Implications of factor analysis in the geochemistry of Nishikhal manganese deposit, eastern ghats, Orissa, India

B.K. NAYAK, Swati MOHANTY, RAJEEV and R.K. SAHOO

*Mineralogy and Metallography Division,
Regional Research Laboratory,
Bhubaneswar-751 013, Orissa, India*

Normalised major and trace element data of manganese ores from Nishikhal are processed by using R-mode factor analysis of correlation matrix. Twenty major and trace elemental variables are expressed in terms of 3 common (rotated) factors to understand the mineralogical occurrences and the processes of formation of the manganese deposit. Varimax factor scores are used to classify in a finer detail the manganese ore types.

Keywords: Factor analysis, R-mode, Geochemistry, Varimax factor scores, Classification, Manganese ore, Nishikhal

I. Introduction

The manganese deposit at Nishikhal (Lat. 19°12'-19°14'N and Long. 83°12'-83°14'E) in the state of Orissa forms a part of the khondalite suite of rocks belonging to the Eastern Ghat Super-Group (Fig. 1). This deposit is considered to be the extension of Koduritic manganese ores of Srikakulam district, Andhra Pradesh (Roy, 1981). Although some work has been carried out on the Nishikhal deposit pertaining to general geology, mineralogy and geochemistry (Ajmal *et al*, 1982 and Acharya *et al*, 1990), a detailed work on the ore geochemistry and statistical modeling are lacking. The present work aims at understanding major and trace elements geochemistry of the ores, bringing out the R-mode factor model for the observed data and classifying the ore types.

II. General geology

The Pre-Cambrian rocks around Nishikhal are comprising metasedimentary sequences of khondalites, calc-granulites, quartzites and

manganiferous quartzites. They form a more or less banded assemblage, metamorphosed under granulite facies condition, and are very often intruded by quartz-feldspar neosomes and pegmatitic veins. The rock-types strike in the NNE-SSW direction with a dip varying between 70° and 85° towards east, but it is observed that there is reversal of dip towards west at a few places. Presence of open, tight and warp folds has also been noticed in the area.

Manganese ore bodies occur as bands running parallel to the foliation of khondalites and quartzites. The bands extend for more than 2 kms and persist up to 100 meters depth, exhibiting intermittent pinch and swell structures. Near the surface grade of the ore remains almost same but towards higher depths it gradually becomes more ferruginous, and highly ferruginous ores are encountered below a depth of 60 m (Chowdhury, 1978). Intercalations of pegmatite veins and quartz-orthoclase neosomes are observed within the manganese ore body. Occasionally fresh chert is found preserved interbedded with manganese ore.

Fig. 1. Geological map of the Nishikhal manganese deposit. In set, an index map of the deposit in India (after Acharya *et al.*, 1990)

Small veins and pockets of manganese are commonly found occurring in the khondalites.

III. Mineralogy

Important ore minerals in the Nishikhal manganese deposit are cryptomelane, psilomelane and pyrolusite with minor amounts of hausmannite, jacobsonite, braunite, bixbyite, hollandite, spessartite and wad. Birnessite, lithiophorite and pyrophanite (Rao *et al.*, 1994) are occasionally found to occur in the ore deposit. Goethite, hematite and limonite are very often intimately associated with the manganese minerals, out of which goethite is the most abundant. Traces of sulphides such as pyrite and chalcocopyrite are also found. The main gangue minerals consist of quartz, orthoclase, calcite, apatite, kaolinite and garnet with subordinate amounts of biotite, muscovite and zircon.

1. Primary manganese ore minerals

Hausmannite forms coarse grained aggregate, subhedral to tabular, exhibiting some-

times mosaic texture. Irregular twinning is commonly observed, twin lamellae often intersecting each other and of unequal width and hardness (the VHN varies between 495 and 685). It shows bluish to brown grey colour in reflected light, distinct birefractance is observed in oil, strong anisotropism with yellowish to bluish grey colours and blood-red internal reflections are common especially in oil immersion.

Jacobsonite forms polygonal grains and sometimes rounded idiomorphic crystals are observed, colour varies from rose brown to brownish grey, isotropic in nature with deep-red internal reflections. Both hausmannite and jacobsonite alter to secondary manganese and iron minerals such as goethite, pyrolusite and hematite.

Braunite, grey in colour with slight brownish tint, weak birefractance in shades of dark grey, undulatory extinction being common, is found to occur as isolated grains and also in combination with other primary minerals like bixbyite, spessartite, etc. surrounded by secondary manganese minerals.

Bixbyite occurs as idiomorphic crystals, characterised by grey colour with a distinct creamy or yellow tint, isotropic in nature without internal reflections, and usually surrounded by pyrolusite, goethite, cryptomelane etc.

Hollandite forms fibrous aggregates of needle-like crystals, sometimes twinning is clearly seen similar to that of hausmannite. Under crossed nicols an extremely fine lattice-like intersecting lamellar texture is visible.

2. Secondary manganese ore minerals

Among the secondary manganese minerals, cryptomelane is the most abundant one which usually forms very fine-grained masses and less commonly botryoidal masses, and also as colloform layers concentric with layers of pyrolusite. In reflecting light its colour varies from grey-white to bluish grey-white. It has distinct bireflectance and fairly strong anisotropism in shades of grey.

Psilomelane forms finely crystalline aggregates and commonly botryoidal masses consisting of concentric layers which may also contain pyrolusite or cryptomelane. It is bluish grey to greyish white in colour, has strong bireflectance and anisotropism, and sometimes exhibit brown internal reflections.

Pyrolusite is white in colour under reflected light and has a distinctly creamy tint. It is the brightest of all manganese minerals, and has distinct bireflectance and very strong anisotropism. It commonly occurs as coarse-grained euhedral tabular to prismatic crystals. It also occurs as fine grained intersecting prisms, massive or as radiating needle-shaped crystals. Banded texture is very common. Sometimes it exhibits parting planes and also zoning. Replacement of cryptomelane and psilomelane by pyrolusite is very common. Pyrolusite is present as cavity fillings, interstitial fillings, veins, oolites or in accicular manner. Sometimes thin veins of pyrolusite are found to intersect each other indicating

different stages of their formations.

Lithiophorite occurs as fine-grained aggregates replacing cryptomelane and pyrolusite, and sometimes enclose quartz, orthoclase and garnet.

Birnessite is found as patches in the oxide and hydroxide manganese-iron minerals and also as rims around gangue minerals (Acharya *et al*, 1990).

3. Iron minerals

Goethite, limonite and hematite are the main iron bearing minerals out of which former is the most predominant one which occurs mainly as fine drop-like, irregular, myrmecitic, oolitic and pisolitic form within secondary manganese minerals. These iron minerals may be the products of weathering of primary manganese ores and a part of them may be the derivatives from weathered country rocks.

4. Gangue minerals

Quartz is the most abundant gangue mineral. Occasionally primary bandings of quartz are found preserved in the manganese ore which indicates rhythmic precipitation of silica and manganese ore at the time of deposition. Manganese ores have been intruded by pegmatitic veins which contribute quartz, orthoclase, garnet and apatite to the ore. Secondary quartz is found in plenty with the siliceous ores. In addition to the primary apatite, secondary microcrystalline apatites occur in the weathered ores also. Small flakes of graphite are found both in the manganese ore and in the associated country rock. Recent mining activity has exposed patchy occurrences of carbonaceous manganese ore at lower horizons. Secondary manganese ores are commonly found to occur along the cleavage and kink planes of graphite indicating the formation of graphite earlier.

5. Paragenesis

Basing on the textural evidences of the mineral phases, the paragenetic sequence

Table 1. Paragenetic sequence of mineral phases at Nishikhal

MINERALS	TIME ----->		
	Metamorphism	Granitisation	Alteration
Jacobsite	-----		
Hausmannite	-----		
Braunite	-----		
Bixbyite	-----		
Hollandite	-----		
Spessartite	-----		
Pyrophanite	-----		
Psilomelane			-----
Cryptomelane			-----
Pyrolusite			-----
Birnessite			-----
Lithiophorite			-----
Wad			-----
Goethite			-----
Hematite			-----
Limonite			-----
Quartz	-----		-----
Orthoclase	-----	-----	
Apatite		-----	-----
Graphite	-----	-----	
Pyrope/Almandine		-----	
Kaolinite			-----
Calcite		-----	-----

(modified after Acharya *et al*, 1990) has been given in Table 1.

6. Mineral composition of ore samples

Polished sections of individual ore samples were studied for a clear understanding of the relative order of abundance of major and minor minerals present in each of them. The details of this study are given in Table 2.

IV. Theory of factor analysis

Factor analysis is a very useful tool in multivariate statistical analysis which can be applied to discover and interpret relations among the variables (samples) or to test hypothesis (Ratha and Sahu, 1993). The general purpose of factor analysis is to find a way of condensing the information contained in a number of original variables into a smaller set of new composite dimensions with a minimum loss of information. The factor analysis is of two types; (a) R-mode and (b) Q-mode, out of which the former extracts relationships among the variables while the latter extracts clusters or groups of samples.

Table 2. Composition of major and minor minerals in individual ore samples

Sample Sl. No.	Minerals
1-5	cry, pyr, psi, goe, hem & cht.
6-12	cry, pyr, psi, goe, ort, cht, qtz, hem & cly.
13-15	cry, pyr, psi, goe, hem, cht & gpt.
16-17	cry, pyr, psi, goe, hem, qtz, cht & gpt.
18-20	cry, qtz, pyr, psi, goe, hem, ort, gnt & apt.
21-22	cry, pyr, psi, goe, hem & cht.
23-27	qtz, cry, pyr, cht, ort, gnt & apt.
28	hem, goe, pyr, cry & cht.
29-31	cry, pyr, psi, goe, ort, cht, qtz, hem & cly.
32-35	cry, qtz, pyr, goe, cal, cly, hem, ort, plg & apt.
36	cry, psi, pyr, goe & hem.
37-41	pyr, cry & psi.
42-47	cry, psi & pyr

Note: pyr, pyrolusite; cry, cryptomelane; psi, psilomelane; goe, goethite; hem, hematite; cht, chert; qtz, quartz; ort, orthoclase; plg, plagioclase; gnt, garnet; gpt, graphite; cal, calcite; cly, clay; apt, apatite.
(The table excludes trace minerals).

The basic factor model (Cooley and Lohnes, 1971; Anderson, 1985; Davis, 1986; and Hair *et al*, 1987) is a linear function of m ($< p$) hypothetical variables or common factors, where p is the number of variables used and m is the number of common factors. The general form of the function is,

$$Z_j = a_{j1}f_1 + a_{j2}f_2 + \dots + a_{jm}f_m + d_ju_j$$

where Z_j is variable j in standardised form, f_m is the hypothetical factor, u_j is the unique factor for variable j , a_{j1} is the relative importance of the common factor 1, and d_j is the standardised regression coefficient of variable j on unique factor u_j .

Generally in geological problems m common factors explain sufficient variance (about 70-80%) of p and the rest of the variance may be due to the errors in sampling, analysis and modeling. The different methods used to find out the number of common factors (m) are screen test, minimum variance of cumulative eigen values for a replicate data, maximum likelihood estimation etc. (Sahu, 1973 and 1982).

The rotation of factors is an important

concept in factor analysis which is used to find new directions so that loadings on a few variables tend to 1 and on others tend to 0. This reduces the ambiguities in data interpretation which accompany the initial unrotated factor loadings. Out of the several methods such as varimax, quatrimax etc. available for factor rotations, the former of Kaiser (1958) is the most useful analytic approach (Ratha and Sahu, 1993).

The varimax criterion involves maximization of the variance of the loadings on the factors. The variance s_k of the loadings on the ' k 'th factor may be defined as,

$$s_k^2 = (m \sum_{j=1}^p (1_{jm}^2 / h_j^2) - (\sum_{j=1}^p 1_{jm}^2 / h_j^2)) / m^2$$

where, m is the number of factors, p is the number of original variables, 1_{jm} is the loading of variable j on factor m and h_j is the communality (defined as the sum within each variable of the square of the elements in a factor matrix) of the ' j 'th variable.

The quantity which is to be maximised may be expressed as,

$$V = \sum_{k=1}^m s_k^2$$

Ultimately, factor scores are computed from original data and rotated factor loadings to create a new set of smaller number composite variable to replace the original set of variables. The calculated factor scores are graphically plotted to understand the nature of the variables for a detailed classification of the ore types.

The programme, 'Factor analysis' (Davis, 1986) which includes varimax rotation as a subroutine, written in Fortran, was partially modified by the authors taking into account the recent developments in the theory and used for all the above computations.

V. Geochemistry and R-mode factor analysis

From Nishikhal 47 manganese ore samples

were collected covering all the ore types of the deposit and they were analysed by XRF for their major (MnO_2 , Fe_2O_3 , SiO_2 , Al_2O_3 , P_2O_5 , CaO , MgO , Na_2O , K_2O , TiO_2 , BaO and LOI) and trace (Pb, Cr, Co, Ni, Cu, Zn, Mo, and V) elemental constituents which are given in Table 3 and Table 4, respectively. Some of the analyses were also done and checked by wet chemical and AAS methods.

1. Data normalisation

In geochemical data presentation, the major elements are reported as oxides which add to $100 \pm 0.5\%$ and trace elements are reported in ppm. From statistical point of view major oxides form a closed-table inducing negative correlations which may confound the true geochemistry of these constituents. Each component exhibits a Binomial distribution with mean ' p ' and variance $p(1-p)N$, where N is sample size. Linear correlation between any two components is dangerous because of the closure constraints and non-consistency of variance (depends on p). To eliminate these two influences each component was converted to odds ratio i.e. $p/(1-p)$, which is approximately normal and independent (Sahu, 1982). Thus $\log(c/(1-c))$, where c is the weight fraction of each major component ($0 < c < 1$) in the rock, is used as the normalising transformation.

2. Correlation and R-mode factors

In the present study, to understand the natural processes and possible source for various elemental components, R-mode factor analysis with rotation was applied to the normalised major and trace element data of the manganese ores. A 20×20 correlation matrix from the normalised variables of major and trace element data was computed (Table 5) giving 20 components, contributing 100% of the total variance. Based on the point of inflection or minima point of cumulative eigen value (Sahu, 1973), 3 common factors were retained for subsequent varimax rotation and interpreta-

Table 3. Major elements (in %) of manganese ores, Nishikhal

Serial No.	Sample No.	MnO ₂	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	P ₂ O ₅	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	BaO	LOI
1	N-1/1	63.07	21.39	0.73	0.81	1.11	0.39	0.100	0.258	2.03	0.063	0.176	10.11
2	N-1/2	65.77	18.31	0.54	0.81	1.01	0.41	0.095	0.258	2.23	0.057	0.171	10.22
3	N-1/3	56.69	25.77	0.62	0.71	1.37	0.34	0.090	0.246	1.72	0.074	0.169	12.25
4	N-1/4	58.31	27.18	0.46	0.59	1.44	0.22	0.100	0.219	0.46	0.076	0.150	10.66
5	N-1/5	60.99	26.41	0.42	0.64	1.31	0.23	0.090	0.246	0.41	0.101	0.168	9.13
6	N-2/1	57.89	16.74	5.39	4.31	1.04	0.41	0.105	0.237	2.46	0.180	0.156	10.85
7	N-2/2	57.56	20.58	3.49	2.95	1.17	0.38	0.095	0.249	2.58	0.181	0.161	10.45
8	N-2/3	61.85	14.56	3.85	4.42	1.09	0.41	0.095	0.246	2.64	0.225	0.166	10.49
9	N-2/4	58.78	19.81	2.98	3.29	1.12	0.39	0.100	0.243	2.53	0.147	0.167	10.24
10	N-2/5	59.47	19.67	2.95	2.95	1.04	0.41	0.095	0.237	2.46	0.178	0.172	10.58
11	N-2/6	61.32	16.56	3.23	3.11	1.01	0.42	0.095	0.243	2.61	0.219	0.165	11.05
12	N-2/7	59.11	19.72	3.43	3.08	1.09	0.41	0.100	0.237	2.52	0.184	0.171	10.09
13	N-3/1	63.86	23.41	0.47	0.59	1.06	0.26	0.100	0.255	0.37	0.054	0.169	9.78
14	N-3/2	67.65	19.61	0.38	0.49	1.03	0.25	0.095	0.252	1.38	0.056	0.175	8.13
15	N-3/3	59.94	25.35	0.34	0.56	1.19	0.25	0.090	0.243	0.37	0.058	0.189	11.28
16	N-3/4	56.92	26.28	2.26	0.71	1.29	0.26	0.095	0.228	0.58	0.078	0.164	10.97
17	N-3/5	63.66	19.64	1.44	0.62	1.16	0.28	0.090	0.231	1.55	0.067	0.184	10.43
18	N-4/1	45.81	11.94	32.11	1.13	0.96	0.24	0.080	0.213	2.01	0.069	0.107	5.09
19	N-4/2	53.46	15.12	17.93	1.39	1.09	0.32	0.095	0.231	2.49	0.077	0.117	7.44
20	N-4/3	49.25	13.78	26.86	1.27	0.96	0.28	0.090	0.225	2.29	0.074	0.113	5.28
21	N-5/1	69.51	12.75	0.46	0.98	0.97	0.35	0.100	0.252	2.96	0.065	0.188	10.87
22	N-5/2	68.55	14.49	0.41	0.68	0.91	0.39	0.105	0.246	3.05	0.052	0.173	11.34
23	N-6/1	51.97	0.81	33.48	3.31	0.62	0.19	0.080	0.159	0.24	0.189	0.090	8.89
24	N-6/2	50.38	0.51	30.55	10.21	0.52	0.25	0.075	0.171	1.21	0.331	0.089	5.65
25	N-6/3	44.69	1.16	45.08	3.38	0.45	0.25	0.070	0.162	0.37	0.199	0.088	4.12
26	N-6/4	52.76	0.36	37.31	3.59	0.61	0.22	0.070	0.174	0.36	0.216	0.096	4.42
27	N-6/5	40.77	0.31	36.71	14.61	0.51	0.31	0.070	0.168	1.61	0.417	0.084	4.61
28	N-8/1	7.13	71.89	2.13	1.91	1.91	0.87	0.095	0.228	0.09	0.129	0.123	13.22
29	N-10/1	68.64	16.19	2.14	3.28	0.91	0.66	0.105	0.276	2.26	0.187	0.119	5.34
30	N-11/1	70.21	14.15	2.16	2.23	0.82	0.51	0.110	0.279	2.89	0.149	0.117	6.34
31	N-11/2	66.67	18.14	2.58	2.31	0.92	0.49	0.100	0.267	2.71	0.142	0.121	5.53
32	N-16/1	38.85	9.95	25.46	10.81	0.71	4.31	0.135	0.429	5.07	0.302	0.203	4.11
33	N-16/2	48.94	4.77	21.58	6.81	0.42	9.77	0.150	0.363	3.04	0.229	0.331	3.87
34	N-16/3	41.45	7.32	24.13	9.23	0.63	6.36	0.140	0.408	4.43	0.287	0.266	5.55
35	N-16/4	45.32	5.89	22.76	7.86	0.54	8.22	0.145	0.387	3.87	0.248	0.315	4.77
36	N-17/1	72.33	8.52	0.42	1.93	0.83	0.31	0.100	0.276	3.47	0.049	0.202	10.81
37	N-17/2	85.72	0.35	0.47	0.43	0.29	0.52	0.140	0.303	4.57	0.045	0.141	7.32
38	N-17/3	86.83	0.35	0.39	0.48	0.26	0.41	0.110	0.288	4.52	0.047	0.149	6.43
39	N-17/4	81.01	0.28	0.47	4.17	0.63	0.27	0.105	0.270	3.78	0.049	0.182	8.87
40	N-17/5	85.99	0.31	0.31	0.41	0.31	0.93	0.110	0.303	4.04	0.048	0.153	7.33
41	N-17/6	83.55	0.29	0.39	2.17	0.48	0.67	0.105	0.285	3.97	0.049	0.168	8.07
42	N-18/1	87.76	1.52	0.46	0.87	0.55	0.39	0.100	0.261	2.51	0.048	0.122	5.56
43	N-18/2	86.79	1.13	0.51	0.63	0.47	0.48	0.115	0.279	3.12	0.048	0.118	6.41
44	N-18/3	86.62	0.96	0.46	1.61	0.67	0.41	0.105	0.264	3.27	0.046	0.121	5.71
45	N-18/4	93.05	0.54	0.31	0.24	0.44	0.42	0.100	0.258	1.84	0.050	0.126	2.95
46	N-18/5	89.34	1.11	0.32	0.55	0.41	0.44	0.105	0.258	2.67	0.046	0.123	4.67
47	N-18/6	91.33	0.89	0.32	0.42	0.42	0.44	0.105	0.261	2.33	0.047	0.124	3.54

tion for geochemical data on major and trace elements. The factor loadings, along with percent of trace, total percent of trace and eigen values are presented in Table 6. Again, the factor scores were computed from the original raw data measurements and the rotated factor loadings, so as to create an entirely new set of variables. The calculated factor scores (Table 7) have been plotted against each other in Figs. 2, 3 and 4 to understand the

compositional distribution and classification patterns of ore types.

3. Factor-1

The first rotated factor explaining 33.39% of the total variance is strongly loaded on CaO(+ve), MgO(+ve), Na₂O(+ve), K₂O(+ve), BaO(+ve), Cr(+ve), Co(+ve), Ni(+ve), Cu(+ve), Zn(+ve) and V(+ve). This factor may be interpreted as the formation of gangue minerals like garnet, feldspar, calcite, biotite and mus-

Table 4. Trace elements (in ppm) of manganese ores, Nishikhal

Serial No.	Sample No.	Pb	Cr	Co	Ni	Cu	Zn	Mo	V
1	N-1/1	20	115	159	57	137	74	34	85
2	N-1/2	20	107	142	60	135	73	34	84
3	N-1/3	24	99	191	61	141	77	33	84
4	N-1/4	23	99	194	61	136	74	31	89
5	N-1/5	23	98	178	62	135	74	33	92
6	N-2/1	21	87	144	62	148	82	36	83
7	N-2/2	21	92	159	63	145	80	32	86
8	N-2/3	20	82	130	66	147	82	34	86
9	N-2/4	20	84	152	62	152	82	35	81
10	N-2/5	20	88	151	63	150	80	32	84
11	N-2/6	20	83	133	64	147	81	34	85
12	N-2/7	21	91	148	63	148	80	32	84
13	N-3/1	21	95	160	68	134	79	30	88
14	N-3/2	19	92	146	61	136	77	31	86
15	N-3/3	24	93	177	64	137	77	32	91
16	N-3/4	22	93	185	66	143	80	30	90
17	N-3/5	20	94	155	61	139	80	29	87
18	N-4/1	21	77	155	57	168	67	39	68
19	N-4/2	20	80	173	58	161	68	35	79
20	N-4/3	21	79	162	58	165	68	37	74
21	N-5/1	18	86	136	56	142	90	32	92
22	N-5/2	20	91	160	57	140	97	33	94
23	N-6/1	27	70	61	58	148	78	51	62
24	N-6/2	26	73	66	58	158	71	49	66
25	N-6/3	29	69	69	56	159	82	51	59
26	N-6/4	22	69	59	54	147	73	50	57
27	N-6/5	27	68	64	56	153	67	56	68
28	N-8/1	77	123	625	79	143	89	36	85
29	N-10/1	19	90	143	117	139	112	36	90
30	N-11/1	29	139	258	177	190	195	58	122
31	N-11/2	30	137	296	217	189	208	54	123
32	N-16/1	36	94	183	163	204	108	88	111
33	N-16/2	34	91	140	112	210	109	87	136
34	N-16/3	35	93	170	149	206	108	88	121
35	N-16/4	34	91	154	127	209	109	87	128
36	N-17/1	19	88	347	72	234	102	33	101
37	N-17/2	16	87	92	63	142	115	32	70
38	N-17/3	17	93	134	64	144	84	32	81
39	N-17/4	17	84	419	144	305	114	35	125
40	N-17/5	16	84	65	64	141	84	31	87
41	N-17/6	16	85	176	92	226	103	33	106
42	N-18/1	16	112	62	56	141	71	30	80
43	N-18/2	16	114	61	54	139	69	32	77
44	N-18/3	16	98	61	55	148	79	32	78
45	N-18/4	16	126	62	51	125	60	32	71
46	N-18/5	17	113	61	53	140	64	31	73
47	N-18/6	17	118	62	52	131	61	32	73

covite by metamorphism and granitisation processes and localised secondary accumulations of calcium oxide and calcium carbonate in the manganese ore giving rise to calcareous manganese ores. Trace elements like Cr, Cu, Zn and V may be occurring mainly in the structure of the gangue minerals while Ba, Co and Ni may be absorbed/adsorbed in the calcareous manganese matrix.

4. Factor-2

The second rotated factor, contributing 23.11% of total variance shows strong loadings on MnO_2 (+ve), SiO_2 (-ve), Al_2O_3 (-ve), TiO_2 (-ve), Pb(-ve), Cr(+ve), Cu(-ve) and Mo(-ve). This factor may be interpreted as the formation of primary manganese minerals such as braunite, bixbyite, spessartite, hausmannite, jacobsonite and pyrophanite by the metamorphism of original manganeseiferous sediments. Quartz, chert and clay minerals may be associated with the original sediments. The strong loadings on MnO_2 - SiO_2 - Al_2O_3 - TiO_2 are suggestive of their derivation from a continental source (Nicholson, 1992; Roy, 1992). Positive loading on MnO_2 against the negative loading on SiO_2 indicates that at the time of precipitation of manganese in the basin silica was remaining in solution and vice versa, which also explains the rhythmic banding of chert and manganese ore (Hem, 1972; Grill, 1982). Cr may occur in the

Table 5. Correlation coefficients for the normalised geochemical data

	MnO ₂	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	P ₂ O ₅	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	BaO	LOI	Pb	Cr	Co	Ni	Cu	Zn	Mo	V
MnO ₂	1.00																			
Fe ₂ O ₃	-0.55	1.00																		
SiO ₂	-0.65	-0.03	1.00																	
Al ₂ O ₃	-0.55	-0.05	0.75	1.00																
P ₂ O ₅	-0.55	0.90	-0.02	-0.01	1.00															
CaO	-0.19	0.01	0.26	0.43	-0.28	1.00														
MgO	0.23	0.02	-0.24	-0.01	-0.28	0.78	1.00													
Na ₂ O	0.21	0.08	-0.25	0.01	-0.20	0.78	0.93	1.00												
K ₂ O	0.49	-0.26	-0.13	0.11	-0.40	0.40	0.57	0.61	1.00											
TiO ₂	-0.65	0.13	0.79	0.87	0.12	0.36	-0.11	-0.12	-0.11	1.00										
BaO	-0.06	0.35	-0.20	0.06	0.15	0.62	0.69	0.74	0.34	-0.01	1.00									
LOI	-0.24	0.58	-0.36	-0.18	0.67	-0.35	-0.12	-0.15	-0.22	-0.16	0.27	1.00								
Pb	-0.85	0.40	0.53	0.50	0.30	0.45	0.04	0.04	-0.44	-0.60	0.10	-0.01	1.00							
Cr	0.29	0.27	-0.56	-0.43	0.11	0.16	0.40	0.43	0.10	-0.36	0.15	-0.03	0.07	1.00						
Co	-0.46	0.64	-0.10	0.10	0.61	0.12	0.20	0.28	-0.06	0.01	0.44	0.52	0.44	0.24	1.00					
Ni	-0.19	0.12	0.18	0.47	-0.01	0.59	0.51	0.58	0.28	0.34	0.36	-0.18	0.45	0.28	0.54	1.00				
Cu	-0.13	-0.18	0.28	0.56	-0.17	0.44	0.33	0.38	0.37	0.20	0.34	-0.17	0.23	-0.14	0.45	0.70	1.00			
Zn	-0.09	0.11	0.03	0.31	-0.03	0.40	0.45	0.45	0.28	0.21	0.27	0.00	0.32	0.27	0.51	0.87	0.58	1.00		
Mo	-0.45	-0.10	0.71	0.72	-0.24	0.72	0.29	0.31	0.11	0.69	0.20	-0.51	0.64	-0.13	0.03	0.63	0.54	0.45	1.00	
V	-0.07	0.31	-0.16	0.23	0.14	0.62	0.68	0.75	0.38	0.07	0.75	0.12	0.27	0.38	0.64	0.81	0.63	0.71	0.38	1.00

Table 6. Rotated factor matrix for Nishikhal manganese ores.

Elements	Factor-1	Factor-2	Factor-3	Communality
MnO ₂	0.087	0.747*	0.595*	0.918
Fe ₂ O ₃	0.115	-0.022	-0.901*	0.825
SiO ₂	-0.161	-0.921*	0.120	0.888
Al ₂ O ₃	0.185	-0.876*	0.067	0.805
P ₂ O ₅	-0.131	-0.032	-0.928*	0.879
CaO	0.773*	-0.376	0.191	0.774
MgO	0.875*	0.163	0.154	0.816
Na ₂ O	0.919*	0.162	0.107	0.881
K ₂ O	0.576*	0.202	0.465*	0.589
TiO ₂	0.011	-0.892*	-0.053	0.799
BaO	0.736*	0.094	-0.256	0.616
LOI	-0.088	0.283	-0.764*	0.671
Pb	0.186	-0.721*	-0.432*	0.741
Cr	0.429*	0.461*	-0.197	0.434
Co	0.468*	-0.069	-0.761*	0.803
Ni	0.795*	-0.389	-0.087	0.791
Cu	0.611*	-0.406*	0.112	0.549
Zn	0.703*	-0.231	-0.122	0.562
Mo	0.435	-0.814*	0.223	0.902
V	0.914*	-0.053	-0.265	0.909
Eigen values	6.678	4.623	3.857	
% of trace	33.388	23.115	19.283	
Cumulative % of trace	33.388	56.503	75.786	

* Indicates a significant value.

structure of manganese minerals while Pb, Cu and Mo may substitute broken bonds of SiO₄-tetrahedra in clays. This factor may also be interpreted as the formation of secondary siliceous manganese ores by removal of manganese from and addition of silica to the primary manganese ores through erosional and depositional processes. Clays may also be the products of secondary processes.

5. Factor-3

The third rotated factor contributes 19.28% of the total variance and is strongly loaded on MnO₂(+ve), Fe₂O₃(-ve), P₂O₅(-ve), K₂O(+ve), Pb(-ve) and Co(-ve). This is a secondary process factor indicating general chemical weathering and lateritization giving rise to mainly cryptomelane, psilomelane, pyrolusite, goethite, limonite, hematite etc. from the primary manganese and iron minerals. K₂O mainly occurs in the structure of cryptomelane and psilomelane while P₂O₅, Pb and Co may dominantly be adsorbed in goethitic and limonitic matrix.

Table 7. Varimax factor scores for 3 retained factors.

Sample Sl. No.	Factor-1	Factor-2	Factor-3
1	-8.53	4.01	3.61
2	-8.52	4.05	3.66
3	-8.55	3.99	3.49
4	-8.63	4.02	3.41
5	-8.63	3.99	3.44
6	-8.58	3.59	3.72
7	-8.57	3.67	3.65
8	-8.57	3.61	3.75
9	-8.57	3.69	3.68
10	-8.57	3.69	3.68
11	-8.57	3.66	3.72
12	-8.57	3.67	3.68
13	-8.61	4.05	3.49
14	-8.56	4.12	3.62
15	-8.61	4.06	3.42
16	-8.64	3.86	3.47
17	-8.59	3.97	3.60
18	-8.74	3.51	3.82
19	-8.66	3.61	3.75
20	-8.69	3.54	3.81
21	-8.50	4.06	3.72
22	-8.48	4.10	3.69
23	-8.92	3.27	4.08
24	-8.83	3.16	4.28
25	-8.90	3.18	4.16
26	-8.92	3.24	4.27
27	-8.84	3.04	4.37
28	-8.65	3.44	2.84
29	-8.48	3.67	3.82
30	-8.35	3.69	3.76
31	-8.35	3.65	3.70
32	-8.28	3.11	3.98
33	-8.23	3.19	4.14
34	-8.25	3.14	4.01
35	-8.24	3.17	4.07
36	-8.40	4.03	3.73
37	-8.44	4.18	4.40
38	-8.45	4.19	4.37
39	-8.35	3.95	4.16
40	-8.43	4.20	4.42
41	-8.37	4.02	4.29
42	-8.54	4.14	4.21
43	-8.52	4.15	4.26
44	-8.53	4.08	4.26
45	-8.56	4.28	4.40
46	-8.53	4.20	4.30
47	-8.54	4.23	4.34

VI. Classification of manganese ore types

This classification is based on the varimax factor score plots, taking 2 factors at a time. Total 3 plots are made taking scores of the factors 1 and 2 (Fig. 2), 2 and 3 (Fig. 3), and 3 and 1 (Fig. 4). Since factors 1, 2 and 3 are dominantly Ca-Mg-Na-K, Mn-Si-Al-Ti and Mn-Fe-P factors, the plots group the samples in terms of relative scores of the grouped elements. Thus, for all the samples, in Fig. 2 four groups are identified such as: (1) low silica Mn-ore, (2) moderate to high silica Mn-ore, (3) fresh

Fig. 2. Plot of factor scores, factor-1 vs factor-2. The figures near a group are serial numbers of samples falling in the group.

Fig. 4. Plot of factor scores, factor-3 vs factor-1. The figures near a group are serial numbers of samples falling in the group.

Fig. 3. Plot of factor scores, factor-2 vs factor-3. The figures near a group are serial numbers of samples falling in the group.

siliceous (high silica) Mn-ore, and (4) calc-siliceous (high silica) Mn-ore. In Fig. 3 total five groups are identified such as: (1) high silica and low iron Mn-ore, (2) low to moderate silica and moderate iron Mn-ore, (3) weathered high iron Mn-ore, (4) fresh Mn-ore (low silica and low iron), and (5) manganiferous iron ore. In Fig. 4 total seven groups are identified such as: (1) fresh Mn-ore, very low iron, $\text{Fe}_2\text{O}_3 < 0.5\%$ (type-A), (2) fresh Mn-ore, low iron, Fe_2O_3 between 0.5-2.0% (type-B), (3) weathered ferrous Mn-ore (type-C), (4) fresh siliceous Mn-ore (type-D), (5) weathered calc-siliceous Mn-ore (type-E), (6) weathered ferro-siliceous Mn-ore (type-F), and (7) weathered manganiferous iron ore (type-G). Thus out of all the three plots, factor 3 vs 1 is found to be the best to distinguish the ore types of Nishikhal deposit. (It is noteworthy to mention here that some of the samples in type-C i.e. weathered ferruginous Mn-ore (sample serial no.13-17) contain carbonaceous material/graphite in

appreciable quantities. This type may be termed weathered carbo-ferruginous Mn-ore (type-H). Since quantification of total carbon has not been studied, factor analysis does not incorporate this type).

VII. Conclusions

Basing on mineralogical, geochemical and R-mode factor analysis the following conclusions are brought out in regard to the Nishikhal manganese ore deposit :

1. The deposit consists mainly primary manganese minerals of hausmannite, jacobsonite, braunite, bixbyite, hollandite, spessartite and pyrophanite, and secondary manganese minerals of cryptomelane, psilomelane, pyrolusite, birnessite, lithiophorite and wad. The secondary minerals constitute about 99% of the total ore.

2. The iron minerals are of secondary in nature consisting of goethite, limonite and hematite, while gangue minerals are chert/quartz, orthoclase, apatite, graphite, calcite, pyrope and almandine, out of which majority of the quartz is of secondary nature.

3. The first rotated factor is interpreted as the formation of Ca, Mg, Na and K bearing gangue minerals by metamorphism and granitisation, and calcareous Mn-ores by localised accumulations of calcareous material in the ores.

4. The second rotated factor represents the formation of primary manganese ore minerals, and also chert/quartz giving rise to fresh manganese ores and fresh siliceous manganese ores. It also suggests the formation of siliceous Mn-ores due to the deposition of quartz in the original Mn-ores by the action of meteoric water.

5. The third factor explains the formation of secondary manganese and iron minerals by chemical weathering and lateritization processes.

6. Nishikhal manganese ores can be

classified into the following types (major minerals for each type are shown within the brackets in decreasing order of abundance) : (1) fresh Mn-ore, very low iron, $\text{Fe}_2\text{O}_3 < 0.5\%$ (pyrolusite, cryptomelane and psilomelane), (2) fresh Mn-ore, low iron, $\text{Fe}_2\text{O}_3 : 0.5-2.0\%$ (cryptomelane, psilomelane and pyrolusite), (3) weathered ferruginous Mn-ore (cryptomelane, pyrolusite and goethite), (4) weathered carbo-ferruginous Mn-ore (cryptomelane, pyrolusite, goethite and graphite), (5) fresh siliceous Mn-ore (quartz, cryptomelane, pyrolusite and chert), (6) weathered calc-siliceous Mn-ore (cryptomelane, quartz, goethite and calcite), (7) weathered ferro-siliceous Mn-ore (cryptomelane, quartz, pyrolusite and goethite), and (8) weathered manganiferous iron ore (hematite, goethite and pyrolusite).

Acknowledgements : The authors thank the authorities of Orissa Mining Corporation, Bhubaneswar, for giving permission to collect samples from the Nishikhal mine. The grant received from the Department of Science and Technology, Govt. of India, under project SR/OY/A-15/92 to BKN is gratefully acknowledged. We thank Dr. B.C. Acharya and Mr. D.S. Rao of RRL for their help during the work. Lastly, we thank the two unknown reviewers of the journal for their constructive comments. This article is published with the permission from the Director, RRL, Bhubaneswar.

References

- Acharya, B.C., Rao, D.S. and Sahoo, R.K. (1990), Nishikhal manganese deposit, Koraput district, Orissa. *J. Geol. Soc. India*, **36**, 644-653.
- Ajmal, M., Ghauri, K.K. and Rao L.A.K. (1982), Distribution of major oxides in manganese ores of Nishikhal area, Koraput district, Orissa. *Quart. J. Geol. Min. Met. Soc. India*, **54**, 64-69.
- Anderson, T.W. (1985), Introduction to multivariate statistical analysis. 2nd ed., Wiley, New York, 675 p.

- Chowdhury, B.C. (1978), Nishikhal manganese deposits. Unpublished report, Geological Survey of India.
- Cooley, W.W. and Lohnes, P.R. (1971), Multivariate data analysis. Wiley, New York, 365 p.
- Davis, J.C. (1986), Statistics and data analysis in Geology. 2nd Ed., John Wiley and Sons, Inc., New York, 550 p.
- Grill, E.V. (1982), Kinetic and thermodynamic factors controlling manganese concentration in anoxic waters. *Geochim. Cosmochim. Acta*, **46**, 233-240.
- Hair, J.F.Jr., Anderson, R.R. and Tatham, R.L. (1987), Multi variate data analysis, 2nd Ed., MacMillan, New York, 449 p.
- Hem, J.D. (1972), Chemical factors that influence the availability of iron and manganese in aqueous systems. *Geol. Soc. Amer. Bull.*, **83**, 443-450.
- Kaiser, H.F. (1958), The varimax criteria for analytic rotation in factor analysis. *Psychometrika*, **23**, 187-200.
- Nicholson, K., (1992), Contrasting mineralogical-geochemical signatures of manganese oxides: guides to metallogenesis. *Econ. Geol.*, **87**, 1253-1264.
- Rao, D.S., Acharya, B.C. and Sahoo, R.K. (1994), Pyrophanite from Nishikhal manganese deposit, Orissa. *J. Geol. Soc. India*, **44**, 91-93.
- Ratha, D.S. and Sahu, B.K. (1993), Source and distribution of metals in urban soil of Bombay, India, using multivariate statistical techniques. *Environmental Geology*, **22**, 276-285.
- Roy, S. (1981), Manganese deposits: London, Academic Press, 458 p.
- Roy, S. (1992), Environments and processes of manganese deposition. *Econ. Geol.*, **87**, 1218-1236.
- Sahu, B.K. (1973), Factor analysis of sphericity and roundness of quartz grains for modern sediments. *Bull. Int. Geol. Asson.*, Chandigarh, **6**, 3-11.
- Sahu, B.K. (1982), Stochastic modelling of mineral deposits. *Mineralium Deposita*, **17**, 97-103.