REPORT ON GEOLOGICAL SURVEY
OF
THE SULTANATE OF OMAN
(SUR AREA)

PHASE 2

JUL. 1982

METAL MINING AGENCY OF JAPAN
JAPAN INTERNATIONAL COOPERATION AGENCY

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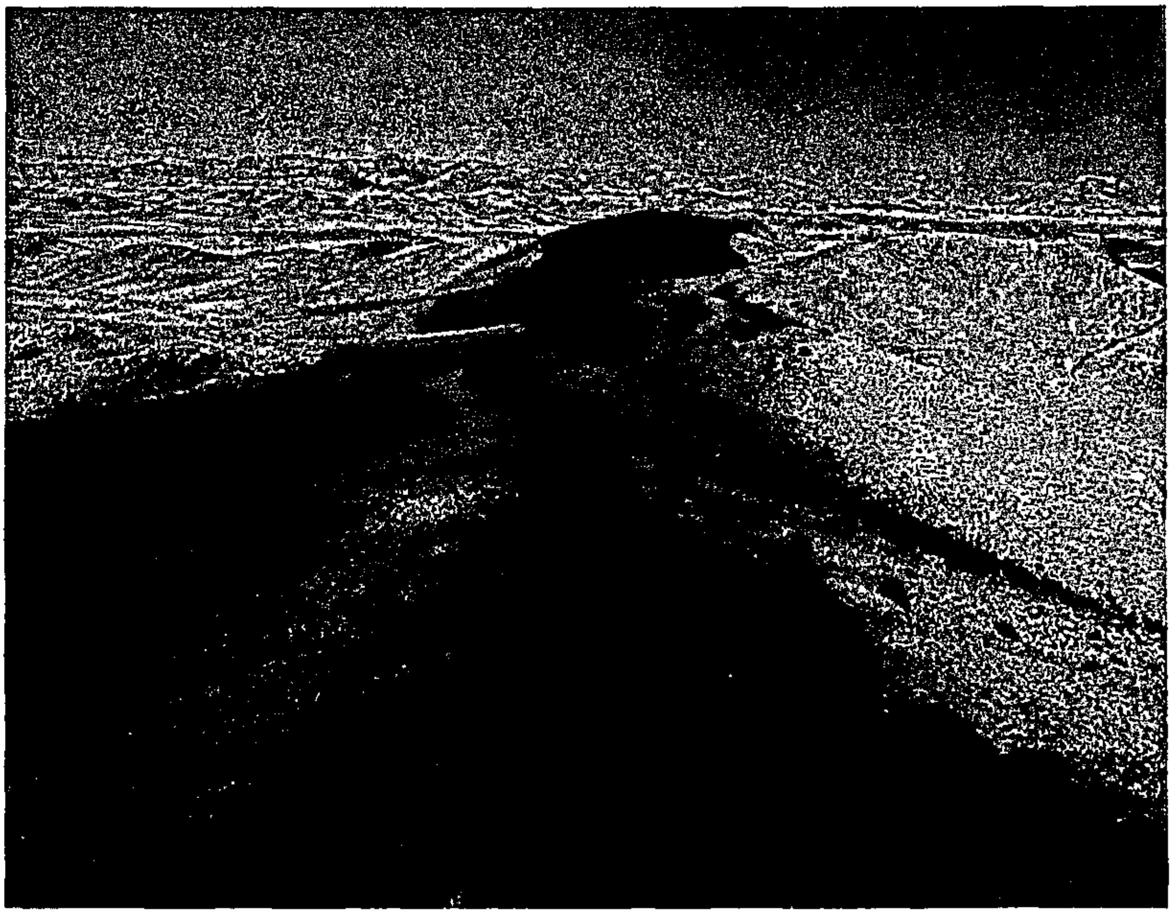
Manganese Outcrop (No. 95) in Halfa Formation
Location: 5km South of Jaramah



Manganese Outcrop (No. 110) in Halfa Formation
Location: 5km South of Jaramah

PREFACE

The Government of Japan, in response to the request of the Government of the Sultanate of Oman, decided to conduct a geological survey for mineral exploration in the Sultanate of Oman, and commissioned its implementation to Japan International Cooperation Agency.

Considering its technical aspects, the agency sought collaboration of the Metal Mining Agency of Japan to accomplish the task within a period of three years.

As for this current year, a survey team was formed consisting of ten members headed by Mr. Hirofumi Taniguchi, staff of the Metal Mining Agency of Japan, and sent to the Sultanate of Oman between October 23 and December 28, 1981 to conduct the second phase of the project.

The survey has been accomplished under close cooperation with the Government of the Sultanate of Oman and its various authorities.

This report hereby summarized the results of the aforementioned undertaking.

We wish to express our heartfelt gratitude to the Government of the Sultanate of Oman and other authorities concerned for their kind cooperation and support extended to the Japanese survey team.

April 1982

Kensuke Arita
President
Japan International Cooperation Agency

Masayuki Nishiie
President
Metal Mining Agency of Japan

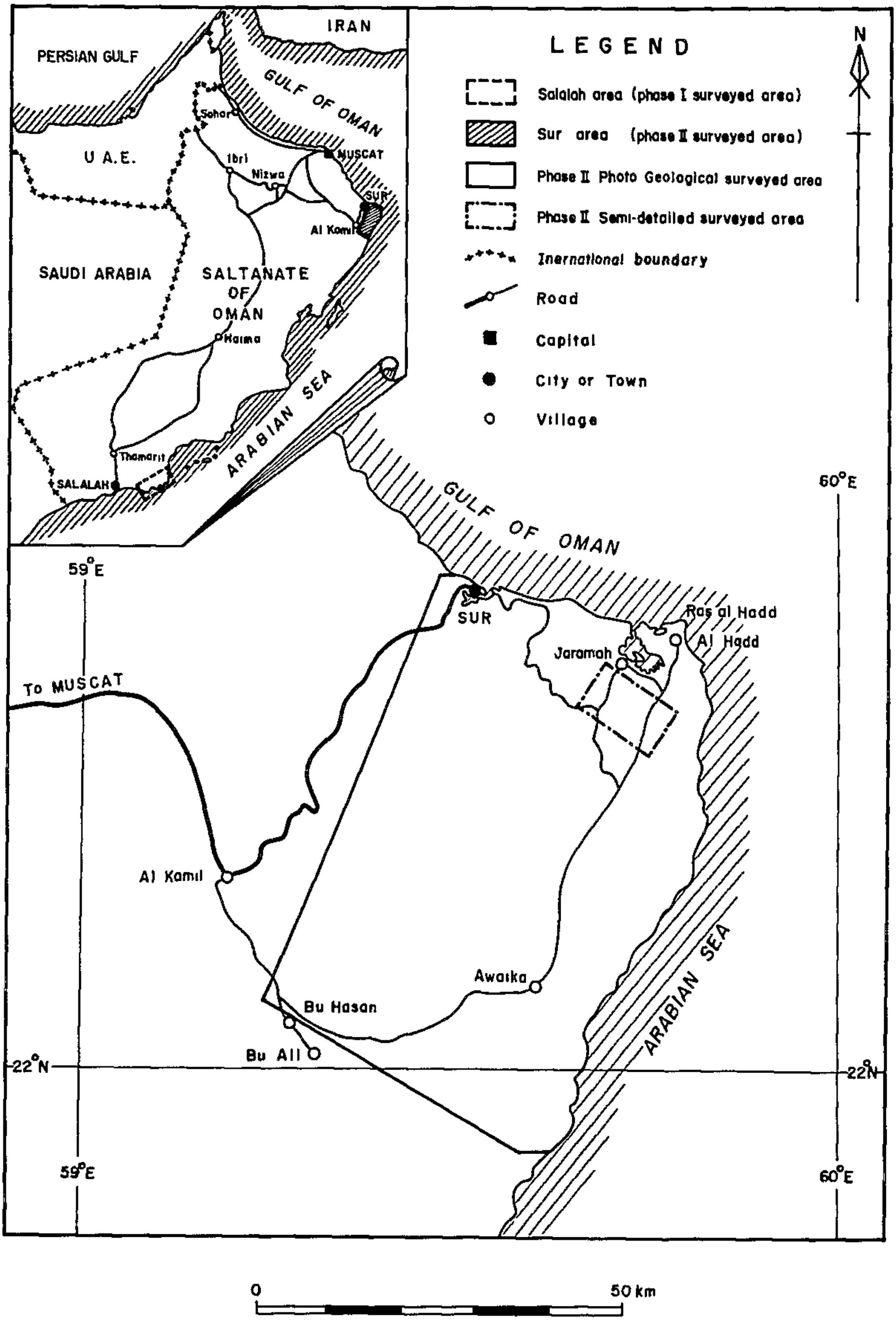


Fig. 1 Location Map of the Project Area

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ABSTRACT

In the survey of the second year in Sur area of the Sultanate of Oman, the semi-detailed geological survey in the known manganese deposits area and the photogeological survey in the whole area were carried out to clarified the geology, stratigraphy, geological structure, igneous activity, as well as distribution and character of ore deposits, and also to establish the useful guide for future exploration.

As the result of the survey, it was clarified that geology and stratigraphy are composed of Pre-Cambrian basement rocks, Triassic to Early Cretaceous Halfa Formation thrusting over the basement, Maastrichtian to Middle Tertiary Limestone Formation unconfomably overlying the basement and Halfa Formation, and Quaternary sediments overlying all of them. The basic and acidic dyke, sheet intrude into the Halfa Formation and Limestone Formation. The Halfa Formation consists of radiolarian chert, shale, limestone and basic lava.

The major geological structure is characterized by the N–S trending of the extension of basement, the complexly folded and faulted beds of the Halfa Formation and the N–S trend of the folding and fault of the Limestone Formation.

Stratiform manganese ore deposit embedded in muddy chert of the Halfa Formation, is composed of several discontinuous small manganese beds with manganese nodule. Although many manganese outcrops were found in the area, it is considered that these mangnese outcrops belong to two or three ore horizons. Mn assay value of ore indicated medium grade. It is considered that origin of the manganese ore deposits in this area is genetically related to submarin volcanic activity.

As for future exploration, the detailed geological survey with trenching and short drilling has to be carried out to determine the scale, grade and character of ore deposits in the south area of Jaramah and the north, northwest area of Awaika.

It is the most important object for exploration to clarify the relation between ore deposits, folding, igneous activity and sedimentary environment.

GENERAL INFORMATION

Chapter 1 Outline of the Survey

1–1 Details and purpose of the survey

The Government of Japan conducted the survey for mineral resources development plan by Japan International Cooperation Agency from March 15 to April 17 in 1979 in order to confirm the possibility of mineral resources in the Oman upon a request of the Government of the Sultanate of Oman. During the survey, preliminary surveys on geology and ore deposits were conducted in three areas such as Salalah, Sur and Batinah Coast, and as the result, Salalah and Sur areas were selected as promising areas to be continued the survey in future.

On the basis of results of survey, the both Governments of Japan and Oman reached agreement for performing the basic survey for mineral resources exploration in the two selected areas from fiscal 1980 as the first year, and the Government of Japan consigned the excurtion of survey to Japan International Cooperation Agency (JICA) and Metal Mining Agency of Japan (MMAJ).

In July 1980, an agreement of the scope of work for this project has been signed by the two agencies and the Ministry of Petroleum and Minerals of the Sultanate of Oman, and the field survey of the first year was commenced in the Salalah area and of the second year was commenced in the Sur area.

The survey in the Salalah area, the southern part of the Sultanate of Oman, was carried out for three months from September 26 to December 25 in 1980. The results showed no existence of significant ore deposit to expect further exploration, although some very small copper showings were discovered, and the survey of the second year has been suspended.

Based on this circumstances, the survey of the second year was conducted only in the Sur area, where manganese ore deposits had been known as the results of survey by the Ministry of Petroleum and Minerals and by JICA.

The first purpose of the second phase survey was to clarify stratigraphy and geological structure as well as distribution, grade and characters of deposits by the semi-detailed geological survey in the known ore deposits area to establish exploration guides for the next phase survey.

The second purpose was also to clarify the distribution of the ore-bearing formation, regional geological structure and to find ore deposit in the southern part of the known ore deposits area by the interpretation of Landsat images and aerial photographs and collection of existing data.

1–2 Substance of the survey

In order to attain the objects mentioned above, semi-detailed survey consisting mainly of investigation for ore deposits and photogeological survey tracing of the ore bearing horizon, were carried out in the area as shown in Fig. 1.

The semi-detailed geological survey was conducted in the area of 77 km^2 including known ore deposits area and surroundings to clarify the relationship of location and continuity of outcrops along the geological survey routes, 120 Km long, in the scale of 1:5,000 which were set up by handy measuring survey. The survey routes have been planned before starting this survey based on the data of the previous works.

It is difficult to know the exact position of the survey route in the field because the semi-detailed survey area consist of flat and low hills as topographically, so that one E–W direction base line through center area and two N–S direction base lines through eastern and western margins were set up in the semi-detailed area, and all the survey routes were connected to these base lines to make accurate the positional relations.

The field work was carried out from October 23 to December 28 in 1981, and the result of survey was compiled on the geological maps of 1:20,000 in scale.

Photogeological survey consisting of the interpretation of Landsat images and the aerial photographs, monochrome print of 1:60,000 in scale and color print of 1:20,000 in scale, with ground-checking work was carried out to clarify the regional geology, geological structure and distribution of ore bearing formation, and to newly find ore outcrops. The interpretation of Landsat images and aerial photographs was conducted from September 10 to November 5 in 1981 and January 6 to February 5 in 1982, and ground-checking work was carried out from November 6 to December 28 in 1981. These results were compiled on the photogeological maps of 1:50,000 in scale.

Topographical maps of 1 : 50,000 in scale for the whole area and 1 : 20,000 in scale for the semi-detailed survey area were prepared in Japan before commencing the field survey. These topographical maps were produced from aerial photographs of 1 : 60,000 and 1 : 20,000 in scale.

The outline of field survey of this year was shown in Table 1.

The brief discussion and investigation for geological survey and photogeological survey were carried out in the base camp by the survey members both of Japan and Oman, and the results of the survey were reported to the Department of Minerals of Ministry of Petroleum and Minerals after field works.

The detailed analytical works on the results of field work were conducted in Japan.

Various samples were taken away to Japan for chemical analysis and various investigations, and these results were compiled in this report.

Authors wish to express appreciation for the useful advice of Professor Terukuni Matsumaru of Saitama University on identification of fossils of large foraminifera Dr. Fujio Kumon of Kyoto University on identification of radiolarian fossils, and further, Professor Shunzo Yui of Hirosaki University and Professor Toshihiko Yajima of Saitama University on investigation of geology and ore minerals.

Table 1 Outline of Field Survey in Phase II

	Survey period	Area	Length of survey route	Number of tested samples (pcs)
Preparatory survey	Oct. 23, 1981 ~ Nov. 5, 1981			
Photo geological survey	Nov. 6, 1981 ~ Dec. 22, 1981	3,400 km²	219.0 km	chemical analysis of ore 15 spectrographic analysis 15 thin section 20 polished section 7 X-ray diffractive analysis 6 determination of fossil 17
Semi-detailed survey	Nov. 6, 1981 ~ Dec. 22, 1981	77 km²	130.5 km	chemical analysis of ore 191 spectrographic analysis 35 thin section 17 polished section 19 X-ray diffractive analysis 24 determination of fossil 9
Compilation of existing data	Dec. 23, 1981 ~ Dec. 28, 1981			

1–3 Member of the survey team

The members participated in the survey for planning, negotiation and field survey are as follows:

(1) Planning and negotiation

Japan	Hisamitsu Moriwaki	JICA
	Toshio Koizumi	MMAJ
	Tadaaki Ezawa	〃
	Hirofumi Taniguchi	〃
	Tsuyoshi Suzuki	〃
Oman	Mohammed Kassim	Ministry of Petroleum and Minerals

(2) Field survey

Japanese survey team

Team leader		
	Hirofumi Taniguchi	MMAJ
Geological survey		
	Masahiko Nouno	〃
	Atsumu Nonami	〃
	Masaaki Matsuoka	〃
	Tadashi Yamakawa	〃
Photogeological survey		
	Yoshiaki Shibata	〃
Oman counterparts		
	Naser Saleem	Ministry of Petroleum and Minerals
	Hareb Hamad	〃

1–4 Previous works

The surveyed area is located in the southern end of the Oman Mountains and forms a part of the Mountains as geologically.

The first geological investigation of the Oman Mountains was conducted by Carter (1850), and after that, a systematic survey was carried out by Lees (1928) over the broad areas. Many surveys and studies have been done since that time, and as for these synthetic survey and description K.W. Glennei et al (1974) is well-known.

According to the report, the geology of the Oman Mountains is roughly divided into (1) basement rocks of Precambrian to Cambrian, (2) autochthonous continental and neritic sediments of Pre-Permian and Middle Permian to Late Cretaceous, (3) allochthonous sediments of Middle Permian to Late Cretaceous and (4) Late Cretaceous to Tertiary sediments.

The allochthonous sediments (3) is considered to have been thrusted over the autochthonous sediments in the later stage of Cretaceous by the tectonic movement of Arabian plate initiated in Late Cretaceous.

Among these four geological units, (1), (3) and (4) are distributed in the surveyed area.

The previous work in the surveyed area and its surroundings were reported by B.M. Reinhardt and K.W. Glennie(1969), L.E. Carlson(1973), and R.G. Coleman and E.H. Bailey (1974), and those of the latest data were carried out by I.M. Elboushi and C. Zachariah (1979), and JICA (1979).

Reinhardt and Glennie (1969) studied the relation between the manganese deposits in the area and the stratigraphy of the Oman Mountains, and explained that formation of the manganese deposits has been related to submarine volcanic activity.

Carlson (1973) also surveyed and clarified the manganese deposits concentrated in the northern part of the area, the structure and continuity of the ore bearing formation, and described occurrences of manganese minerals.

Coleman and Bailey (1974) clarified the lithology of the hanging wall and foot wall of the manganese deposits, and carried out analysis of the ore.

Elboushi and Zachariah (1979) surveyed on the manganese deposits and variation of rock facies of the ore bearing bed, and considered that formation of the manganese deposit has been related to submarine volcanic activity

JICA (1979) conducted a preliminary survey for geology and ore deposits, and studied the characteristics of the host rocks, the occurrence of the ore deposits, and carried out identification of compositional ore minerals and its analysis.

On the basis of these numerous previous works, the geology and ore deposits of the surveyed area is summarized that the area consists of Precambrian basement rocks, and overthrusted allochthonous sediments in Late Cretaceous and Maastrichtian to Tertiary sediment overlying the basement.

The manganese ore deposits are concentrated mainly in the northern part of the area, and they seem to have been derived from submarine volcanic activity and formed in the allochthonous sediments.

Thus it can be said that such area is expected to be a promising area for occurrence of manganese resoruces.

1–5 Reference

Bamba, T. (1976)	Ophiolite and related copper deposits of Ergani mining district, southeastern Turkey, Bull. Miner. Res. Expl. Inst. Turkey, 86, p.36 – 50.
Borchert, H. (1970)	On the ore deposition and geochemistry of manganese, Mineral. Deposita (Berl.) 5, p.300 – 314.
Carlson, L.E. (1973)	Ras Al-Hadd area, Oman manganese deposit, Granges International Mining.
Carney, J.N. and Welland, M.J.P. (1974)	Geology and mineral resources of the Oman Mountain. Institute Geol. Soc., London Rept. No.27, p.1 – 49.
Coleman, R.G. and Bailey, E.H. (1974)	Mineral deposits and geology of Northern Oman, U.S.G.S. Project Report, Oman Investigations (IR) OM–1.
Elboushi, I.M. and Zachariah, C. (1979)	Ras Al-Hadd Manganese deposits, The Sultanate of Oman, Mineral department directorate general of petroleum and minerals, Muscat.
Glennie, K.W. and others (1974)	Geology of the Oman Mountains, Pt.I (Text) and Pt.II (Tables and Illustrations). Verh. Konink, Netherland Geolo. Mijnbowkundig Genootschap, Deel 31, p.1 – 423.
Gealey, W.K. (1977)	Ophiolite obduction and geologic evolution of the Oman Mountains and adjacent area, Geol. Soc. America Bull. v.88, p.1183 – 1191.
Graham, G.M. (1980)	Structure and sedimentology of the Hawasina Window, Oman Mountains, Unpub. report, Department of Earth Science, The Open Univ. p.1 – 422.
Hewett. D.F. (1966)	Stratified deposits of the oxides and carbonates of manganese, Econ. Geol. vol.61 No.3, p.431 – 461.
JICA (1979)	Report on the survey for mineral resources development in the Sultanate of Oman.
Krauskopt, K.B. (1979)	Introduction to geochemistry, 2nd ed., New York, Mc Graw Hill p.617.
Pettijohn, F.J. (1957)	Sedimentary rocks, Harpper and Brothers, New York, N.Y.
Reinhardt, B.W. and Glennie, K.W. (1969)	Some observation on mineral resources in the Oman Mountains, Koninklijke/Shell Exploration En Produktie Laboratorium, Rijswijk, The Netherland.
Roy, S. (1976)	Ancient manganese deposits, in Wolf, K.H., ed., Handbook of strata-bound and stratiform ore deposits. : Amsterdam, Elsevier Sci. Pub. Co. V7, p.395 – 476.
Shooji, R. (1971)	Petrology of sedimentary rocks, Asakura-shoten, p.1 – 285 (in Japanese).

Strakhov, N.M. and others (1967)	Behavior of minor elements in sedimentary manganese mineralization, Bulletin of Geological Survey of Japan, vol.19, No.5 (Translated in Japanese by Moritani, T., 1968).
Zantop, H. (1980)	Trace elements in volcanogenic manganese oxides and iron oxides, The San Francisco Manganese deposit, Jalisco, Mexico, Econ. Geol. vol.76, No.3, p.545 – 555.
Watanabe, T., Yui, S. and Kato, A. (1970)	Bedded manganese deposits in Japan, a Review, Tatsumi, T. (editor), volcanism and ore genesis, Tokyo Univ. Press, Tokyo, p.119 – 142.

Chapter 2 Outline of the Surveyed Area

2–1 Location and access

The surveyed area of this year is situated about 150 kilometers southeast from Muscat, the capital city of the Sultanate of Oman, and also located in the southern end of the Oman Mountains, with Wahiba Sands on the southwest of the area. The area has an area of 3,400 square kilometers and is appliximately bounded by following lines, as shown in Fig. 1.

Northern limit	:	Gulf of Oman
Western limit	:	A line connecting N 22°26' latitude, E 59°29' longitude and N22°05' latitude, E 59°33' longitude.
Southern limit	:	A line connecting N 22°05' latitude, E59°15' longitude and N 21°51' latitude, E 59°33' longitude.
Eastern limit	:	Arabian Sea.

As for the main town and villages in the surveyed area and the surroundings, Sur is located at the northwestern end of the area, Bu Hasan and Bu Ali at the southwestern end, Al Hadd and Jaramah at the northeastern end, and Awaika in the center. Among these, Sur is the largest town and the fishing port in the district.

The base camp for the field survey was established in Jaramah, the nearest village from semi-detailed surveyed area.

A road is connected Muscat and base camp in Jaramah, 360 kilometers long, through Bid Bid, Ibra, Al Kamir and Awaika, and it takes eight hours to travel by vehicle.

Among the road, a pavement road is 260 kilometers long between Muscat and Al Kamir, and a gravel road is 100 kilometers between Al Kamir and Jaramah.

The surveyed area consists mainly of gentle hills except highland distributed limestone, and it is available to access to the whole area by four-wheel drive vehicles.

2–2 Topography

The geology of the surveyed area consists mainly of allochthonous sediments such as alternation of chert and shale, and Tertiary limestone.

The topography of the area well reflects these geological features which is characterized by flat land or gentle undulating low hills consisting of alternation of chert and shale, and plateau or steep highland with escapement consisting of limestone.

The northern rim of the surveyed area consists of limestone plateau, 100 to 200 meters above sea level, and the coast facing the Arabian Sea presents a sea cliff about 100 meters height.

The surface of the plateau shows a small-scale karst topography.

The western rim of the surveyed area shows a steep highland, 500 to 1,400 meters height, overlain by limestone with extending approximately north to south direction.

The highest point in the area is the altitude of 1,442 meters in the southwestern part. From the center part to Arabian Sea, alternation of chert and shale distributes forming gentle slopes and hills 50 to 150 meters height, and small hills about 100 meters height consisting of limestone scattered in the lowlands.

The terraces showing two different height are forming a plateau in the central part to western part.

The wadi run from the highland of the western part to the lowland of the eastern part forming the deep valley, and becomes the underflow before entering the lowlands. In the some places of the downstream, oasis are observed, but no flood has been recognized during the field survey.

2–3 Climate and vegetation

The more than 80 percent of the country of the Sultanate of Oman is occupied with desert, 15 percent of the country is mountains and the remain is the lowland. Most of the country including the surveyed area belongs to arid climate.

Because of hot wind blown from Al Rub Al Khali Desert of Saudi Arabia, the temperature rises above 40°C in summer season from May to October, and the temperature is high even in winter from November to April, although it is a little lower than summer, but difference of temperature between day and night times is great in summer.

Although the precipitation in the surveyed area has not been clarified because of absence of observational data, the annual precipitation is very small, which is concentrated in January in the winter season, and when stream of wadi flows and the lowland becomes mashland.

Chapter 3 General Discussion

Numerous basic data on geology and ore deposits were obtained by this phase survey.

The survey result will be described in the each paragraphs in detail, so that the following is discussion of stratigraphy, especially ore horizon, and ore genesis which are very important for future exploration, and is based on the result of this phase survey in addition to data of previous studies.

3–1 Stratigraphical classification

The stratigraphic sequence in the surveyed area is divided into Pre-Cambrian basement rocks, Triassic to Early Cretaceous Halfa Formation and Maastrichtian to Middle Tertiary Limestone Formation in ascending order and Quarternary sediments covering formers.

Basement rocks are composed of metamorphic rock, gneiss and amphibolite intruded by granite, basic and acidic dykes, which is exposed in the southeastern part of the area.

The Halfa Formation is one constituent of Hawasina Group which is allochthonous sediments thrusting over the autochthonous sediments in Late Cretaceous, and is widely distributed in the lowland of the area. It consists mainly of the alternation of chert and shale, intercalated with thin bed of shale which is pelagic sediments, and contains manganese ore deposits.

The Maastrichtian to Tertiary Limestone Formation unconformably covers the basement rocks and the Halfa Formation; and is distributed in north and west rim of the area. It consists of limestone, sandy limestone, sandstone and conglomerate.

Quaternary sediments are widely distributed covering more than 60 % of the area, which are terrace deposits and wadi sediments.

The above stratigraphic classification in the surveyed area is in agreement with the result of previous studies on the whole, excepting the Ibra Formation underlying the Halfa Formation reported by those studies.

In this report, however, it is considered that the Ibra Formation is not exposed in this area, which is different from the previous results.

Many manganese ore deposits occur in the relatively small area such as the semi-detailed survey area, which suggests that ore deposits have been formed at the limited horizon.

From mentioned above, the classification of the Halfa Formation is attempted and the relation between ore deposits and Halfa Formation is discussed. The thickness of the Halfa Formation is estimated more than 700 m, which is more thicker than that of type locality.

The following is mentioned about the Ibra Formation, the lithological classification and thickness of the Halfa Formation.

(1) On the Ibra Formation

Many previous studies such as Glennie et al (1974), Elboushi and Zachariah (1979) and JICA (1979) mentioned that the Ibra Formation is distributed in this area, underlying the Halfa Formation with tectonic contact, and is composed of grainstone, shale, sandstone and chert in type locality near Ibra, but predominant sandstone in this area.

In this survey, it was concluded that the Ibra Formation is not exposed in this area, because dark gray limestone and sandstone are observed at the place reported to be the outcrop of Ibra Formation, and these limestone and sandstone overlie the Halfa Formation, in addition to this, large foraminifera which indicates Maastrichtian were observed in other limestone correlated with above mentioned limestone.

(2) Lithological classification of the Halfa Formation

The Halfa Formation, which contains manganese ore deposits, consists of alternation of chert and shale, shale bed, muddy chert, conglomerate and limestone facies. The Formation covering the most part of the surveyed area has been characterized by intense folding and repeating of the above-mentioned rock facies and shows highly complecated geological structure.

In this phase survey, the lithological classification of the Halfa Formation was attempted to clarify geological structure and general feature of the manganese ore horizon, and this Formation was divided into three members such as : Lower member, middle member and upper member, based on the relative quantity of chert and shale.

The lower member is composed of alternation of chert and shale and shale bed. It is narrowly distributed in the semi-detailed survey area and the western part of Awaika. The middle member consists mainly of alternation of chert and shale with sparse muddy chert, shale bed and conglomerate. This member has the widest distribution in the surveyed area. The upper member consists of alternation of chert and shale with limestone, and exposed narrowly in the western part of Awaika and the southern end of the photogeological surveyed area.

Generally, it is very hard to distinguish one member from other two members because the Halfa Formation has no characteristic rock facies like so-called key bed. However, the lower and upper members can be distingush from others by existence of gray chert and yellowish white shale in the lower member and limestone in the upper member, respectively.

Most of manganese ore deposits occur concentrically in the middle member with the exception of some ore deposits in the lower member. As described above, the middle member is composed of alternation of chert and shale with muddy chert, and ore deposits are formed in this muddy chert. The combination of rock facies around a ore deposit is as follows ; ore deposit–muddy chert–shale rich alternation of chert and shale–chert rick alternation of chert and shale, and this combination is observed in both sides or one side of the deposit.

The ore deposits are formed in the muddy chert without exception although the muddy chert is not always accompanied with manganese ore deposits. Usually, manganese ore deposits consist of several ore beds in the muddy chert and manganese nodules are often observed around the ore bed.

As mentioned above, the combination of rock facies around the manganese ore bed and the existence of muddy chert show the close relationship with the formation of ore deposits, and the detailed observation and description on the combination of rock facies are considered to be very useful for the prospecting and tracing of manganese ore horizon.

(3) Thickness of the Halfa Formation

The Halfa Formation distributed in this surveyed area was divided into the lower, middle and upper members and their thickness were estimated around over 200 m, over 300 m and over 200 m, respectively, and more than 700 m in total. On the other hand, Glennie et al (1974) has reported that the Halfa Formation was composed chiefly of alternation of red to green chert and siliceous shale, and its estimated thickness was more than 130 m.

This difference on the thickness of the Halfa Formation may be considered to be due to its distribution feature in both areas. On the basis of the correlation of rock facies, the lower and middle members seem to be lack and only upper member is distributed at the type locality. The thickness of more than 130 m is considered to show the thickness of the upper member of this surveyed area.

3–2 Genetic consideration on manganese ore deposit

Based on the synthesized discussion on the results of the second phase survey and previous work, the genetic consideration on the manganese ore deposits was attempted for future exploration of the same type ore deposits. The result is described as follows:

The manganese ore deposits distributed in this surveyed area are stratiform deposits occurred in muddy chert and several ore beds are discontinuously formed in the same horizon. The main part of ore bed consists of black silicious part with manganese minerals showing various concentration forms, and accompanied with manganese nodules around the ore bed.

Manganese bed contains high content of SiO_2.

Alternative bed is generally chert rich alternation, however, in the vicinity of muddy chert shale rich alternation or shale bed can be recognized.

The variation of rock facies near the ore deposits shows chert rich alternation–shale rich alternation–muddy chert–manganese ore deposits.

There are various theories in regard to the formation of chert, and origin of silica, main constituent of chert, is considered to be extracted from continent(continental origin) or to be related with submarine volcanic activity (submarine origin) (Pettijohn (1957).

According to Shooji (1971), chert of alternative bed was formed by silica of continental origin and massive chert was formed by silica of submarine volcanic origin, and massive chert is often accompanied with manganese ore deposits and moreover, massive chert was formed by the rapid supply of large amount of silica genetically related to submarine volcanic activity which seems to be accompanied with the formation of manganese ore deposits.

It is clarified that the formation of manganese ore deposits accompanies with enrichment of silica through the process decreasing silica. Therefore, it can be considered that remarkable concentration of silica is related to submarine volcanism rather than continental origin.

Strakhov (1967) points out that manganese deposit related to SiO_2 is volcanogenic sedimentary deposit.

Range of the content of minor element in this manganese ore, is similar to those of the volcanogenic sedimentary manganese ore studied by Strakhov (1967).

Minor element Sr and Ba indicate the same behavior with Mn. According to Borchert (1970), Zantop (1980) it is considered that Sr and Ba concentrate in volcanogenic

Sedimentary manganese deposit.

From mentioned above, it is considered that the manganese ore deposits in this area were formed relating with volcanic activity and primary ore deposits were formed accompanying abundant silica.

It is presumed that the primary ore deposits changed the shape by thrusting and upheaval movement, and ore minerals also changed during diagenesis.

Primary ore texture is remained in the ore.

The rich zone of ore deposits appears to be controlled by sedimentary environment in ore forming stage rather than diagenesis or folding.

Halfa Formation is remarkably folded, such as the shape of ore deposits reflects folding structure. It is necessary for exploration to clarify the relation between ore deposit and fold.

In the Halfa Formation, basic dyke, sheet or lava occur, one of dykes accompanies with red siliceous rock containing veinlet of manganese minerals, and one of dykes belongs to alkali rock. It is important for exploration to clarify the relation between ore deposits and igneous activity.

Chapter 4 Conclusion of the Survey and Suggestion for the Future Exploration

4–1 Conclusion

In the survey of the second year in Sur area of the Sultanate of Oman, the semi-detailed geological survey and photogeological survey were carried out to clarify the stratigraphy, geological structure, igneous activity, as well as distribution, character of ore deposits and ore horizon.

As the result of synthetic discussion on survey results and existing data, the following conclusions were obtained.

1) The formation in the surveyed area was lithologically divided into, such as Pre-Cambrian basement rocks consisting of metamorphic rocks and granite, Triassic to Early Cretaceous Halfa Formation consisting mainly of chert and shale and Maastrichtian to Middle Tertiary Limestone Formation consisting of thick limestone. This stratigraphical classification was also established by the fossils.

The Halfa Formation is autochthonous pelitic sediments, thrusting over the basement rocks in Late Cretaceous.

2) The geological structure in the area is characterized by the N–S trending of extension of the basement rocks, the complex fold and fault of the Halfa Formation by thrusting and the N–S trending fold and fault of the Limestone Formation. Especially, folding structure of the Halfa Formation is recognized in its whole distribution area, and shows the complicated structure with many repetition of the formation.

3) Ore deposits are stratiform manganese deposits embedded in muddy chert, as host rock, of the Halfa Formation. Their distribution concentrate in the middle member of the Halfa Formation.

4) The ore deposits consist generally of several discontinuous small manganese beds in the same horizon and show several 100 m in strike length and several meters in width. Individual manganese bed shows 20 ~ 30 m in strike length and 10 ~ 30 cm in width. The largest ore deposits show 1,500 m in strike length, 0.6 m in width in semi-detailed surveyed area and 300 m in strike length, 9 m in width in the photogeological surveyed area.

5) Ore mineral is mainly pyrolusite, with small amount of manganite and cryptomelane. These minerals occur in layered, lenticular, spotty and impregnated aggregates in black siliceous part, and in nodular shape in muddy chert.

6) Ore samples of more than 200 peices were collected from the semi-detailed surveyed area and photogeological surveyed area. Chemical analysis of ores were conducted for element Mn, MnO_2, SiO_2, Fe, S and P. As the result of chemical analysis, Mn grade indicates ranging from several % to 80 %, and 20 ~ 40 % in general. These ores are characterized by high SiO_2 content and low Fe, S, P contents.

7) Ore deposits are embedded in only muddy chert in the alternation of chert and shale, and it is considered that ore deposits are sedimentary ore deposits which are genetically formed relating with volcanic activity.

8) Investigation on ore deposits in this year was carried out in the known ore deposits area in the vicinity of Jaramah. In the photogeological surveyed area, many manganese outcrops were discovered, and there are large scale and high grade of outcrops among them.

Therefore, in the next year it is necessary that the more detailed survey should be carried out for the main outcrops in both areas.

4–2 Suggestion for the future exploration

Based on the above-mentioned result, the following survey guides and areas, showing Fig. 2, are recommended for future exploration.

1) Mutual location of many manganese outcrops which are distributed in the surveyed area was almost clarified by this phase survey. But the occurrence, scale and continuity of ore deposits were not sufficiently clarified because of complicated folding structure and long interval of survey route.

The survey for the deeper part of the ore deposits was not carried out in this year.

The detailed geological survey in next year with trenching and short drilling should be conducted in order to clarify the lateral and vertical continuity and grade of ore deposits in the area A which is located in south of Jarawah.

2) Ore deposits which are distributed in the photogeological surveyed area were confirmed their localities, and only little tested samples were collected.

In next year, the detailed survey should be conducted in the area B and C which are located in north and north west of Awaika.

3) In order to consider about the genesis of ore deposits, quantitative chemical analysis of ore and related igneous rock should be conducted.

4) It is necessary to consider the relation between the sedimentary environment of the Halfa Formation, even the middle member of the Halfa Formation which contains many

manganese outcrops and ore deposits.

5) From existing data, Jurassic to Early Cretaceous the Wahrah Formation is located in the area near Ibra, and contains manganese impregnation.

This formation is correrated to the Halfa Formation lithologically. It is expected to make correrative consideration to the Wahrah Formation by collecting bibliography.

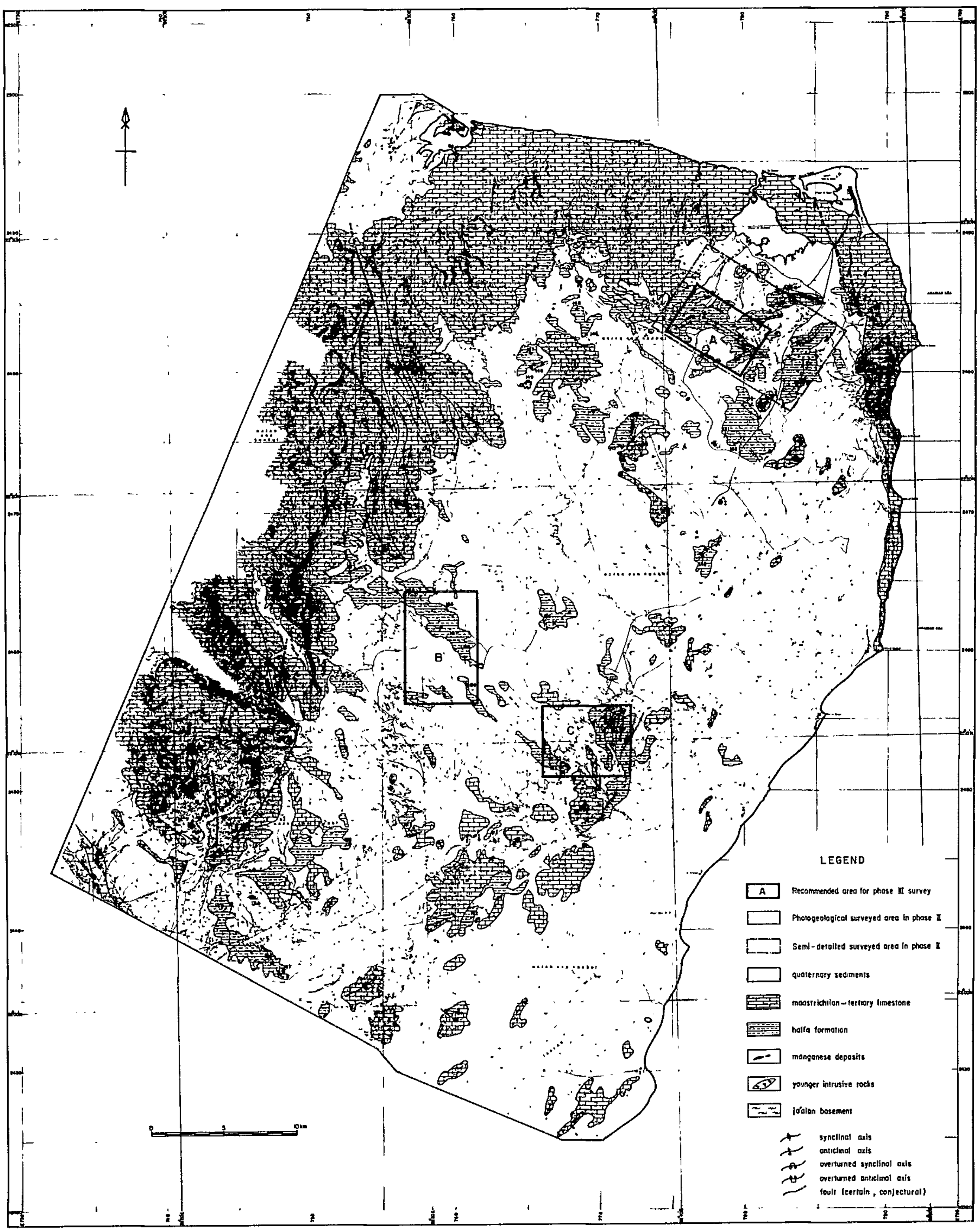


Fig. 2 Recommended Area for Phase Ⅲ Survey

DETAIL DESCRIPTION

PART I

PHOTOGEOLOGICAL SURVEY

Chapter 1 Introduction

The main purpose of the survey of this year is to understand the regional geology, geological structure, and to find out ore deposit where occurrence of the ore horizon have been known as the results of previous data.

The surveyed area is 3,400 km^2, arid climate and scanty of vegitation. It is considered that the Landsat images interpretation and aerial photo-interpretation are effective to obtain the useful information in such the area. From this reason the photogeological survey was carried out in the area.

Interpretation work was carried out in Japan for about two months from September 10 to November 5 in 1981, using the Landsat images of 1:250,000 in scale and aerial photographs of 1:60,000 in scale of monochrome print, and aerial photographs of 1:20,000 in scale of color print, and preliminary photo-interpretation maps of 1:50,000 in scale were produced.

The field checking survey was conducted along the survey routes, selected on the preliminary photo-interpretation maps, from November 6 to December 28 in 1981 to confirm and clarify the lithology and geological structure.

After the field survey, re-interpretation work was carried out from January 6 to February 5 in 1982 to improve the accuracy of geological maps.

As the result of this survey, the outline of the geology, especially the distribution of manganese ore deposits and geologic structure were clarified and numerous outcrops of manganese deposits were found out, neverthless poor exposure of the beds because of about 60 % of the area was covered by Quaternary sediments.

Chapter 2 Interpretation Method

2–1 Landsat images interpretation

The Landsat images of the area, overlapping each other, can be obtained, and the data of good quarity on each images were selected to produce false color images which to be expressed excellent geological information by digital processing including geometrical correction, noise removal and accentuation of contrast.

The geological units were classified by stereoscopic observation of the obtained images of 1:250,000 in scale on the basis of tone and color, drainage density, texture and resistance, and the lineament also was extracted at the same time.

The data of the images are shown in Table I–1, and the location of the images is shown in Fig. I–1.

2–2 Aerial photo-interpretation

In order to carry out the classification of the formation, identification of rock type, interpretation of gological structure, extraction of lineament and studies of these characters, the stereographic observation was conducted using of 68 sheets of monochrome aerial photographs of 1:60,000 in scale along eight lines and 412 sheets of color aerial photographs of 1:20,000 in scale in addition to 22 lines, these photographs were lent from the Ministry of Petroleum and Minerals of the Sultanate of Oman.

For the identification of these items, detailed and comprehensive investigation have been carried out about the tone and color, texture, pattern and density of the drainage system, and resistance of rocks against erosion.

Ther results of interpretation were described on the overlay on the aerial photograph, and compiled in the topographical maps of 1:50,000 in scale as preliminary photo-interpretation maps.

These works were carried out on the monochrome aerial photographs of 1:60,000 in scale in the first, and then more detailed works were carried out on the color aerial photographs of 1:20,000 in scale.

The numbers and the position of principal points of the aerial photographs used for these works are shown in Fig. I–2.

The details and the results of photo-interpretation and field survey are described in the followings.

Table I–1 Landsat Data Used

	(1)	(2)
Imagery type	Landsat-3 (MSS)	Landsat-1 (MSS)
Identification No.	30073-05495	1197-05565
Exposed date	17 MAY 78	05 FEB 73
Scene center point	N 23° 01′ 59″ E 59° 08′ 06″	N 21° 02′ 48″ E 60° 00′ 44″
Path and Row	169, 44	168, 45
Products	Color composite Black & White (Band 7)	Color composite Black & White (Band 7)

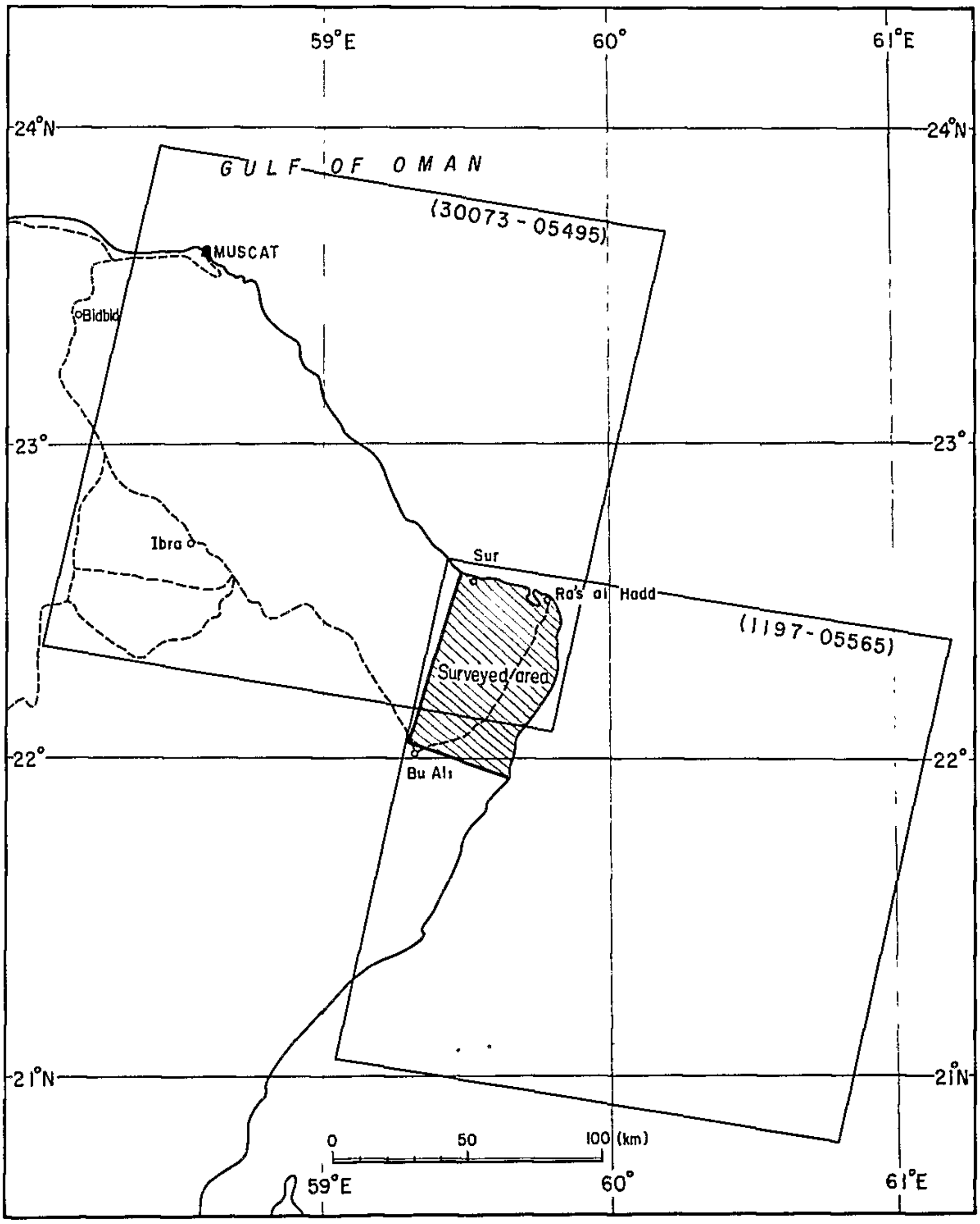


Fig. I-1 Index Map of Landsat Data

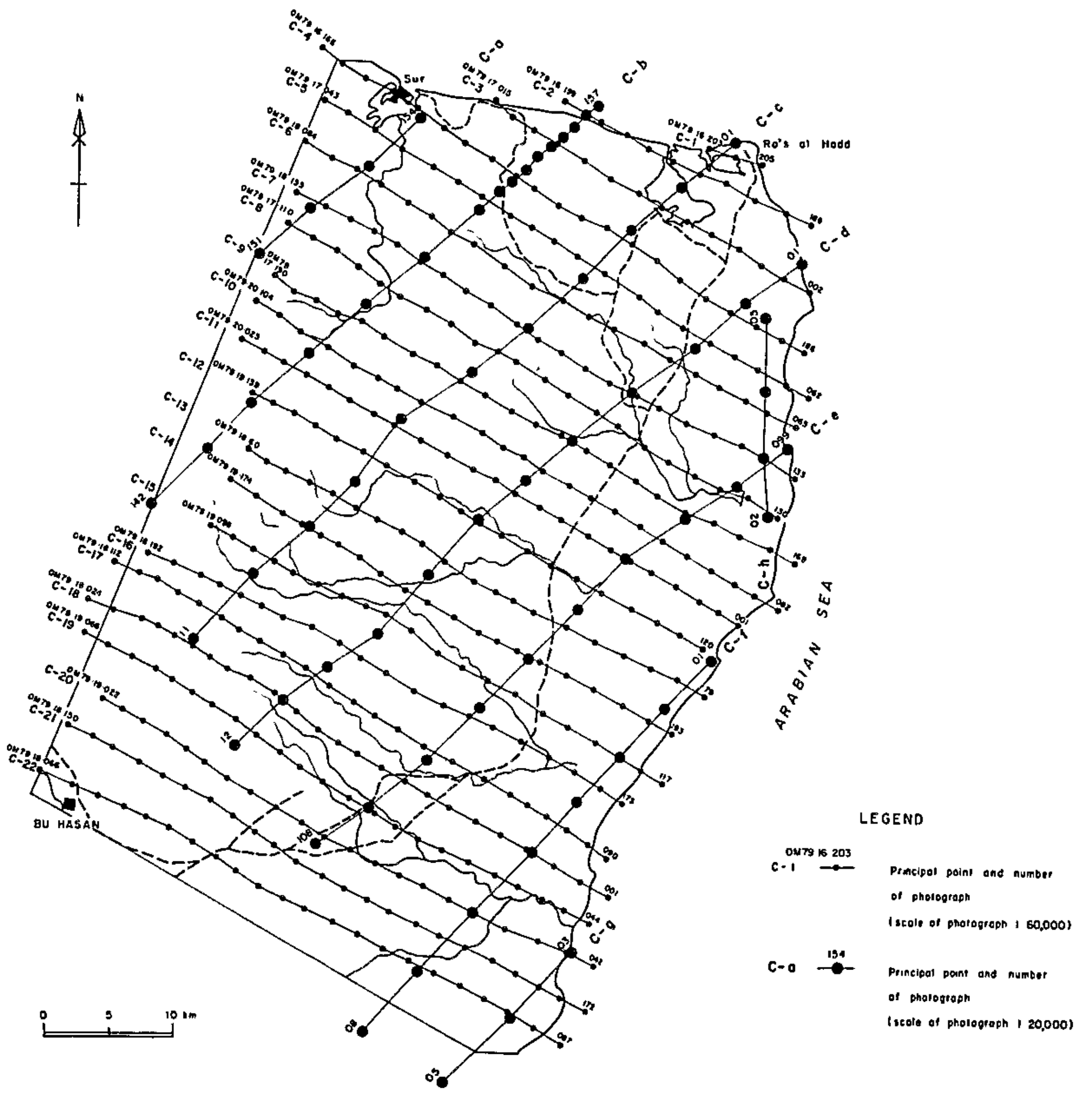


Fig. I-2 Index Map of Aerial Photographs

Fig. I-3 Landsat False Color Image and Interpretation Map

Table I-2 Characteristics Chart of Photogeological Units

Units \ Characteristics	Photo-characteristics		Morphological expression						Remarks	Lithology			
			Drainage			Rock properties							
	Color	Texture	Pattern	Density	Cross section of Valley or Gully	Resistance	Bedding	Jointing					
A_1	light greenish grey	rough	parallel, trellis	high	V-form	moderate to high	none	medium density		Gneiss			The precambrian
A_2	light green to dark green	rough	parallel, trellis	high	V-form	low	none	medium density		Amphibolite			The precambrian
B_1	red to reddish brown	rough	fine dendritic, trellis	very high	gentle V-form	very low	well bedded	low density		Reddish alternation of chert and shale	Lower	Halfa Formation	The triassic to the middle cretaceous
B_2	white to light grey	rough	fine dendritic, trellis	very high	gentle V-form	very low	well bedded	low density		White alternation of chert and shale	Middle	Halfa Formation	The triassic to the middle cretaceous
B_3	light brownish grey	rough	parallel, trellis	medium	gentle V-form	low	well bedded	low density	limestone shows relatively high resistance	Buff chert, shale and limestone	Upper	Halfa Formation	The triassic to the middle cretaceous
C_1	light brown to dark brown	uneven	subdendritic	medium to low	U-form	low	none, partly bedded	none	forming gentle escarpment	Sandy limestone, Massive limestone	Lower	Maastrichian ~ Tertiary limestone	The upper cretaceous to the middle tertiary
C_2	brown	rough	fine dendritic	high	U-form	low	none	low density		Basalt lava	Lower	Maastrichian ~ Tertiary limestone	The upper cretaceous to the middle tertiary
C_3	buff to light brown	smooth, even	trellis, parallel	low	V-form	high	well bedded	low density		Bedded limestone	Upper	Maastrichian ~ Tertiary limestone	The upper cretaceous to the middle tertiary
D_1	brownish grey	very smooth, even	braided	low	U-form	low	none	none		Higher terrace deposits			The quaternary
D_2	brownish grey	very smooth, even	braided	low	U-form	low	none	none	showing lighter tone and coarser texture than unit D_1	Lower terrace deposits			The quaternary
E	buff to light brown	smooth	braided	—	—	very low	—	—	loose materia	Wadi sediments Talus deposits Beach&eaolian sand			The quaternary
F_1	light yellow	rough	parallel, trellis	high	V-form	low	—	medium density		Granite		Older Intrusives	Intrusive Rocks
F_2	brown	rough	—	—	—	low	—	—	intruded into unit A_1, A_2 and F_1	Basic dike		Older Intrusives	Intrusive Rocks
F_3	light orange	rough	—	—	—	low	—	—	intruded into unit A_2	Acidic dike		Older Intrusives	Intrusive Rocks
G_1	dark green to black	rough	—	—	—	low, moderate	—	—		Basic intrusives		Younger Intrusives	Intrusive Rocks
G_2	white	rough	—	—	—	moderate	—	—		Acidic intrusives		Younger Intrusives	Intrusive Rocks

Chapter 3 Geology

3–1 General geology

The area is located in the southeastern part of the Oman Mountains, and a part of the formations composing the Oman Mountains is distributed in the area.

According to Glennie et al (1974), the geology of the Oman Mountains consist of in ascending order,

(1) basement

(2) pre-Permian continental sediments,

(3) Hajar Super Group comprised of Permian to late Cretaceous neritic sediments,

(4) Sumeini Group comprised of Middle Permian to Late Cretaceous continental shelf sediments,

(5) Hawasina Group comprised of Permian to Middle Cretaceous sediments,

(6) Semail ophiolite of Late Cretaceous, and

(7) Neritic limestone of Maastrichtian to Middle Tertiary.

Among these, the basement rocks, pre-Permian continental sediments, and the Hajar Super Group are autochthonous, and the Sumeini Group, the Hawasina Group and the Semail ophiolite are allochthonous formations overlying the above autochthonous sediments. The limestone of Maastrichtian to Middle Tertiary was deposited unconformably upon the autochthonous and allochthonous sediments.

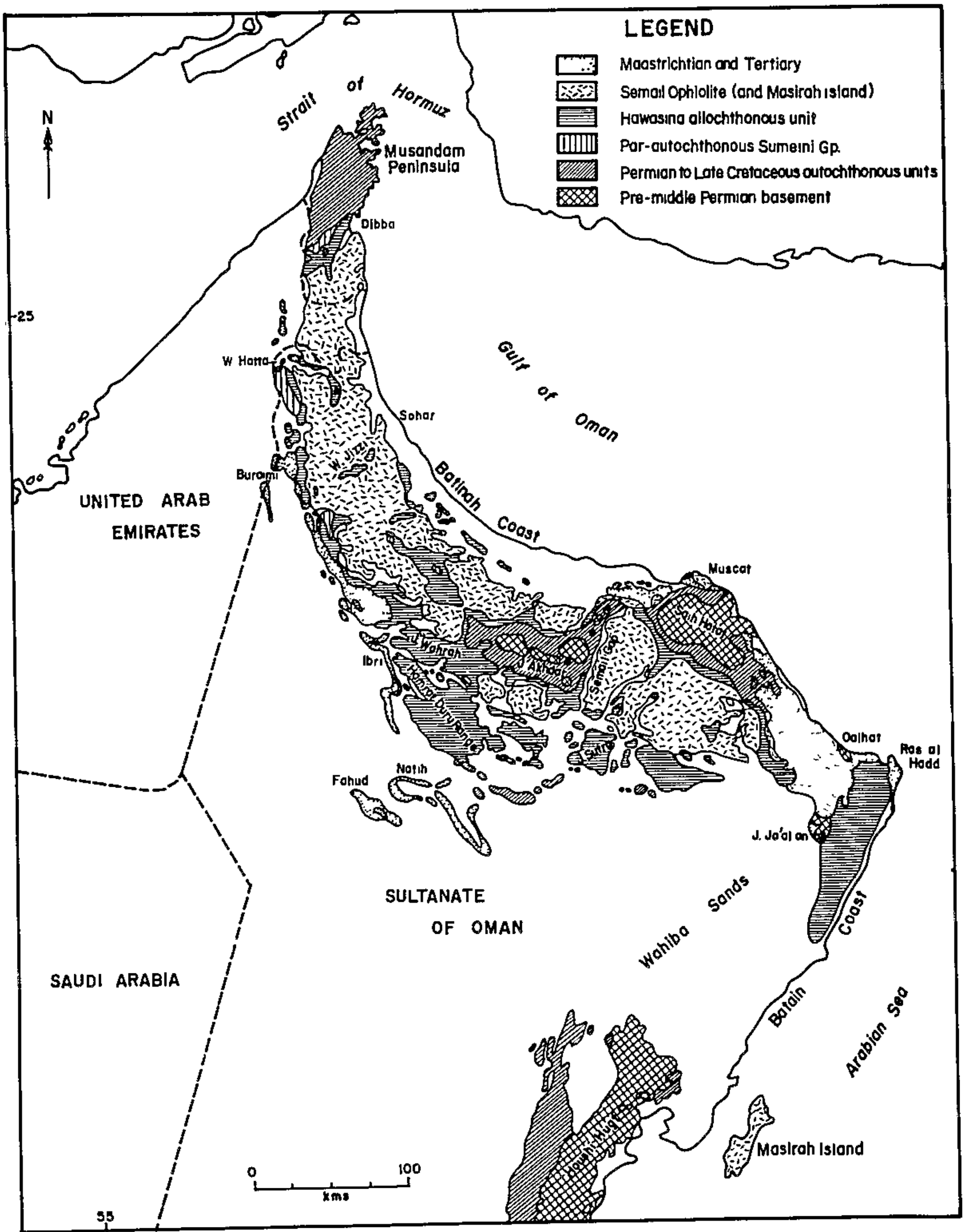
The general structure shown by these formations is a single curved anticline, having two remarkable culmination.

In this surveyed area, Pre-Cambrian basement rocks, Triassic to Early Cretaceous Halfa Formation of the Hawasina Group, Maastrichtian to Middle Tertiary Limestone Formation are distributed and are covered by Quaternary sediments. Basic and acidic intrusive rocks are also recognized in this area.

The basement rocks consisting of amphibolite and gneiss are distributed at Jabal Ja'alan, and intruded by numerous basic and acidic dykes.

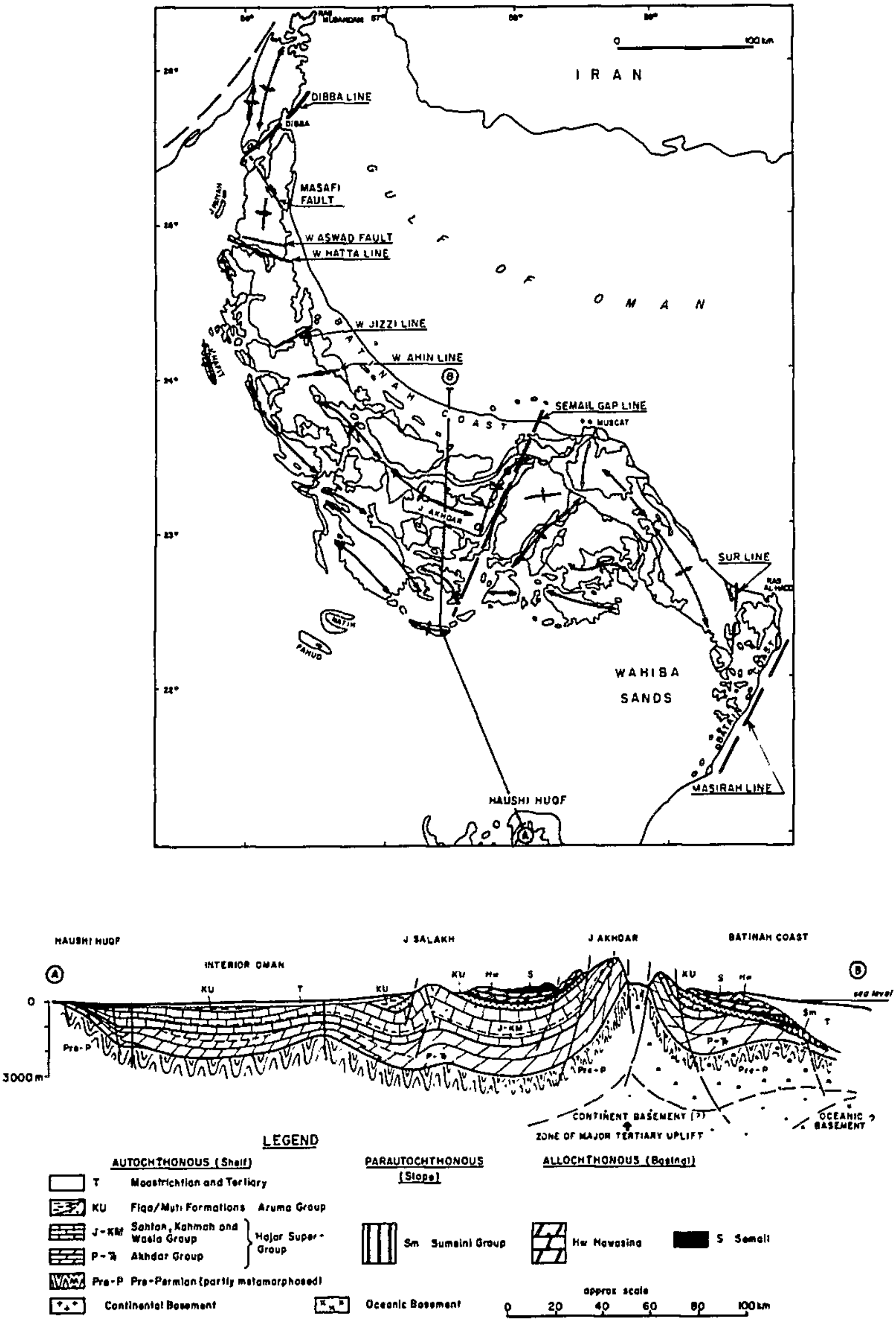
The Halfa formation widely distributed in the area, consists mainly of alternation of red or gray chert and shale. The chert contains abundant radiolaria and embedded manganese deposits.

The Halfa Formation is divided lithologically into the upper and lower members.



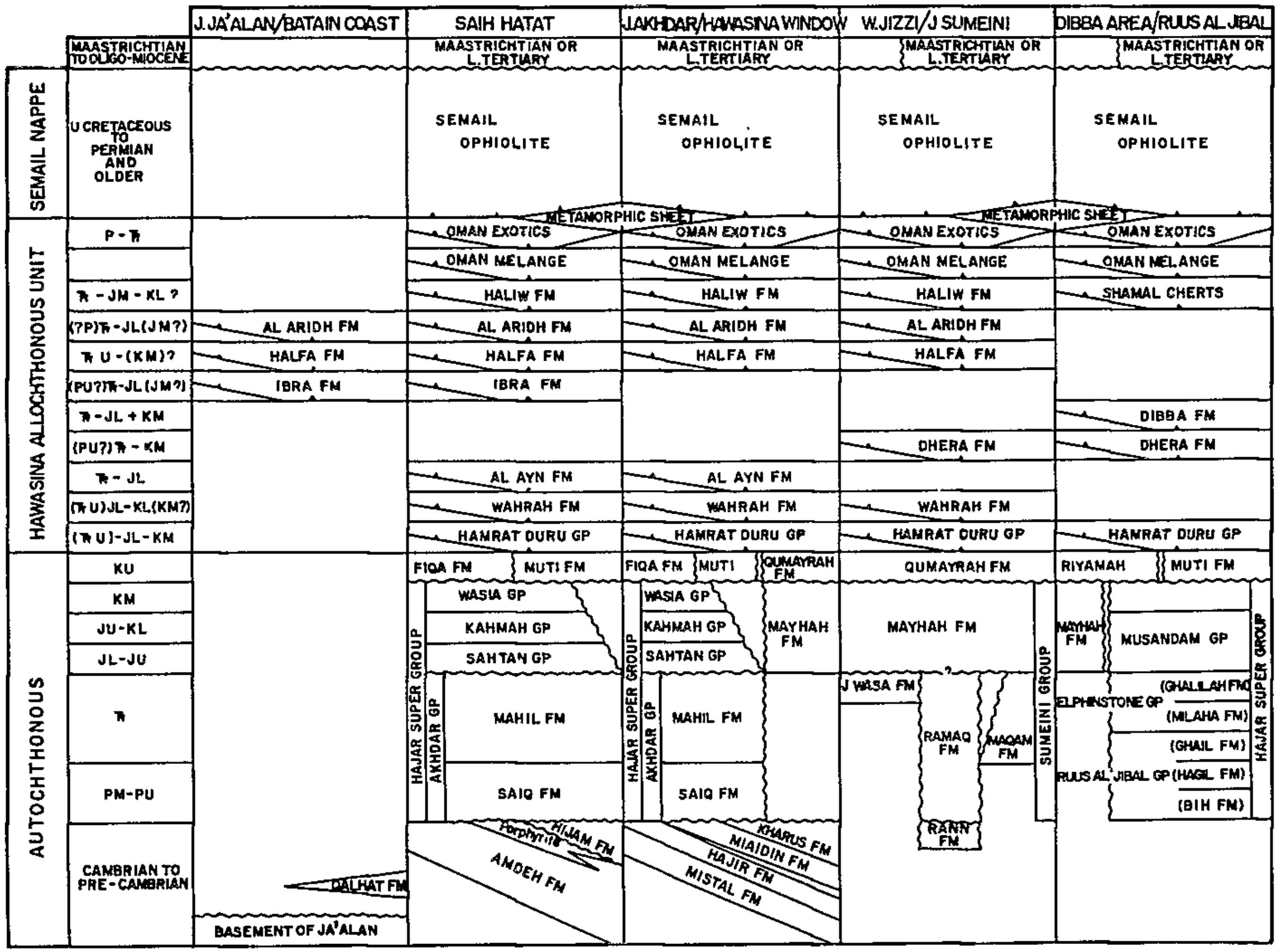
(after K.W. Glennie et al, 1974)

Fig. I-4 Geological Map of the Northern Oman



(after K.W. Glennie et al, 1974)

Fig. I-5 Geological Framework of the Northern Oman



K : Cretaceous
J : Jurassic
Ŧ : Triassic
P : Permian
U : Upper
M : Middle
L : Lower

(after K.W. Glennie et al, 1974)

Fig. I-6 Schematized Correlation of the Stratigraphic Units in the Oman Mountains

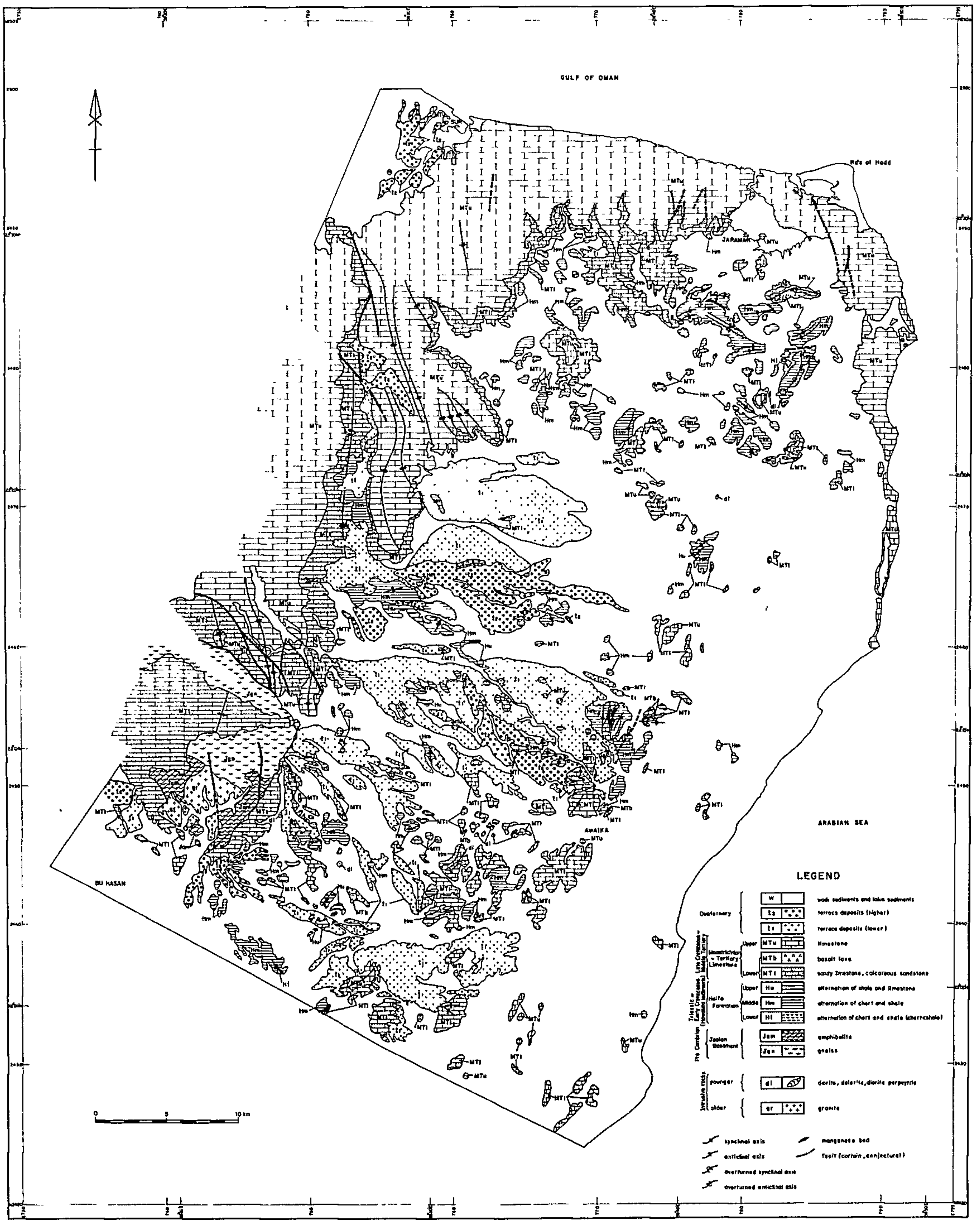


Fig. I-7 Geological Map of the Surveyed Area

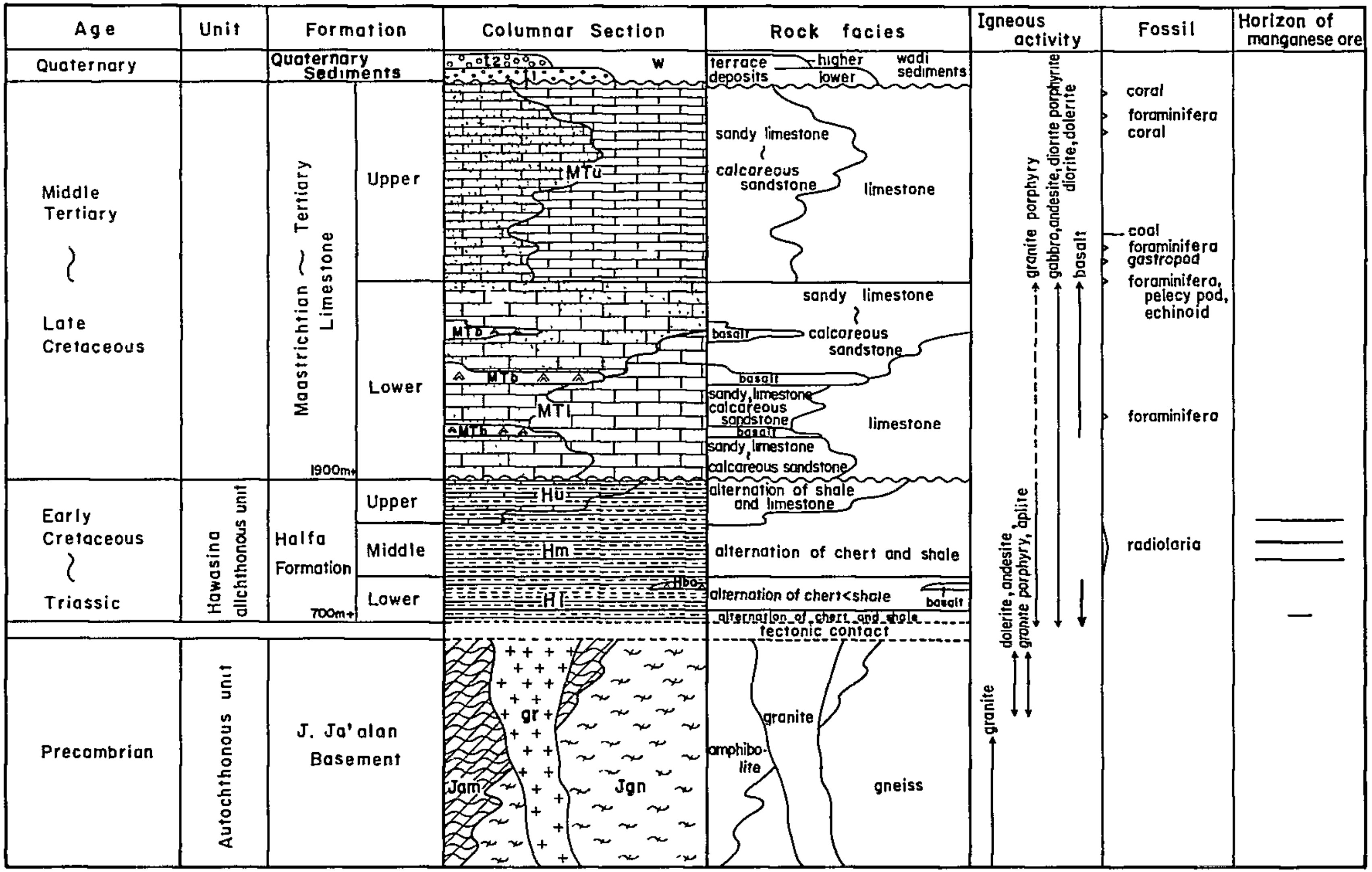


Fig. I-8 Generalized Stratigraphic Section of the Surveyed Area

The Limestone Formation covers unconformably the basement rocks and the Halfa Formation, and consists mainly of limestone containing abundant large foraminiferas, and interbedded quartzose sandstone and sandy limestone. The formation is divided lithologically into upper and lower members.

The Quaternary sediments consist of terrace deposit, wadi sediments, coastal sand and aeolian sand.

The intrusive rocks are granite, dolerite and granite porphyry dyke intruded in the Precambrian metamorphic rocks, and are basalt, andesite, diorite and diorite porphyry intruded in the Halfa Formation and a part of the Limestone Formation.

The geological structure of the area is very complicated and strongly affected by the tectonic movements formed the thrust fault of the Halfa Formation in late Cretaceous and faulting and folding in Middle Tertiary. Frequent faults and folds can be observed. In the Halfa Formation, many folding with two kind of wave length such as 1 ~ 5 m, 50 ~ 200 m showing various directions of axis, are observed. In the Limestone Formation, folding with wave length of 1 ~ 5 km, striking N–S and NNW–SSE, are often found, and the faults showing the same trend are observed to cut all the aboves.

3–2 Stratigraphy

3–2–1 Basement rocks

Distribution : Basement rocks are exposed at Jabal Ja'alan in the southwestern part of the area.

Lithology : The rocks consist of metamorphic rocks, granite and dykes of basic and acidic rocks having intruded the metamorphic rocks, and the metamorphic rocks are described in this section and the others will be explained later.

The metamorphic rocks consist of amphibolite and gneiss, with massive appearance, poor gneissose texture. Amphibolite shows dark green in color, and coarse hornblende, plagioclase and epidote are observed and partially it shows rock facies of diorite and diorite porphyrite. Gneiss shows pinkish to grayish white in color containing quartz, potash feldspar and plagioclase.

The result of microscopic observation of amphibolite and diorite porphyrite are as follows :

Amphibolite (E096)

Texture : equigranular texture.

Constituent minerals : Plagioclase shows anhedral crystal, 2 ~ 3 mm in size, and exists between biotite and hornblende. Biotite shows the flake, 1 ~ 2 mm in size, and has been chloritized. Hornblende occurs as abundant subhedral crystals, 2 ~ 3 mm in size, partially have been epidotized. Titanite is observed in small amount.

Diorite porphyrite (E095)

Texture : fine-grained equigranular texture

Constituent minerals : The rock consists of subhedral potash feldspar, plagioclase, biotite and anhedral hornblende, 1 ~ 2 mm in size, and a very small amount of anhedral quartz is observed. Chlorite and epidote are found as altered minerals. The lithology and the relationship of the intrusive rocks are similar to those of the metamorphic rocks in the Salalah area.

Structure : No special feature is not observed, but small dykes in the east to west direction are often found.

Stratigraphical relation : The rocks constitute the basement of the area, are unconformably covered by the Limestone Formation of Maastrichtian to middle Tertiary. The relation with the Triassic to early Cretaceous Halfa Formation seems to be tectonic although not directly observed in the field.

The metamorphic rocks is considered to be in Precambrian because age determination of granite in these rocks by K.W. Glennie et al (1974) showed 858 ± 16 m.y., and those of Juffa gneiss and granodiorite in the Salalah area by JICA (1979) showed 770 to 660 million years.

Photo-characteristic : Gneiss (unit A_1) in these metamorphic rocks assumes a pale grayish green color and has a relatively high resistance. The drainage density is high and the drainage patterns consist mainly of parallel pattern, and partly of trellis. The valleys show V-shape and the ridges are angular with considerable relief, showing rough texture. Many joints and faults are observed. Amphibolite (unit A_2) shows pale green to dark green color, low resistance, and can be distinguished easily from granite (unit F_1) on the color aerial photograph. The drainage density is high similar to gneiss, presenting lattice-like and parallel patterns. The valley shows open V-shape, and the ridges are angular but not so steep as in gneiss. It is distinct on the aerial photograph that both gneiss and amphibolite have been intruded by numerous dykes (unit F_2 and F_3) striking in the same direction.

3–2–2 Halfa Formation

The Halfa Formation was named by Glennie et al (1974) according to the type locality surrounding area of Halfa on the north of the Wahiba Sands. The formation is distributed almost throughout the area except marginal part of the surveyed area, showing hills topographically.

The formation can be classified, from the base upward, into three members such as lower, middle and upper, as described in the following.

(1) Lower member (Hl)

Distribution : It occurs on a small scale at 10 km to the north of Awaika, 5 km to the west of Jawaybi, and in the eastern part of the area of semi-detailed survey.

Lithology : The rocks consist of alternation of chert and shale, and shale bed. Chert in the alternation shows red and grayish white, the latter color being dominant, and shale is reddish brown. The shale bed also shows pale yellow to pale brown color in the upper part of the member. The shale bed is interbedded with basalt lava about 10 m thick in the semi-detail surveyed area. Manganese ore deposit is found in a part of the lower member.

Stratigraphical relation : Because of absence of exposure of the underlying formation, the relation has not been clarified. Glennie et al (1974) reported that the Halfa Formation is in the relation of tectonic contact with the underlying Ibra Formation.

Thickness : It was estimated to be more than 200 meters in the area of semi-detailed survey.

(2) Middle member (Hm)

Distribution : The middle member is widely distributed in the whole area.

Lithology : It consists mainly of alternation of chert and shale, interbedded with muddy chert and thin beds of shale. The unit of chert is 2 ~ 20 cm thick, shows the colors of red to grayish white. The surface of the outcrop of chert are brecciated and show white color and present an appearance of mudstone or sandstone. Spherical radiolarias are contained in abundance in chert.

The unit of shale is 3 ~ 5 cm thick showing reddish brown to purplish brown color. The alternation of chert and shale is composed of chert rich alternation and shal rich one, the latter being observed near the horizon of manganese ore deposit.

Muddy chert is intercalated in the alternation of chert and shale and constitutes the host rock of manganese deposit. It shows a pale brown color and lamina of the reddish brown banding, and partially seems to correspond to siliceous shale lithologically.

The result of microscopic observation of red chert and muddy chert will be described in the clause of the area of semi-detailed survey.

A conglomerate bed composed of chert and shale gravels is found in the western part of the area of semi-detailed survey. It is in the upper sequence of the middle member, and is presumed to have been formed by tectonic movement or subaqueous gliding, but the detail has not been made clear.

Stratigraphical relation : It conformably overlies the lower member. Shale in the alternation of chert and shale gradually becomes dominant toward the lower and gradually changes into the shale bed of the lower member.

Thickness : The thickness of the bed was estimated to be over 300 m in the area of semi-detailed survey, and over 230 m in the southern part.

(3) Upper member (Hu)

Distribution : It is distributed in the west and southwest of Awaika.

Lithology : Alternation of chert and shale, and limestone are repeatedly observed. The unit bed of chert in the alternation of chert and shale is reddish brown in color, and 5 to 10 cm in thick. The unit bed of shale is calcareous, and pale gray to purplish pale gray color, and 10 ~ 30 cm in thickness. Limestone is pale gray, showing distinct bedding. Fossils of bivalves were observed in limestone of the upper part. The member is considered to be correlated, based on its lithology, to the Halfa Formation of Glennie et al (1974) at the type locality.

Stratigraphic relation : Although the relation with the middle member has not been clarified, but it seems to be in the relation of conformity.

Thickness : The thickness was estimated more than 200 m.

Glennie et al (1974) described that the relation between the Halfa Formation and the upper or lower formation was tectonic contact, although it is not clear because of lack of exposure of Al-Arid Formation as the upper and the Ibra Formation as the lower.

The relation with the Precambrian basement exposed in the southwestern part of the area is indistinct because the contact is covered by the Maastrichtian to Tertiary limestone, but it is assumed to be in the relation of tectonic contact on the basis of the position of the front of nappe of the Halfa Formation shown in Fig. 7.17 of Glennie et al (1974).

It is very difficult to estimate the thickness of the Halfa Formation in the area because of absence of exposure of the upper and the lower members, and presence of repetition of the beds by the intense folding. The thickness of the Halfa Formation was calculated in this survey to be more than 700 m by the correlation of the shale rich alternation and the shale bed.

Although the thickness of the formation is only 130 m in the type locality, which is thinner than that of the surveyed area, it is considered that the middle and the lower members which occur in the surveyed area are not exposed in the type locality.

The time of deposition of the Halfa Formation was considered by Glennie et al (1974) in the range of late Triassic to early Cretaceous because the manganese impregnated chert in the Halfa Formation and the manganese impregnated chert and mudstone in the late Triassic to early Cretaceous Warah Formation can be correlated and that the fossils of late Triassic were obtained from the Halfa Formation.

Stratigraphical analysis and identification of radiolarias contained in chert of the middle member of the Halfa Formation have been done in this time semi-detail surveyed area.

Radiolarias in the chert were well preserved, which were extracted from chert by the treatment of fluoric acid. Radiolarian fossils extracted from the chert were as follows.

Sample C123 red muddy chert

Pantanellium corriganensis Pessagno

P. sp.

Parvicingula cosmoconica (Foreman)

Mirifusus mediodilatatus (Rust)

Pseudodictyomitra sp.

Mita sp. B. Pessagno

Thanarla aff. conica (Aliev)

Sample F001-1 red chert

Pantanellium Corriganensis Pessagno

P. sp.

Acaeoniotyle umbilicata (Rust)

Archaeospongoprunum sp.

Alievium helenae Schaaf

Pseudocrucella (?) sp.

Parvicingula boesii (Parona)

P. cosmoconica Foreman

P. cf. citae Pessagno

Hsuum sp.

Xitus (?) sp.

Archaeodictyomitra sp.

Mita sp.

Thanarla aff. conica (Aliev)

T. aff. conica (Aliev)

Sethocapsa trachyostraca Foreman

S. trachyostraca Foreman

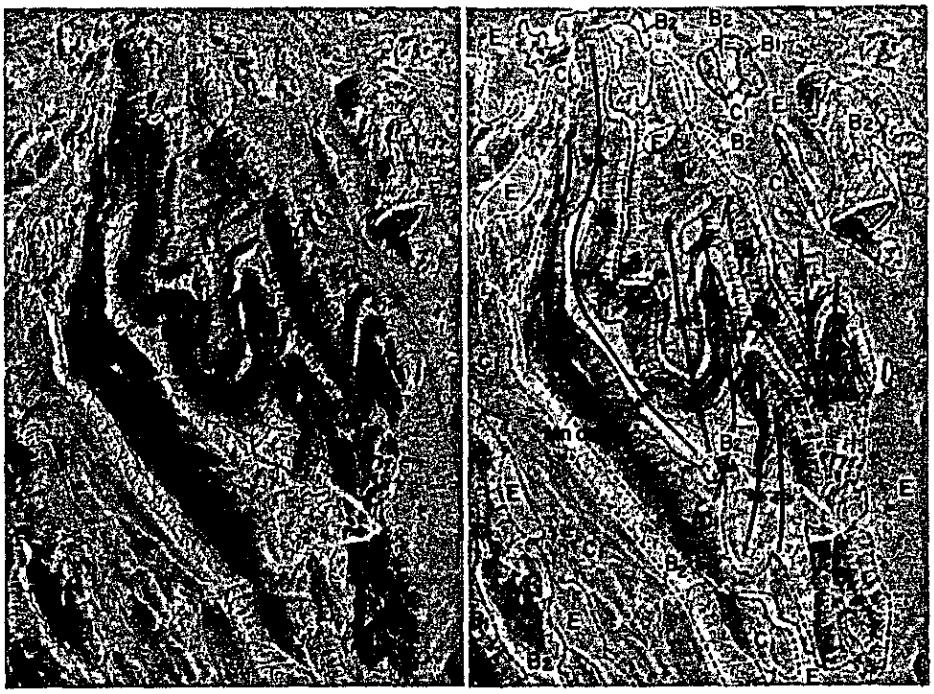
S. leiostraca Foreman

Syringocapsa agolarium Foreman

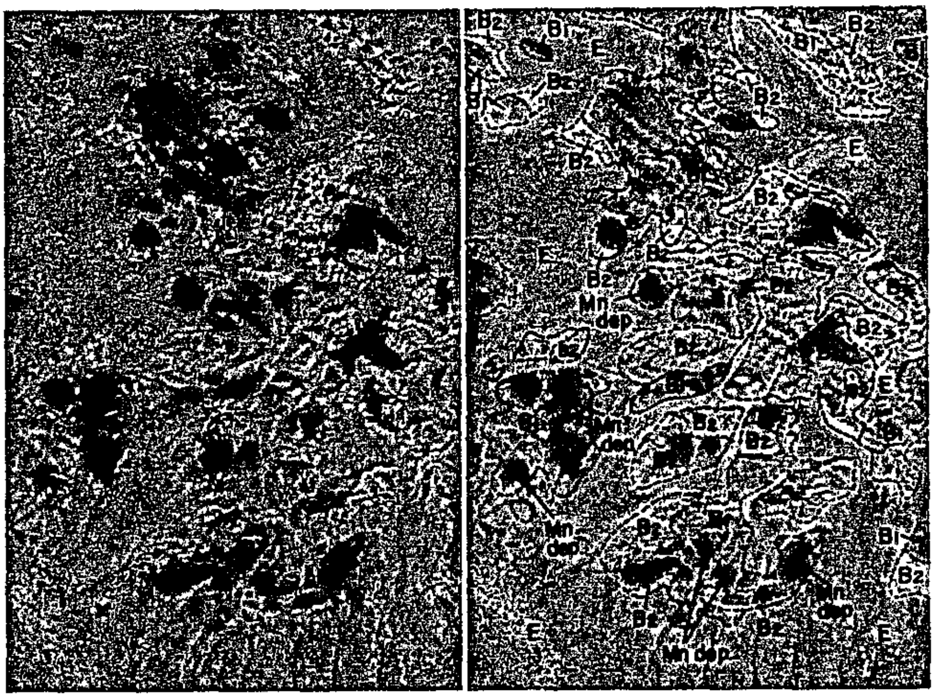
S. agolarium Foreman

The radiolarias obtained from other chert are shown in Table A–4–2. The result of identification of these fossils revealed that radiolaria in the middle member of the Halfa Formation belonged to latest Jurassic (Tithonian) to Early Cretaceous (Valanginian).

Photo-characteristics : Alternation of chert and shale of red to reddish tint (unit B_1) and white color (unit B_2) are clearly distinguished from each other on the color aerial photograph, and they are easily traced except for a complicate structured area. Furthermore an upper formation (unit B_3) which consists of shale, chert and limestone can be distinguished. Unit B_1 and B_2 have similar characteristics such as very low resistance, high drainage density, fine dendritic and trellis drainage pattern, and rough texture. The shale rich part in the unit B_2 shows, however, a smooth texture. Unit B_3 has a little different chatacters from B_1 and B_2, such as pale grayish brown color, moderate drainage density, parallel and trellis drainage pattern, and resistance shown higher in limestone than chert and shale.



Halfa Formation shows folding structure,
north of Awaika, Photo no. OM 79·19·187-188



Mn deposits in Halfa Formation, South of
the semi-detailed survey area, Photo no. OM 79·17·138-139

0 1 km

Fig. I-9 Geological Interpretation of Aerial Photograph

The characteristics of the manganese ore deposit and ore horizon in the aerial photograph, show dark brown to reddish brown color, and alternation of chert and shale shows white color in general. Thus it can be said that photo interpretation is very effective for the trace of ore horizon.

3–2–3 Limestone Formation

The Formation consists of limestone and sandy limestone, and is divided into the lower member dominated by sandy and massive limestone, and the upper member dominated by bedded limestone.

(1) Lower member (MTl)

Distribution : The member is distributed along the marginal part and in the center of the surveyed area except the southeastern part, forming small hills.

Lithology : The rocks consist mainly of sandy limestone and a poor consolidated limestone interbedded with coarse-grained quartzose sandstone of poor consolidation and bedded limestone. Sandy limestone is gray in generally, showing dark brown tint on the surface of the rock, and contain abundant quartz grain with small amount of muscovite. The result of microscopic observation of limestone will be described in the clause of the semi-detailed survey.

An outcrop of limestone interbedded with basalt lava is found to the northeast of Awaika. Basalt is accompanied by fine-grained to coarse-grained basaltic tuff, and has amygdaloidal structure and pillow structure. Since the outcrop of limestone and basalt occurs independently in the wadi sediments, the relation with other limestone beds is not clear and it is likely that it differes from the limestone of the member (Oman Exotics?), it was, however, determined to be Maastrichtian to Tertiary limestone because of similarity of lithology. The result of microscopic observation of basalt is as follows.

Basalt (E065)

Texture : porphyritic texture.

Constituent minerals : The rock contains abundant euhedral crystals of plagioclase of 1 ~ 5 mm in size and augite of 1 ~ 2 mm in size. Euhedral hypersthene of 1 ~ 2 mm in size is observed in small amount. Groundmass consists of euhedral crystals of plagioclase and clinopyroxene. Alteration minerals are epidote and carbonate.

Stratigraphical relation : The member unconformably covers the basement rocks and the Halfa Formation, and the unconformity with the basement rocks can be recognized in the southwestern part of the surveyed area. Limestone directly above the unconformity consists mainly of subrounded pebbles of limestone accompanying subrounded pebbles of granite and chert.

Fossils and age : The member contains abundant fossils of larger foraminifera, bivalves, corals and gastropods. The identified fossils are shown in Table A–4–1. The result of identification of these fossils clarified that the member belongs to latest Cretaceous (Maastrichtian) to early Eocene.

Thickness : The thickness of the member is more than 860 m.

Photo-characteristics : The general characteristics of sandy limestone and massive limestone (unit C_1) of the lower member are pale brown to dark brown in color, low resistance and form slope of plateau-like hills which consists of the upper member (unit C_3) mentioned later. The drainage density is moderate to low, subdendritic drainage pattern, and the U-shape valleys, the rounded ridge are observed. The unit C_1 is interbedded with the high resistance as those distributed at Jabal Ja'alan. Basalt lava (unit C_2) is also intercalated in the unit C_1 and shows brown color and low resistance in general, however, a little higher on the north of Jawabi. Drainage density is high, showing a fine dendritic pattern.

(2) Upper member (MTu)

Distribution : It is distributed on the marginal part of the surveyed area except the southeastern part.

Lithology : The rock consist mainly of well bedded and fossiliferous pale gray limestone, it tends gradually to become sandy toward the south in the vicinity of Masathene, however, sandy limestone occurs predominantly. 'in the vicinity of Mesathene. White limestone of poor consolidation is also observed in the area of semi-detailed survey.

Stratigraphical relation : The member conformably overlies the lower member.

Fossils and age : The member contain abundant larger foraminifera and echinoids in some part. The fossils are shown in Table A–4–I, and the result of the identification of these fossils clarified that the member belongs to early Eocene (Cuisian).

Thickness : The thickness of the member is more than 1,060 m.

Photo-characteristics : In limestone (unit C_3) of the upper member, fine and distinct bedding can be observed on the aerial photographs. The characteristics of unit are high resistance, low drainage density, coarse trellis and parallel drainage pattern, flat topography, and smooth texture.

3–2–4 **Quaternary sediments**

The Quarternary deposit of the area consists of the higher terrace and lower terrace conglomerates, the wadi sediments, talus deposits, coastal sand and aeorian sand.

Photo-characteristics : The conglomerate (unit D_1) of higher terrace shows grayish brown color, low draingae density, drainage pattern of braided channels, flat topography and very smooth texture. Although conglomerate (unit D_2) of lower terrace shows almost similar characteristics to unit E_1, more bright in tone and a little rough in texture, and scattered vegetation can be observed on the surface. The wadi sediment, talus deposit, coastal sand and aeorian sand (unit E) show pale yellow to pale brown color, and smooth texture. Scattered vegetation is observed on the wadi sediments.

3–3 **Intrusive rocks**

3–3–1 **Older intrusive rocks**

(1) Granite

Distribution : Jabal Ja'alan

Lithology : The rock is coarse to medium-grained granite and contains hornblende, and well developed with joint. Pegmatite veinlets comprised of potash feldspar and quartz occur in the granite. The result of microscopic observation is as follows.

Granite (E092)

Texture : equigranular texture.

Constituent minerals : Anhedral quartz, potash feldspar and plagioclase 1 ~ 5 mm in size are observed. Subhedral to anhedral biotite, common hornblende are also present. Biotite has been partly chloritized.

Photo-characteristics : The rock shows pale yellow color and low resistance. The high drainage density and parallel and lattice-like drainage pattern are observed.

Although the V-shaped valleys and the angular ridges, topography is not so steep as the gneiss area. It is easy to distinguish granite and amphibolite by the difference of tone.

(2) Basic dykes

Distribution : Jabal Ja'alan

Lithology : Andesite and dolerite are included in the basic rocks. Andesite dykes are small in scale of 1 ~ 3 m width. They intruded into the metamorphic rocks and granite, strike N70°W and dip 45°N, with the intervals of 10 ~ 50 m.

Dolelite occurs as small dykes about 3 m wide.

The result of microscopic observation is as follows.

Andesite (E093)

Texture : subophitic Texture.

Constituent minerals : euhedral to subhedral plagioclase 1 ~ 5 mm in size and subhedral augite 1 mm in size are abundant. Opaque minerals are observed in abundance. Alternation minerals are chlorite and epidote throughout the rock.

Dolerite (E097)

Texture : porphyritic texture.

Constituent minerals : euhedral plagioclase, and subhedral augite and hypersthene are observed in abundance, and small amount of chlorite has been produced.

Photo-characteristics : Basic dykes (unit F_2) shows a brown color, and low resistance as amphibolite and granite.

(3) Acidic dykes

Distribution : Jabal Ja'alan

Lithology : Acidic dykes consist of pinkish aplite dyke and reddish brown, fine-grained granite porphyry.

The result of microscopic observation is as follows.

Aplite (E082)

Texture : graphic texture.

Constituent minerals : anhedral quartz about 1 mm in size occurs in graphic intergrowth with potash feldspar and plagioclase of 1 ~ 2 m in size, and small amount of common hornblende are observed.

Granite porphyry (E094)

Texture : porphyritic and micrographic texture

Constituent minerals : phenocrysts consist of anhedral quartz of 2 ~ 3 mm in size, and subhedral potash feldspar and plagioclase about 5 mm in size. Very small amount of biotite is also observed. Groundmass is comprised of anhedral quartz, subhedral potash feldspar and plagioclase, about 0.1 mm in size. Alteration minerals are chlorite and sericite.

Photo-characteristics : Acidic dykes (unit F_3) shows a pale orange color, and the low resistance as basic dykes.

3–3–2 Younger intrusive rocks

(1) Basic intrusive rocks

Basic intrusive rocks consist of dolerite, diorite, diorite porphyrite, gabbro and andesite.

Dolerite occurs as dyke rocks in the west of Awaika and in the area of semi-detailed survey. The dolerite dykes of the west of Awaika intruded into the Limestone Formation and into chert of the Halfa Formation. On the dolerite and diorite porphyrite in the semi-detail surveyed area will be described later. The result of microscopic observation of dolerite intruded the Halfa Formation is as follows.

Dolerite (E062)

Texture : Pyramidal porphyritic texture.

Constituent minerals : phenocrysts consist of potash feldspar, euhedral alkali hornblende about 1 mm in size and euhedral augite 1 ~ 2 mm in size. Euhedral biotite is also observed as phenocryst. Small amount of apatite is observed in addition, epidote and zeolite are alteration minerals. The rock is considered to be alkali dolerite because of containing of alkali hornblende. Sample E062 belongs to alkali dolerite.

It has been known geochemically that alkali rocks contain more manganese than kalk-alkaline rocks. It has been reported that the manganese ore deposits in the Ergani district in Turkey, in the Alpine orogenic belt, are accompanied with alkali diabase (Bamba 1976). It seems, therefore, to be important, for the study of origin of manganese ore deposit of the area, that the alkali rock closely related to the origin of manganese deposit occurs in the Halfa Formation although it takes a form of intrusive rock.

It was observed that diorite had intruded into the bedded limestone of the west of Awaika showing a sheet-like occurrence with chilled margin. The result of microscopic observation is as follows.

Diorite (E064)

Texture : subophitic texture.

Constituent minerals : The rock contains abundant euhedral plagioclase. Phenocrysts consist of subhedral augite, subhedral common hornblende, subhedral hypersthene and subhedral to euhedral biotite. Biotite is also observed in the groundmass as microlite. Alteration minerals include sericite and carbonate minerals.

Gabbro has a compact lithology showing a dark green color, and being considered intruded as dykes or sheets, although the relation with the Halfa Formation and the Limestone Formation has not been made clear. The result of microscopic observation is as follows.

Hornblende gabbro (E047)

Texture : cataclastic texture.

Constituent minerals : subhedral plagioclase and anhedral common hornblende 1 ~ 2 mm in size are commonly observed, and augite occurs in small amount. A part of common hornblende has been altered to chlorite.

Andesite is found in the wadi sediments the west of the area of semi-detailed survey, and seems to have intruded as dykes although the relation with the Halfa Formation has not been clarified. The result of microscopic observation is as follows.

Andesite (E024)

Texture : porphyritic texture.

Constituent minerals : phenocrysts mainly consist of euhedral plagioclase. Euhedral augite, common hornblende, hypersthene and subhedral quartz are also included.

Photo-characteristics : The rocks (unit G_1), dark green to black color, show the low and moderate resistance.

(2) Acidic intrusive rocks

Granite porphyry occurs as dykes in the vicinity of the andesite dyke mentioned above. The result of microscopic observation is as follows.

Granite porphyry (E025)

Texture : porphyritic texture.

Constituent minerals : Phenocrysts consist of subhedral quartz, euhedral plagioclase 1 ~ 2 mm in size, and groundmass consists of silica minerals and plagioclase. Alteration minerals include chlorite and carbonate minerals.

Photo-characteristics : The rock (unit G_2) is distributed on a small scale, and shows white tone and moderate resistance.

3–4 Geological structure and geological history

The surveyed area is located in the southeastern part of the Oman Mountains, and has a series of geology and geological structure similar to those of the Oman Mountains.

Graham (1980) considered that the geological structure of the Oman Mountains was formed as the result of the following three tectonic movements.

(1) Folds and thrust faults related to the emplacement of nappe in Late Cretaceous.

(2) Faults intersecting the above folds and thrust fault, and

(3) Tertiary folding

The area is composed of basement rocks, the Halfa Formation and the Limestone Formation. The Halfa Formation, in which the manganese ore deposits, show a complicated geological structure affected by the major tectonic movements mentioned above.

3–4–1 Geological structure of the basement

The basement rocks comprised of Precambrian gneiss, amphibolite and granite are exposed at Jabal Ja'alan in the southwestern part of the area. Glennie et al (1974) considered that the basement is a part of block extending in the north to south direction. Granite intruded into gneiss and amphibolite, and small basic and acidic dykes are observed to extend in the direction from northwest to southeast.

3–4–2 Geological structure of the Halfa Formation

The Halfa Formation is one of the formation constituent of the Hawasina Group, and consists of chert and shale deposited in Triassic to early Cretaceous period. The geological structure of the Hawasina Group is characterized by the development of folds and faults caused by the major tectonic movements mentioned above.

The directions of these folding axes and thrust faults are almost parallel to the present coast line, showing the trends, from the western part of the Oman Mountains toward the east, such as N–S, NW–SE, E–W and N–S directions.

The surveyed area located in the place changing form E–W to N–S direction, and a complicated geological structure with repetition of the formations caused by short wavelength folds. The N–S and NE–SW directions are dominant among the directions of folding axes of the Halfa Formation in the area, and, however, systems such as E–W and NW–SE are also found. It seems, therefore, that the trend of folding axis are not constant.

Many faults were formed associated with the folding, and main directions of those are NE–SW and NW–SE systems.

These structures are considered to have been formed by a large-scale thrust movement in Late Cretaceous and upheaval movement which formed the Middle Tertiary foldings. Although the relation between the Halfa Formation and the basement has not been clarified, it is presumed that the relation of tectonic contact such as the former have thrust over the latter.

Small scale basic and acidic dykes and sheets in the Halfa Formation show predominantly trend N–S and NNE–SSW, and these directions are similar to the dominant directions of folding axis in the Halfa Formation and in those of the Limestone Formation.

As for the period of emplacement of these intrusive rocks, a part of it appears to be related to the igneous activity at the time of deposition of the Halfa Formation because of the occurrence of basic lava in the formation. However, the detail has not been clarified, since there is a possibility that some of them were formed by the igneous activity after the deposition of the formation.

3–4–3 Geological structure of the Limestone Formation

The Limestone Formation is distributed in the marginal part of the surveyed area unconformably covering the basement rocks and the Halfa Formation.

Foldings with the wavelength of one to five kilometers trending in N–S and NNW–SSE occur in the Limestone Formation, and the faults intersecting these folds almost in the same direction are observed. It seems that these folds and faults were formed by the Tertiary upheaval movement, and Glennie et al (1974) considered that these trends were the reflection of the structure of the basement extending in the north to south direction.

Basic sheets are observed in the Limestone Formation, of which the details have not been clarified.

3–4–4 Geological history

The outline of the geological history of the surveyed area is described in the following on the basis of the geological structure and distribution of the basement rocks, the Halfa Formation, the Limestone Formation and the intrusive rocks, with reference of the history of structural development of the Oman Mountains reported by Glennie et al (1974).

From Permian to Triassic, the area on the northeast of the surveyed area was under the shallow sea, where coral limestone formed, and basic igneous activity took place in the same period.

In Triassic period, clastics were transported from the land and mixed with the calcareous neritic sediments (Ibra Formation). Further subsidence of this area during the period from Late Triassic to Early Cretaceous and the Hawasina basin was formed. Deposition of the Halfa Formation initiated at that time, and a forming ridge and submarine volcanic activity took place in the period. From Middle Jurassic to Middle Cretaceous, the characteristic sediments (Hawasina Group), showing sedimentary environment, were formed in the Hawasina basin.

The Halfa Formation consists of pelagic sediments such as chert and shale, and it is presumed that the manganese ore deposits were formed during this period. Submarine volcanic activity took place in the period of deposition of the Halfa Formation, and basic dykes, sheets and lavas were formed, ophiolite was formed near the ridge in the latter half of the period. After that, from Late Cretaceous to the final stage of Cretaceous, major thrust movement took place and the Hawasina Group over the autochthonous Arabian platform, and further the ophiolite thrusted over the Hawasina Group.

In the surveyed area the Halfa Formation thrusted over the basement rocks, and this thrust fault seems to have caused severe folding and faulting in the Halfa Formation. From Latest Cretaceous to Middle Tertiary, the area was under the neritic sedimentary environment, and thick limestone was formed.

Upheaval movement after Middle Tertiary formed gentle foldings and faults. After that the area was uplifted and eroded to have formed the present geology.

Chapter 4 Manganese Ore Deposits

4–1 General description

The existence of manganese deposits in this surveyed area was previously known but more manganese outcrops have been discovered in this year and it has become clear that outcrops are distributed throughout the whole area of the Halfa Formation, as indicated in Plate I–4 and Table A–1.

The host rock of the manganese ore deposits is the muddy chert intercalated in alternation of chert and shale. They are stratiform deposits composed of two to five manganese beds that are 10 cm ~ 200 cm thick and have a strike length of 20 m ~ 30 m. The largest unit of manganese bed has a tichkness of 9 m and its strike length is 150 m.

Generally, individual manganese ore beds are discontinuous, but the ore horizon are continuous in strike direction.

Some of ore bed can be traced for 1,500 m in its strike direction. Manganese nodular zones exist around manganese ore beds.

Main ore mineral is pyrolusite, but manganite and cryptomelane are also observed. The ores can be divided into layered ores where manganese minerals concentrate in layered. lenticular or disseminated form with a black siliceous part and nodular ores where manganese minerals concentrate in lenticular or spot form in muddy chert.

A chemical analysis has disclosed that ores in this area have a medium Mn grade and are characterized by a high SiO_2 content.

The manganese deposits repeatedly appear on the ground surface due to the extreme folding of Halfa Formation but it is considered from the distribution of muddy chert, the host rock, that there are two or three ore horizons.

Geological structure analysis using aerial photographs is, indeed, effective in tracing ore horizon due to the fact that manganese deposits and muddy chert are red or black. Hereunder is the description of ore deposits discoverd by the interpretation of aerial photographs and a field survey. Ore deposits in the semi-detailed geological surveyed area will be described later.

4–2 Distribution of ore deposits

In this area, terrace deposits and wadi sediments which are Quaternary sediments are widely distributed over the Halfa Formation. Therefore, the Halfa Formation is exposed only slightly but, as indicated in Plate I–4, manganese outcrops were found throughout most of the area of distribution of the Halfa Formation. The ore deposits mainly exist in the middle member of the Halfa Formation. None are found in its upper member and only a few are found in its lower member.

Of these many manganese outcrops, those which are relatively large in scale and Mn grade are distributed in the semi-detailed geological serveyed area and in the north and northwest of Awaika.

4–3 Scale and character of ore deposits

4–3–1 Scale

The scale of ore deposits is described hereunder separately by areas: northern part, central part and southern part into which the surveyed area is conveniently divided for the reason of distribution of manganese outcrops.

1) Northern part

There are many manganese outcrops in this area. Of these outcrops, nine of them are relatively large, ranging in width 0.10 m ~ 2.00 m, and can be traced, though discontinuously, for 20 m ~ 500 m. Their Mn grades ranged 34.59 % ~ 63.59 % (MnO_2). The largest of these outcrops is folded but shows a general strike directon of NE–SW and averages 0.40 m in width. It can be traced, though discontinuously, for 500 m in its strike direction.

2) Central part

This area has many manganese outcrops and nine of them are relatively large. These outcrops range in thickness 0.10 m ~ 9.00 m and can be traced, though discontinuously, for 50 m ~ 600 m in their strike direction. Their Mn grades range 13.08 % ~ 53.43 % (MnO_2).

The largest outcrop is located 13 km northwest of Awaika. Its strike is N20W, its dip is 50 NE, its maximum thickness is 9 m and it continues for 300 m in its strike direction. Its Mn grade is 25.86 % (MnO_2) at a sampling width of 9 m. This outcrop is thicker than any other outcrop in this surveyed area. Its high-grade part has a thickness of 40 cm and is found in layered form in the black siliceous part. In the black siliceous part, fine-grained manganese minerals are disseminated and quartz veinlets are developed.

There is a well-developed terrace conglomerate to the southeast of this outcrop and, though the continuity of the outcrop is not clear, it may continue to the manganese outcrop that exists 1.5 km to the southeast and has a thickness of 2 m and an Mn grade of 32.34 % (MnO_2).

Besides, an outcrop composed of two manganese ore layers with an Mn grade of 60.62 % (MnO_2) that is 2 m thick and can be traced for 600 m in its strike direction is located 8 km north of Awaika.

The scale of manganese ore deposits in the central area is larger than that of manganese ore deposits in the northern and southern parts.

3) Southern part

Six manganese outcrops were discovered. These outcrops range in width 0.3 m ~ 1.5 m and can only be traced for 30 m ~ 200 m in their strike directions; thus, they are smaller than the outcrops in the northern and central parts. Yet, their Mn grades are high, ranging 36.60 % ~ 71.04 % (MnO_2).

4–3–2 Ores and manganese minerals

1) Layered ores

Layered ores comprise manganese minerals concentrated in layered, lenticular or disseminated form in compact and massive black siliceous part, and the manganese deposits consist mostly of layered ores. The black siliceous part contains fine grained manganese minerals in disseminated form. In some layered ores, manganese minerals exist like veinlets and quartz is found as network veins. Also, some layered ores are brecciated.

2) Nodular ores

Nodular ores are composed of manganese mineral concentrated in lenticular and spot form developed in muddy chert, which is the host rock of layered ores, and are found in so-called manganese nodular zone.

Pyrolusite is the main ore mineral in both layered ore and nodular ores. Manganite and cryptomelane are found in some ores. The results of microscopic observation and X-ray diffractive analysis of ore minerals will be described in the section of semi-detailed geological survey.

4–3–3 Results of chemical analysis of ores

Chemical analysis was conducted on 15 ore samples from photogeological surveyed area. Six elements: Mn, MnO_2, SiO_2, S, Fe and P were obtained from the analysis. The results of this analysis are shown in Table A–6 together with the results of chemical analysis of ores from the semi-detailed surveyed area. Ore samples having undergone channel sampling were used in this analysis.

Mn grades obtained ranged from the maximum of 71.04 % (MnO_2, sampling width 30 cm) to the minimum of 13.08 % (MnO_2, sampling width 2.5 m). The mean value was 43.05 % (MnO_2), which is higher than the Mn grade in the semi-detailed surveyed area to be described later.

The mean SiO_2 analyzed value of 43.68 % is attributable to the fact that ores in this area are mainly layered ores composed of black siliceous parts. The values obtained of Fe, S and P were low, their respective maximam being 0.39 %, 0.25 % and 0.083 %.

It can be said from the results of this chemical analysis of ores that the Mn grade of manganese ores in this area is medium, that the ores are remarkable for a high SiO_2 content and that the Fe, S and P contents of the ores are small.

The manganese coefficient (Mn/Fe) greatly varies 56.31 ~ 346.69 but it can be said that the ores are manganese monometallic ores.

Table I–3 shows the mean values, maximum values and minimum values of analyzed elements.

Minor element analysis was also conducted on the 15 ore samples. The results of this study will be described in the section of semi-detailed surveyed area.

Table I–3 Mean, Maximum, Minimum Content of Elements in Manganese Ore Samples

element	photo geological surveyed area		
	average (%)	maximum (%)	minimum (%)
Mn	27.46	45.07	8.77
MnO_2	43.05	71.04	13.08
SiO_2	43.68	77.02	4.31
Fe	0.23	0.39	0.12
S	0.13	0.25	0.04
P	0.036	0.083	0.008
number of analized samples : 15			

4–4 Relation between ore deposits and geological structure

Manganese deposits in this area are enclosed in muddy chert as the host rock, in Halfa Formation and are distributed throughout the whole of the surveyed area.

Those of the many outcrops which are relatively large are found in the semi-detailed surveyed area and in the north and the northwest of Awaika and all these strike in the same direction of the folding axis of the Halfa Formation.

The Halfa Formation shows extreme folds due to the thrust of the Late Cretaceous period and the upheaval of the Middle Tertiary period.

The manganese deposits are extremely folded with the muddy chert as the result of these tectonic movement and that, it seems, explains why the deposits repeatedly appear on the ground surface. Therefore, the shape of deposits are closely related to the geological structure of the Halfa Formation.

Further, the manganese deposits in this area seem to be syngenetic ore deposits in the Halfa Formation and it is considered that the rich zones of manganese deposits are greatly controlled by the sedimentary environment that prevailed when the primary ore deposits formed.

The Halfa Formation contains dykes, sheets or lava, though on a small scale. From the minor elements to be described later, the formation of the deposits seems to be related to volcanism but the details are unknowsn.

PART Ⅱ

SEMI-DETAILED GEOLOGICAL SURVEY

Chapter 1 Introduction

In Sur area where the existence of manganese outcrops was known previously, geological survey (semi-detailed survey) was conducted on an area of 77 km^2 located 10 km southwest of Ras Al-Hadd and 5 km south of Jaramah Village, as indicated in Fig. 1.

This surveyed area consists entirely of a desert.

The surveyed area is 20 m ~ 197 m above sea level and composed mostly of hills of 50 m ~ 100 m. Hills extending in the approximate NW–SE direction lie in the central part of the area.

More than 50 % of the surveyed area is covered with sand and gravel.

In the field survey, a base-line was set in the surveyed area in consideration of topography with little elevational difference and without characteristics, survey routes that orthogonally crossed the base-line were set at intervals of 500 m along the base-line and the route maps of 1:50,000 in scale were prepared along these survey routes, using 100-m tape and pocket compass.

As the result of this survey, it is clarified that Halfa Formation is widely distributed in the surveyed area and that many manganese outcrops exist in this formation.

Chapter 2 Geology

2–1 General Geology

The stratigraphic sequences in the semi-detailed surveyed area are divided into Triassic to Early Cretaceous Halfa Formation and Maastrichtian to Middle Tertiary Limestone Formation in ascendin order, and Quarternary sediments covering formers. The basic intrusive rocks can be observed in the eastern part of the area.

The Halfa Formation is widely distributed in this area, and is composed mainly of alternation of chert and shale, muddy chert, thin shale bed, basalt lava and conglomerate. The lower and middle member mentioned in the former chapter, are distributed and the upper member, however, is not exposed in the surveyed area. Manganese ore deposits can be observed in the Halfa Formation, and these ore deposits are composed of the several discontinuous manganese beds with manganese nodule, and are embedded in muddy chert.

Limestone Formation overlying unconformably the Halfa Formation forms small hills, more than 100 m height, and is exposed in the lowland scatteringly.

Quarternary sediments are wadi sediments composed of sand and gravel covering more than 50 % of the surveyed area.

Dolerite sheet intrudes into the Halfa Formation and diorite porphyrite dyke is recognized in the wadi sediments in the eastern part of the area.

Geological structure of this area is very complicated by many small fold of N–S, E–W, NW–SE and NE–SW trend in the Halfa Formation. Small scale of fault related with fold, develp in the Halfa Formation. Large fault, extracted by photo-interpretation, trends E–W and NW–SE.

2–2 Stratigraphy and intrusive rocks

2–2–1 Halfa Formation

Halfa Formation mainly consists of the chert and shale alternation, and is distributed in the hills of this area. It is divided into three members such as the lower, middle and upper member mentioned in the former chapter. In this area, the lower and middle member are distributed, and the upper member, however, is not exposed. The lower member consists of alternation of chert and shale (Hla), shale bed (Hls) and basalt lava (Hba). The middle member consists mainly of alternation of chert and shale, and muddy chert as the host rock of manganese ore deposits.

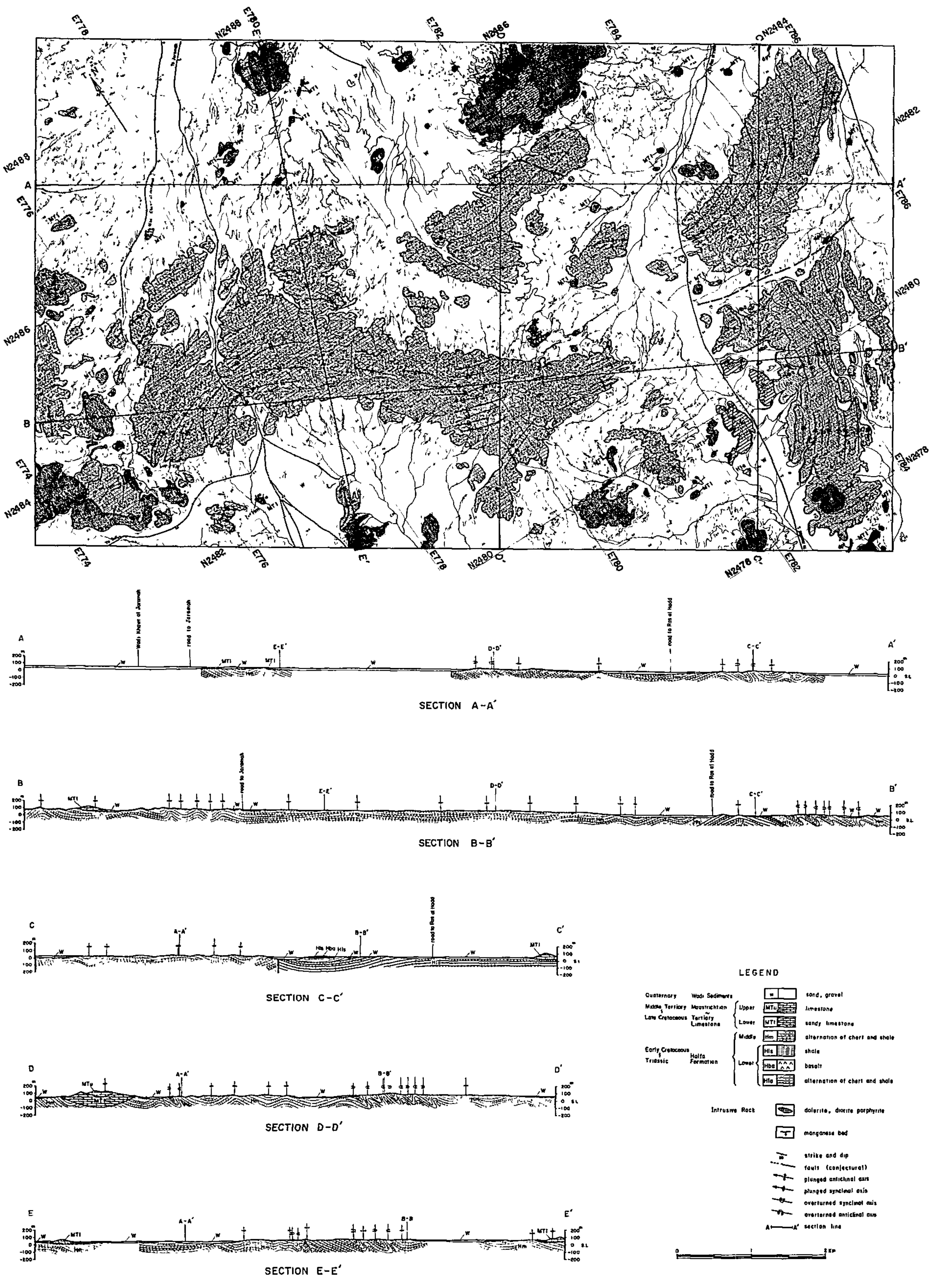


Fig. Ⅱ-1 Geological Map of the Semi-detailed Surveyed Area

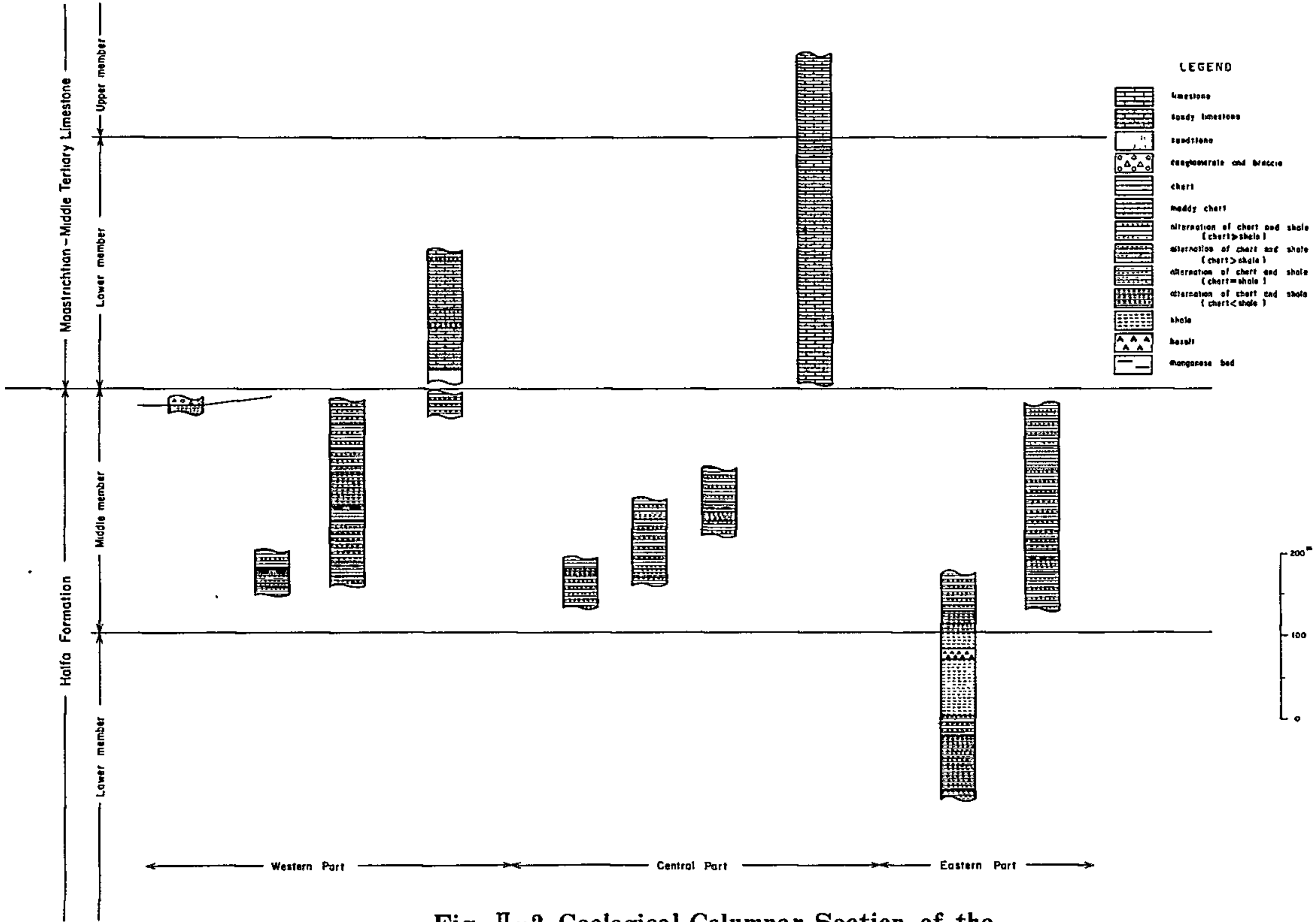


Fig. Ⅱ-2 Geological Columnar Section of the Semi-detailed Surveyed Area

The estimated thickness of the Halfa Formation exceeds 500 m.

1) Alternation of chert and shale (Hla) of the lower member

Distribution : This alternative bed is distributed at the low land and hills in the vicinity of Ras Al Hadd–Awaika road in the southeastern part of the area.

Lithology : Alternation of chert and shale is main lithology. Chert shows red and grayish white color, but the surface of chert changes to white color and presents an appearance of sandstone or mudstone by bleaching. The upper part of this alternative bed gradually changes to chert rich alternation. This alternative bed contains small scale of manganese bed, 5 cm in width, which is conformably embedded in red muddy chert. Dolerite sheet which is microscopically alkari dolerite, intrudes into this alternative bed which alters to greenish to grayish white siliceous rock at the contact part.

Stratigraphic relation : Because of absence of exposure of the underlying formation, the relation with lower formation has not been clarified.

Thickness : The estimated thickness of this alternative bed exceeds 100 m.

2) Shale bed (Hls) of the lower member

Distribution : This shale bed is distributed in the eastern area of Ras Al Hadd–Awaika road extending north to south.

Lithology : This shale bed is composed of shale and basalt lava. Shale shows yellowish white color and lamina. Basalt, about 10 m in thickness, shows greenish gray to dark green color and amygdaroidal structure with numerous cavities filled by secondary calcite. It also shows onion structure by weathering.

Stratigraphic Relation : The shale bed is conformably overlying the alternative bed (Hla).

Thickness : The estimated thickness of this shale bed is 100 m.

3) Middle member (Hm)

Distribution : This member is widely distributed in the whole area.

Lithology : This member is composed mainly of alternation of chert and shale, interbedded with muddy chert and thin shale bed. Conglomerate is distributed in the western part of the area.

Alternation of chert and shale is composed generally of chert bed of 10 ~ 15 cm thick and shale bed of 3 ~ 5 cm thick. In general, quantity of chert is dominant, and partially, however, the quantitative ratio of chert to shale as 1:1 or 1:2, is also recognized. It seems to be shale rich alternation gradually changes to the shale bed, and can be recognized in the vicinity of muddy chert of ore horizon.

Chert shows clear red or grayish white color, and the surface of chert presents the appearance of porous sandstone or mudstone by bleaching.

The result of microscopic observation of red chert is as follow:

Red chert (F001)

Red chert consists of aggregation of microcrystalline quartz, with partly chalcedonic quartz and contains many spherical radiolaria. This sample shows brecciated texture by contraction and dehydration of chert, and quartz filling the fructure and formed by recrystallization.

Shale of alternative bed shows reddish brown color, rarely gray color, and small amount of radiolaria also can be recognized in this shale bed.

Pale brown to reddish brown muddy chert is lithologically considered to be siliceous shale and shows lamina.

In the alternation of chert and shale, 2 to 3 muddy chert of 30 meters in maximum width are interbedded as the host rock of manganese ore deposits accompanying with manganese nodular zone.

The result of microscopic observation of muddy chert is shown as follows;

Muddy chert (D016)

Muddy chert consists of abundant clay minerals and contains many spherical radiolaria. Clastic materials are not recognized in muddy chert.

Muddy chert (C123)

Muddy chert consists mainly of microcrystalline quartz, clay minerals and a little piece of sericite and contains radiolaria, and partially accompanies with chalcedonic quartz.

Muddy chert (C124)

Muddy chert mainly consists of microcrystalline quartz, clay minerals and small amount of sericite. It contains spot of manganese minerals, spherical radiolaria and chalcedonic quartz. Lamina is recognized in the muddy chert.

Thin shale bed which shows red to pale brown color, is embedded into alternation of chert and shale. The result of microscopic observation of the shale is shown as follows:

Red shale (A006-b)

Red shale contains many clay minerals, a small piece of sericite and network of iron mineral. Lamina is formed by iron minerals. A small amount of spherical radiolaria can be observed and clastic materials have not been recognized in red shale.

Conglomerate composed of subrounded and rounded boulder to granule, and distributed in the western part of the area. Gravels mainly consist of chert, shale and alternation of chert and shale, and limestone fragments have not been recognized. The matrix is composed of fine grained chert and shale. This conglomerate shows partly grading, is situated on the alternation of chert and shale of the middle member. Therefore this conglomerate seems to be formed by tectonic movement or submarine landsliding after the deposition of the Halfa Formation.

Stratigraphic relation : The middle member conformably overlies the lower member of the Halfa Formation.

Thickness : The estimated thickness of the middle member exceeds 300 m.

In this surveyed area, the estimated thickness exceeds 500 m, however the repetition of the beds is recognized by remarkable folding. Moreover, the lower formation does not expose and the upper part of the Halfa Formation is covered unconformably by the Limestone Formation. Therefore it is very difficult to estimate the thickness of the Halfa Formation. In this report, the thickness is estimated by correlation of key beds of shale rich alternation, shale bed and muddy chert.

2–2–2 Maastrichtian to Tertiary Limestone Formation

The Limestone Formation is divided into the lower member and the upper member by the rock facies. The total thickness is estimated to be more than 400 m.

1) The lower member (MTl)

Distribution : This lower member is distributed in the northern, southern and western part of the area, moreover, small outcrops is scattered in the lowland of the area.

Lithology : The lower member is composed mainly of sandy limestone, and intercalate with calcareous conglomerate, sandstone and shale. Sandy limestone shows pale gray to gray color, containing quartz grain and muscovite. The surface of limestone shows dark brown color in many case. The result of microscopic observation is shown as follows:

Limestone (F023)

This limestone is sparitic limestone containing pellets of 50 μ in size.

Limestone (D003)

This limestone is sparitic limestone which contains pellets of 50 μ in size, and quartz grain of 50 μ in size as clastic materials.

Calcareous conglomerate composed of gray to light gray rounded pebble, with calcareous matrix, and distributed in the eastern part of the area.

Sandstone is gray to greenish medium grained calcareous sandstone, and is interbedded with limestone. The result of microscopic observation of sandstone is shown as follows:

Sandstone (A055, B135)

Sandstone is composed of the quartz fragments, potash feldspar and plagioclase, and the matrix of micritic carbonate minerals. Sample A055 shows similar to the rock facies of the Ibra formation. In the sample B135, the fragment of red calcareous mudstone is recognized.

A small amount of shale showing light gray color can be recognized as intercalation with light gray limestone.

Stratigraphic relation : Although the boundary between the lower member and the Halfa Formation has not been recognized exactly, it is consider that the lower member overlies uncomformably the Halfa Formation.

Thickness : The estimated thickness of this member exceeds 300 m.

2) The upper member (MTu)

Distribution : This member is distributed in the northern part of the area.

Lithology : This member is composed of porous, white to light gray limestone with poor consolidation, and calcites can be recognized in the cavities.

Stratigraphic relation : Although the relation with the lower member is not clear because the member is covered by debris, the comformity is considered.

The Limestone Formation is seems to be formed in the neritic environment because of the rock facies of limestone.

.Thickness : The estimated thickness of this member exceeds 100 m.

2–2–3 Quarternary sediments

Quarternary sediments consist of sand and gravel and is distributed widely in the lowland of the area. The distributed area of Quarternary sediments occupy more than 50 % of the area.

2–2–4 Intrusive rocks

Dolerite and diorite porphyrite is exposed in the eastern part of the area.

Dolerite shows dark green to grayish green color, and intruded as sheet form, 2 m width, along the bedding plane of alternation of chert and shale in the Halfa Formation. The result of microscopic observation is shown as follows:

Dolerite (D075)

Texture : porphyritic texture

Constituent minerals : Phenocrysts consist of anhedral hornblend, augite 1 mm ~ 2 mm in size and opaque minerals. Groundmass is composed of hornblende, monoclinic pyroxene, plagioclase and titanite. Alteration mineral is zeolite. This rock is considered to be alkali dolerite because augite contain the element of titanaugite, and absent the clinopyroxene.

Diorite porphyrite, 2 ~ 5 m in width, occurs in the quarternary sediments, trending NE–SW, and considered to be dyke or sheet, accompanying red to yellowish white silicified rock with quartz network veins in the marginal part. In the fractures of red silicified rock, hematite is recognized and manganese minerals are recognized, and however, it is not clear to be primary or secondary manganese. The result of microscopic observation of diorite porphyrite is shown as follows:

Diorite porphyrite (B131–1, B131–3)

Texture : porphyritic texture, subophitic texture

Constituent minerals : phenocrysto is anhedral augite 2 ~ 3 mm in size. Groundmass is composed of plagioclase and biotite, 1 ~ 0.1 mm in size. Chlorite is observed as alteration mineral. In the Sample B131–3, plagioclase and hypersthene are also recognized as phenocrysto, and zeolite and carbonate can be recognized as alteration minerals.

2–3 Geological structure

Geology of the surveyed area is composed of Triassic to Early Cretaceous Halfa Formation, Maastrichtian to Middle Tertiary Limestone Formation and Quarternary sediments.

In the Halfa Formation, many folds with short wave length and accompanying small faults are recognized. The geological structure of the Halfa Formation is remarkably complecated by numerous folds and faults.

The axis of fold show N–S and NE–SW direction in the eastern part, E–W direction in the central part, E–W and NE–SW direction in the central to western part and NE–SW direction in the western part of the area.

As for the axis of the fold in the central area, the axis of eastern side plange to the west and the axis of the western side plange to the east.

On the basis of these fold structure, it is considered that the eastern part of the surveyed area have been uplifted and the lower member was exposed, and the middle member of the Halfa Formation distributed in the central to western part of the area.

In the Limestone Formation, the foldings show direction of E–W, NE–SW and NW–SE with long wavelength.

E–W and NW–SE trend faults were detected by the aerial photo-interpretation.

As for the basic intrusive rocks, dyke and sheet occur in the eastern part of the area, and the direction of dyke trend NE–SW. The sheet occurs in the lower member of the Halfa Formation.

It is considered that the folding and fault of this area are formed by thrust movement of Late Cretaceous and upheaval movement of Middle Tertiary.

Conglomerate, situated on the middle member of the Halfa Formation in the western part, it has not been clarified that caused by tectonic movement or submarine landslide.

Chapter 3 Manganese Ore Deposits

3–1 General description

The existence of manganese deposits in this surveyed area was known previously, but more manganese outcrops have been discovered by the survey in this year, as indicated in Plate II–4 and Table A–1.

These manganese outcrops are distributed throughout most of the surveyed area but relatively good outcrops are found in the central part of the area to its western part. The biggest of the outcrops has a average 0.6 m in width and can be traced, though discontinuously, for 1,500 m in the direction of strike. Its Mn grade is 23.90 % (MnO_2).

The manganese ore deposits enclosed in muddy chert as the host rock, in the Halfa Formation, are stratiform deposits composed of several manganese ore beds having a thickness of 10 cm ~ 30 cm and a strike length of 20 m ~ 30 m. These ores are divided into layered ore where manganese minerals occur in layered, lenticular or disseminated form in the black and compact siliceous part and nodular ores where manganese minerals exist in lenticular or spot form in muddy chert.

The main ore mineral is pyrolusite but manganite and cryptomelane are recognized in some parts. The ores contain many radiolarian fossils and show colloform texture.

As the results of chemical analysis of ores, manganese ores in this area are of the medium Mn grade and characterized by high SiO_2 content. Further, the analysis of minor elements has revealed that the formation of the manganese ore deposits seems to be related to submarine volcanic activity.

It is presumed from the results obtained in this year that the manganese ore deposits in this area are stratiform sedimentary ore deposits formed in sedimentary environments under which the alternation of chert and shale forms as pelagic sediments and related to submarine volcanic activity. The results of the survey are described as follows.

3–2 Distribution of ore deposits

Manganese ore outcrops were found throughout most of the area of distribution of the Halfa Formation and, as indicated in Plate II–4, as many as 143 outcrops listed in Table A–1 exist in the whole surveyed area. Outcrops are particularly concentrated from the central part of the area to its western part.

Some manganese outcrops exist in the lower member of the Halfa Formation but their number is small and most outcrops are distributed in the middle member of the Halfa Formation. In the middle member, two or three horizon of muddy chert, the host rock, are intercalated and, due to extreme folding, these horizon repeatedly appear on the ground surface.

3–3 Scale and character of ore deposits

3–3–1 Scale of ore deposits

The manganese ore deposits are composed of small-scale manganese ore bed running discontinuously in the direction of strike in muddy chert. In the vertical direction, too, there are several manganese ore beds. The average scale of individual manganese ore bed is 20 m ~ 30 m in strike length and 10 cm ~ 30 cm in thickness. Maximum scale of manganese ore bed has a strike length of 150 m and a thickness of 3 m.

Manganese minerals concentrate in lenticular or spot form in the muddy chert and form so-called manganese nodular zone. This manganese nodular zone shows various thickness, but maximum 30 m in thick.

The largest one of many manganese outcrops in this area is Outcrop No. 110. It can be traced in the strike direction for 1,500 m though its manganese ore bed is discontinuous. The mean thickness of this ore bed is 0.6 m and its maximum thickness is 1.7 m. Its Mn grade averages 23.90 % (MnO_2). Manganese nodular zones form on its hanging and foot walls and are 30 m thick at some points. Good parts of these manganese nodular zones have a width of 2 m and their Mn grade is 8.70 % (MnO_2).

The manganese outcrops which can be traced for more than 300 m in its strike direction are shown in Table II–1.

3–3–2 Character of ore deposits

1) Host rock and hanging, foot wall rocks

The manganese ore deposits are formed in muddy chert as the host rock. The muddy chert has well-developed lamina and it may be considered that muddy chert has possibility to be siliceous shale in lithology. However, other shale bed and shale in the alternation of chert and shale can be distinguished from muddy chert because they are not siliceous. Muddy chert contains manganese nodule as lenticular or spot shape and form manganese nodular zone. Muddy chert in manganese nodular zone shows light brown in color. Usually a few manganese ore beds are found in a manganese nodular zone.

Table II–1 Brief Description of Main Manganese Outcrops

outcrop No.	strike	dip	length (m)	mean width (m)	MnO_2 (%)
30	N75E	70S	350	0.3	15.41
69	N80E	90	300	0.6	16.51
71	N80E	55N	350	0.4	21.49
76	N85E	80N	300	0.3	13.24
95	N50W	45S	350	1.0	19.40
110	EW~N45W	90~60S	1,500	0.6	23.90
116	EW	50S	430	0.3	16.18
117	N80W	55S	500	0.3	19.94
123	N75W	40S	650	0.3	29.11
136	N70E	80S	500	1.7	15.41
146	N30~50E	55S	500	0.4	27.52

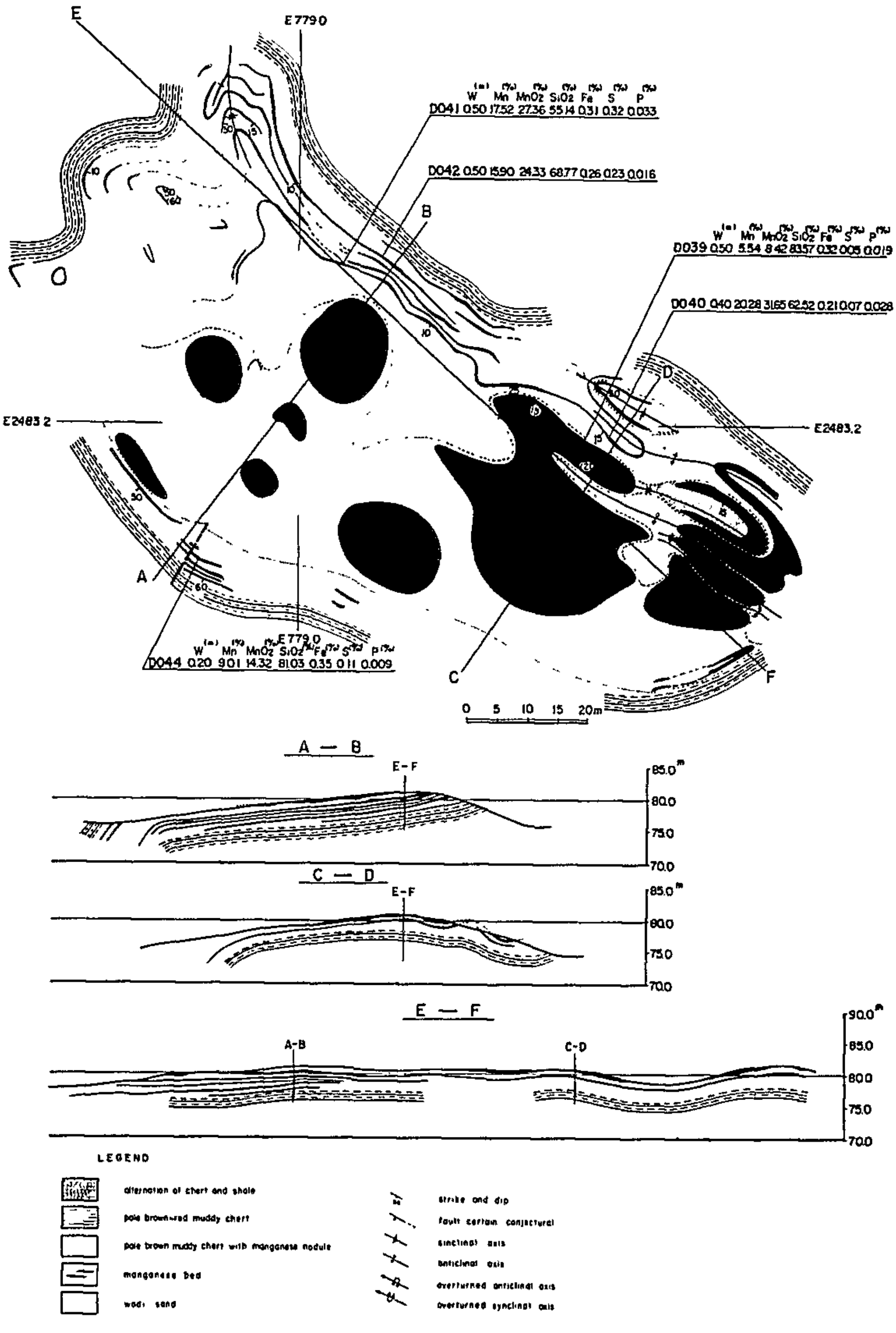


Fig. II-3 Distribution Map of Manganese Outcrop No.95

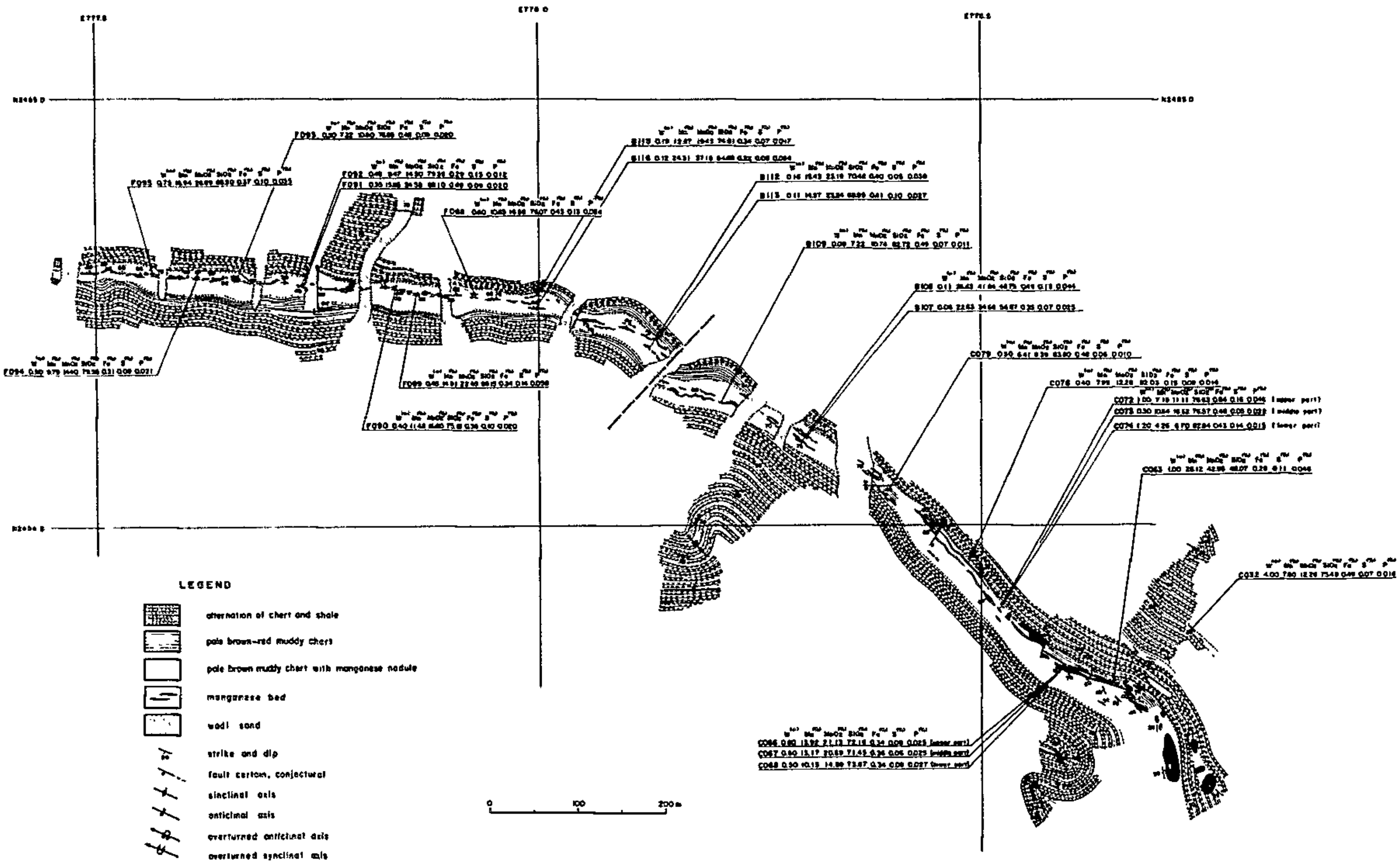


Fig. Ⅱ-4 Distribution Map of Manganese Outcrop No.110

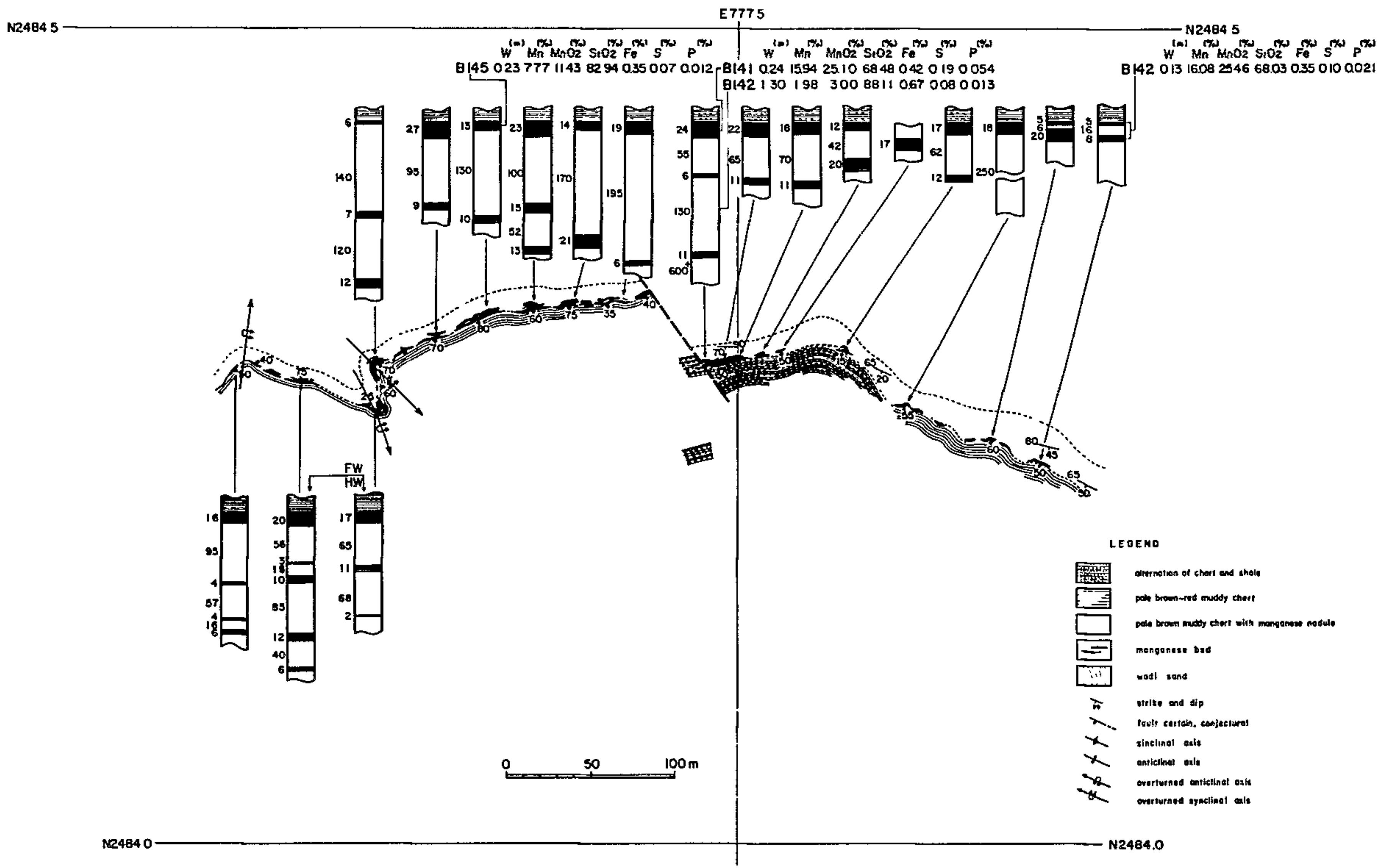


Fig. II-5 Distribution Map of Manganese Outcrop No. 117

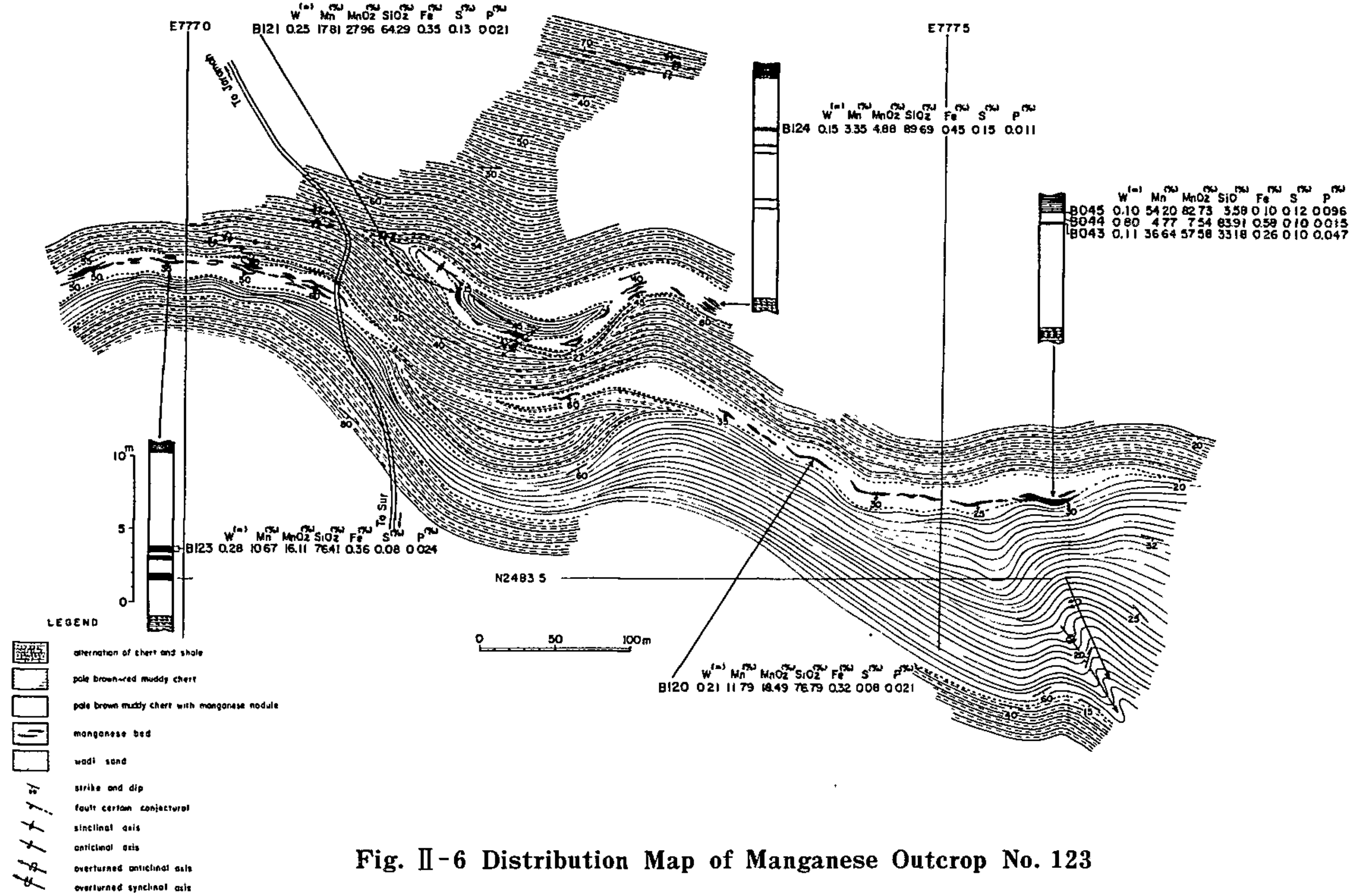


Fig. II-6 Distribution Map of Manganese Outcrop No. 123

Generally, alternation of chert and shale is chert rich alternation with chert/shale quantitative ratio of 2:1 ~ 3:1. But in alternation forming the hanging wall and foot wall of muddy chert, the chert/shale quantitative ratio is 1:1. Some such walls lack chert and are composed solely of shale. The hanging wall and foot wall of the horizon of manganese ore deposits show rock facies where shale is predominant.

According to Elboushi and Zachariah (1979) and JICA (1979), manganese ore deposits and their hanging, foot walls are lithologically characterized by (1) gray colored siliceous shale, (2) mineralized zone, (3) reddish brown shale in ascending order. In this phase survey, there were manganese outcrops that shows this lithological combination but in other outcrops both the hanging wall and the foot wall are the alternation of chert and shale. Thus, it seems that the arrangement is changeable. However, the manganese ore deposits and the vicinity of the horizon of ore deposits shown usually reddish color show a sharp contrast to the color of the alternation of chert and shale which shows white in general. Thus, it is possible to trace a horizon of ore deposits by the difference of color tone. The white tone of the alternation of chert and shale is due to the fact that the surface of chert becomes white through bleaching but the interior of the chert is red or grayish white.

2) Manganese ores

Ores in the manganese ore deposits can be generally divided into layered ores and nodular ores, as described in 4–3–2.

In layered ores, manganese minerals form layered or lenticular concentrations of 1 cm ~ 3 cm in thickness and are sometimes disseminated (Figs. II–7 and II–8). In a thick manganese layer, concentrations of manganese minerals have a thickness of 10 cm ~ 15 cm and are found in the ore body close by the hanging and foot wall. The layered form and the lenticular form are combined and the concentration shows network form. In layered ores, segregation quartz is developed in network of veinlet. Also, colloform texture was found in some layered ores (Fig. II–8).

The black siliceous part that constitutes layered ores is black due to the concentration of fine-grained manganese minerals and the results of its microscopic observation were as follows:

Black Siliceous part (F049)

Microcrystalline quartz and fine-grained manganese minerals were noted and the manganese minerals concentrated in layered form. The lower surface of the concentration showed a clear boundary and it is considered that manganese minerals settled and formed on a bedding plane. Many radiolaria are contained. They are preserved particularly well in the concentrations of manganese minerals and are not at an advanced stage of silicification. The manganese minerals could not be identified by X-ray diffractive analysis and are believed to be amorphous.

In some layered ores, the black siliceous part is brecciated and manganese minerals are found in their fractures. Also, coarse-grained manganese minerals are found in veinlet but these veinlets are developed only in black siliceous parts (Fig. II–8).

Nodular ores are found around layered ores and form a manganese nodular zone (Figs. II–7 and II–8). Manganese minerals in a nodular ore concentrate in lenticular or spot form. The size of lenticular form ranges 0.5 cm ~ 2 cm in thickness and 3 cm ~ 10 cm in length. The plane shape of the lens is irregular and sometimes amebic. Further, its thickness increases to make it ellipsoidal. These ellipsoids join together, which are shown in the botryoidal surface. Though only rarely, manganese minerals with segregation quartz in veinlet fill some fractures in muddy chert.

Sketches of typical manganese ore are shown in Fig. II–7 and Fig. II–8.

3) Manganese minerals

The results of X-ray diffractive analysis and microscopic observation showed that the manganese minerals consisted mostly of pyrolusite and partially of manganite, which had not been reported in previous surveys. Cryptomelane was also found.

Pyrolusite

Pyrolusite shows megascopically light steel-gray or iron-gray metallic luster and its streaks are black. It is found as very fine-grained~coarse-grained tabular crystals. It is the most important of all ore minerals contained in the manganese ore deposits. Microscopically, its color of reflection is yellowish white, its pleochroism is light yellowish white ~ dark gray and its anisotropy is remarkable, and it is columnar, fibrous or radial. Further, it often shows coloidal texture, oulitic texture or colloform texture (Table A–3). Fibrous or radial pyrolusite is considered to be the pseudomorph of manganite. Radiolaria are often found in aggregates of pyrolusite and, in some instances, radiolarian shells are replaced by pyrolusite.

Manganite

Manganite was detected by the microscopic observation and X-ray diffractive analysis of Sample E030 from a photogeological surveyed area but it was also found in samples

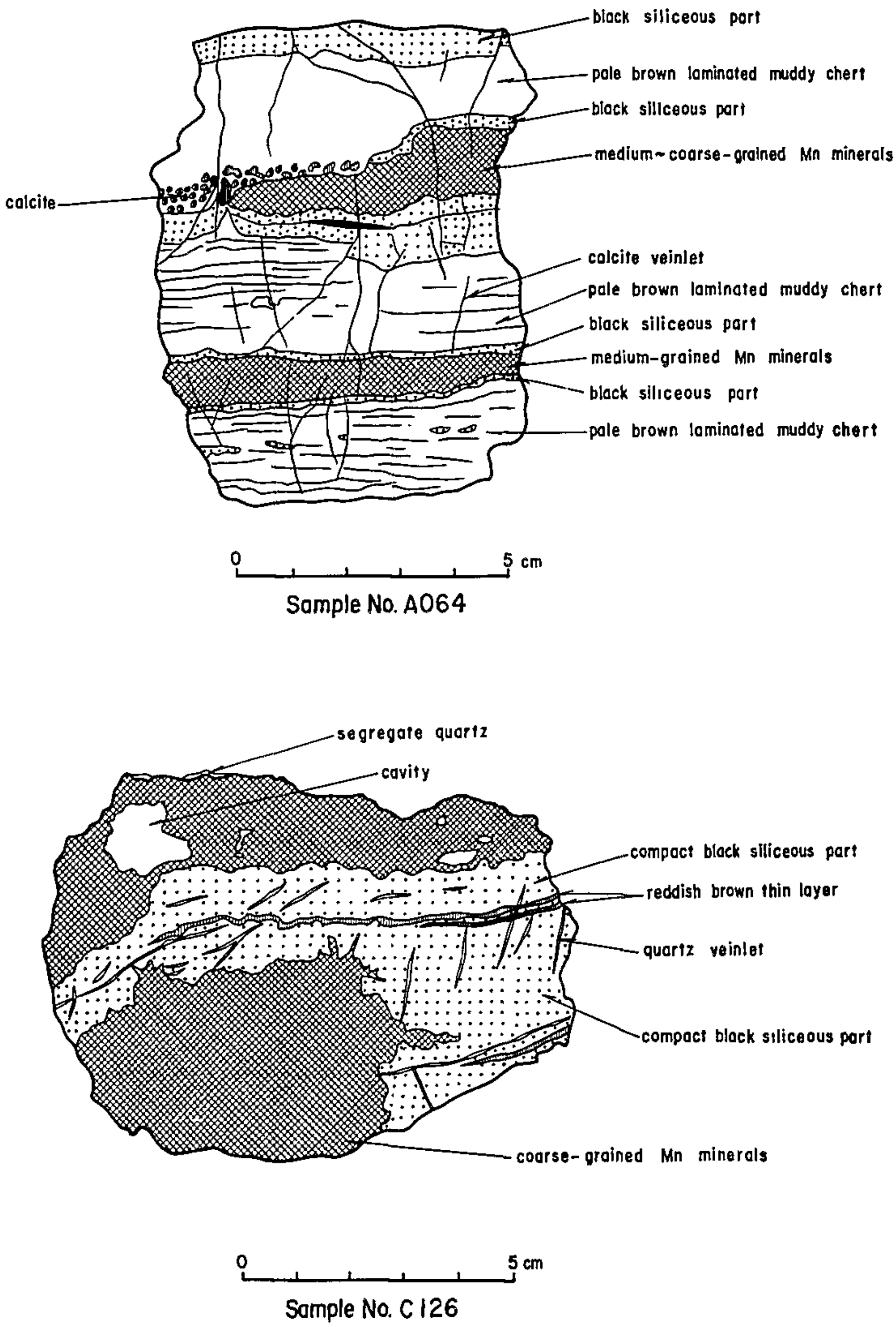
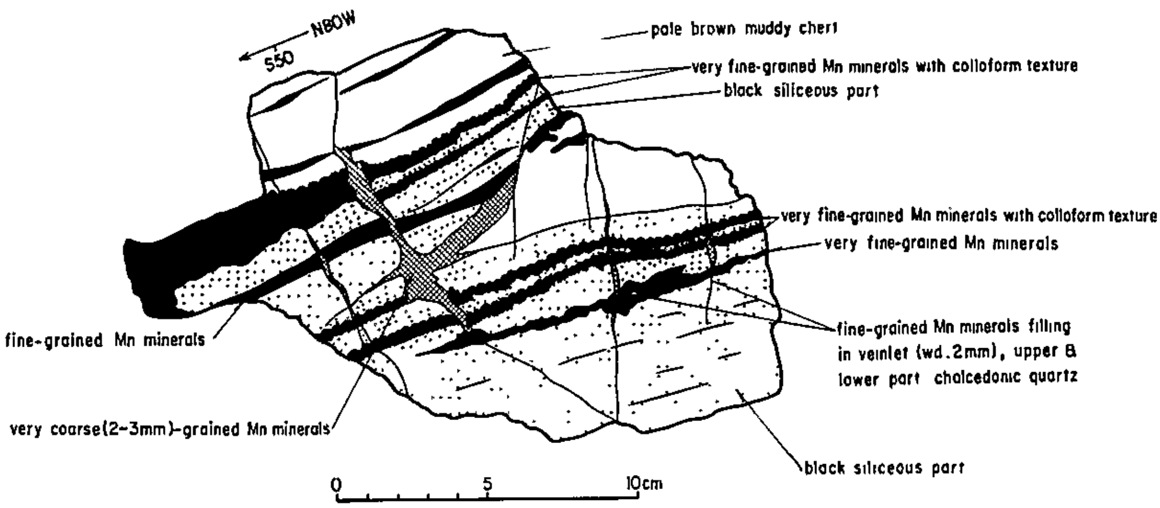
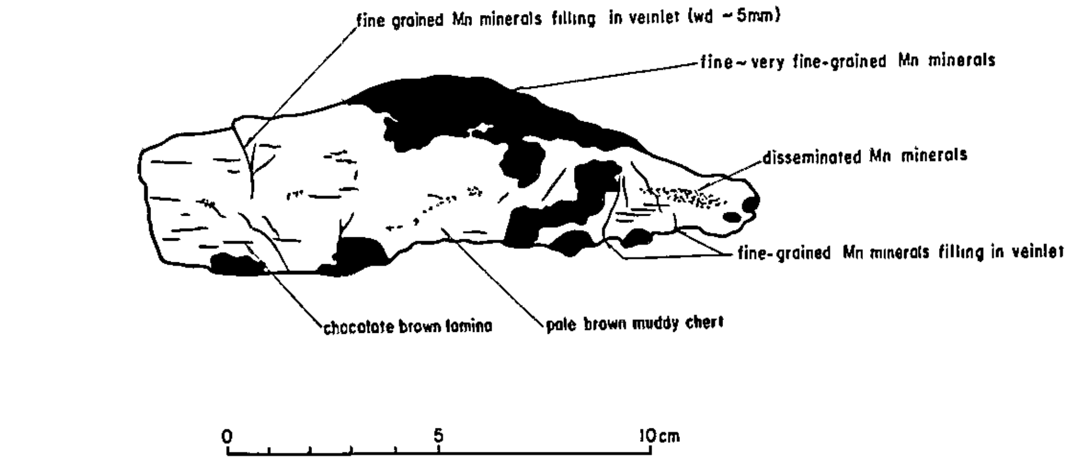


Fig. II-7 Sketch of Manganese Ore (A064, C126)



Sample No C087



Sample No E011

Fig. II-8 Sketch of Manganese Ore (C087, E011)

Table II-2 X-ray Powder Diffraction Data of Pyrolusite, Manganite and Cryptomelane

ASTM						Samples			
Pyrolusite		Manganite		Cryptomelane		E030		B106	
d(A)	I	d(A)	I	d(A)	I	d(A)	I	d(A)	I
				6.90	90			6.96	58C
				4.90	80			4.90	47C
						4.24	35Q	4.25	16Q
								4.09	100S
3.48	10								
				3.45	10				
		3.40	100			3.40	100M		
						3.34	100Q	3.35	100Q
3.14	100			3.10	80	3.12	100P	3.12	100P+C
						3.03	100Cl		
		2.64	60			2.64	25M		
		2.53	5						
				2.46	10	2.46	9Q	2.46	5Q
2.41	50	2.41	20			2.41	27M	2.41	55P
				2.39	100	2.40	21P	2.40	100C
		2.28	50			2.28	7M+Q	2.28	7Q
2.21	10	2.23	5						
		2.20	5	2.19	20				
				2.15	60	2.12	8Q	2.13	6Q
2.13	25					2.11	13P	2.11	14P
1.98	15					1.98	5P+Q	1.98	11P+Q
				1.92	10				
				1.83	60	1.82	16Q	1.82	23P
1.81	5								
		1.78	20			1.78	9M		
		1.71	40			1.72	9M		
1.68	1								
		1.67	30			1.67	30M		
		1.64	40	1.64	30	1.64	9M		
1.63	50					1.63	24P	1.62	25P
						1.61	2Q		
1.56	25					1.56	9P	1.56	13P
				1.54	60	1.54	11Q	1.54	6Q
				1.52	40				
		1.50	20						
		1.44	30						
1.43	15								
1.40	15								
				1.35	50				
		1.33	10						

Abbreviations Q : quartz Cl : calcite S : stilbite
P : pyrolusite M : manganite C : cryptomelane

from semi-detailed surveyed areas. Microscopically, its color of reflection is gray~ brownish gray and its anisotropy is strong and it contains scattered rhombic crystals.

Cryptomelane

Cryptomelane was detected as the result of the microscopic observation and X-ray diffractive analysis of Sample B045. Microscopically, its color of reflection is bluish gray and its anisotropy is strong and it is recognized in vein form in pyrolusite.

4) Other minerals

Quartz is the most predominant gangue mineral in manganese ores. Otherwise, small quantities of calcite and stilbite fill fractures in veinlets.

From Sample C083, goethite was detected by X-ray diffractive analysis (Table A–5). This sample had been taken from a small iron bed (thickness 8 cm, lenght 10 m) in muddy chert.

3–4 Chemical analysis of ore

The ore analysis was conducted on 191 ore samples. The elements of analysis are six : Mn, MnO_2, SiO_2, S, Fe and P. The samples were collected by channel sampling at intervals of 50 ~ 100 m from each manganese outcrop. The results of the analysis are shown in Table A–6.

The highest assay value of Mn is 82.73 % (MnO_2, sampling width 10 cm) for Sample B045 and the lowest assay value of Mn is 0.78 % (MnO_2, sampling width 12 m) for Sample D066. The mean value is 21.00 % (MnO_2). Sample B045 is a layered ore which composed of coarse grained manganese minerals, and contained almost no black siliceous part (SiO_2 3.58 %). Sample D066 is a nodular ore. The Mn grade of nodular ores is, on the average, as low as 5.95 % (MnO_2), compared with layered ores, but Sample C098 shows 14.12 % (MnO_2) at a sampling width of 3 m. The low assay value with layered ores is 4.88 % (MnO_2, sampling width 16 cm) for Sample B 124. The plane distribution of Mn assay value (Fig. II–9) shows that ore samples with Mn assay values of more than 30 % (MnO_2) are obtained from the central part to the west part with concentrated manganese outcrops, though some are also obtained from a portion of the eastern part. The correlation between Mn and other elements of analysis is shown in Table II–4; Mn shows a negative good correlation with SiO_2 and shows a positive good correlation with P. Mn is not closely correlated with Fe and S.

The highest value of SiO_2 is 90.53 % for Sample D006 which consists of nodular ore and the lowest value of SiO_2 is 3.58 % for Sample B045. The mean value of SiO_2 is 69.79 %. Nodular ores show high values and contained SiO_2 at more than 75 %. The layered ores that compose the main part of manganese deposits in this area is also high in SiO_2 content, because these layered ores considerably contain black siliceous parts. This is characteristic of manganese ores in this area. SiO_2 shows negative good correlations with Mn and P but is not closely correlated with Fe and S.

The Fe content is, as a whole, low, averaging 0.43 %, and the highest value is 1.76 % for Sample B126. The lowest value of Fe content is 0.10 % for Sample B045. Sample B126 is an ore composed of secondary manganese minerals filling a fracture in a grayish white chert and yellowish brown iron oxide was found in its veinlet. The probable reason for the high Fe content in this sample is the existence of this iron oxide. The Mn grade of this sample is only 3.92 % (MnO_2, sampling width 38 cm). The mean Fe content of layered ores is 0.40 % but the mean Fe content of nodular ores is as high as 0.76 %. The plane distribution of Fe contents does not show any special tendency. It is generally said that a negative correlation exists between Mn and Fe but in this area, their correlation is not clear as the Mn-Fe correlation coefficient is –0.36636. Also, no correlation is found between Fe and other elements.

The S content is, as a whole, low, averaging 0.11 % and ranging from the highest value of 0.41 % to the lowest value of 0.04 %. As can be seen from Table II–4, no correlation exists between S and other elements.

The P content averages 0.025 % and is lower than the S content. It ranges from the highest value of 0.176 % to the lowest value of 0.005 %. As indicated in Table II–4, P shows positive good correlation with Mn, negative good correlation with SiO_2 but P is not correlated with Fe and S. The mean P content of layered ores is 0.025 % and the mean P content of nodular ores is 0.020 %; thus the value is slightly higher than layered ores.

The ratio of Mn and Fe (manganese coefficient) contained in ores in this area is, as a whole, high but it is characterized by the fact that its variation is wide 0.46 ~ 542.00. As indicated in Fig. II–11, there is no tendency in the plane distribution but there are slight differences by types of ore. Layered ore is higher in manganese coefficient than nodular ore. According to Strakhov (1967), manganese coefficient varies by types of manganese deposits and shows characteristic values as it is 0.3 ~ 1.6 with manganese ores on the recent

Table Ⅱ-3 Mean, Maximum, Minimum Content of Elements in Manganese Ore Samples

element	semi-detailed surveyed area		
	average (%)	maximum (%)	minimum (%)
Mn	13.64	54.20	0.62
MnO_2	21.00	82.73	0.78
SiO_2	69.79	90.53	3.58
Fe	0.43	1.76	0.15
S	0.11	0.41	0.04
P	0.025	0.176	0.005
number of analized samples : 191			

Table Ⅱ-4 Correlation Coefficients amang Content of Element

Element	Correlation Coefficient
Mn–SiO_2	− 0.95063
Mn–Fe	− 0.36636
Mn–S	0.05880
Mn–P	0.65828
SiO_2–Fe	0.27228
SiO_2–S	− 0.03198
SiO_2–P	− 0.64497
Fe–S	0.00471
Fe–P	− 0.18716
S–P	0.08294
number of analized samples : 206	

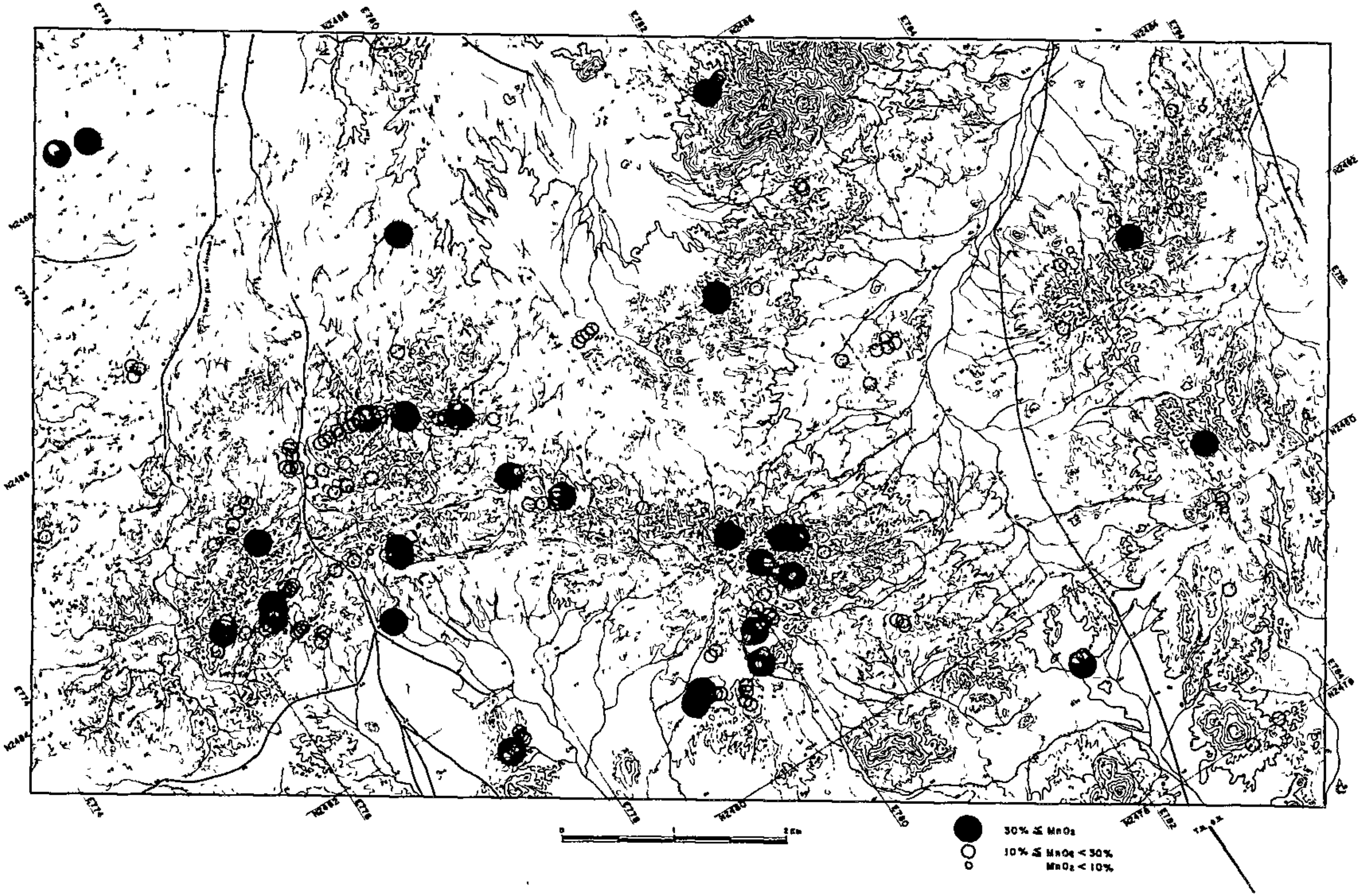


Fig. II-9 Distribution Map of MnO_2 Content

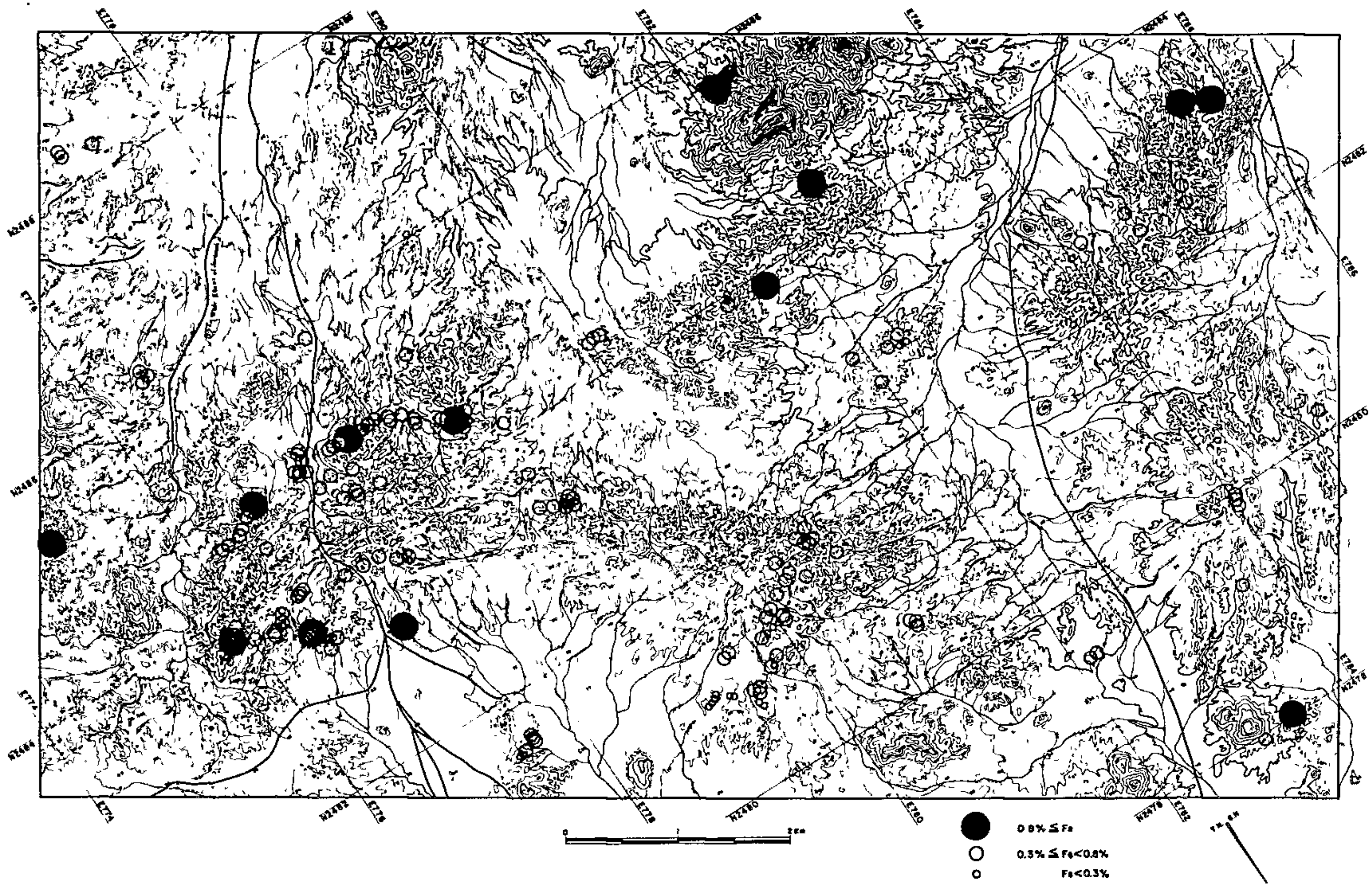


Fig. Ⅱ-10 Distribution Map of Fe Content

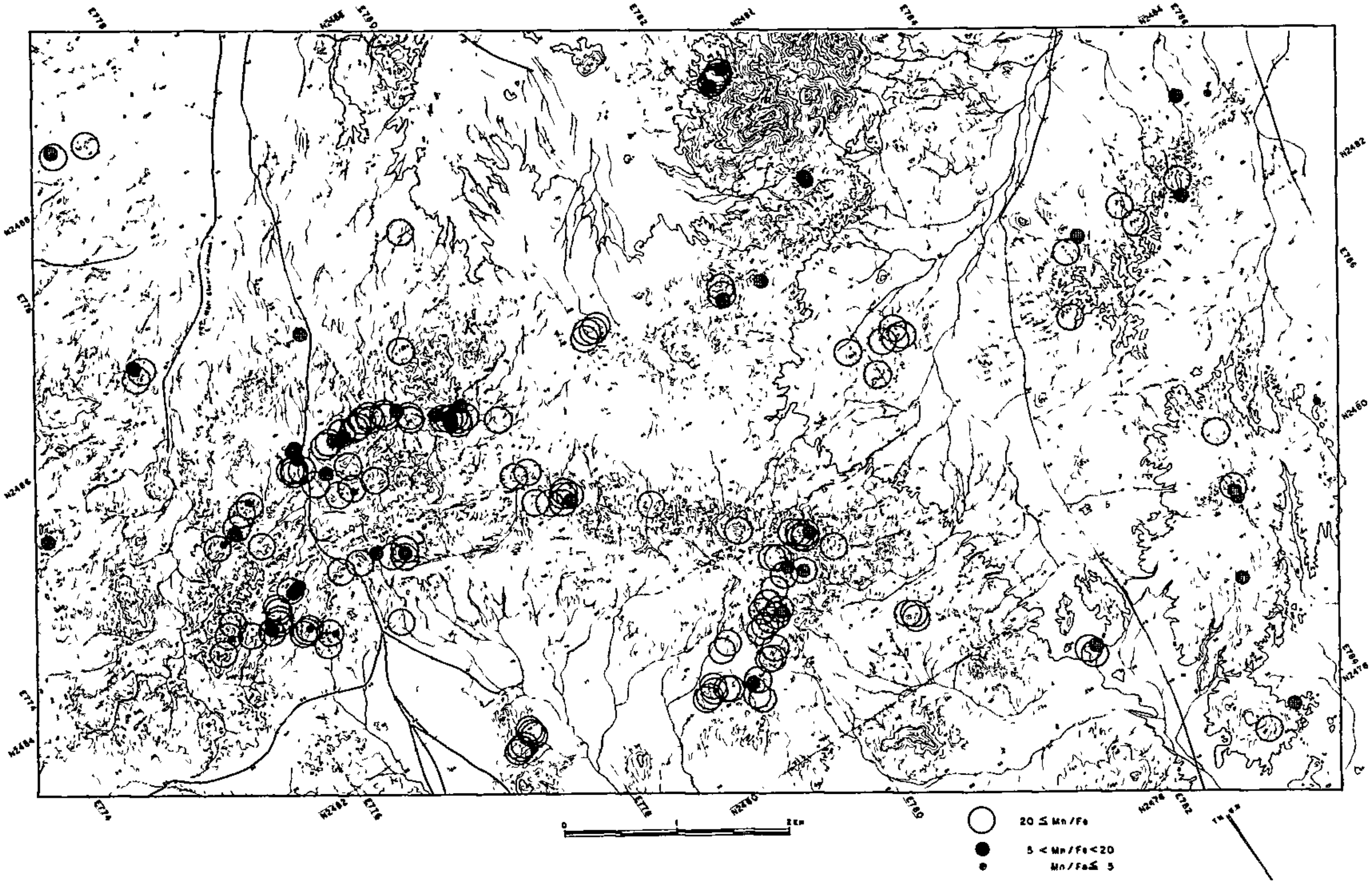


Fig. Ⅱ-11 Distribution Map of Manganese Coefficient (Mn/Fe)

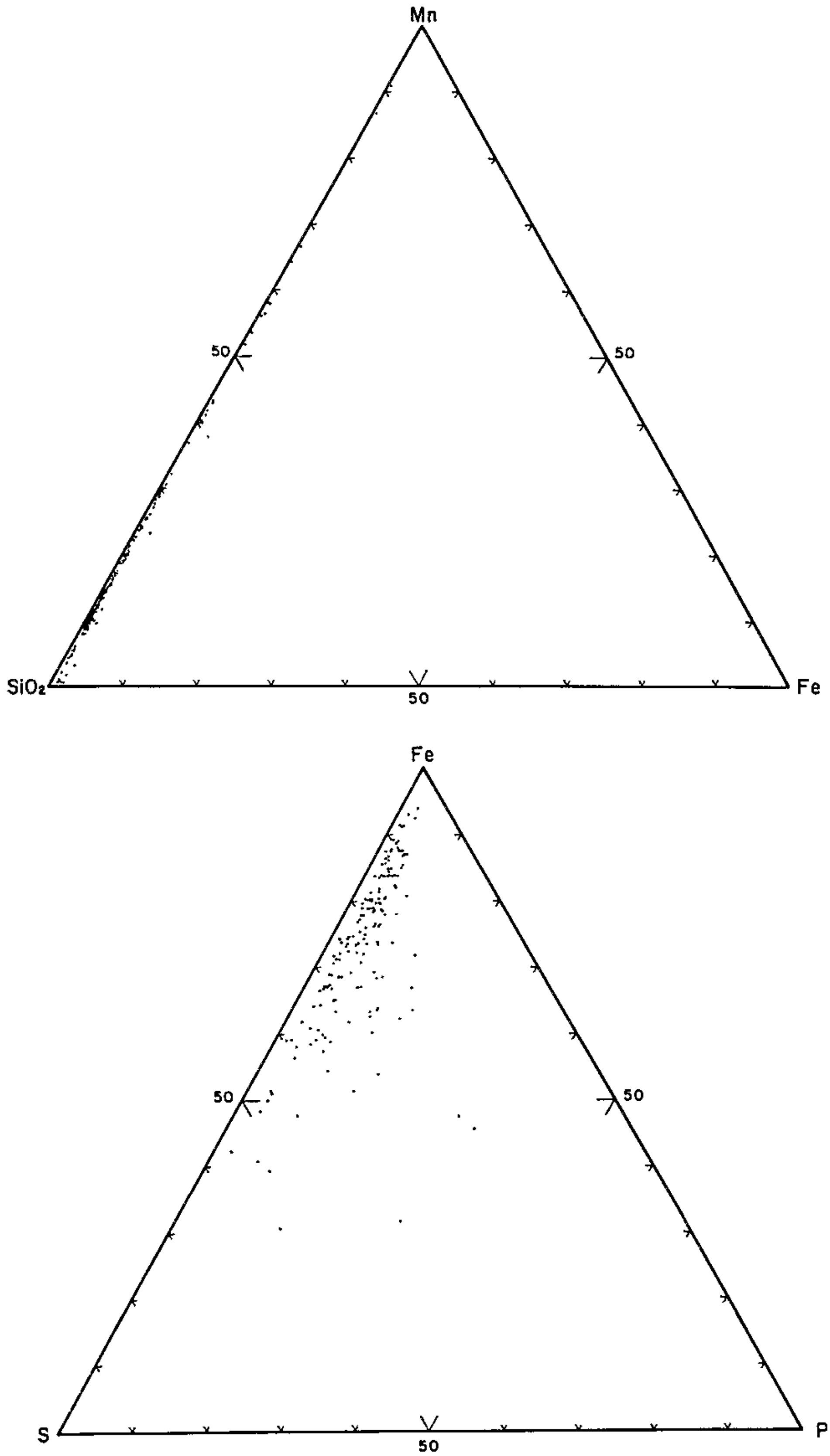


Fig. Ⅱ-12 Triangle Correlation Diagram for Mn-SiO_2-Fe and Fe-S-P

ocean floor, 10 ~ 70 with oxide ores in the oligocene sedimentary ore deposits and 1.5 ~ 18 in the volcanogenic sedimentary ore deposits. Since the variation of manganese coefficient of ores in this area is wide, these ores may belong in the category of either oligocene oxide ores or volcanogenic sedimentary ore deposits.

Fig. II–12 shows triangle diagrams illustrating the correlation in three elements Mn–SiO_2–Fe and Fe–S–P.

The results of the chemical analysis of ores show that the Mn grade in this area is at a medium level but these ores are characterized by a high SiO_2 content. The analysis further clarified that their Fe, S and P contents are low. It also seems that the layered ores and nodular ores differ in Mn, SiO_2, Fe and P contents.

3–5 Minor element analysis

Minor elements in ores and cherts were analyzed by spectrographic analysis. Total number of samples : 50, i.e., 15 from the photogeological surveyed area and 35 from the semi-detailed surveyed area. This analysis covered 26 minor elements and the results of the analysis are shown in Fig. II–13, II–14 and Table A–7. The results of the analysis of samples from the photogeological survey were included in the study of this section.

Equipment used in this spectrographic analysis and the conditions are as follows:

Type of machine used : Jaco, Evato type 3.4 m

(Diffractive grid : 1500 pcs/inch, slit width 20 μ)

Terminal : Hitachi R class $\phi = 6$ mm

(Perforation $\phi = 4$ mm x 4 mm)

Gas atomosphere : O_2 0.8 ℓ/min, Ar 3 ℓ/min

Photographic plate : Ag fa 2

Sample treatment : Re-ground, using as a buffer Li_2CO_3 added by 0.2 g to 0.8 g of original sample.

Spectro condition : Power source DC 10 amp. exposure 30 seconds

Each sample was analyzed twice, and peak on recording paper of microphotometer (Rigaku Denki product) was read and D value (density in emission spectrography) was obtained from mean value of readings. D value is indicated by $D = \log To - \log T$. To is transmittance 100 % and T is transmittance (%) of target spectrum emission line.

Density in emission spectrography (D value) indicates the semi-quantative content of a minor element in sample by numerals expressed 0 ~ 2. The contents of elements contained in a sample cannot be compared from D value but the relative comparison between samples with respect to the contents of elements and the tendency of their variations can be made from D value.

Fig. II–13 shows the D value variations of minor elements between samples and between outcrops. From this figure, remarkable variation tendencies between samples or between outcrops cannot be clearly seen because of great D value variations. However, the values of Ag and Zn seem to be somewhat high at Outcrop No. 71. Also, Ba and B are considered to have high contents, as a whole. At Outcrop No. 110, which is the largest outcrop in the semi-detailed surveyed area, no remarkable concentration of minor elements can be seen but from the behaviors of elements in that outcrop, one can faintly note the tendency that V, Mo, Sr, Ba, B, Si and Sn are concentrated on the east and west sides of the outcrop and G, Ag, Al, Na and K are concentrated in the central part. These behaviors of minor elements are presumed to be related to the concentration of Si, namely, the thickness of manganese layers which are thick on the east and west sides of the outcrop.

Fig. II–14 shows the tendencies of variation of minor elements in the black siliceous part of the layered ore and other cherts. Sample F049 is a black siliceous part of layered ore, Sample C124 is a muddy chert in a manganese nodular zone, Sample C123 is a muddy chert which does not contain manganese nodule, Sample F001 is a red chert in an alternation of chert and shale and Sample D033 is a yellow chert.

Elements whose contents increase in black siliceous parts and the muddy chert in a manganese nodular zone are Mn, Co, Mo, Sr, Ba and Sn. Tendencies of element Co, Ba and Sr are very similar to elements whose contents are high in a red chert are Fe, V, Cr, Ni and Sr. Particularly, Si and Cr are remarkably concentrated in it, compared with other cherts. Elements whose contents are high in a yellow chert are Fe, V, Mo and Ba. Of these, Fe and V show remarkable concentration. Elements whose contents increase in a muddy chert are Ga, Mg, Al, Ca and K.

It is considered that Co, Ba and Sr concentrated with Mn by similar behavior. According to Borchert (1970) and Zantop (1980), Ba and Sr are believed to be elements concentrating in volcanogenic sedimentary deposits. Therefore the concentration of Co, Ba, Sr and Mn may be related to volcanic activity.

The element Si and Cr are greatly concentrating in a red chert. Si is a component of chert and concentrated when the chert formed. Meanwhile, Cr is considered by Strakhov (1967) to concentrate and migrate by diagenesis and is considered to have concentrated by

diagenesis after the formation of the chert.

As for Fe and V which greatly concentrate in a yellow chert, Zantop (1980) believes that V concentrates in volcanogenic iron ore deposits. The formation of a yellow chert may be related to volcanic activity.

Of elements that concentrate in a muddy chert, Mg, Al, Cu and K are considered to due to clay minerals in the muddy chert.

Since spectrographic analysis is semiquantitative anlysis, the quantitative analysis of seven minor elements was conducted on three samples representative of the 50 samples (Table II–5), correlation curves for analyzed values and D value were obtained (Fig. A–6) and the contents of the seven elements in other samples were determined (Table A–8). Of the seven elements, Mo was analyzed by colorimetric analysis while Co, Cr, Cu, Ni, Pb and Zn were analyzed by the atomic absorption method. These contents are not absolute values but Fig. II–15 shows the distribution range of these values separately by elements. This figure also shows for comparison Strakhov (1967)'s distribution range of the contents of minor elements in ocean floor ores, oligocene oxide ores and volcanogenic sedimentary ores. Compared with ocean floor ores, the Cr content of ores in this area is extremely high and the contents of all other elements are within the range of low values. Compared with oligocene ores, which are regular sedimentary deposits, the Cr content of ores in this area is high, the distribution range of Mo and Pb contents is somewhat high but the distribution range of Co and Ni contents is low. Then, compared with volcanogenic sedimentary ores, ores in this area have a high Cr content, their distribution range of Co, Ni and Mo contents is somewhat high but their distribution range of Zn is rather low. Thus, ores in this area, with the exception of Cr, show values close to the distribution range of minor elements in oligocene ores and volcanogenic sedimentary ores. Regarding the mean values of the six elements other than Cr, there are peaks in the values of Cu and Zn. This tendency resembles the distribution tendency of minor elements in volcanogenic sedimentary ores. Ores in this area are characterized by the fact that the Cr content is abnormally high. Since Cr concentrates in a red chert, it seems that this area, as a whole, was under environments conducive to the concentration of Cr.

From the above results of analysis of minor elements in ores and cherts, it is considered likely that manganese deposits in this area were formed in relation with volcanism.

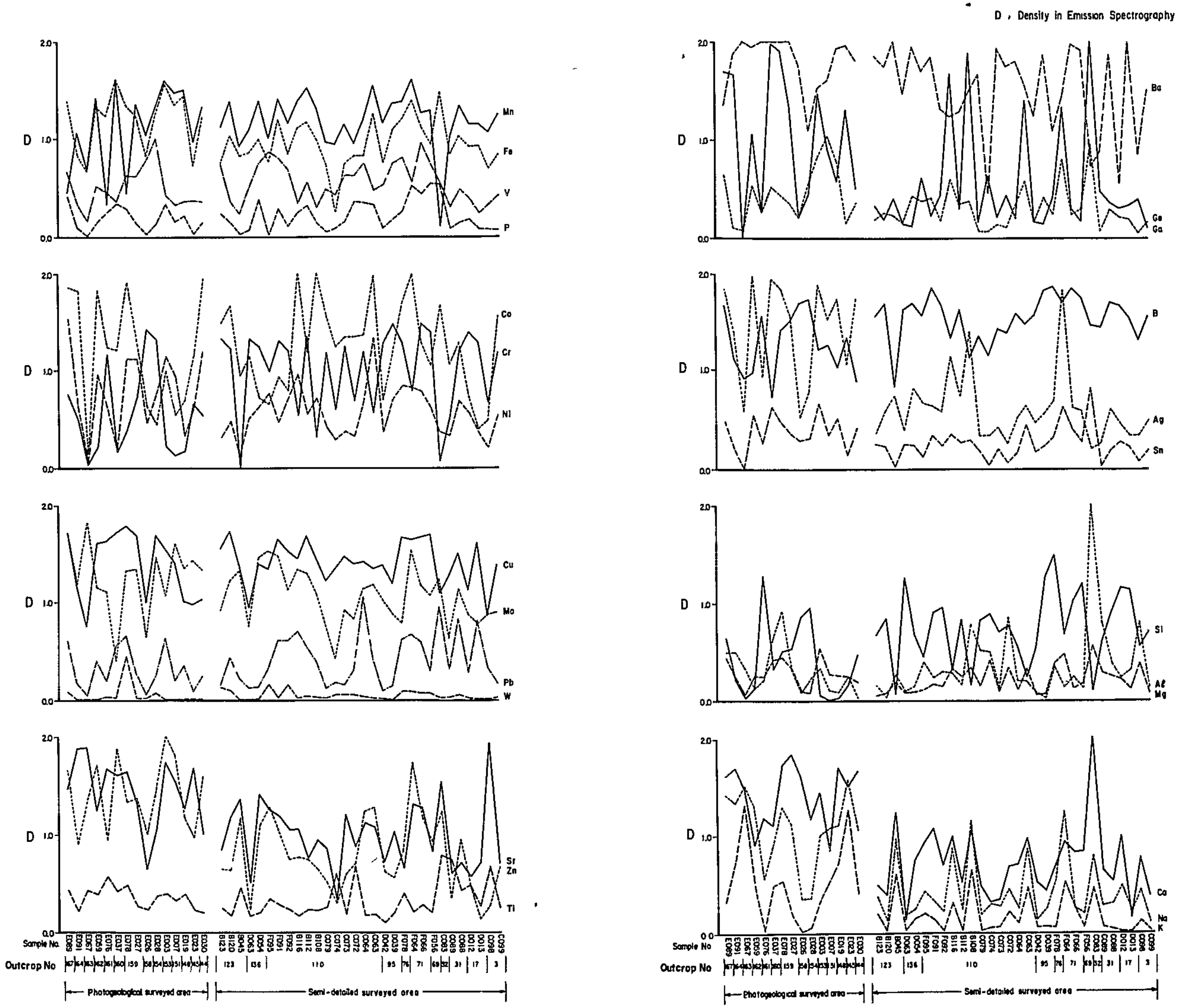


Fig. Ⅱ-13 Trend of Density in Emission Spectrography of Minor Elements in Manganeoe Ore

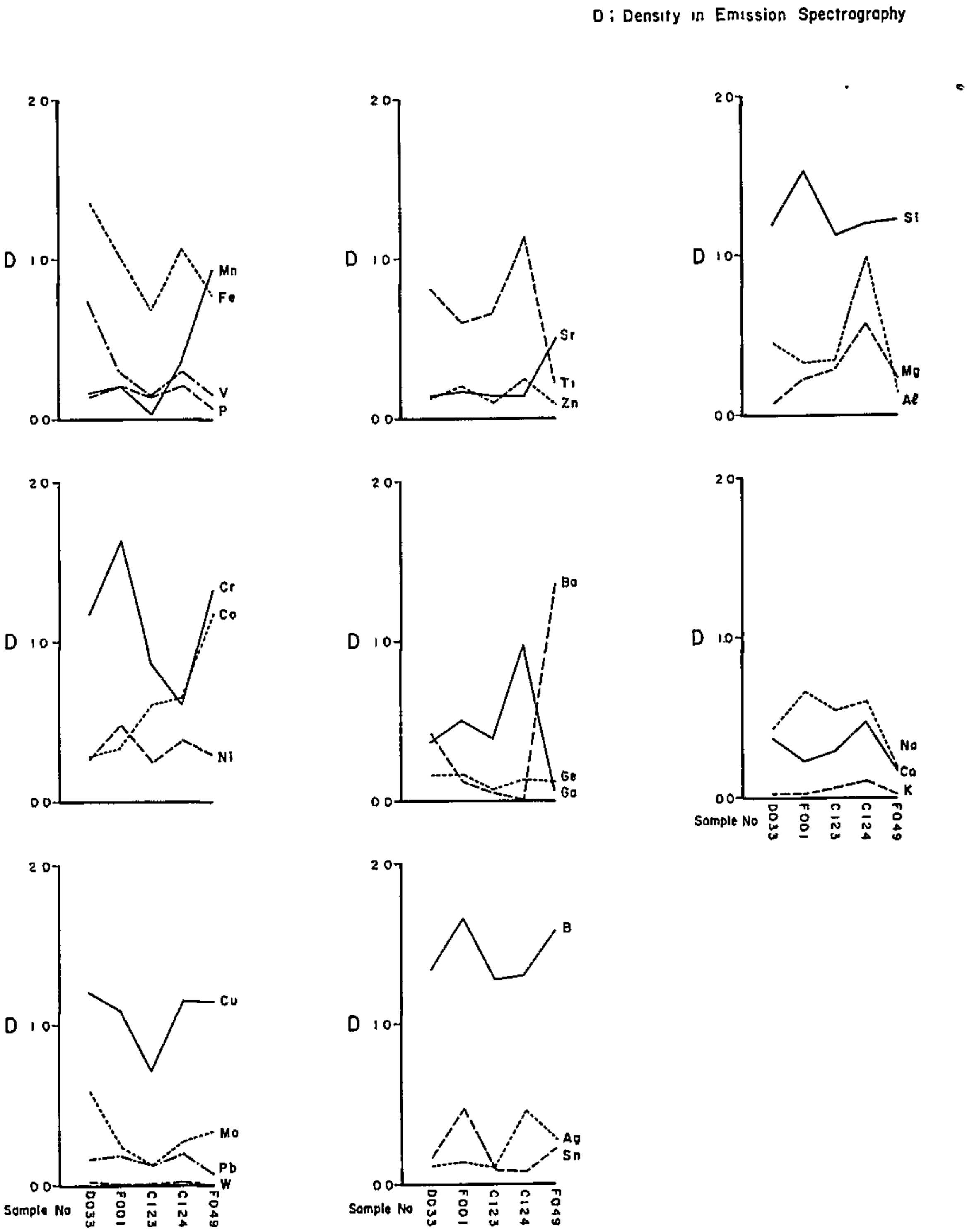


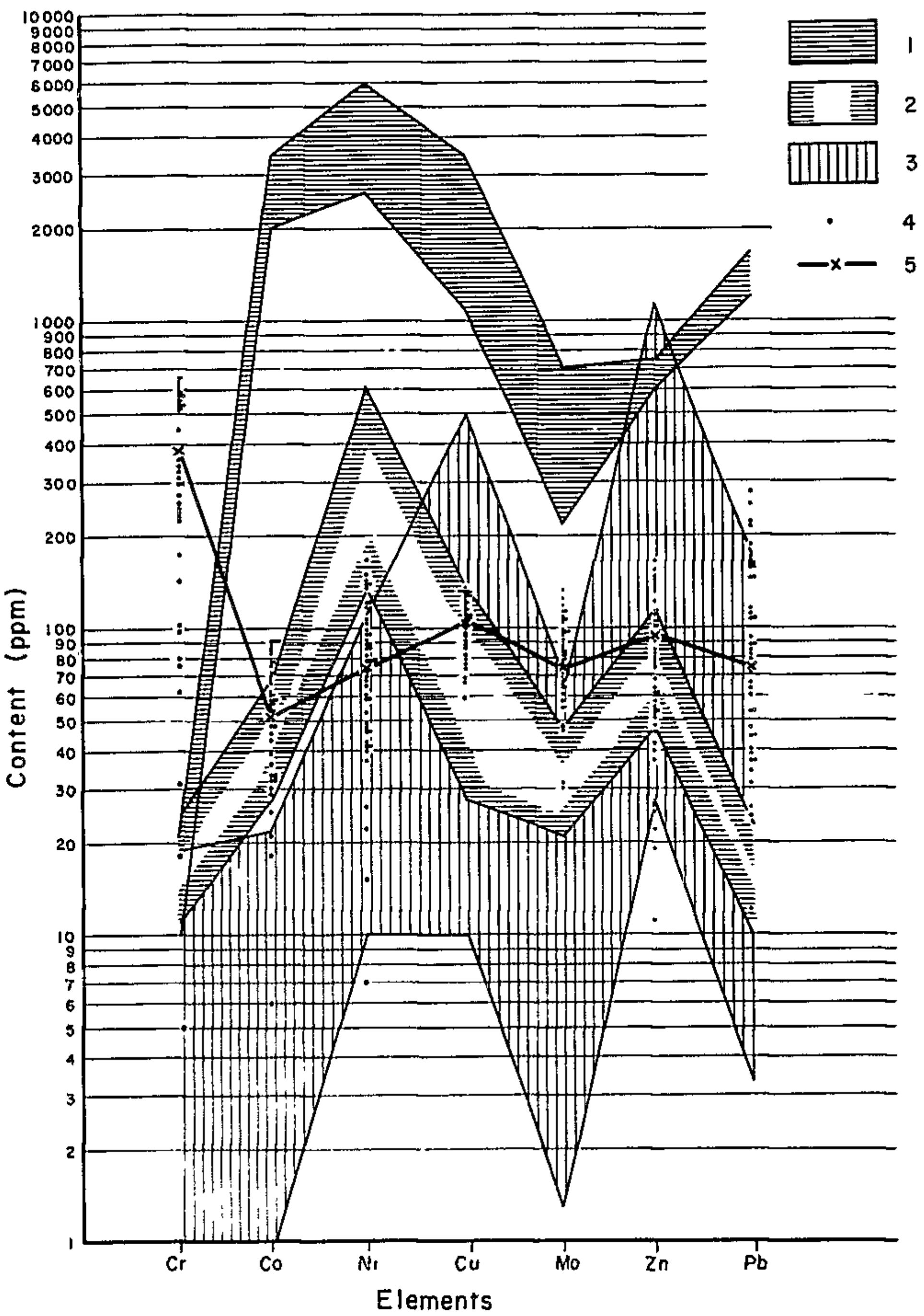
Fig. II-14 Trend of Density in Emission Spectrography of Minor Elements in Chert

Table Ⅱ-5 Content of 7 Minor Element in 3 Manganese Ore Samples

Element \ Sample No.	C063	C088	E037
	ppm	ppm	ppm
Co	80	30	90
Cr	350	390	220
Cu	70	70	180
Mo	120	50	30
Ni	150	70	50
Pb	150	130	250
Zn	140	70	80

Table Ⅱ-6 Correlation Coefficients between Mn and Minor Elements

Element	Correlation Coefficient
Mn–Cr	– 0.77353
Mn–Co	– 0.02228
Mn–Ni	0.09659
Mn–Cu	– 0.06982
Mn–Mo	0.49310
Mn–Pb	0.00154
Mn–Zn	0.72563



1 manganese ore in recent ocean floor
2 oligocene manganese oxide ore
3 volcanogenic sedimentary manganese ore
4 manganese ore in sur area
5 mean values

Fig. Ⅱ-15 Range of Content of 7 Minor Elements in Manganese Ore

3–6 Relations between ore deposits and geological structure

Manganese ore deposits are found in almost the distribution area of a Halfa Formation but particularly large and dense deposits are located in the sector from the central part of the area to its western part. A middle member of the Halfa Formation is distributed from the central part to the western part and E–W and NE–SW folding axis systems exist there. In the eastern and northern parts, middle and lower members of the Halfa Formation are distributed and the ore deposits are, as a whole, small and E–W, N–S and NNE–SSW folding axis systems exist there. Ore deposits in this area are considered to be syngenetic and it is presumed that the distribution and scale of these deposits are mainly controlled by the sedimentary environments of the Halfa Formation. The eastern part has basic lava, dykes and sheets. These seem to have affected the formation of the deposits in one way or another but the details are not known.

As to the relation to folding, these manganese ore deposits are extremely folded by the effect of thrust and lifting after ore formation. Some of the veinlet of manganese minerals filling fractures in the ores and the muddy cherts were formed as segregation veins in the process of diagenesis but most are considered to have been formed mainly by folding because there are many minor faults accompanying folds. However, the veinlet of manganese minerals are on a small scale and found only in ore deposits and muddy cherts and the control of ore deposits by folds is considered to be rather small. Thus, it is considered that the rich zone of these ore deposits is controlled more by sedimentary environments in time of ore formation than by the tectonic movement post ore formation.