brecciated structure is common. Breccia ranges in size from 10 cm to several metres. Dark green to bluish–green mineral veinlet fills the interstices of fragments. Brown carbonatite veins are observed in the brecciated zone. Weak bedding planes are observed in the black shale. Quartzite is light greenish–grey to white. A grading structure is observed in some of quartzite blocks. Grit and arkose is greyish white to light green , and includes large amount of quartz and feldspar grains. This sequence seems entirely brecciated and the distribution of each facies is not concordant with the occurrence estimated by strikes and dips of bedding planes. Therefore, the lithostratigraphy of each facies is not well known.

4. Marinkas Quelle Carbonatite Complex (MQC)

The MQC exhibits an elliptical shape elongated in a NE–SW direction and occurs as a pluton which intrudes the Namaqua Metamorphic Complex and the Nama Sequence.

The MQC is subdivided broadly into four bodies, i.e. a syenite body (Msw and Msp), sovite–syenite body (Mcs, Msu, Msrm and Msm), a beforsite body (Mcb1) and a northeast befrsite body (Mcb2) .

(a) Syenite body (Msw and Msp)

The body is situated in the north of the area in a half moon shape. It consists of white to grey porphyritic syenite (Msw) and porphyritic nepheline syenite (Msp). The later is expected the significant concentration of heveay rare–earth elements (Schommarz, 1988).

The white to grey porphyritic syenite (Msw) is creamy white to grey, partly greenish grey. Brecciated structure is common. The various size of Fragments of gneiss and black shale includes as xenolith in the body. The syenite composed of white feldspar wherein the grain size is around 5 mm in diameter, and contains a characteristically small amount of mafic minerals. Brown carbonatite veins fill interstatically in the split of breccied fragments.

The predominant minerals are composed of albitized plagioclase, albite, potassium feldspar, nepheline, cancrenite, analcime, and aegirine–augite, and subordinate minerals are of quartz, sphene, hornblende, riebeckite, biotite, phlogopite, muscovite, calcite, opaque minerals, zircon, and apatite. Epidote, sercite and chlorite contain as hydrothermal alteration product.

The porphyritic nepheline syenite (Msp) is creamy white to light greyish–green, partly pinkish in colour. It commonly contains white to light yellow feldspar and aegerine–augite phenocryst whose grain sizes range from 1 to 5 mm in diameter, and phenocrysts of biotite whose grain size is 0.1 to 1 mm in diameter. Aggregate of alkali–feldspar around 5 cm in diameter occurs at some outcrops. Brecciated structure and calcitic carbonatite dykes within a few tens cm in wideth are commonly observed in the body.

The predominant minerals are composed of albitized plagioclase, potassium feldspar, nepheline, cancrenite, analcime, and aegirine–augite, and subordinate minerals are of sphene, biotite, phlogopite, calcite, opaque minerals, and apatite. Epidote, sercite, chlorite, and goethite contain as hydrothermal alteration product.

(b) Sovite–syenite body (Mcs, Msu, Msr and Msm)

This body exhibits a ring structure in the north–central portion of the area, and is partly deformed to ellipsoid. It consists of sovite (Mcs), porphyritic syenite (Msr), undifferentiated syenite (Msu), and fine–grained syenite sill (Msm).

Sovite (Mcs) is widely distributed in the area, especially in the north–central portion. At the portion, a basin–like landscape is formed by the difference in resistivity for erosion between dolomite–dominated beforsite and gneiss around the basin, and calcite–dominated sovite. Phlogopite aggregates at the contact zone with the beforsite bodies (Mcb1 and Mcb2), and foliates concordant with the contact plane.

Calcite about several millimetres in diameter is a principal component of sovite. It composed subordinately of quartz, albite, potassium feldspar, nepheline, cancrinite, sodalite, analcime, riebeckite, aergirine–augite, phlogopite, dolomite, magnetite, and apatite. Chlorite and goethite contain as hydrothermal alteration and weathering products. Barite, barytocarcite, kutnohorite, and magnesite from a float of iron ore in the basin are identified by the XRD analysis.

$\delta^{13}C$ values of calcite and dolomite range from −5.5 to −5.9 ‰ and from −4.7 to −5.4 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite range +6.5 ‰ and from +7.7 to +8.3 ‰, respectively. Dolomite is slightly enrich in ^{13}C and ^{18}O compared to dolomite.

Reddish porphyritic syenite (Msr) is distributed at the east of the contact zone with the Namaqua Metamorphic Complex. It characteristically contains phenocryst of pink feldspar.

It is composed predominantly of albite and potassium feldspar, and subordinately of nepheline, cancrenite, kalsilite, analcime, aegirine-augite, garnet, sphene, biotite, calcite, opaque mineral and apatite.

Undifferentiated syenite (Msu) is widely distributed within the Complex. It shows a creamy white, greenish-grey, grey to light grey, and includes a variety of grain size of component minerals. It shows a brecciated structure at the contact zone with the beforsite bodies, and green veinlets fill the interstices of the fragments.

It is composed predominantly of albite, potassium feldspar, and biotite / phlogopite, and subordinately of nepheline, kalsilite, cancrenite, analcime, aegirine-augite, garnet, sphene, riebeckite, biotite, phlogopite, muscovite, calcite, opaque minerals such as magneteite and pyrite, rutile, and apatite. Epidote, allenite, sercite, chlorite, calcite, and goethite contain as hydrothermal alteration and weathering products. Pseudomorph of olivine is replaced by serpentine and talc.

The fine-grained syenite sill (Msm) intruding the central portion of the complex has a width of about 1 metre.

(c) Beforsite body (Mcb, Mfn and Mgr)

The ankeritic beforsite (Mcb) is subdivided into the central beforsite (Mcb1) and the northeast beforsite (Mcb2).

The central beforsite (Mcb1) exhibits a ring structure. The surface of the outcrops present dark brown to brown due to weathering, and shows a distinct difference in colour of surface compared to the surrounding rocks, such as sovite, gneiss and syenite. Banding structure with steep dips is developed in the body, and strike of that is concordant with the ring-shaped body. Aggregates of phlogopite and of goethite are observed in part of this body. Euhedral quartz lacking of prism fills in open-fracture about 2 mm in width are observed at the western portion of the body.

It is composed predominantly of dolomite and phlogopite, and subordinately of quartz, potassium feldspar, melilite, analcime, olivine, garnet, sphene, muscovite, calcite, siderite, opaque minerals such as magnetite, hematite, pyrite, and pyrrohotite, perovskite, apatite, and pyrochlore.

Euhedral pyrochlore about 0.1mm in diameter is found out in the body. Pyrochlore contains from 48.8 to 50.3 weight % of Niobium, and from 0.50 to 0.56 weight % of Cerium. The atomic ratio of Na : Ca is approximately 1 : 1. Chemical formula of pyrochlore on the average is determined as $(Na_{0.97},Ca_{0.92},Sr_{0.06},Ce_{0.01})_{1.96}(Nb_{1.94},Ta_{0.00},Zr_{0.00},Ti_{0.05},Si_{0.00})_{2.00}O_{5.67}F_{1.59}$ assuming $A_2B_2O_6F$. It contains excess fluorine more than that of the ideal formula.

$\delta^{13}C$ values of calcite and dolomite range from −3.7 to −4.1 ‰, and from −3.5 to −3.9 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite range form +8.6 ‰ to +10.5 5 ‰, and from +8.5 to +9.8 ‰, respectively. Dolomite is slightly enriched in ^{13}C, and slightly diminished in ^{18}O compared to calcite.

The northeast beforsite (Mcb2) has a rounded shape elongated to the N-S direction. It is hosted by gneiss of the Namaqua Metamorphic Complex, shale and quartzite of the Nama Sequence, and syenites and sovite of the MQC. All, except sovite, are strongly brecciated, and interstatically filled with carbonatite veins and dykes. The surface of the body shows a dark brown to light brown due to weathering. The banding structure parallel with the shape of the body become clear on surface caused by different resistivity for weathering. Apatite is contained characteristically along the banding structure with a light green in colour and about 5 millimetres wide.

It is composed predominantly of dolomite and apatite, and subordinately of quartz, albite, potassium feldspar, garnet, sphene, riebeckite, phlogopite, muscovite, calcite, opaque minerals such as magnetite, hematite, pyrite, pyrrohotite, and pyrochlore.

Pyrochlore is frequently observed under microscope, and analysed by EPMA. Pyrochlore contains from 45.8 to 50.2 weight % of Niobium, and from 0.17 to 0.41 weight % of Cerium. The atomic ratio of Na : Ca is approximately 1 : 1. Chemical formula of pyrochlore on the average is determined as $(Na_{0.98},Ca_{1.00},Sr_{0.04},Ce_{0.01})_{2.03}(Nb_{1.90},Ta_{0.00},Zr_{0.00},Ti_{0.08},Si_{0.01})_{2.00}O_{5.68}F_{1.63}$ assuming $A_2B_2O_6F$. It contains excess fluorine more than that of the ideal formula.

$\delta^{13}C$ values of calcite and dolomite range from −4.9 to −5.0 δ and from −4.8 to −4.9 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite range form +8.0 to +8.5 and from +8.1 to +8.4 ‰, respectively. Dolomite is enriched in ^{13}C and diminished in $\delta^{18}O$ compare to dolomite.

Fenite (Mfn) is formed at the marigin of the central beforsite (Mcb1).

It is composed predominantly of albitized plagioclase, potassium feldspar and aegirine, and subordinately of sphene, riebeckite, phlogopite, calcite, magnetite, apatite, and sericite.

Granophyre and micro-granite (Mgr) is found in the centre of the central beforsite (Mcb1) and at the southern margin of the northeast beforsite (Mcb2). It is white to light grey in colour, and exhibits a holocrystalline texture.

It is composed mainly of quartz, albite and potassium feldspar, and of small amount of aegirine, calcite, pyrite, and marcasite and apatite.

Normative minerals and average norms, calculated from whole rock chemical compositions of the central beforsite, are magnetite (1.52%), hematite (2.10%), rutile (0.01%), apatite (0.45%), forsterite (0.08%), fayalite (0.30%), calcite (57.30%), magnesite (31.41%), siderite

(4.49%), and strontianite (1.11%). Those of the northeast beforsite are magnetite (0.66%), hematite (1.01%), rutile (0.05%), apatite (4.39%), forsterite (0.14%), fayalite (0.71%), calcite (54.67%), magnesite (29.07%), siderite (5.61%), and strontianite (1.46%). The central beforsite is enriched in magnetite, hematite, calcite, and dolomite, while the northeast beforsite is enriched in apatite and strontianite. Contents of forsterite, fayalite and siderite in both beforsites are similar according to the statistic τ-test.

The Pb-Pb age of galena from the central beforsite, based on the model age method after Stacy and Kramers (1975), is estimated 329 Ma with 38.286 ± 0.0548 (2σ of $^{208}Pb/^{204}Pb$, 15.648 ± 0.0141 (2σ) of $^{207}Pb/^{204}Pb$, and 18.139 ± 0.0021 (2σ) of $^{206}Pb/^{204}Pb$.

(d) Carbonatite dyke (Mcd)

The carbonatite dyke (Mcd) intrudes most of the rock facies in the area. It is made up of both ankeritic carbonatite (beforsite) and calcite carbonatite (sovite). The surface of both rock facies is brown due to weathering.

It is composed predominantly of calcite or dolomite – ankerite, and subordinately of albite, potassium feldspar, manganocalcite, siderite, strontianite, bastnaesite, hematite, apatite, and monazite (?). Goethite is commonly observed as a weathering product.

The chemical formula of bastnaesite on the averge from the beforsite dyke is determined as $(La_{0.12},Ce_{0.41},Nd_{0.21},Pr_{0.08},Ca_{0.14},Fe_{0.02},Sr_{0.02})_{1.00}(CO_3)_{0.94}(F_{0.48},Cl_{0.00},OH_{0.49})_{0.97}$.

$\delta^{13}C$ values of calcite and dolomite range from –3.4 to –5.9 ‰ and from –3.2 to –5.4 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite range from +7.5 to +14.5 ‰ and from +8.1 to +11.2 ‰, respectively. Dolomite and calcite have a variety of ranges of $\delta^{13}C$ and $\delta^{18}O$ compared with those of the sovite body (Mcs) and the beforsite bodies (Mcb1 and Mcb2).

5. Syn– to post–Karoo Intursions (Kdd and Ktd)

The Intrusions are made up of dolerite (Kdd) and trachyte (Ktd). Both have a relatively narrow width of around 2 metres. The dykes intrude all the rock facies. Most of these dykes strike in NE–SW or NW–SE directions. The strikes of the dykes are concordant with those of the banding structures in the northeast beforsite (Mcb2).

The main minerals of the dolerite are plagioclase, clinopyroxene, hornblende and biotite. Subordinate minerals are sericite, chlorite, calcite, perovskite and opaque minerals under the microscope. The main minerals of trachyte dyke are quartz, albite, potassium feldspar, nepheline, aegirine–augite and biotite. Subordinate minerals are fluorite, sericite, chlorite, calcite and pyrite.

2-3 Geochemical Survey

2-3-1 Survey Method

The geochemical survey was carried out during 1993 and 1994. Rock samples are collected for this survey. In 1993, 50 m by 75 m sampling grids were adopted in the MQC area. 100 m by 150 m grids were adopted in other rock facies. In 1994, the geochemical survey concentrated on the central beforsite and northeast beforsite. 25 m by 25 m grids were adopted in the two beforsites. These grids bridge the grids of the survey in 1993.

The geochemical analysis were carried out for the following 19 elements;
La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sc, Y, U, Th, Nb, Ta, Zr, Mn, Sr, P and Fe

2-3-2 Survey Results

Fig.II-2-6 shows the geochemical analysis map. Table II-2-2 shows the geochemical statistic data. Appendix B-3 shows the geochemical analyses. Appendix B-4 shows frequency and cumulative Frequency for geochemical analyses. Appendix B-5 shows Scattering Diagram of the Geochemical Analyses.

1. Rare-earth elements (REEs; La, Ce, Nd, Sm, Eu, Tb, Yb and Lu)

REEs have similar chemical behaviors. Rare earth oxides, assuming R_2O_3, are concentrated in the sovite (Mcs), the central beforsite (Mcb1), the northeast beforsite (Mcb2), and the carbonatite dyke (Mcd) in the MQC and the contents of REEs show the tendency to increase in this order. In the sovite, the maximum value of R_2O_3 is 5,500 ppm, and the mean value is 1,029 ppm. In the central beforsite, the maximum is 32,716 ppm, and the mean is 1,665 ppm. In the northeast beforsite, the maximum content is 27,224 ppm, and the mean is 1,252 ppm. In the carbonatite dykes, the maximum content is 21,657 ppm and the mean is 9,871 ppm.

In the central beforsite body (Mcb1), REEs distribution shows that R_2O_3 more than 1,000 ppm concentrates at the rim of this body, rather than at the core. In places, R_2O_3 exceed 10,000 ppm. Some portions of the fenitized syenite (Mfn) and gneiss (Ngn) have concentrations of over 1,000 ppm. These portions are situated in the intrusive boundary between beforsite and syenite or gneiss, in which beforsite networks are dominant.

The Northeast beofrsite (Mcb2) has portions where the concentration exceeds 1,000 ppm in outer zone of this body, rather than the inner zone. In place the concentration exceeds 10,000 ppm.

The Nama Sequence has a few point of concentration, in which beforsite networks have REEs. The porphyritic nepheline syenite (Msp) has 2,763 ppm at maximum. But the contents in this syenite are not so high compared with the two beforsites.

Through XRD analysis, Ce-Nd-La-bearing bastnaesite and monazite were identified.

Contents of light REEs (La, Cd, and Nd) are coinciding between the two of the beforsites. But middle to heavy REEs (Eu, Tb, Yb and Lu) are concentrated more in the northeast beforsite (Mcb2) than in the central beforsite (Mcd1).

2. Scandium and yttrium

Zones where concentrations zone exceed 100 ppm of these elements are distributed in the northern part of the area, which is underlain by the Nama Sequence. On the other hand, low value zones are found in the MQC area.

3. Uranium and Thorium

Th maximum content of Th is 716 ppm in the carbonatite dyke (Mcd). There are several zones in the survey area where concentrations of these elements are comparable to those in the Kalkfeld area. The outer zones of the central beforsite have relatively high portions of these elements.

4. Niobium and tantalum

Niobium are concentrated in the MQC, especially both of the central befofsite and the northeast beforsite. In the central beforsite, Nb concentrates more than 1,000 ppm in the inner zone, and shows a distinctive distribution compared to that of R_2O_3 which has a tendency to concentrate in the outer zone of the body. The northeast beforsite also has values in excess of 1,000 ppm in the inner zone. According to the result of XRD and EPMA analyses, one of the most important Nb-bearing minerals is pyrochlore in the area.

Ta is concentrated weakly in the two beforsites (Mcb1 and Mcb2), the syenites (Msu and Msr), the fenite (Mfn) and the carbonatite dyke (Mcd), but highly concentrated zones are not distinct.

5. Zirconium

Beforsite bodies (Mcb1 and Mcb2) are characteristically lack of Zr content less than 100 ppm compared with surrounding silicate-dominant rocks. No significant concentration is not distributed in the area.

6. Manganese

Zones where concentration of Mn exceeds 5,000 ppm are distributed in the central and northeast beforsite bodies. The variation of content within the bodies is limited to compare with that of other rock facies. There is no difference of Mn contents between two of the beforsite bodies.

7. Strontium

Sr is highly concentrated in the carbonatite dyke, the central beforsite, the northeast beforsite and the sovite, and is concordant with their distributions. In the central and northeast beforsite bodies, the concentration of Sr distinctively reach up to 22,060 ppm. Through XRD analysis, strontianite is identified in the highly Sr concentrated zones.

8. Phosphorus

Concentration of P over 5,000 ppm is observed in the northeast beforsite. In contrast, the central beforsite body has no concentration of P, and the marginal zone of the body composed peripheral gneiss and syenite shows relatively high concentrations. Apatite is the commonly observed as phosphorus mineral, and monazite is identified through XRD analyses.

9. Iron

The two beforsite bodies and the carbonatite dyke are enriched in Fe. These rock facies have mean values of form 3.73 to 5.74%. The peripheral rocks of the beforsites have aegirine and / or aegirine-augite which lead to an increase in Fe contents. The central beforsite is enriched in Fe rather than the northeast beforsite.

2-4 Drilling Survey

2-4-1 Survey Method

From the results of the literature search and the geochemical survey in phase I, it was seen that the two beforsite bodies of the MQC in the Orange area show concentrations of rare-earth elements, niobium, and phosphorus. Therefore, a drilling survey was conducted to reveal the underground distribution and continuity of these elements in the beforsite bodies.

Fig.II-2-1 shows the drilling sites. The drilling sites total 8 holes. Five of the holes were situated in the central beforsite and the other three holes were situated in the northeast beforsite. These holes are were drilled vertically to a depth of 150 meters , each by the wire-line method.

The drilling operation was carried out by the Namibian company, Rosond Exploration and Foundation (Pty.) Ltd. Drilling machines, drill bits, mud materials, oil, and cements were supplied from Namibia and South Africa. The drilling sites were located on the steep slopes of a mountainous area. Therefore, assembly and dismantling of the drilling equipment was done using helicopters.

The drilling operation was performed under a system comprised of one supervisor, one foreman, three drilling crews and two water supply crews. Each drilling crew was comprised of one driller and 4 assistants. Each water supply crew was comprised of one driver and one assistant.

Initially, one working shift of 11 hours work per day was used, but two shifts were used in the last stage of drilling to stay on the proposed schedule.

There are no river or water resources in the survey area, therefore, the water for drilling was transported rapidly from the Orange river, 30 km away from the survey area, by two 4-ton trucks, each carrying a 3-ton water tank.

The results of drill core observations are described in the geologic columnar sections at the scale of 1 to 200. Rock specimens were sampled every five meters in sections of the beforsites which were believed to show concentrations of rare-earth elements and other elements by geochemical analyses and whole rock analyses (Appendix B-2). Specifically, sections of the beforisite, which have variable components, were analyzed in narrow sampling spans.

To clarify the beforsite occurrences, representative rock samples from each drill core were collected for observation of polished sections, XRD, and oxygen-carbon isotopic analysis. Samples with concentrations of rare-earth elements were analyses quantitatively by EPMA.

2-4-2 Survey Results

Appendix B-6 shows the drilling logs.

(1) MJNO-1

The section from 0.0 to 52.5 m is composed of weathered light brownish-grey to fresh very light grey beforsite (Mcb1). Magnetite and its weathering products of iron oxides and hydroxides are common in this section. It is somewhat rich in phlogopite and pyrite. This section shows distinct banding which dips 60 to 70 °. The section from 52.0 to 109.6 m is composed of light grey arkose which is partly brecciated with a matrix of beforsite. The section from 109.6 to 150.4 m is composed of carbonitized syenite (Msu) with light grey sovite (Mcs) veins and networks.

Normative minerals and average norms of beforsite are magnetite (2.39%), hematite (0.51%), rutile (0.28%), apatite (5.20%), forsterite (0.26%), fayalite (0.86%), calcite (48.67%), magnesite (13.62%), siderite (4.56%) and strontianite (1.15%).

Pyrite, pyrrhotite, sphalerite and galena were identified under the microscope.

$\delta^{13}C$ values of calcite and dolomite are -4.6 and -4.7 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite are +8.0 and +8.5 ‰, respectively. Calcite is enriched in ^{13}C, and dolomite is enriched in ^{18}O.

(2) MJNO-2

The section from 0.0 to 136.0 m is composed of weathered brown beforsite and fractured beforsite (Mcb2) in which goethite and montmorillonite were formed by weathering. The section is somewhat rich in phlogopite and muscovite. The section from 136.0 to 150.4 m is composed of silicified trachyte (Ktd).

Normative minerals and average norms of beforsite are magnetite (5.23%), hematite (3.80%), rutile (0.07%), apatite (3.04%), forsterite (6.68%), fayalite (0.34%), calcite (46.60%), magnesite (24.19%), siderite (0.73%) and strontianite (1.07%).

(3) MJNO-3

The section from 0.0 to 15.0 m is composed of weathered light brown beforsite (Mcb1), and very light grey sulphide-rich beforsite (Mcb1) which includes in pyrite and pyrrhotite. The shallower part of this section is accompanied by dark brown ankeritic beforsite, and the deeper part is accompanied by light brownish-grey magnetite-rich beforsite.

Normative minerals and average norms of beforsite are magnetite (3.14%), hematite (0.08%), rutile (0.01%), apatite (0.02%), forsterite (0.03%), fayalite (0.59%), calcite (56.50%), magnesite (34.85%), siderite (1.81%) and strontianite (1.96%).

Euhedral pyrochlore contains from 50.67 to 51.90 weight % of Nb, and from 0.47 to 0.84 weight % of Ce. Chemical formula of pyrochlore on the average is determined as $(Na_{0.93},Ca_{0.92},Sr_{0.04}Ce_{0.02})_{1.91}(Nb_{1.97},Ta_{0.00},Zr_{0.00},Ti_{0.03},Si_{0.00})_{2.00}O_{5.72}F_{1.43}$ by EPMA analyses.

$\delta^{13}C$ values of calcite and dolomite range from -4.0 to -4.6 ‰, and from -4.0 to -4.6 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite range from +8.2 to +8.5 ‰, and from +8.2 to +8.5 ‰, respectively. $\delta^{13}C$ values of dolomite are slightly higher than that of calcite. $\delta^{18}O$ values of calcite are nearly same as that of dolomite. Samples for isotopic analyses are taken from several depths. It show that $\delta^{13}C$ values increase and $\delta^{18}O$ values decrease in proportion to depth.

(4) MJNO-4

The section from 0.0 to 150.2 m is composed of weathered light brown beforsite and fresh very light grey beforsite (Mcb2) which are accompanied by pyrite and pyrrhotite-rich portions and phlogopite and magnetite-rich portions. The beforsite shows distinct banding which dips 60 to 70 degrees.

Normative minerals and average norms of beforsite are magnetite (0.51%), hematite (0.02%), rutile (0.04%), apatite (0.64%), forsterite (0.97%), fayalite (2.74%), calcite (53.45%), magnesite (35.27%), siderite (3.67%) and strontianite (1.09%).

$\delta^{13}C$ values of calcite and dolomite are the same at -3.7 ‰. $\delta^{18}O$ values of calcite and dolomite are the same at 8.8 ‰.

(5) MJNO-5

The section from 0.0 to 105.1 m is composed of very light grey beforsite with alternating of phlogopite-rich, magnetite-rich and sulphide-rich portions. The surface section shows weathering. The section from 34.0 to 39.0 m is intruded by dolerite. The section from 105.1 to 108.4 m is composed of dark green metasomatic syenite (Msu) blocks. The section from 108.4 to 150.3 m is composed of very light grey micro-granite (Mgr).

Normative minerals and average norms of beforsite are magnetite (2.89%), hematite (0.00%), rutile (0.02%), apatite (0.74%), forsterite (10.30%), fayalite (4.90%), calcite (47.21%), magnesite (30.87%), siderite (0.14%) and strontianite (1.03%).

Pyrite, magnetite, marcasite, and sphalerite were observed under the microscope in the beforsite.

(6) MJNO-6

The section from 0.0 to 101.0 m is composed of very light grey beforsite (Mcb2) which is accompanied by alternating sulphide-rich and phlogopite-rich portions. The section from 101.0 to 147.2 m is composed of very light grey beforsite (Mcb2) which is enriched in apatite with phlogopite and sulphides such as pyrrhotite. The beforsite shows distinct banding which dips 60 degrees. In this section, black dolerite dyke intrudes.

Normative minerals and average norms of beforsite are magnetite (0.91%), hematite (0.02%), rutile (0.04%), apatite (3.94%), forsterite (0.02%), fayalite (2.52%), calcite (56.28%), dolomite (27.29%), siderite (2.15%) and strontianite (1.93%).

Euhedral pyrochlore contains from 48.18 to 50.21 weight % of Nb, and from 0.40 to 0.41 weight % of Ce. Chemical formula of pyrochlore on the average is determined as $(Na_{0.88},Ca_{0.94},Sr_{0.08}Ce_{0.01})_{1.91}(Nb_{1.91},Ta_{0.00},Zr_{0.00},Ti_{0.08},Si_{0.01})_{2.00}O_{5.72}F_{1.48}$ by EPMA analyses.

$\delta^{13}C$ values of calcite and dolomite are the same at −4.9 ‰. $\delta^{18}O$ values of calcite and dolomite are also the same at 8.3 ‰.

(7) MJNO-7

The section from 0.0 to 150.5 m is composed of very light grey beforsite (Mcb2). The shallower section is accompanied by alternating of sulphide-rich and magnetite-rich portions. The intermediate to deeper section is accompanied by pale green apatite-rich beforsite. The beforsite shows distinct banding which dips 60°. The section from 24.5 and 30.5 m is intruded by a black dolerite dyke .

Normative minerals and average norms of beforsite are magnetite (0.09%), hematite (0.13%), rutile (0.01%), apatite (6.63%), forsterite (0.03%), fayalite (0.41%), calcite (56.06%), magnesite (31.26%), siderite (3.12%) and strontianite (1.26%). Pyrite, magnetite and pyrochlore are observed under the microscope.

The pyrochlore contains from 48.98 to 49.62 weight % of Nb, and 0.27 to 0.39 weight

% of Ce.

$\delta^{13}C$ values of calcite and dolomite are −4.7 and −4.8 ‰, respectively. $\delta^{18}O$ values of calcite and dolomite are the same at +8.3 ‰.

(8) MJNO-8

The section from 0.0 to 150.4 m is composed of very light grey beforsite (Mcb2). The shallower section is accompanied by phlogopite-rich beforsite, dark green metasomatic slate blocks and dolerite dyke. The intermediate to deeper section is accompanied by pale green apatite-rich beforsite and trachyte dyke. The beforiste shows distinct banding which dips 60°.

Normative minerals and average norms of beforsite are magnetite (0.23%), hematite (0.02%), rutile (0.04%), apatite (4.85%), forsterite (5.37%), fayalite (2.74%), calcite (48.27%), magnesite (28.73%), siderite (1.92%) and strontianite (1.09%). Pyrite, magnetite, pyrrhotite and pyrochlore are observed under the microscope.

$\delta^{13}C$ values of calcite and dolomite are the same at −4.7 ‰. ‰^{18}O values of calcite and dolomite are the same at +8.2 ‰.

2. Geochemical Survey by core drilling

Rock specimens were sampled every five metres in sections bearing beforistes. The sections which were believed to show concentrations of rare-earth elements were sampled with spans closer than five metres.

Appendix B-3 shows the geochemical analyses. Table II-3-1 shows the statistical data of geochemical analyses. Appendix B-7 shows the geochemical distributions along the drill cores.

Geochemical analyses were carried out for the following 19 elements;
La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sc, Y, U, Th, Nb, Ta, Zr, Mn, Sr, P and Fe

(1) Rare-earth elements (REEs: La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu)

The MJNO-1 drill section shows an average content of 1,150 ppm of Ce, but other sections show contents of less than 1,000 ppm.

The maximum contents in MJNO-1 of La and Ce are 10,930 and 10,023 ppm, respectively. The average content of rare-earth oxides in MJNO-1 exceeds 3,000 ppm, other sections show contents of less than 1,000 ppm.

REEs are more concentrated in the central and northeast beforsites than in other rock facies. But rock facies with beforsite networks in contact with beforsites have high contents of REEs.

Total rare-earth oxides contents of the central and northeast beforsite are the same according to the statistic τ-test. But middle and heavy REEs are concentrated more in northeast beforsite compared with the central beforsite.

Each section has variable contents of REEs. REEs have no tendency to increase with depth.

(2) Scandium and Yttrium

Each section shows an average content of less than of 100 ppm of Sc. The central beforsite shows an average content of 47.3 ppm. The northeast beforsite shows an average content of 4.3 ppm. Sc is concentrated in the central beforsite, compared with the north beforsite.

Each section shows an average content of less than 100 ppm of Y. The central beforsite shows an average content of 10 ppm. The northeast beforsite shows an average content of 35 ppm. Y is more concentrates in the northeast beforsite compared with the central beforsite.

(3) Uranium and Thorium

Each section shows an average content of less than of 100 ppm of U. The central beforsite shows an average content of 6 ppm. The northeast beforsite shows an average content of 3 ppm. U is concentrated in the central beforsite, compared with the northeast beforsite.

Each section shows an average content of less than 100 ppm of Th. The central beforsite shows an average content of 24 ppm. The northeast beforsite shows an average content of 17 ppm. The content of Th in the central beforsite is the same as that in the north beforsite.

(4) Niobium and Tantalum

Sections of MJNO-4, 5, 6 and 7 show average contents of over 1,000 ppm of Nb. The other sections show averages of more than 500 ppm. The maximum content is 5.2% in MJNO-7, but the high contents are not continuous. The central beforsite shows an average content of 1,111 ppm, while the northeast beforsite shows an average content of 2,073 ppm. The content of Nb in the central beforsite is same as that in the northeast beforsite.

Each sections show an average contents of less than 30 ppm of Ta. The central beforsite shows an average content of 8 ppm. The northeast beforsite shows an average content of 2 ppm. Ta is concentrated in the central beforsite, compared with the northeast beforsite. Each section has variable contents of Ta

Nb and Ta have no tendency to increase with depth.

(5) Zirconium

Each section shows average contents of from 3 to 136 ppm of Zr. The central beforsite shows an average content of 20 ppm. The northeast beforsite shows an average content of 14 ppm. The content of Zr in the central beforsite is the same as that in the northeast beforsite.

(6) Manganese

Each section shows average contents of from 4,700 to 7,600 ppm of Mn. The central beforsite shows an average content of 6,971 ppm, while the northeast beforsite shows an average content of 6,293 ppm. The content of Mn in the central beforsite is the same as that in the northeast beforsite.

MJNO-1 in the central beforsite shows higher contents in shallow portions and lower contents in deeper portions. In other sections, there is no tendency such as this. In relation to other elements, Mn decreases in portions where Fe increases.

(7) Strontium

Each sections shows average contents from 3,651 to 6,329 ppm of Sr. Central beforsite shows an average content of 6,329 ppm. Northeast beforsite shows an average content of 6,249 ppm. The content of Sr in central beforsite is same as that in northeast beforsite.

MJNO-1 in central beforsite and MJNO-8 of northeast beforsite shows wide variations of contents. But the other sections have small variations of contents. Sr has no tendency to increase in the depth.

(8) Phosphorus

Sections MJNO-3 and 4 show average contents of less than 1,000 ppm of P. The other sections show average cntents of 1,000 ppm and more of P. In particular, sections of MJNO-1,7 and 8 exceed the average content of 1%. An maximum content of 7.7% is attained in sections of MJNO-1. Portions with high content are not continuous.

The central beforsite shows an average content of 2,602 ppm. The northeast beforsite shows an average content of 12,224 ppm. P is concentrated in the northeast beforsite, compared with the central beforsite.

Sections MJNO-1, 2 and 5 show wide variations in contents. Sections of MJNO-3 and 4 do not have high content. Sections of MJNO-6, 7 and 8 have continuous high contents at depth. and relatively low content near surface.

(9) Iron

Each sections shows an average content of from 3.63 to 6.77 % of Fe. The central beforsite shows an average content of 4.49 % of Fe. The northeast beforsite shows an average content of 3.35 %. Fe is concentrated in the central beforsite, compared with the northeast beforsite.