11. HEAVY MINERAL STUDIES OF SAMPLES FROM DEEP SEA DRILL CORES OF SITES 223 AND 224, LEG 23, GLOMAR CHALLENGER CRUISE IN THE ARABIAN SEA

Tapas K. Mallik, Geological Survey of India, Calcutta, India

INTRODUCTION

Site 223 (18°45'N, 60°08'E) is situated at the foot of the continental rise off the coast of Muscat and Oman at a depth of 3633 meters. It is on the Arabian plate, on the west side of the Owen Fracture Zone, which forms the northwest boundary of the Indian plate. A sequence of 740 meters of Pleistocene to Upper Paleocene sediments and underlying basalts was penetrated. Site 224 is situated south of Site 223 (Figure 1) on the Owen Ridge (16°33'N, 59°42'E) off the Muscat coast where 787 meters of sediments ranging in age from Pleistocene to Early Eocene were cored. Heavy mineral fractions were studied from sandy and silty layers in the two holes in order to compare the composition of the terrigenous material and to determine their source areas.

GEOLOGY OF THE ADJACENT LAND AREAS

A vast complex of igneous and metamorphic rocks occupies roughly one-third of the Arabian Peninsula and adjacent areas. Powers et al. (1966) described two major structural provinces–the stable Precambrian basement within the Arabian Peninsula and the great mobile belt of Taurus, Zagros, and Oman mountains bordering the stable regions to the north and east. Crystalline gneisses form the coastline in some areas and are also exposed on Kuria Muria Island. On Masira Island, gabbros, peridotites (often serpentinized), basaltic volcanics, altered pillow lavas, radiolarian cherts, and cherty shales occur. In Ras Madrakah, opposite Site 223, the rocks are mainly ophiolites similar to the basic igneous rocks described from Masira Island (Verspyck, 1972, personal communication). Highly folded and faulted Precambrian basement rocks occur in the Zalwat Sellha coastal plain, 90 km east of Salalah and nearest to Site 224. They can be divided into three units of increasing metamorphism: (1) Ayn Sarit metaclastics containing chlorite-sericite cemented sandstone, phyllite, and vein quartz; (2) Erkahol metamorphics containing dolomite, quartz conglomerate, biotite schists, and diorite sills; (3) Sadh gneiss and schist, oldest and most severely metamorphosed, containing light-colored granite diorite gneiss and dark green schist intruded by pegmatite sills and basic igneous dykes. These contain biotite, hornblende, and pink garnet.

METHODS AND PROCEDURES

Twelve samples from Site 223 and five samples from Site 224 were selected for study. Four beach sand samples from Salalah, Arabian coast, obtained from R.A.F., Salalah were also examined to compare their mineralogy with the above two sites. The samples studied are listed in Table 1 together with their ages, the quantity of heavy minerals present, and their general lithologic character.

The samples were washed with water to remove salt and sieved through -120 +230 A.S.T.M. mesh (0.063-0.125 mm) and the portion retained was dried and weighed. The samples were then treated with bromoform of specific gravity 2.89. Hydrochloric acid treatment was avoided to preserve the carbonates and apatites. The heavy fraction was mounted in Canada Balsam and 300 to 400 grains were counted in each slide using a mechanical stage and petrographic microscope. Grain counts were made and, in addition, color, elongation, shape, alteration, and etching were noted. A portion of the heavy fraction was mounted in bakelite and polished to study the opaque minerals. The opaque minerals were identified using standard techniques of ore Microscopy, i.e., studying the various properties such as color, bireflectance, anisotropy, reflectivity, internal reflection, and reaction to etch tests.

RESULTS

Light fraction: The light fraction, studied under a binocular microscope, contains the remains of mollusks, ostracods, foraminifera, radiolarians, sponge spicules, pelecypods, as well as quartz, feldspar, muscovite grains, plus plant and rock fragments. Plant fragments are most common in 223-2-6, 98-100 cm and 2, 2, 143-145 cm. The relative amounts of the different constituents vary with depth; however, the light fraction was not studied quantitatively.

Heavy mineral fraction: The heavy mineral content varies from 1.7 to 6.3 and 0.6 to 3.5 percent (by weight) for Sites 223 and 224, respectively (Table 1). The average heavy mineral content for the two sites is 3.1 and 2.2 percent of the total sediment fraction of the samples analyzed.

Nonopaque heavy mineral fraction: A large variety of nonopaque heavy minerals as listed below is present in the sediments. Nearly 30 species have been identified. A detailed percentage compilation for each sample is presented in Table 2. A graphical comparison of some of the important minerals is shown in Figure 1. For convenience of comparison, a listing of percentage ranges of the different heavy minerals is given in Table 3.

Opaque minerals constitute an important portion of the heavy fraction (7%-58%, Figure 1, Tables 2 and 3). The opaque minerals observed were magnetite, hematite, rutile, goethite-lepidocrocite, and other hydroxides of iron and pyrite. Most of the grains are subround to round, though some angular grains were observed. Magnetite is the most important constituent within the opaques. Exsolution laths of hematite inclusions were noticed. Only few free hematite grains were found. In some

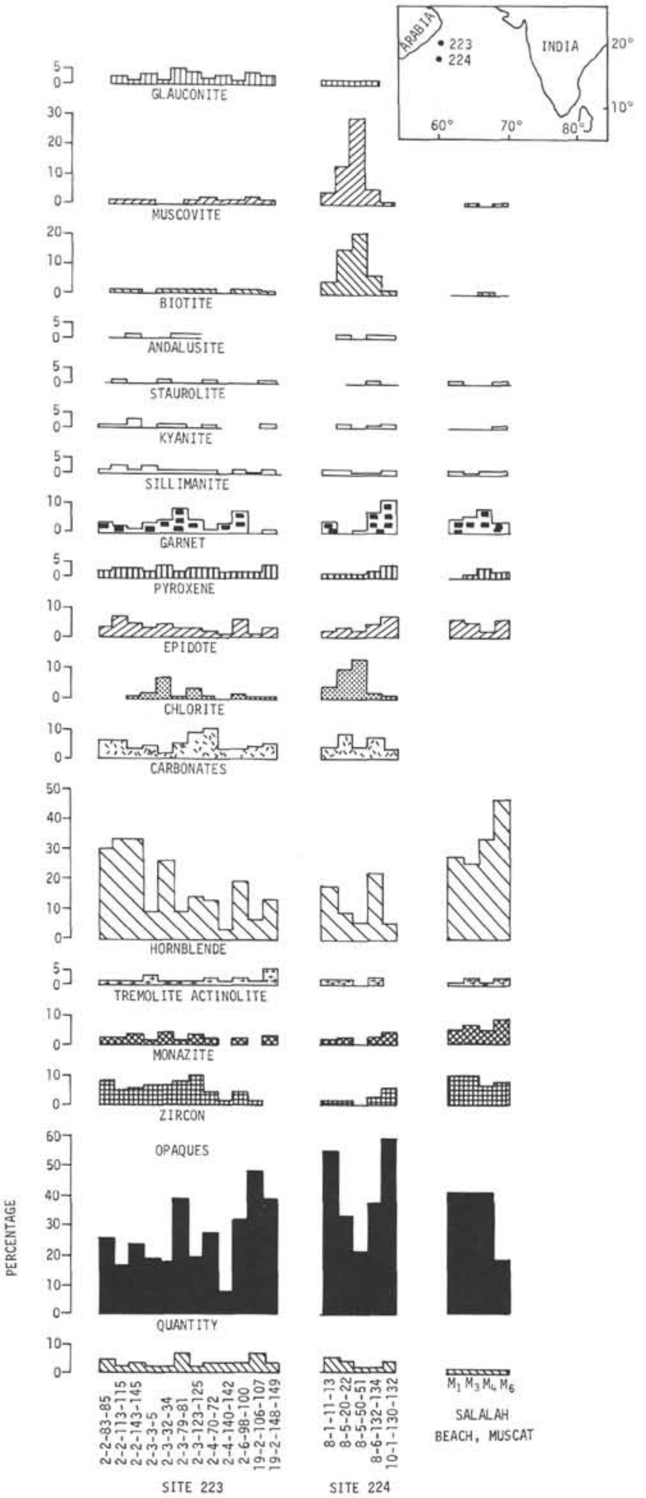

Figure 1. *Histograms of heavy minerals distribution patterns for Sites 223, 224, and the beach samples.*

cases goethite shows a colloidal texture. Pyrite is an important constituent of the sediments observed in the opaque portion of some samples. It shows well-developed framboidal texture similar to that occurring in the Recent shelf sediments off Mangalore Western India (Mallik, 1972). Sometimes the opaque minerals (pyrite in most cases) occur within shell fragments.

DISCUSSION

It will be clear from Tables 2 and 3 and Figure 1, that opaques and hornblende constitute the major part of the heavy mineral assemblage for Sites 223, 224, and the beach samples from the Arabian coast. Biotite and muscovite occur in greater abundance at Site 224 compared to Site 223. Zircon, epidote, monazite, and garnet also occur in fair abundance at both sites. Other minerals such as kyanite, tourmaline, sphene, apatite, topaz, etc. occur in minor amounts. The mineralogy of Sites 223 and 224 is similar and shows a striking similarity to the mineralogy of the beach sands (Table 3). The heavy mineral assemblages do not differ much throughout Sites 223 and 224 (Table 2) indicating that the terrigenous detritus at these sites was probably derived from the same source. Minor differences in mineral percentages may be due to provenance variations, removal of unstable minerals by differential solution, and reworking by marine currents prior to their incorporation in the sediment section. Perhaps it is even more likely that these differences simply reflect original inhomogeneities in the heavy mineral population within the sediments.

The abundance of hornblende, opaques, monazite, and zircon clearly indicates that most of the sediment has been derived from an igneous source with a lesser contribution from the metamorphic rocks as indicated by smaller amounts of garnet, staurolite, sillimanite, andalusite, and kyanite. Considering the geology of the adjacent area, discussed earlier, the possible sources of the different minerals are listed in Table 4.

Thus, the heavy minerals found at Sites 223 and 224 were apparently derived from the Arabian coastal plain and from small islands in the Arabian Sea such as Masira, Kuria Muria, etc. This interpretation is also supported by the mineralogical similarities of the sediments at these sites to the beach sands of the Arabian coast as illustrated in Table 3 and Figure 1. The only other possible source is from turbidites of the Indus Cone. Some heavy minerals, such as staurolite, kyanite, and sillimanite, have been considered as markers for the lower, middle, and upper Siwaliks of the Himalays by Chaudhri (1972). However, the possibility of sediment transport to these sites from the Indus Cone is not plausible as the Owen Ridge would have acted as a barrier to bottom sediment transport since the time of its uplift in Early Miocene or Late Oligocene time.

When a percentage plot (Figure 1) is made of the total heavy minerals, there are some intervals of high content which could indicate a more rapid influx of detrital material. However, these intervals do not correspond to intervals of greater sediment immaturity relative to those intervals containing lesser amounts. Alternatively, these differences could be due to climatological variation through time.

A majority of grains are well rounded indicating a long transport history. The high degree of rounding the ultrastable minerals–zircon, rutile, staurolite, and sillimanite–may reflect a polycyclic abrasion history. It is also

TABLE 1
List of Samples Studied and Per Cent Heavy Minerals Present

Age	Core	Section	Interval (cm)	Heavy Mineral (% by wt)	General Lithology
Site 223					
Pleistocene	2	2	83-85	4.10	Olive to yellowish gray
			113-115	1.80	detrital rich nanno ooze/
			143-145	2.48	and chalk with intercalated
	2	3	3-5	2.39	thin layers of terrigenous
			32-34	1.66	sand, silty sand, and silt
			79-81	6.28	of varying thickness,
			123-125	1.75	Some of the terrigenous
	2	4	70-72	3.45	sediments have turbidite
			140-142	2.48	characteristics.
	2	6	98-100	2.44	
Miocene	19	2	105-107	3.07	
			148-149	5.87	
Site 224					
Oligocene	8	1	11-13	3.53	Brownish gray detrital sandy
	8	5	20-22	3.37	to clayey siltstone.
			50-51	0.63	
Eocene	8	6	132-134	0.84	
	10	1	130-132	2.69	

Beach Samples M_1, M_3, M_4, M_6

quite likely that these minerals have experienced wave reworking as documented by Hails (1969).

Some of the hornblende grains have a saw-toothed appearance. Corrosion structure, hummocky surfaces, solution features, and embayments occur especially in garnets, epidotes, hornblendes, and carbonates. These might have been formed by intrastratal solutions. In the Site 223 heavy mineral fractions, a large quantity of shell fragments occurs (Table 2) which is not present at Site 224.

CONCLUSIONS

1) The heavy mineral assemblages at Sites 223 and 224 and the assemblage from the Southern Arabian beaches, except for the large amount of mica at Site 224, closely resemble each other, suggesting a common source.

2) The mineralogy of the sands shows only minor differences in the various stratigraphic intervals, indicating that the provenance area remained unchanged from Eocene to recent time.

3) The heavy mineral suites found at Sites 223 and 224 represent a mixed igneous and metamorphic source such as occurs along the Arabian coastal plain and on Masira and the Kuria Muria islands in the Arabian Sea. The diverse composition of the heavy mineral assemblage indicates a complex provenance.

ACKNOWLEDGMENTS

The author is grateful to Dr. John H. Hails, Unit of Coastal Sedimentation, Taunton, Somerset, England, and Dr. S. V. P. Iyengar, Director, Geological Survey of India for critically going through the manuscript and for helpful suggestions in improving the manuscript. He is thankful to the Co-Chief Scientists and other shipboard participants for various thoughts and suggestions and to the Director General, Geological Survey of India, for his interest in the work.

REFERENCES

Beydoun, Z. R., 1960. Synopsis of the geology of East Aden Protectorate: Int. Geol. Cong. Rept. 21st session, Worden, pt. XXI, p. 131-149.

Chaudhri, R. S., 1972. Heavy minerals from the Siwalik formations of the North Western Himalayas: Sed. Geol., v. 8, p. 77-82.

Hails, J. R., 1969. The nature and occurrence of heavy minerals in three coastal areas of New South Wales: J. Proc. Roy. Soc., New South Wales, v. 102, p. 21-39.

Mallik, T. K., 1972. Opaque minerals from the shelf sediments off Mangalore, Western Coast, India: Mar. Geol., v. 12, p. 207-222.

Powers, R. W., Ramirez, L. F., Redmond, C. D., and Elberg, E. L., Jr., 1966. Geology of the Arabian Peninsula, sedimentary geology of Saudi Arabia: U. S. Prof. Paper 560-D, p. D1-D147.

TABLE 2
Heavy Mineral Analysis of Deep Sea Core Samples From Sites 223 and 224

Sample	Hornblende		Opaques	Carbonates	Chlorite	Trem/ Act.	Pyroxene		Epidote	Monazite	Zircon	Garnet	Sillimanite	Staurolite	Kyanite
	Green	Brown					Clino	Ort							
Site 223															
2-2, 83-85	28.26	1.60	24.80	6.40	–	0.80	2.13	–	4.00	1.86	8.00	2.93	1.06	–	1.33
2-2, 113-115	32.42	0.82	15.93	6.04	–	0.82	2.74	–	6.87	2.47	5.49	2.47	1.92	0.55	0.55
2-2, 143-145	31.86	1.37	22.86	2.75	0.55	0.82	3.31	–	4.96	2.75	6.33	1.10	1.37	–	2.48
2-3, 3-5	9.21	–	17.61	3.79	1.62	2.71	1.89	–	2.71	0.54	6.50	2.98	1.62	–	–
2-3, 32-34	25.14	0.57	17.14	2.28	7.42	1.43	3.43	0.86	4.28	3.71	6.86	3.71	1.43	0.57	0.57
2-3, 79-81	9.03	–	37.65	5.12	1.20	0.60	2.41	–	3.31	1.20	7.83	7.53	0.90	–	0.60
2-3, 123-125	13.92	0.63	18.67	8.54	3.48	0.63	2.21	0.63	3.16	2.85	10.44	3.79	0.95	–	–
2-4, 70-72	12.91	0.25	26.83	9.87	0.76	1.52	2.02	0.51	1.52	1.52	3.54	0.76	0.51	0.25	0.25
2-4, 140-142	3.19	–	7.03	3.19	–	0.32	0.63	–	1.28	–	0.32	2.87	–	–	–
2-6, 98-100	18.80	0.29	31.04	3.28	2.38	2.09	0.89	–	6.26	2.38	8.95	7.46	0.89	–	–
19-2, 105-107	6.36	–	47.27	3.93	0.91	1.21	1.21	–	0.91	–	0.60	–	0.30	–	–
19-2, 148-149	12.83	–	37.91	5.37	0.59	5.07	3.88	0.59	2.98	2.68	–	0.59	0.59	0.59	–
Site 224															
8-1, 11-13	17.43	–	54.13	3.67	3.06	0.91	1.22	–	1.83	0.30	0.91	3.67	0.61	–	–
8-5, 20-22	7.6	0.28	32.39	8.17	10.42	0.56	0.84	–	3.09	1.12	1.41	–	0.56	–	0.28
8-5, 50-51	4.64	–	20.29	4.05	12.75	–	0.58	–	2.02	–	–	0.58	0.29	–	–
8-6, 132-134	21.49	–	35.81	6.88	1.65	1.65	1.65	0.82	3.58	1.65	1.65	7.16	–	0.55	0.27
10-1, 130-132	3.89	–	58.08	2.69	0.59	–	3.59	–	7.18	2.69	5.39	10.78	0.59	–	0.59
Beach Samples															
M 3	24.46	0.61	40.36	–	–	1.83	1.22	–	5.19	5.50	8.56	6.42	–	–	–
M 1	26.96	–	40.45	–	–	1.40	–	–	5.89	5.05	9.26	5.33	1.40	0.56	–
M 4	31.23	2.10	39.65	–	–	1.05	2.45	0.70	2.45	4.51	6.31	8.07	0.70	–	–
M 6	44.17	1.84	16.56	2.45	–	2.45	2.45	–	6.44	7.66	7.05	4.29	0.60	0.30	0.61

[a]Samples not treated with acid.

TABLE 2 – *Continued*

Sample	Andalusite	Biotite	Muscovite	Tourmaline	Sphene	Apatite	Rutile	Augite/ Diop.	Aegirine	Topaz	Glass	Glauco- nite	Shell Fragment	Unidentified
Site 223														
2-2, 83-85	–	–	–	–	0.53	–	0.80	0.53	–	–	2.66	–	12.00	0.26
2-2, 113-115	–	0.55	1.37	0.27	0.82	0.55	0.55	–	–	–	–	1.65	14.56	0.55
2-2, 143-145	0.55	0.82	0.55	0.27	0.55	0.55	0.82	–	–	0.27	–	0.55	12.12	0.55
2-3, 3-5	–	–	0.81	–	0.54	–	–	0.54	–	–	0.54	2.71	43.36	0.27
2-3, 32-34	–	0.86	–	0.57	1.14	–	0.57	0.57	–	0.86	–	1.43	13.42	1.14
2-3, 79-81	0.60	0.60	–	–	–	–	–	–	–	–	–	5.12	16.26	–
2-3, 123-125	–	1.26	0.95	0.31	0.63	0.31	0.95	–	1.26	–	–	4.43	19.93	–
2-4, 70-72	1.26	0.51	1.52	0.25	0.51	–	0.25	–	–	–	0.76	1.77	29.50	0.51
2-4, 140-142	–	–	1.28	–	–	–	0.32	–	–	–	–	2.87	79.81	–
2-6, 98-100	–	0.59	0.89	–	0.59	–	–	–	0.59	–	–	1.49	10.74	0.29
19-2, 105-107	–	1.21	1.51	–	0.30	–	–	0.30	–	–	0.60	4.24	29.09	–
19-2, 148-149	–	0.29	0.89	0.59	0.29	0.29	–	0.59	–	–	–	3.28	19.70	0.29
Site 224														
8-1, 11-13	–	3.97	3.67	0.91	–	–	–	–	–	–	1.83	1.83	–	0.30
8-5, 20-22	0.56	15.49	13.23	0.28	–	0.56	–	–	0.56	0.28	0.28	1.97	–	–
8-5, 50-51	–	20.29	29.27	–	–	0.58	–	–	–	–	2.34	1.74	–	0.58
8-6, 132-134	0.55	5.51	4.96	0.27	–	1.37	0.27	–	–	–	–	1.93	–	–
10-1, 130-132	0.59	0.89	1.19	0.59	–	–	–	0.59	–	–	–	–	–	–
Beach Samples														
M 3	0.30	–	0.61	1.22	–	–	0.61	0.30	–	–	–	–	–	2.75
M 1	0.28	–	–	–	–	–	0.56	–	–	–	–	–	–	1,12
M 4	–	0.70	–	0.70	–	0.35	0.30	0.70	–	–	–	–	–	–
M 6	–	–	0.30	0.61	0.30	0.92	–	–	–	0.60	–	–	–	–

TABLE 3
Percentage Range of Heavy Minerals at Sites 223, 224, and in Salalah Beach Samples

	223	224	Beach Sample
Opaques	7-47	20-58	16-40
Hornblende	3-33	4-21	25-46
Carbonates	2-10	3-8	0-2
Chlorite	0-7	1-13	–
Tremolite/Actinolite	1-5	0-2	1-2
Monazite	0-4	0-3	4-8
Epidote	1-7	2-7	2-6
Zircon	0-10	0-3	6-9
Pyroxene	1-4	1-4	0-2
Staurolite	0-1	0-1	0-1
Garnet	0-8	0-11	4-8
Sillimanite	0-2	0-1	0-1
Kyanite	0-2	0-1	0-1
Andalusite	0-1	0-1	0-1
Muscovite	0-2	1-29	0-1
Biotite	0-1	1-20	0-1
Tourmaline	0-1	0-1	0-1
Sphene	0-1	–	0-1
Apatite	0-1	0-1	0-1
Rutile	0-1	0-1	0-1
Augite/Diop.	0-1	0-1	0-1
Aegirine	0-1	0-1	–
Topaz	0-1	0-1	0-1
Glauconite	0-5	0-2	–

TABLE 4
Possible Source Rocks of the Different Minerals

Minerals	Possible Source
Hornblende, zircon, monazite, sphene, apatite, opaques, rutile, muscovite, biotite	Igneous source, intrusives and volcanics in the nearby coastal areas of Arabia, Masira, and Kuria Muria islands in the Arabian Sea. Some of these minerals such as zircon, rutile, apatite, and tourmaline are considered to be characteristic assemblages from the Aruma sandstone and the Tawil group in eastern Arabia (Powers et al. 1966)
Garnet, sillimanite, staurolite, kyanite, andalusite, epidote	High-grade metamorphic rocks of the Sadh gneiss and schist from the Zalwat Sellah coastal plain, (90 km east of Salalah, nearest to Site 224). Garnet and staurolite have also been considered as index minerals in the Eastern Aden Protectorate (Beydoun, 1960).
Muscovite, biotite, chlorite	Ayn Sarit metaclastics containing low-grade metamorphic rocks and from Erkahol metamorphics, and pegmatites.
Pyrite, glauconite, some carbonates	Authigenic