Characteristics of Cr-Spinel and Whole Rock Geochemistry of the Nuasahi Igneous Complex, Orissa, India

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The Precambrian Nuasahi Igneous Complex (NIC) is located in the southern part of the Singhbhum North Orissa Province in Eastern India and contains one of the largest and richest chromite deposits in India. The NIC occurs in a terrain of the Archaean Iron Ore Group (IOG) of rocks of 3.1-3.3Ga age. The NIC consists of three principal components (1) chromiferous ultramfic rocks with four chromitite lodes; (2) massive gabbroic rocks with titaniferous magnetite bands; (3) later intrusives of diabases and pyroxenite (Fig.1). The field relations of these three components define the following stratigraphic sequence:

Laterite	
Ultramafic-mafic complex	(3) Dykes and sills of diabase and pyroxenite (2) Gabbroic rocks with titaniferous magnetite bands (1) Chromiferous ultramafic rocks – interlayered sequence of enstatitite, olivine-orthopyroxenite/harzburgite, dunite, orthopyroxenite and chromitite
Iron Ore Group of Rocks – mainly quartzite and phyllite	

The ultramafic component (0.3-0.4km wide, ~5km long) consists of elongated bodies of enstatitite, olivine-orthopyroxenite/harzburgite, dunite, and chromitite trending NNW-SSE. The gabbroic component is present both to the west and east of the ultramafic bodies, with an intrusive contact with ultramafic bodies along the eastern side. Recent studies (Nanda et al., 1996; Mondal and Baidya, 1997; Auge′ et al., 1999; Mondal et al., 2001) show the occurrence of platinum-group elements (PGE), Au, and Ag mineralization, closely associated with sulfides in a breccia zone at the interface between the ultramafic and gabbroic rocks along the eastern portion of the complex (Fig.1). Ore-grade Cr-spinels are present as lodes in the ultramafic bodies including Durga, Laxmi2, Laxmi1 and Shankar lodes. Different types of chromitite are present in these lodes. They are leopard, clot-textured, massive, spotted and schlieren banded chromitites. The Cr-spinel cumulates in the massive chromitite bands (>90-95 modal% Cr-spinel) of the lodes are usually fresh and contain minor interstitial phases such as serpentine, chlorite, talc, magnesite and sulfides. Disseminated Cr-spinels occur as both cumulus and intercumulus phase in ultramafic cumulates and are commonly altered to ferritchromite/magnetite, particularly in highly serpentinized rocks. The ferrianchromite grains are irregularly distributed in the sulfide-rich assemblages of the breccia zone and in the matrix of the breccia.

Chemical Composition

The composition of olivine from both dunite and olivine-orthopyroxenite/harzburgite units is similar, with Fo and NiO contents ranging from 92 to 94 and 0.21 to 0.40wt%, respectively. The composition of orthopyroxene from enstatitite and olivine-orthopyroxenite/harzburgite is En ~91-94 and from orthopyroxenite in the middle part of the ultramafic sequence the composition is En ~84-91. The content of CaO in opx from the enstatitite and olivine-orthopyroxenite/harzburgite units ranges from 0.33 to 0.80wt%. The orthopyroxene from the middle orthopyroxenite unit contain slightly higher CaO, ranging from 0.97 to 2.45wt%. The content of NiO in opx from different units ranges from 0.02 to 0.15wt%.

Chromian spinel chemistry. The compositions of Cr-spinel from lode chromitite are characterized by high Cr/(Cr+Al) ratio (~0.81) and high $Mg/(Fe^{2+}+Mg)$ ratio (~0.80). Minor, disseminated Cr-spinel from silicate cumulates shows significant variation in both Cr/(Cr+Al) ratio and $Mg/(Fe^{2+}+Mg)$ ratio (Table1). The strongly depleted character of the enstatitite unit is depicted by the very high Cr/(Cr+Al) ratio (0.86-0.89) and $Mg/(Fe^{2+}+Mg)$ ratio (~0.62) of associated Cr-spinel. In the olivine-orthopyroxenite/harzburgite unit, the Cr/(Cr+Al) ratio (~ 0.80) is similar to that of massive chromitite bands with low $Mg/(Fe^{2+}+Mg)$ ratios (~0.60). In the dunite and middle orthopyroxenite units, the composition of Cr-spinel is characterized by significant enricment in Al and Fe^{2+} .The ferrianchromite in the sulfide-rich assemblage of the breccia zone has high Cr/(Cr+Al) ratios (0.68-0.91) with $Fe^{2+}/(Fe^{2+}+Mg)$

ratios near unity. The minor Cr-spinel in silicate cumulates, generally shows Al-enrichment, whereas those in the sulfide-rich assemblage show Fe^{3+} enrichment.

Primary chromian spinel composition and chromian spinel as a petrogenetic indicator

It has been recognized that the composition of Cr-spinel is strongly related to parameters such as parent magma composition (Irvine, 1965; Thayer, 1970; Roeder, 1994; Barnes and Roeder, 2001), the history of magmatic crystallization, and metamorphic modification. The tectonic setting of a particular chromite deposit may be evaluated by geochemical modeling of the liquidus Cr-spinel composition, which in turn varies with the composition of the parental magma (e.g. Roeder and Reynolds, 1991). In NIC, Cr-spinels from lode chromitite show a refractory composition, whereas silicate cumulates are distinctly different. Mass balance calculations suggest that the primary composition of Cr-spinel has been well preserved in Cr-spinel dominated rocks such as lode chromitites. We have thus selected Cr-spinel from fresh massive chromitite bands of lode chromitite to represent the liquidus Cr-spinel composition. In the trivalent Cr-Al-Fe^{3+} plot (after Jan et al., 1982) and the Fe^{2+}/Mg versus TiO_2 plot (after Dicky, 1975) the NIC liquidus Cr-spinels fall within the residual peridotites/ophiolites or podiform chromitite fields. Table1 summarizes the compositions of chromian spinel from NIC and other deposits with known tectonic settings from the world. The compositions of the liquidus Cr-spinel from the NIC are similar to those from Archaean ultramafic-mafic complexes of greenstone belts (e.g. Seluke, Zimbabwe with very high Cr/Fe_{total} and very low Ti content).

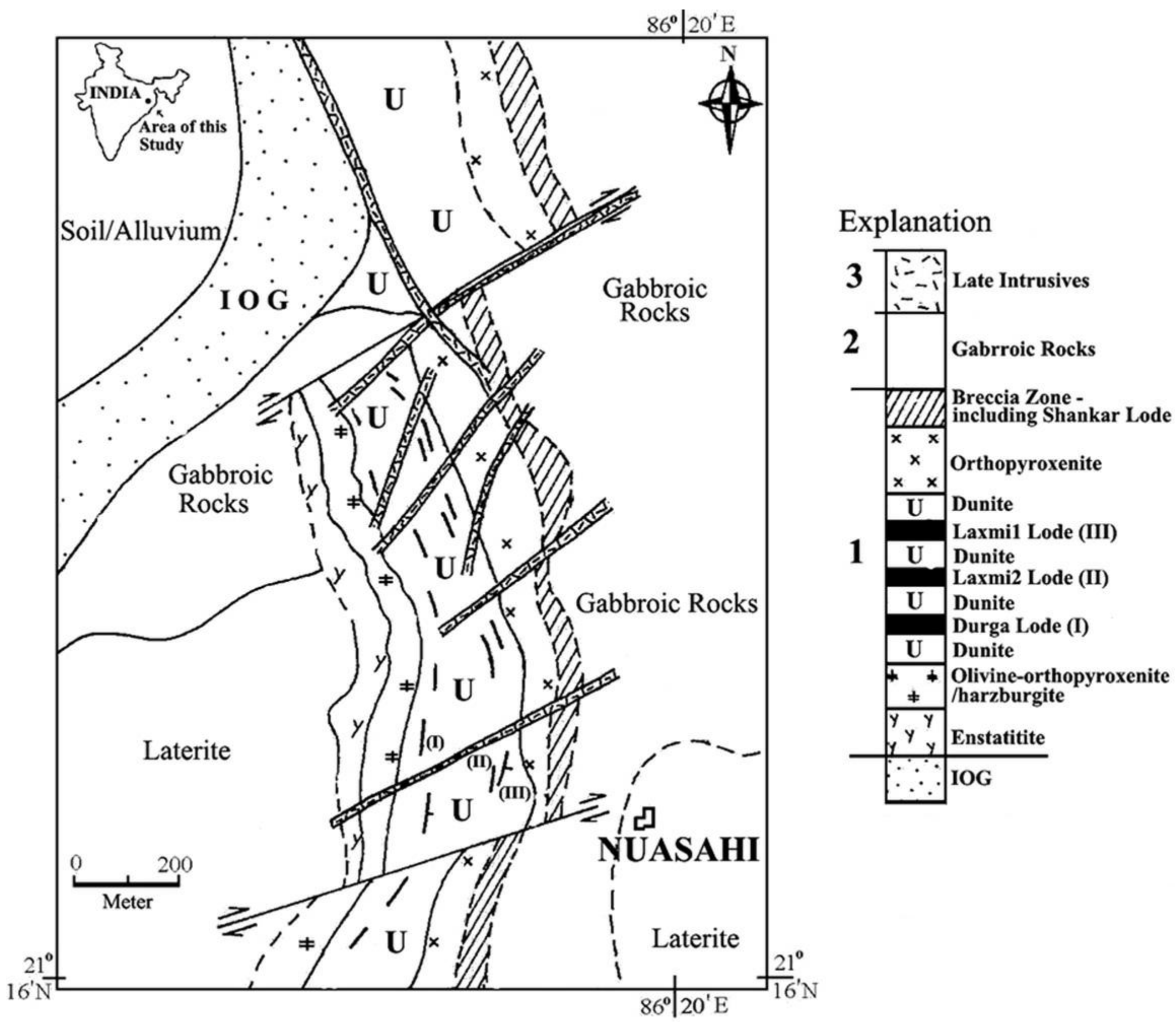

Figure 1. *Geological Map of the Nuasahi Igneous Complex, Orissa, India.*

Composition of parental magma. When compared to those from boninitic basalts, ocean-island basalts and mid-ocean-ridge basalts (after Roeder, 1994; Barnes and Roeder 2001), the liquidus Cr-spinel from NIC plot within the boninitic field. In a Cr/(Cr+Al) versus TiO_2 plot (after Arai, 1992), the Cr-spinel compositions also plot within the boninitic field. Thus, the parental magma for the ultramafic rocks of the NIC appear to be of boninitic affinity. We have calculated the Al_2O_3 content of the liquids in equilibrium with the chromite deposit by using the equation proposed by Maurel and Maurel (1982): $(Al_2O_3)_{spinel} = 0.035 (Al_2O_3)^{2.42}{}_{liquid}$ (Al_2O_3 in wt%). The results show (Table2) that the Al_2O_3 content of the liquid in equilibrium with the lode chromitite and accessory Cr-spinels in silicate rocks and sulfide-rich assemblages of the breccia zone are similar. The FeO/MgO ratio of the melt is determined by using the following formula as given by Maurel (1984):

$$L_n\left(\frac{FeO}{MgO}\right)_{spinel} = 0.47 - 1.07\,Y^{Al}_{spinel} + 0.64\,Y^{Fe^{3+}}_{spinel} + L_n\left(\frac{FeO}{MgO}\right)_{liquid}$$

FeO and MgO in wt% and Y^{Al}_{spinel} = Al/(Cr + Al + Fe^{3+}) and $Y^{Fe^{3+}}_{spinel}{}^{+}$ = Fe^{3+}/(Cr + Al + Fe^{3+}). FeO/MgO ratio calculations were undertaken only for lode chromitite. The results (Table2) show little variation in melt composition from west to the east in the ultramafic component. The liquids of the massive chromitite of the NIC are estimated to have contained 10.27-11.01wt% Al_2O_3 with low FeO/MgO ratios (0.29-0.65). Parental melts of other occurrences, such as the Bushveld and the Great Dyke, have slightly higher Al_2O_3 (11.50 and 11.06wt% respectively). Parental melts of ophiolitic chromitites, such as Oman and Thailand, also have higher Al_2O_3 (>11.4wt%). The NIC chromitites are rather similar to MOF massive chromitite of Kazakhstan (Al_2O_3=9.0-10.6wt% and FeO/MgO = 0.3 - 0.5). Compositions of the parental melts in equilibrium with the chromites of the NIC are similar to low-Ti siliceous high-Mg basalts (Al_2O_3 10.05-13.41wt%) from Archaean greenstone belts, or boninites (Al_2O_3 10.6-14.4wt%) in subduction and back-arc rifting settings.

Whole rock geochemistry

Representative samples from the ultramafic and gabbroic rocks have been analyzed by NAA and wet chemical methods for major and trace elements. Dunite shows similar chemical composition from west to east. The normalized REE patterns for all the samples show three distinct trends; one for the gabbroic rocks, one for the sulfide rich samples of the breccia zone and one for the ultramafic rocks. The trace element concentrations in ultramafic rocks show extreme LREE enrichment, defined especially by Ce and Nd. In general, the ultramafic rocks from the NIC show enrichment of incompatible trace elements, which may be due to a high degree of partial melting of a depleted peridotite. Nuasahi ultramafic and mafic rocks show a general enrichment in Zr, Yb, and Ba relative to chondritic abundances. The Ti/Zr ratio for the Nuasahi ultramafic rocks is in the range of 9.7 and 28.7, which suggests that the Ti concentration has been unaffected by later alteration processes. The low concentration of Ti suggests that the source magma was derived from a depleted mantle source.

Table1. Comparison between Cr-spinel compositions from the Nuasahi Igneous Complex and other known tectonic settings of the world (data of other occurrences from Stowe 1994).

Deposits	$Mg/(Mg+Fe^{2+})$	Cr/(Cr+Al)	$Cr/Fe_{(total)}$	Fe^{3+}/Fe^{2+}	Ti^{4+} (4 oxygen basis)
Nuasahi Complex:					
Lode chromitite (massive bands)	0.68 – 0.82	0.78 – 0.81	3.86 – 5.67	0.09 – 0.62	0.003 - 0.006
Accessory chromian spinel in sulphide-rich assemblage of breccia zone	0.01 – 0.19	0.68 – 0.91	0.51 – 1.24	0.19 – 0.87	0.01 – 0.11
Accessory chromian spinel in silicate lithounits	0.14 - 0.69	0.60 – 0.89	1.59 – 3.59	0.02 – 0.408	0.001 – 0.009
Archaean ultramafic-mafic complex in greenstone belt:					
Selukwe	0.68 – 0.78	0.72 – 0.77	2.7 – 4.8	0.00 – 0.25	0.06 – 0.10
Continental Layered Complex:					
Bushveld	0.24 – 0.58	0.60 – 0.75	0.95 – 3.0	0.16 – 1.12	0.13 – 1.06
Great Dyke	0.36 – 0.67	0.70 – 0.80	2.1 – 3.9	0.14 – 0.26	0.02 – 0.13
Ophiolite segregated (Layered Cumulates):					
Cyprus (stratiform)	0.47 – 0.74	0.52 – 0.84	1.9 – 3.8	0.02 – 0.48	0.02 – 0.04
Ophiolite podiform (Tectonite mantle):					
Semail (Oman)	0.47 – 0.71	0.11 – 0.80	0.8 – 3.9	0.00 – 0.24	0.01 – 0.04

Table 2. Calculation of Al_2O_3 content and FeO/MgO ratio of the melts in equilibrium with chromitite from the Nuasahi Igneous Complex and other occurrences of the world.

	Al_2O_3 liquid (wt%)	**FeO/MgO liquid**
Nuasahi Complex		
Lode chromitite		
Durga lode (western most lode)	*10.27 – 10.58*	*0.29 – 0.41*
Laxmi2 lode	*10.70 – 11.01*	*0.42 – 0.50*
Laxmi1 lode	*10.43 – 10.86*	*0.42 – 0.58*
Shankar lode (eastern most lode in breccia zone)	*10.28 – 10.85*	*0.52 – 0.65*
Accessory Cr- spinel in silicate cumulates	*9.43 – 14.30*	
Accessory Cr-spinel in the chromite-sulphide assemblage, Breccia zone	*8.79 – 12.08*	
Kempirsai Ophiolite chromite deposit [1]		
MOF massive chromitite	9.0 – 10.6	0.3 – 0.5
BAT chromitite	13.5 – 16.7	0.8 – 1.0
Oman chromitite [2]	11.4 – 16.4	0.62±0.02
Nan Uttaradit chromitite [3]	11.6 – 12.0	
Layered Intrusions (parental magma)		
Bushveld (Average ‘U’ Type) [4]	11.50	
Great Dyke [5]	11.06	
Archaean low-Ti siliceous high-Mg basalts		
Barberton [6]	12.65 – 13.41	
Pilbara [7]	10.05 – 11.74	
Boninites [8]	10.6 – 14.4	0.7 – 1.4
MORB [8]	~15	1.2 – 1.6

[1]Melcher et al. (1997); [2]Augé (1987); [3]Orberger et al. (1995); [4]Sharpe and Hulbert (1985); [5]Wilson (1982); [6]Jahn et al. (1982); [7]Sun and Nesbitt (1978); [8]Wilson (1989).

Summary

The gabbroic component of the NIC is distinctly discordant and in fault contact with the ultramafic component in the east, where PGE, Au, and Ag mineralization occur with sulfides in a breccia zone. The refractory chemical compositions of olivine, opx and Cr-spinel in ultramafic rocks suggest a residual depleted peridotite source that had experienced a high degree of partial melting. The calculated compositions of liquids in equilibrium with the Cr-spinel from the lode chromitite are similar to low-Ti, siliceous high-Mg basalts or boninites. The enrichment in LREE and relatively high total REE and other incompatible elements may be ascribed to the metasomatism of a depleted mantle by a hydrous fluid (i.e. a common process thought to proceed the production of boninitic magma) or contamination of a primary komatiitic magma with the Iron Ore Group of rocks that are characterized by a high concentration of incompatible trace elements. Current work on the NIC includes stable isotopic studies and detailed microprobe analyses of the PGE, Au, and Ag mineralization.

References

The references are omitted.