

**Occurrence and Emplacement of Chromite Ores in Sindhudurg District,  
Maharashtra, India**

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## **ABSTRACT**

We present the occurrence and emplacement of chromite ore deposits of two abandoned mines (Kankavali/Janoli and Wagda) in the Sindhudurg district of Maharashtra, India. These ores, that occurred as lenses and associated with metamorphic and ultrabasic rocks, consist of octahedral grains of chromite while clinocllore is present between the interstices of these grains. The Kankavali (Janoli) and Wagda ores revealed a dominance of  $\text{Cr}_2\text{O}_3$  followed by FeO and variable proportions of  $\text{Al}_2\text{O}_3$ , MgO and  $\text{SiO}_2$ . The former deposits have a slightly higher  $\text{Cr}_2\text{O}_3$  (av 52 wt.%) and FeO (~18 wt.%) than those from Wagda ( $\text{Cr}_2\text{O}_3$  ~50 wt.%, FeO ~25 wt.%). The similar Cr# values (0.73 for Kankavali (Janoli) 0.74 for Wagda) correspond to those reported for typical podiform-type chromite deposits. We suggest that the ores were emplaced as phacoliths in the folded outcrops that have a steep easterly dip and a NW-SE trend. We postulate the continuation of the fold structure from Janoli to Wagda (~ 4.5 km apart) and the probable (sporadic) occurrence of chromite along this stretch. The possibility of contribution of chromite grains from these areas to the coastal placer deposits can not be ruled out.

**Keywords:** Chromite, Podiform, Formation, Placers, Sindhudurg, India

## 1. INTRODUCTION

Chromite, the only ore of chromium belongs to the spinel family and is generally associated with ultrabasic rocks such as dunites, pyroxenites, serpentinites, norites, saxonites and ophiolites. Chromite ore bodies occur either as podiform or stratiform deposits with the former deposits formed by reaction between ascending melts and the host peridotites (Robinson et al., 1997) while the stratiform deposits indicate crystallisation from mafic magmas probably by mixing of evolved and more primitive melts (Irvine, 1977). Chromite deposits occur most commonly as bands, beds, pockets, lenses, veins and disseminations in the host ultrabasic rocks. Generally, chromite has 68 wt.% of  $\text{Cr}_2\text{O}_3$  and 32 wt.% of FeO but in nature the chromium content is usually lower (40-45 wt.%) due to replacement of Cr by Al. Similarly, Fe is partly replaced by Mg (Gokhale and Rao, 1973). Chromite being highly stable under oxidising conditions tends to remain quite unaffected in the host rocks (e.g., Deer et al., 1962). Chromite-rich placer deposits have been reported from the exclusive economic zones of the USA (Ritchey, 1988), New Foundland (Emory-Moore et al., 1989) and the continental shelf of Cyprus (Varnavas, 1990).

A summary data of Indian chromite deposits with reference to their occurrence, age, associated rock types and ore grade are presented in Table 1. It is apparent from this description that the Precambrian chromite deposits of India are mainly in the states of Orissa and Bihar (both to the east), Karnataka, Tamil Nadu, Andhra Pradesh (all in the south) and Maharashtra and Goa (both in the west) whereas Phanerozoic deposits are in Ladakh (in the north), Nagland and Manipur (in north-east) and in Andaman-Nicobar Islands. Podiform chromitites are found in Orissa and Bihar whereas stratiform type is in Tamil Nadu while the Byrapur-Nuggihalli deposits in Karnataka occur in tectonised ultramafics present in a major shear zone (Mookherjee 1999). Among these deposits those of Orissa are the richest and are being mined in the districts of Sukinda, Nausahi, Maruabil and Maulabhaj areas. In Maharashtra the occurrence of chromite is reported from Bhandara, Chandrapur, Nagpur and Sindhudurg districts. It is evident from table 1 that the occurrences of chromitites in India are associated more commonly with ultra-basics and ultramafics of Pre-Cambrian age than with ophiolites of Cretaceous times.

In this paper we deal with the chromite deposits of the Sindhudurg district (formerly under Ratnagiri district), Maharashtra. Although the occurrences of chromite are reported from Kankavali (Janoli), Wagda and Gosaviwadi from the Sindhudurg district (Fig. 1) but these areas were explored from view points of exploitation of the ores (Chari et al., 1975). Therefore, a lacuna exists regarding the mineralogy, texture, composition and type of chromite ores and their mode of emplacement.

## 2. METHODOLOGY

After a detailed literature survey of the geology, geomorphology and tectonic features of the area, we visited the abandoned chromite mines located at Kankavali (Janoli) and Wagda. At places sampling was hampered as the mine pits were water logged. Several rock samples and very

few chromite ore lumps were collected from the cross-sections available in the study areas (Figs. 1 and 2). The collected samples were bagged and labelled for laboratory investigations. The positions during the sampling operation were obtained by using a Global Position Fixing (GPS) Maglan NAV-5000 PRO model which has an accuracy of  $\pm 5$  m.

Thin and polished sections of the rocks and grain mounts of the chromite ores were examined for their texture and mineralogy. To understand their surface textures and elemental composition, grains prised out from the chromite ores were mounted onto stubs while a few grains were embedded in an epoxy resin and polished. All these samples were initially examined using a JEOL Scanning Electron Microscope with an Energy Dispersive Spectrometre (SEM-EDS). A few grains were carefully removed from a lumpy ore and powdered for X-ray studies. In addition, a portion of the lumpy ore was manually disintegrated, washed and filtered. The residue obtained on the filter paper was dried and powdered for X-ray analysis. X-Ray diffraction (XRD, Philips 1480) was carried out and the peaks were identified following Anon (1981). The chemical analysis of the ore was carried out using an Inductively Coupled Plasma - Optical Emission Spectrometre.

A CAMECA SX-100 electron probe microanalyser (EPMA) was used to analyse the minerals present in the chromitite samples. The instrument was equipped with three vertical and one inclined spectrometers and operated at an accelerating voltage of 20kV, beam current of 20 nA. The peak counting time was 20 seconds while the background counting time was 10 seconds. Data reduction was carried out following the AX programme of Tim Holland and Roger Powell (University of Cambridge, U.K.) distributed along with their Thermocalc 3.2 Windows software. A total of 109 grains (av 36) were analysed on three samples and on each grain three spots were analysed. Wherever feasible the matrix too was analysed. The final composition and cation distribution are presented in table 2. A few back scattered electron (BSE) images were also obtained of the samples.

### **3. PHYSIOGRAPHY AND REGIONAL GEOLOGY**

The rivers in the studied areas (Achara, Gad, Janoli and Pangara, Fig. 1) are deeply entrenched in the lateritic plateau. The region has several detached residual hills that form outliers and are underlain by basalts. The more resistant of the Deccan lavas form chains of hills that run east-west and are perpendicular to the north-south trending Sahyadrian range. In the studied areas, the granite / granitic gneiss of Precambrian and the Dharwar group of Archean age are commonly followed by Lower Kaladgis Series (Proterozoic group). As one approaches the Sahaydris, lying to the east of the studied areas, the Deccan Trap lavas become predominant (Gazetteer of Maharashtra, 1962). Lateritic cappings are ubiquitous and these at many places obscured a proper identification of the country rocks (Fig. 1).

### **4. GEOLOGY OF THE STUDY AREA**

The occurrence of chromite along the bank of Janoli river ( $16^{\circ} 15' N / 73^{\circ} 42' E$ ) (Fig. 1) and the ultramafics occurring in the Sindhudurg district, viz., Wagda and Kankavali (Janoli),

possibly correspond to those at Mysore (present day Karnataka) and belong to the Dharwarian orogeny of Precambrian age (Chari and Maggirwar, 1968). The country rocks are serpentine-talc-tremolite schists and talc-chlorite schists that intrude into the gneissic and schistose rocks of the Dharwar group (Anon, 1976). Chromite occurs as irregular masses and discontinuous lenses (Fig. 2) that are 30 to 450 m long and 8 to 20 m wide (Banerjee and Haldar, 1972).

The Geological Survey of India conducted detailed gravity and magnetic surveys in an area of approximately 1 sq km to locate chromite deposits in the Kankavali (Janoli) and Wagda regions. The surveys revealed the presence of two prominent isolated gravity anomalies and an eastward sub-surface extension of the main ore body that was exposed at Kankavali (Janoli). In the Wagda area a significant gravity anomaly of low magnitude was postulated but the presence of amphibolites limited the usefulness of the gravity method (Records GSI, 1964).

**4.1 Kankavali (Janoli) deposits:** (Location: 16° 16' 47.0" N / 73° 43' 25.2" E). At this abandoned mine three pits are exposed that were cut from a hillock (Fig. 2A) and Janoli River (a tributary of Gad River) flows through the mine (Fig. 1). There are exposures of ultrabasic rocks such as serpentinite-talc-tremolite schists that dip south, trend along WNW-ESE, have lateritic cappings (Fig. 2B) and intrude in to the Dharwarian schists and amphibolites. Exposures of mica schists containing grains of chromite are common in the eastern part and at the hill top a thick quartz vein is present. At most locations alteration of the schists to laterite is evident. A similar association of chromite ores and ultrabasic rocks is found at Byrapur and other mining belts in Mysore (Karnataka) (Chari and Maggirwar, 1968).

Downstream of Janoli River and on its west bank there are occurrences of amphibolite, phyllite / talc schists and a quartz vein. The amphibolites (~5 m wide) and the quartz vein (~15 m wide and 4 m high) overlie the phyllite / talc schists (~15 m wide). Samples of asbestos, serpentine and chromite were collected in the vicinity of the river. It appears that the rocks that are in immediate contact with the chromite ores are the schists that are embedded with chromite grains. The serpentinites that form the host rock for the chromite ores have a limited extent, have resulted from the alteration of the parent ultrabasic rocks and were subsequently lateritised.

The chromite grains are uniform in composition, fairly evenly granular and are intimately linked with and set in in a matrix of serpentine and chlorite. The chromite ores and the associated lithology follow the regional strike (N 40°W to N60°W) of the gneissic country rock. The chromite ores occur as irregular veins and lenses and can be traced for a distance of over 0.8 km along the strike and the maximum visible width occupied by the ore body is 30.48 m to 45.72 m (Chari and Maggirwar, 1968) and occur at depth between 20 and 50 m (Mane et al., 1977). The Directorate of Geology and Mines (D.G. M.) Maharashtra drilled 34 boreholes (1972 and 1974) for prospecting of the chromite deposits and estimated the ore reserve to be 96,800 tonnes (D. G. M., 2000). The reported analysis of the chromite ore of this area is given in table 2.

**4.2 Wagda deposits** (Location: 16° 15' N / 73° 42' E): Chromite deposits were found in the western and eastern low lying ridges located to the south and SW of the village of Wagda (Fig. 1).

According to Chari and Maggirwar (1968) the ridges consist of serpentinites that intrude into the hornblende schists and three distinct lenses of chromite ores outcrop at the top that form two large linear mounds situated south of Gad River. These are surrounded by a low ground underlain by biotite-gneisses and mica schists. The serpentinites, chromite lenses and the amphibolites strike N45°W and dip steeply 70°-80° SW (Fig. 3A). Reportedly, the chromite deposit extends up to Gosaviwadi (Fig. 1). From the base of the mine to the top of the hillock the height is ~30-35 m and the chromite bands probably occurred at a depth of ~5-15 m.

Bands and lenses of chromite/chromiteferous rocks (~0.5 m wide) cut across the schists (Fig. 3B). Asbestos fragments were found but no outcrops were noticeable probably due to the fact these were excavated during mining operations and also asbestos being fragile may have been eroded and transported. According to Iyer (1939) and Chari and Maggirwar (1968) the Wagda ores were richer than those of Kankavali but the reserves, as estimated by the D. G. M., was only 5600 tonnes of chromite. The analysis of the chromite ores from the Wagda mine is given in table 2.

## 5. RESULTS AND INTERPRETATIONS

Petrography of the Kankavali (Janoli) ores revealed the chromite grains to be rounded and of variable size (Fig. 3A) while the ultrabasic rocks have few chromite grains that are tabular to irregular in shape (Fig. 3B). The schists from the Wagda mine show the presence of rounded grains of chromite without any intergrowth (Fig. 3C). Chromite grains are also seen to be associated with other ilmenite (Fig. 3C). BSE images (Figs. 3 D to F) display the variable morphology and cumulus texture of the studied samples. In one instance (Fig. 3D) a metallic phase (FeCrNiMn) is seen to occur between the chromite grains and this needs future confirmation. Interestingly, exotic accessory minerals in layered chromitites of the Campo Formoso complex (Brazil) reportedly contain monzonite, apatite and three unknown minerals of Pb-Sb (Zaccarini et al., 2006).

XRD profiles of chromite grains from Kankavali (Janoli) (Fig. 4A) reveal Fe-rich chromite (ferrochromite) to form a major phase while magnesium rich (magnesio-chromite) is a minor phase. In the lumpy chromite ore the associated predominant mineral is clinocllore which occurs as flaky, shiny grains (Fig. 4B). The presence of clinocllore is also noted in the BSE image (Fig. 3E) wherein it occurs within the grains of chromite and in the matrix. This observation is similar to that present in the chromitites of the Campo Formoso complex (cf. Zaccarini et al., 2006).

SEM of individual chromite grains reveals their octahedral form with well-developed crystal faces (Figs. 5A, B). Because of the relatively greater hardness (H= 5.5) features of alteration, impact and fracturing of the grains are less common (Figs. 5C, D). SEM of the polished specimens of chromite (Fig. 6) confirms the orthocumulus texture and also the presence of clinocllore (Fig. 3E).

Microprobe analysis of the chromite grains in the ores of Kankavali (Janoli) and Wagda mines are presented in table 3A. The table also provides the range of the various oxides and the Cr#, Fe<sub>3</sub># and Mg# values (see Table 3 for calculations). It is seen that Cr<sub>2</sub>O<sub>3</sub> ranges from 49-55% with the 'fresh' samples from Kankavali (Janoli) being slightly richer (av 52%) as compared to the Wagda sample (av ~50%) while the altered sample from Kankavali (Janoli) has the least Cr<sub>2</sub>O<sub>3</sub> (av 47%). The latter sample also has higher Fe<sub>2</sub>O<sub>3</sub> (av ~12%). In all the samples studied iron oxides dominate over MgO attesting to the fact that the ores have ferro-chromite, as also noted in the XRD (Fig. 4A). TiO<sub>2</sub> shows a broad range of content (0.18-0.65%) in the Kankavali (Janoli) ore in contrast to the narrow range in the Wagda ore (0.29-0.52%). The above observations are also attested by the bulk ore analyses that show similar differences in the two areas (Table 2).

The chromite sample from Wagda has depleted Al, Mg and Si as compared to the Kankavali (Janoli) ore (Tables 2 and 3) because in the latter case clinocllore is commonly present. The microprobe analysis supplements the findings from the XRD and confirms the presence of Fe- and Mg- rich chromites. In the samples of Kankavali (Janoli), clinocllore is present between the interstices and within the chromite grains (Figs. 3E, 6D). This is confirmed by the XRD peaks (Fig. 4B) and also by the microprobe analysis that indicate the occurrence of chromiferous clinocllore (Table 3B). The Cr# (atomic ratio of Cr/[Cr+Al] cf. Arai, 1997) was calculated (Table 3A) and it was found the Kankavali (Janoli) ores have a wider range of Cr# (0.68 to 0.77) while the Wagda ores have a narrower spread of Cr# (0.71 to 0.80) but both the areas, on an average, have 0.74 Cr#.

The binary plots of TiO<sub>2</sub> vs Cr# and Cr# vs Mg# and Fe# vs Mg# (Fig. 7) and the ternary plot of trivalent cations (Fig. 8) depict clustering of Kankavali (Janoli) and Wagda ores in two distinct groups. It can be noted that irrespective of the geographical locations all the samples have a high Cr# (0.68-0.80).

## 6. DISCUSSION

Podiform chromites are reportedly common in ophiolite complexes (Paktunc, 1990) and at oceanic and arc-related setting. Amongst these areas, podiform deposits occur as economically exploitable ores in arc-related environment (Arai, 1997). It can be noted that several of the chromite ores occurring in India, including those in the Sindhudurg District, are associated with ultramafic rocks (Table 1). Interestingly, these deposits rarely conform to a site of neither ophiolite nor arc-related assemblages.

It is well known that chromite deposits occur in two forms: as layered intrusives (stratiform type) or as podiform (alpine type) with the former representing magmatic sediment layers while the latter is related to orogenic belts (Craig and Vaughan, 1981). To distinguish between these two types of chromite deposits, norms such as mineralogy, grain size, texture, chemical composition and associated rock types have been proposed (Mookherjee, 1999). These criteria are not very rigid since there could be an inter- or intra-depositional variation in the mineralogy.

Despite the above limitations the criteria serve as a broad outline to identify the two types of chromite deposits. Stanton (1972) proposed certain compositional guidelines to distinguish between the stratiform and podiform deposits. In podiform deposits the MgO/FeO ratio is higher (1 to 2.3), Fe<sub>2</sub>O<sub>3</sub> content is lower (< 8%) and Cr/Fe ratio is higher (~1.5 to 4.5, mean 2.5). In contrast, layered chromites have lower MgO/FeO (0.6 to 1), higher Fe<sub>2</sub>O<sub>3</sub> (~10 to 24% Fe<sub>2</sub>O<sub>3</sub>) and lower Cr/Fe ratio (0.75 to 1.75, mean ~1.0). According to Thayer (1964) in podiform chromite ores Al<sub>2</sub>O<sub>3</sub> and Cr<sub>2</sub>O<sub>3</sub> show reciprocal relations with Cr<sub>2</sub>O<sub>3</sub> ranging from about 65 to 16% and Al<sub>2</sub>O<sub>3</sub> from about 6 to 52% but these values vary widely in layered deposits. This lead to identify two varieties of podiform deposits: high-Cr and high-Al chromites.

Based on the above norms, the bulk and microprobe analyses and ratios of cations of chromites from the Sindhurg district are analogous to those of the podiform type. According to Arai (1997) podiform ores show a variable Cr# (0.2 to 0.9) but is mostly higher than 0.4 and in the range of 0.7 to 0.8. Our values (0.68 to 0.80) for the Sindhurg ores fall well within Arai's values. Studies have brought to light that several chromite deposits could be transitional in their characters that overlap the typical stratiform and podiform types. This probably either implies that the association of ultramafic rocks and chromite indicates a unique thermally and geochemically distinctive source region or alternatively, the apparent characteristics of the two types may have been influenced by the respective tectonic environment (Banerjee, 1972; Mookherjee, 1999). Although the chromite ores from our study areas more closely resemble the podiform type but the possibility of these being a transitional type can not be ruled out. This is because much of the deposits have been mined making it difficult either to obtain fresh, in situ samples or to detail the association of the ore with the host rocks.

Several views exist concerning the emplacement of chromite in association with ultrabasic rocks. According to Mookherjee (1999), the proposed genetic models for podiform chromites are (Cr-rich) liquid immiscibility, hydrothermal precipitation, fractional crystallisation of mantle magma and their subsequent uplift, fractional crystallisation of deep-seated crustal magma chamber and their solid-state uplift, formation in oceanic crust and subsequent sinking into a tectonised harzburgite layer, and in situ formation within fissures in harzburgite from a basaltic melt passing through and generating a convective cell within the conduit. Furthermore, the podiform deposits have diverse modes of occurrence that suggest multistage intrusion episodes along with their host and signify a very complex post- or syn-emplacement history of brittle and ductile deformation, metasomatism, recrystallisation and/or local remobilisation.

In contrast, the stratiform deposits appear to have been injected into comparatively stable tectonic environments. While all have suffered some folding, faulting, or tilting, none have been extensively deformed and metamorphosed. These facts indicate the emplacement of chromite ores by later tectonic activities. Another aspect is that the chromite-containing host is mafic and not ultramafic rocks. ON the contrary, the podiform type is injected into highly unstable environments, in most cases into geosynclinal zones of volcanism, folding and faulting (Stanton, 1972). Although the composition of the intrusion is largely peridotitic but the chromite may be



associated with a variety of rocks that are quite definitely ultramafic. Furthermore, a high degree of serpentinisation is quite ubiquitous. Virtually all intrusions of alpine type are clearly related to early faulting of major scale and most of them have been modified by faulting and squeezed and moved about by plastic flow – probably semi-continuously ever since their first injection (Stanton, 1972).

Stanton (1972) believed that the occurrence of chromite in alpine type intrusions is widespread and common. There is hardly an orogenic belt, particularly on post-Precambrian terrains, devoid of serpentine and there is probably no known serpentine belt that does not host chromite concentrations of sufficient size and richness to constitute an ore. Also, even those ultramafic lenses with no actual ore deposits have conspicuous chromite that may be locally concentrated but such deposits are not commercially viable to be mined due to their small size.

It was generally assumed that the alpine type is probably mantle derived material that have pinched into and squeezed up along very deep faults. Alternatively, field evidences and compositions suggest that the alpine type may represent comparatively shallow differentiates of volcanic magma chambers that were subsequently serpentinised and squeezed into the faults. Interestingly, the alpine type intrusions are metamorphosed in contrast to the layered ones (Stanton, 1972), as is the case in the presently studied area of the Sindhudurg District. Therefore, chromite ores probably form by a process of segregation that occurs either during early or late stages of magmatic crystallisation, as also attested by the textural features (Craig and Vaughan, 1981). Ramdhor (1980) opined that chromite is almost always a very early product of magmatic crystallisation and as a rule Mg-rich varieties are related to peridotites, while Fe-rich varieties are limited to pyroxenitic rocks. From a detailed study Arai (1997) concluded that podiform deposits form by the interaction between the peridotite wall and an ascending magma in the upper mantle. According to Zhou and Robinson (1997) although melt-rock interaction is a well known process but it does not always result in podiform deposits rather the degree of melt-rock reaction is the main influencing factor.

An enigmatic question is: how is that the primitive mantle melts that have low chromium concentrations (~200-500 ppm) get enhanced manifold to form economic deposits of chromite (~30% Cr) (Matveev and Ballhaus, 2002). To explain the ways by which monomineralic chromite layers form, several mechanisms have been proposed such as: concentration by current sorting or preferential precipitation brought about by changes in pressure, water content, oxygen fugacity or through multiple injections of magma (Stanton, 1972; Craig and Vaughan, 1981). After reviewing the various processes Paktunc (1990) proposed that the emplacement of podiform chromite deposits could be accounted by partial melting, magma segregation and magma mixing. The theme of magma mingling was later revoked by Ballhaus (1998) who suggested that mingling of low-silica, low-viscosity, high-pressure melt with more siliceous and more viscous low-pressure liquid would result in the formation of nodular and orbicular ore textures. Although the melts that are involved are saturated with chromite but nucleation of chromite is more prominent in that melt in

which the interfacial energy of chromite is lowest. As a result, the richest ores will form where the melt fraction nucleating chromite is small relative to the ambient melt.

It was proposed that chromite might precipitate when the parental basic magma is unexpectedly contaminated by a more acidic one. This addition of the silica-rich material compels the composition of the crystallising melt to move from the olivine + chromite cotectic curve (along which disseminated chromite admixed with olivine forms) into the field of primary chromite crystallisation (in which only chromite forms) (Irvine, 1974, 1977). Based on their experiments Matveev and Ballhaus (2002) found that olivine need not be suppressed from the liquidus of a primitive basaltic melt. It was shown that in immiscible basalt-water systems, chromite and olivine are strongly and individually fractionated; with chromite partitioning into the exsolved fluid while olivine (and possibly other silicate phases) resides in the melt.

The steep dip and the NW-SE trend of the foliation present in the rocks of Kankavali (Janoli) and Wagda are suggestive of the existence of an eastward plunging fold composed of ultrabasic rocks. The chromite ores might have been emplaced as phacoliths i.e., in the anticlinal part of the fold at Kankavali (Janoli) and in the synclinal portion at Wagda. The profusion of quartz veins, especially at Kankavali (Janoli), suggests their occurrence along weak fissures and fractures zones of the folded sequence. We postulate the continuation of the fold structure to at least ~4.5 km i.e., from Kankavali (Janoli) to Wagda and the probable occurrence of chromite along this stretch. We opine that the chromite may represent products of early magmatic segregation that subsequently ascended and were emplaced contemporaneously with the ultramafic rocks prior to the onset of orogenic activities.

A similar occurrence has been reported from the Bhandara district (Maharashtra) where the ores occur as concordant pods and thin layers in highly altered and sheared suite of ultramafics (dunite and steatitised and silicified serpentinite). The ultramafics appear to have been emplaced along the troughs of synclinal folds in a tightly folded sequence of the Sakoli meta-sediments represented by phyllite, quartzite, gneiss and amphibolite. The pods and lenses roughly parallel the foliation and the plunge of the long axes of the folded rocks (Records GSI, 1968). The ultramafics containing pods of chromite have been shredded due to regional deformation and by the granitic intrusion. An equivalent situation prevails in southern Mysore (Karnataka) where the trend of chromite bearing ultramafics follows the regional formation in a discontinuous band. Field, structural and textural studies revealed that the steeply dipping, en-echelon distributed lensoid bodies are of alpine type, emplaced in a solid state as 'cold intrusion' along the axial planes of folded Dharwar schists (Varadarajan, 1970).

As previously mentioned, there are reports on occurrences of chromite grains in placer deposits (e.g., Ritchey, 1988; Emory-Moore et al., 1989; Varnavas, 1990; Pal et al., 2003) but such deposits, in contrast to ilmenite-magnetite-rich sands, may not be economically viable for exploitation. Recent reports by Gujar et al. (2008, 2009) revealed that along the coast of South Maharashtra there are incidences of chromite grains in the placer deposits. Those authors

suggested that the chromite grains have been derived from the lenses and chromite-bearing rocks present in the Kankavali (Janoli) and Wagda mines of the Sindhudurg District. The erosion and transportation of the chromite grains from these source areas and their subsequent deposition along the coast have resulted in an inferred reserve of 0.032 million tonnes of chromite.

## **CONCLUSIONS**

An investigation of the chromite ores from Kankavali (Janoli) and Wagda mines of the Sindhudurg district has revealed the following: 1) the ores are composed of rounded chromite grains forming lenses and do not display features of intergrowth, clinocllore is the main mineral in the matrix, 2) compositionally the Kankavali (Janoli) deposit has a slightly enhanced  $\text{Cr}_2\text{O}_3$  than those from the Wagda mine but in both the cases the Cr# identical to that of podiform type chromites, 4) the ores are magmatic in origin and were emplaced simultaneously during the formation of the host metamorphic and ultrabasic rocks that form a plunging fold with steep dip and NW-SE trend, and 5) significant contribution of chromite grains to the coastal placer deposits.

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**Table 2.** Composition of the chromite ores from Sindhudurg district, Maharashtra. Analyses #1 to 4 are from Gazetteer of Maharashtra (1962), #5 and 6 are from D.G.M (2000), #7 is from Chari and Maggriwar (1968), # 8 and 9 are from Peravadhanulu et al. (1979) and # 10 (present study). Analysis 11 and 12 are average values. FeO is recalculated from Fe<sub>2</sub>O<sub>3</sub>.

**Table 3.** Microprobe analysis of chromite (A) and clinocllore (B) from Sindhudurg District. 1 = 'Fresh' chromite from Kankavali (Janoli) mine; 2 = 'Altered' chromite from Kankavali (Janoli) mine; 3 = Chromite from Wagda mine. n = number of grains analysed. Cr# = Cr/Cr+Al; Fe3# = Fe<sup>3</sup>/Fe<sup>3</sup>+ Al+Cr; Mg # = Mg/Mg+Fe<sup>2</sup>

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**Fig.1.** General geology and drainage of the study area. (Base map modified after Anon, 1976). Legends: 1 = Pleistocene laterite, 2 = Upper Cretaceous to Lower Eocene Deccan Trap basalt, 3 = Proterozoic Group, 4 = Precambrian Granite / Granitic gneiss, 5 = Archean / Dharwar, Group, 6 = Chromite lenses, 7 = Dip direction, 8 = Approximate boundaries of the lithology.

**Fig. 2.** (A) Janoli mine pits. (B) Laterite capping, Janoli. (C) Weathered serpentinised schist and associated chromite lump, Janoli. (D) Chromite bearing ultrabasic rocks (marked by arrows) and laterite, Wagda.

**Fig. 3.** Chromite grains occurring in lenses (A) and in the associated ultrabasic rocks (B and C). A and B are thin sections while C is a polished section. D, E and F are BSE of chromite grains. Near the fractured grain (D) are white streaks composed of a metallic phase (FeCrNiMn). Chromiferous clinochlore (E) is present within the grains of chromite. The typical orthocumulus texture (F) seen in the chromitites.

**Fig. 4.** (A) X-Ray diffractogram of chromite grains. (B) X-Ray diffractogram of clinochlore from chromite lenses (value in parentheses indicate the interplanar spacing [hkl]).

**Fig. 5.** SEM of chromite grains. (A) General shape of grains from chromite lenses. (B) Chromite grain with well defined octahedral crystal faces. (C) Octahedral chromite with fractures and pits. (D) Octahedral chromite grain showing conchoidal fractures and rounded edges.

**Fig. 6.** SEM of chromite grains. (A) Agglomeration of chromite grains. (B) Well polished sections of quite fresh chromite grains. (C) Equidimensional, rounded and sub-rounded chromite grains. (D) Clinochlore grain.

**Fig. 7.** Binary plots for chromitites clearly show two distinct groups. Solid triangles = 'Fresh' sample from Kankavali (Janoli) mine; Solid square = 'Altered' sample from Kankavali (Janoli) mine, Solid diamonds = sample from Wagda mine.

**Fig. 8.** Ratios of trivalent cations in the podiform chromitites of Sindhudurg District.



**Table 1**

<b>Sr. No.</b>	<b>Area of occurrence</b>	<b>Associated Rocks</b>	<b>Structure</b>	<b>Age</b>	<b>Type of chromite and mode of origin</b>	<b>Remarks</b>
1	Usgaon, Goa	Serpentinised-dunite, trocolite peridotite, meta-gabbro,	NW-SE synform	Dharwar Supergroup	Irregular blebs, patches	Jena (1985)
2	Rutland coast, Andaman	Ophiolite, (serpenitised-dunite, harzburgite)	-	Cretaceous	Stringers, lenses	Chromite placers (Pal et al., 2003)
3	Sindhudurg District, Maharashtra	Altered serpentinites, biotite gneiss	-	Pre-Cambrian	Lenses N40°W-S40°E to N60°W-S60°E, steep dips	Low grade chromite (Cr <sub>2</sub> O <sub>3</sub> 32-38%; Rec. GSI, 1964)
4	Hassan and Mysore Districts	Brownish serpentinites, soapstones, unaltered pyroxenites	-	Pre-Cambrian	Veins, lenses trend N-S, near vertical dips	Rec. GSI (1964)
5	Pauni, Bhandara District, Maharashtra	Dunites, stearised and calcified serpentinites	Synclinal trough	Pre-Cambrian	Interstratified layers, pods	Cr <sub>2</sub> O <sub>3</sub> 33.94-52.48% (DGM. 2000)
6	Taka, Nagpur District, Maharashtra	Cherty silicified and calcified serpentinites	-	Pre-Cambrian	Segregates, veins, stringers, disseminated	Cr <sub>2</sub> O <sub>3</sub> 31.21-49.89% (DGM, 2000)
7	Kankavali Janoli, Sindhudurg District	Serpentine-talc-tremolite-biotite schists,	Strike WNW-ESE, southerly dip	Pre-Cambrian	Lenses	Cr <sub>2</sub> O <sub>3</sub> 30.98-36.46%, low grade (Chari and Maggirwar, 1968)
8	Wagda, Sindhudurg District	Hornblende schist, serpentinites	-	Pre-Cambrian	Lenses, steep dips	Cr <sub>2</sub> O <sub>3</sub> 34.21% (DGM, 2000)
9	Gosaviwadi, Sindhudurg District	Hornblende-talc-tremolite-schists, serpentinites	Strike NW-SE	Pre-Cambrian	Lenses, NW-SE, dips NE	Cr <sub>2</sub> O <sub>3</sub> 35.33-39.07% (DGM, 2000)
10	Chandrapur District, Maharashtra	Granite gneiss, amphibolite, ultrabasic dykes	-	Pre-Cambrian	Lenses	Cr <sub>2</sub> O <sub>3</sub> 30-45% (DGM, 2000)
11	Bihar	Dunite, saxonite	Fold NNE plunging	Pre-Cambrian	Veins, lenses	Cr <sub>2</sub> O <sub>3</sub> 48% (Rec. GSI, 1968)
12	Coimbatore District, Tamil Nadu	Acid charnockite with segregations of pyroxenite	-	-	'Float' chromite (2-5 cm long). Magmatic segregation	Records GSI (1968)

13	Salem District, Tamil Nadu	Anorthosites, amphibolites, eclogite	-	Pre-Riphean	Dipping layers. Magmatic differentiation,	Cr <sub>2</sub> O <sub>3</sub> 33-36% (gangue free). (Subramaniam, 1955, 1956)
14	Sukinda District, Orissa	Montmorillonite-serpentine, limonite and silicified ultramafics, talc-chlorite-tremolite-schists, talc-serpentine	-	Pre-Riphean	Lenses, tabular bodies. Elutriation differentiation from a basic magma	High grade Cr <sub>2</sub> O <sub>3</sub> >50% (Banerjee and Haldar, 1972)
15	Kondapalle, Andhra Pradesh	Dunite, pyroxenite	-	Pre-Riphean	Pockets, disseminated. Early magmatic crystallisation.	Cr <sub>2</sub> O <sub>3</sub> 39-55% (Krishna Rao, 1964)
16	Ladakh Himalaya	Peridotite, ophiolites	Fold, fault, brecciated	Late Cretaceous	Pods, lenses, pencil-ore, schlieren, streak	Cr <sub>2</sub> O <sub>3</sub> 50-62% (Dessai et al., 1992)
17	Usgaon, Goa	Mafic-ultramafic complex (dunite, serpentinite, peridotite, chromitite)	Overturned anticline trending NW-SE, plunging NW	Late Archean Early Proterozoic	Stratiform deposits. Thin layer (1-4 cm thick) alternating with olivine-rich layers (3-10 cm thick)	Cr <sub>2</sub> O <sub>3</sub> 51-54% (Dessai et al., 1995, 2009)

**Table 2**

Oxides (%)	Kankavali/Janoli (1)	Kankavali/Janoli (2)	Wagda (3)	Wagda (4)	Kankavali/Janoli (5)	Wagda (6)	Kankavali/Janoli (7)	Kankavali/Janoli (8)	Kankavali (9)	Janoli (10)	Janoli/Kankavali (11)	Wagda (12)
SiO <sub>2</sub>	7.36	9.28	4.12	9.21	13.14	6.96	3.44	9.60	14.74	5.32	8.98	6.76
Fe <sub>2</sub> O <sub>3</sub>	23.73	26.20	24.63	25.40	24.81	25.27	10.12	23.89	23.89	25.88	-	-
Al <sub>2</sub> O <sub>3</sub>	11.40	13.60	12.02	12.60	10.54	15.17	10.59	14.74	11.00	14.96	12.40	13.26
CaO	nil	nil	nil	nil	na	na	0.21	2.00	2.24	2.25	-	-
MgO	15.35	17.02	15.64	16.29	14.77	14.89	15.66	17.21	14.50	12.61	15.30	15.60
Cr <sub>2</sub> O <sub>3</sub>	36.49	31.63	39.30	33.43	30.98	34.21	36.46	34.73	33.14	33.62	33.86	35.65
FeO	21.35	23.58	22.16	22.86	22.32	22.74	23.52	21.50	21.51	23.29	22.44	22.59

Table 3

Oxides	A			B			
	Sample 1	Sample 2	Sample 3	Chromiferous Clinocllore			
SiO <sub>2</sub>	0.20	0.25	0.16	SiO <sub>2</sub>	31.60	31.42	31.12
TiO <sub>2</sub>	0.27	0.34	0.37	TiO <sub>2</sub>	0.04	0.03	0.02
Al <sub>2</sub> O <sub>3</sub>	13.06	10.09	9.79	Al <sub>2</sub> O <sub>3</sub>	15.34	15.54	15.99
Cr <sub>2</sub> O <sub>3</sub>	52.22	47.00	50.16	Cr <sub>2</sub> O <sub>3</sub>	2.58	2.63	2.62
Fe <sub>2</sub> O <sub>3</sub>	4.39	11.89	7.89	FeO	3.62	3.53	3.45
FeO	17.92	22.07	25.05	MgO	31.71	31.63	31.68
MgO	10.59	7.71	5.62	Totals	84.94	84.82	84.95
n	44.00	31.00	34.00	Oxygens	14	14	14
Cr#	0.73	0.75	0.74	Si	3.077	3.063	3.029
Fe3#	0.05	0.15	0.11	Ti	0.003	0.002	0.001
Mg#	0.51	0.38	0.32	Al	1.761	1.786	1.835
Oxides	Sample 1	Sample 2	Sample 3	Cr	0.199	0.203	0.202
SiO <sub>2</sub>	0.15-0.46	0.14-0.81	0.14-0.93	Fe2	0.295	0.288	0.281
TiO <sub>2</sub>	0.18-0.65	0.20-0.43	0.29-0.52	Mg	4.602	4.595	4.596
Al <sub>2</sub> O <sub>3</sub>	10.16-15.54	10.01-10.85	8.65-12.87	Sum	9.942	9.942	9.955
Cr <sub>2</sub> O <sub>3</sub>	49.21-54.83	45.75-48.25	46.12-52.39				
Fe <sub>2</sub> O <sub>3</sub>	1.69-5.19	10.16-12.84	6.77-9.00				
FeO	17.14-20.44	21.67-23.01	23.64-25.30				
MgO	8.81-11.34	7.02-7.92	5.31-7.28				
Cr#	0.68-0.77	0.74-0.76	0.70-0.80				
Fe3#	0.02-0.06	0.13-0.17	0.09 - 0.12				
Mg#	0.43-0.54	0.36-0.39	0.27-0.35				

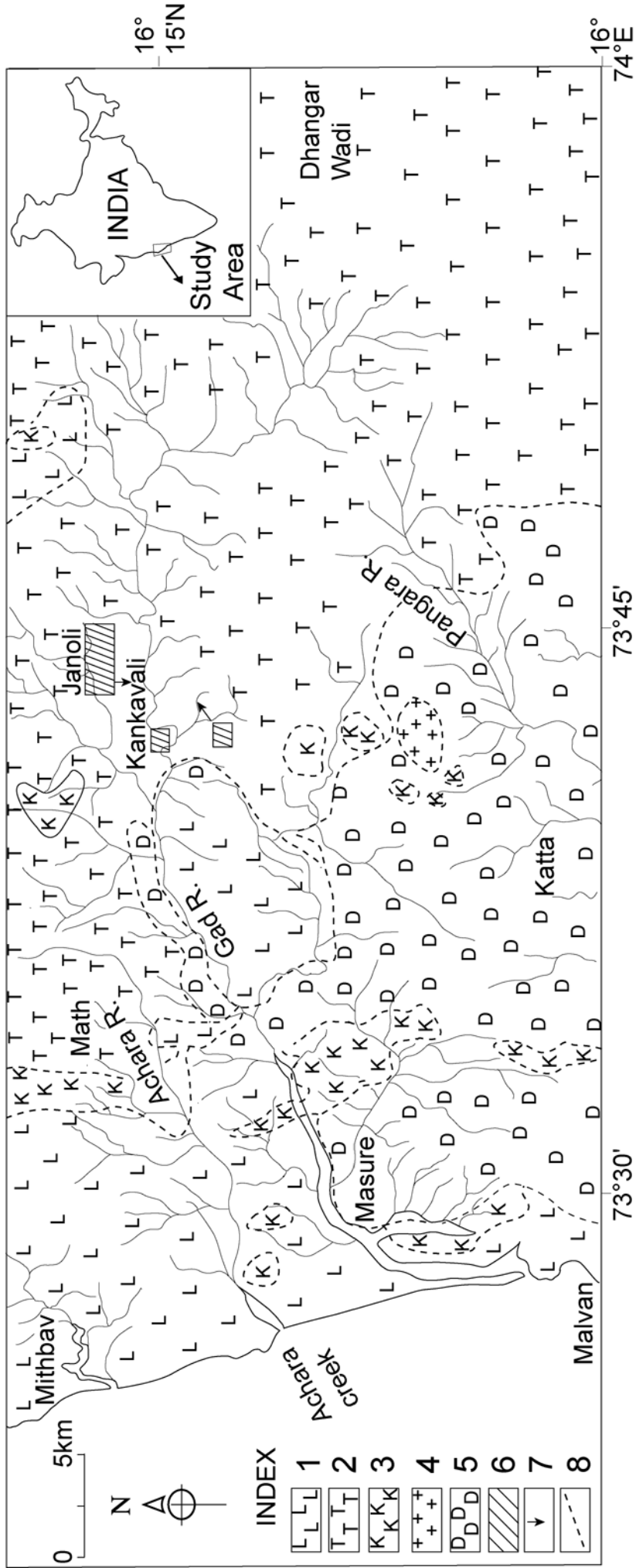


Fig. 1



(A)



(B)

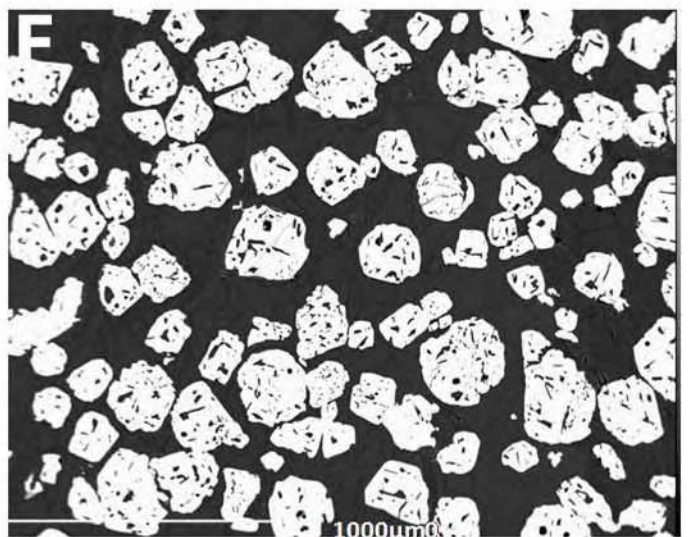
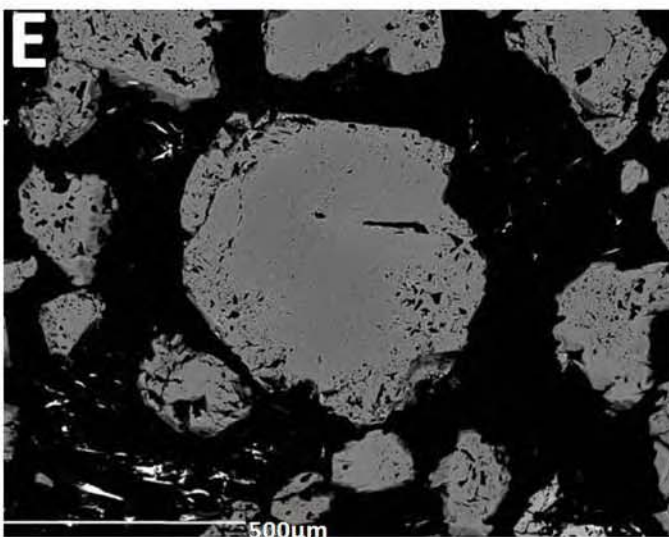
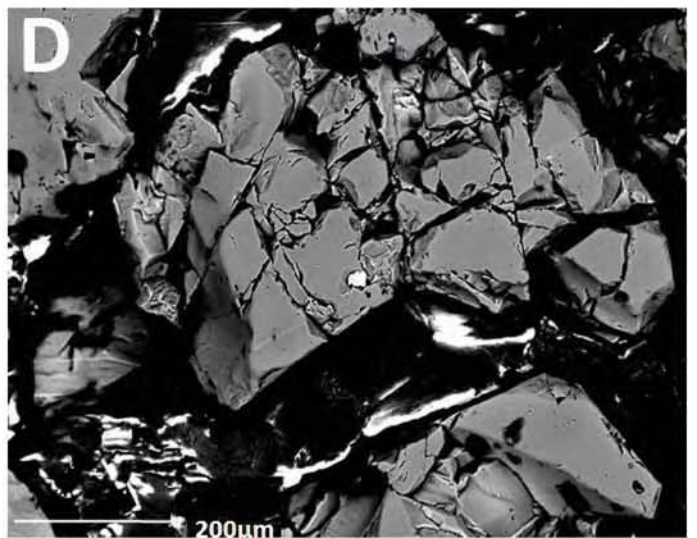
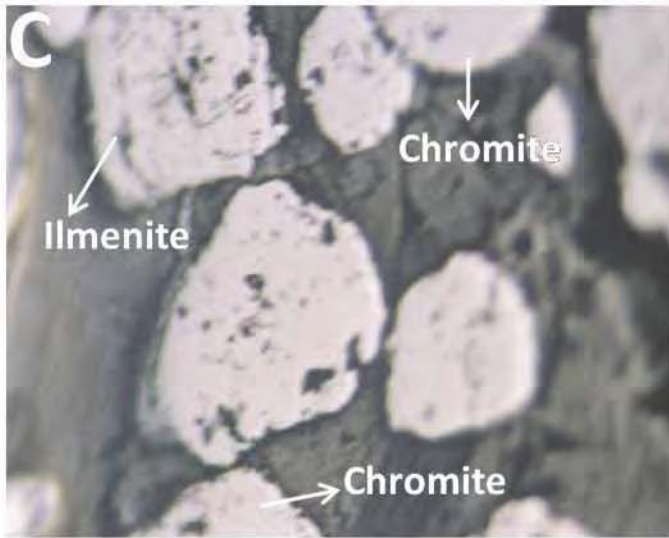
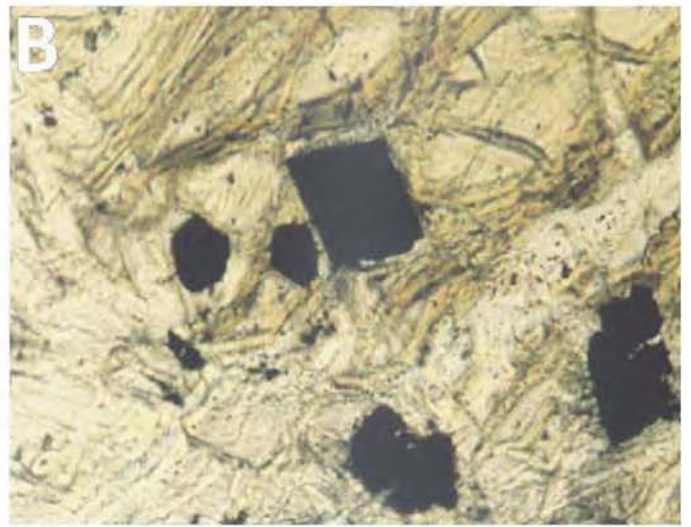
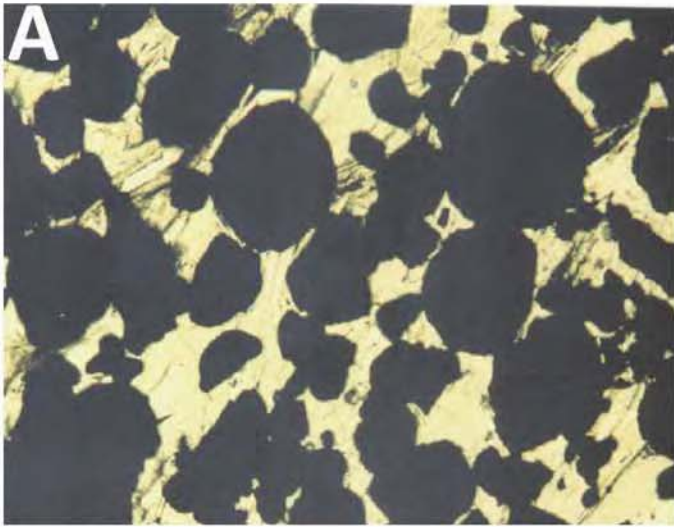


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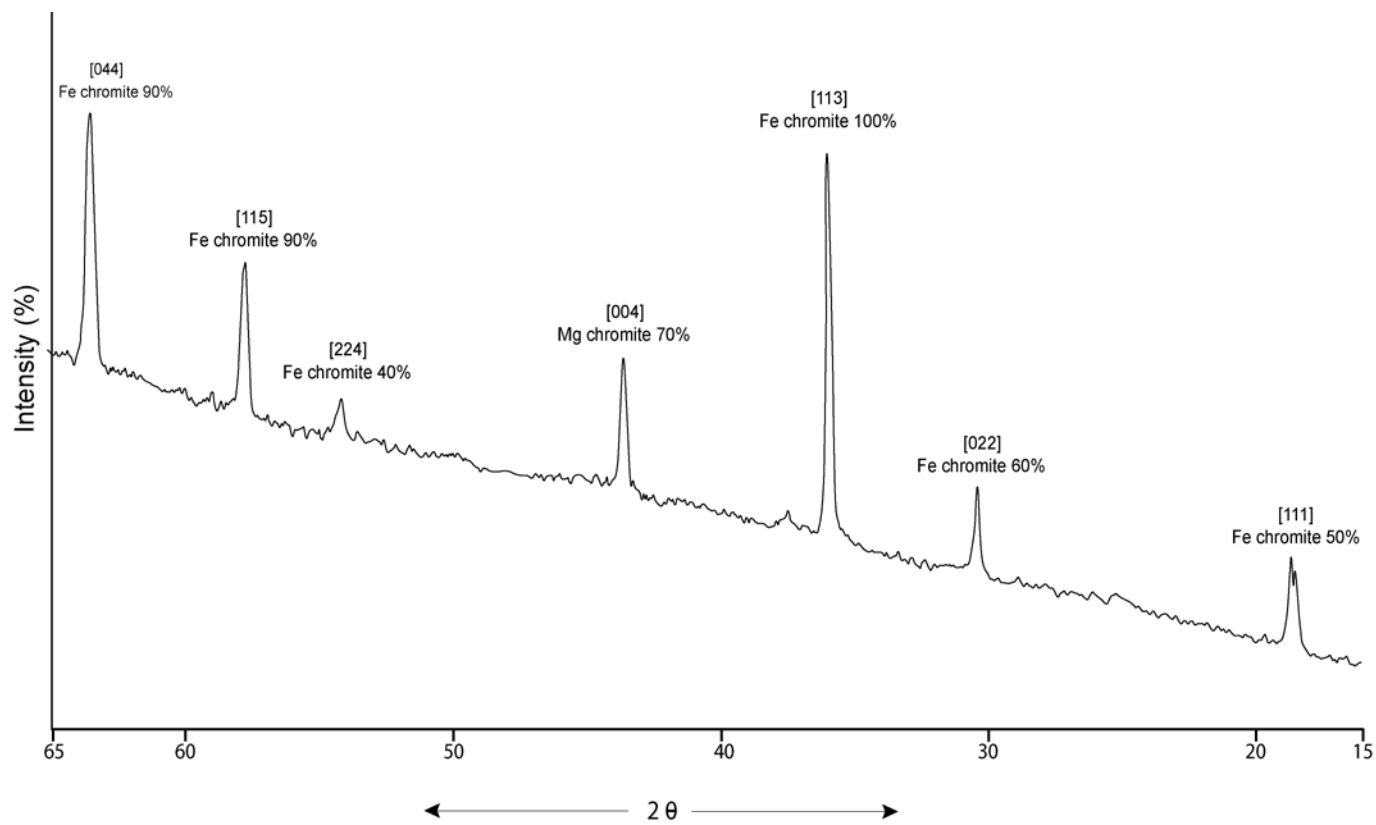


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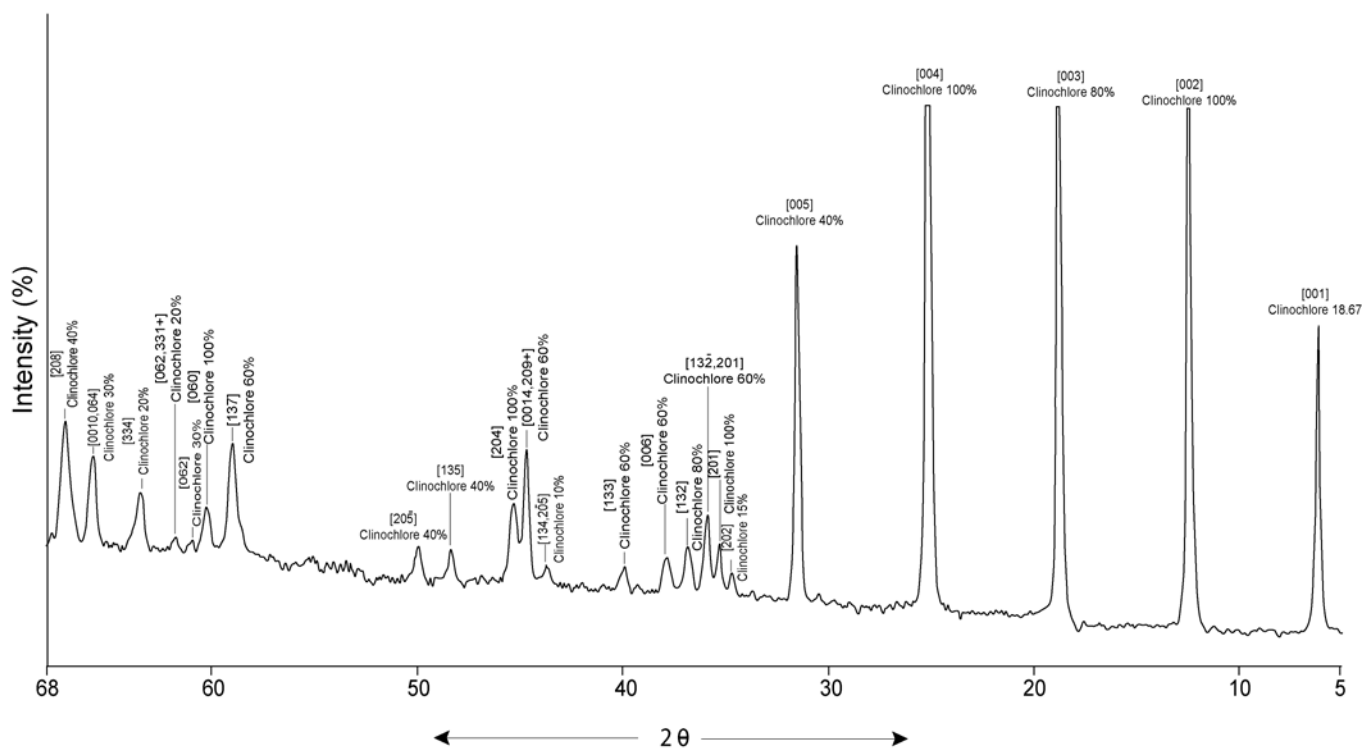
Fig. 2



**Fig. 3**



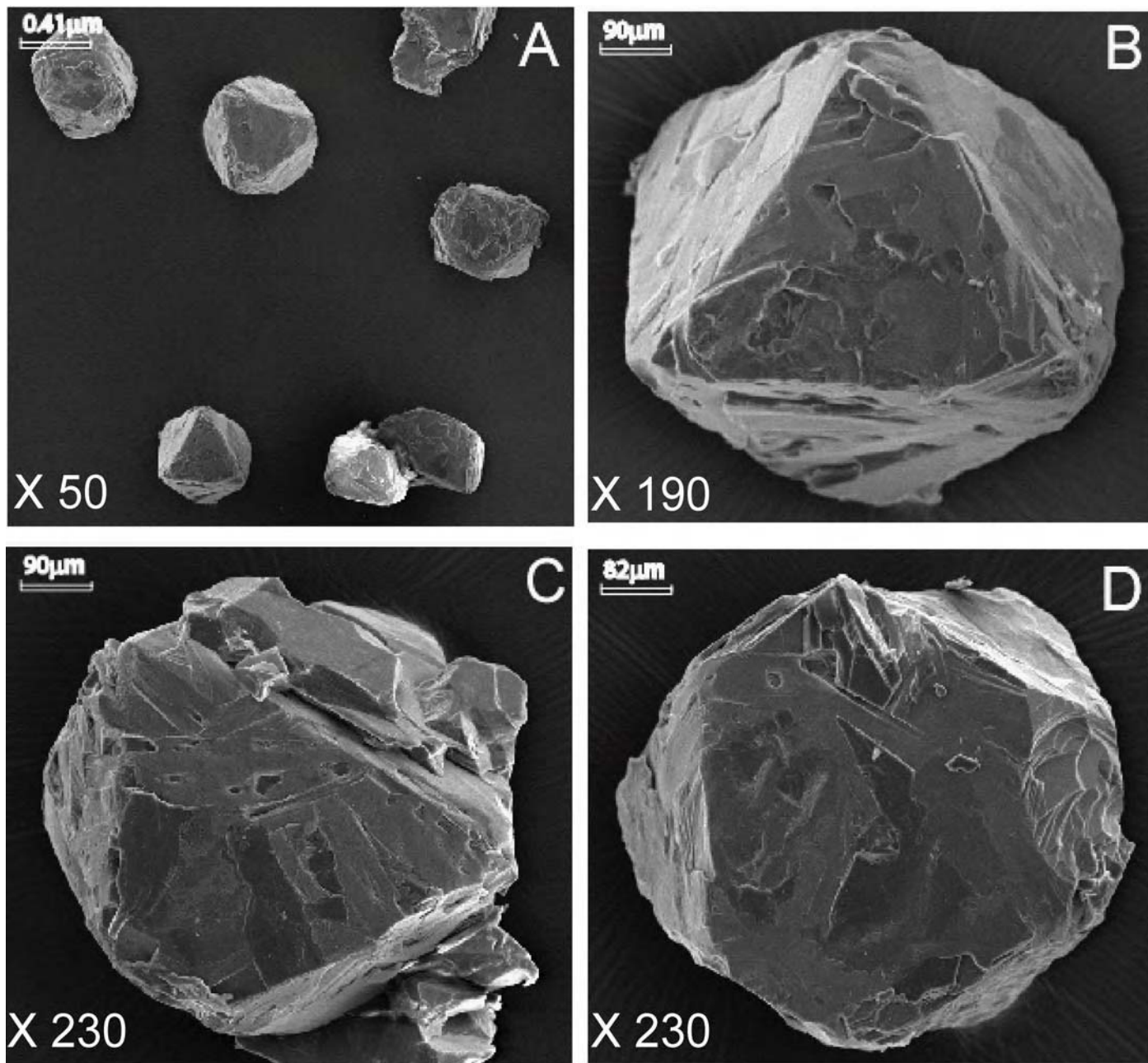
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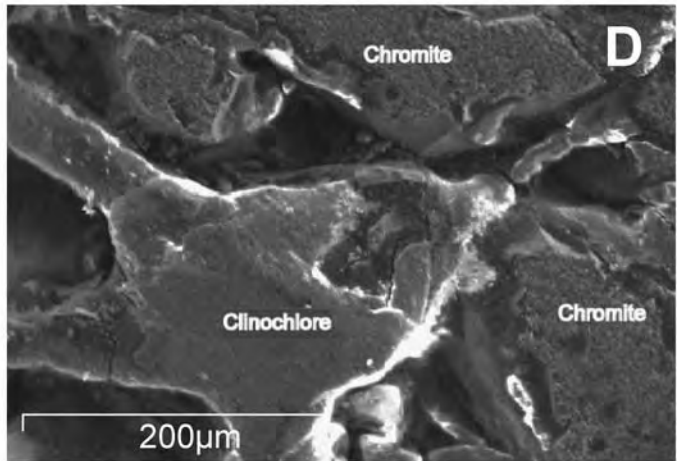
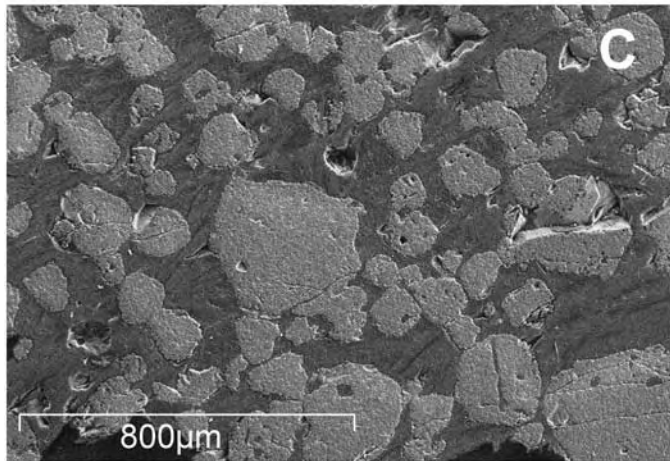
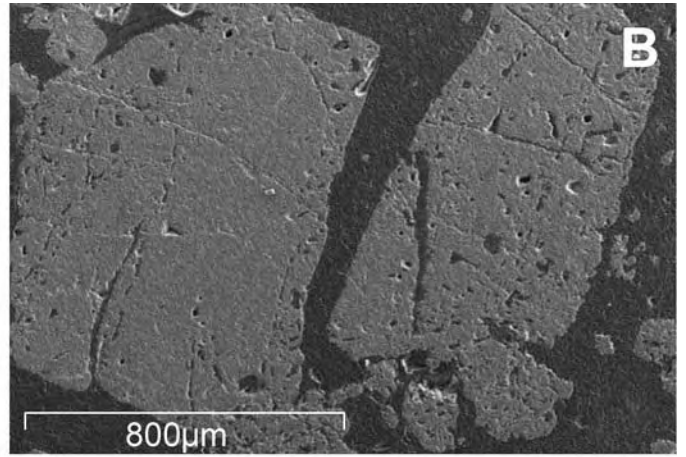
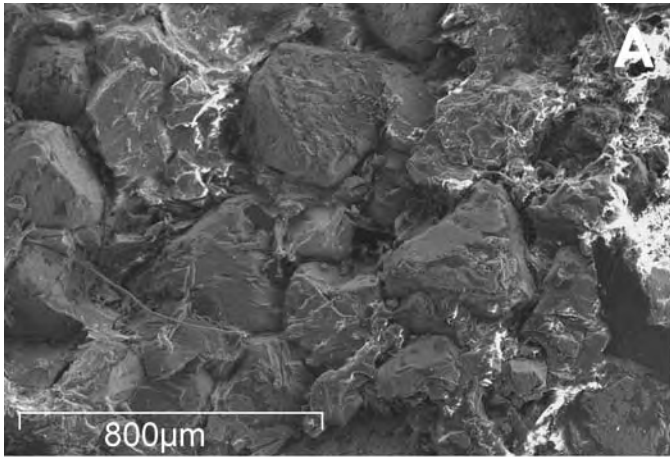
(B)

Fig. 4





**Fig. 5**



**Fig. 6**

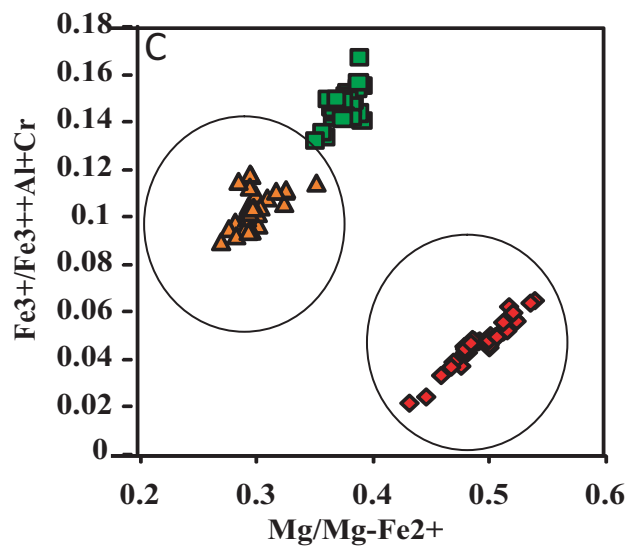
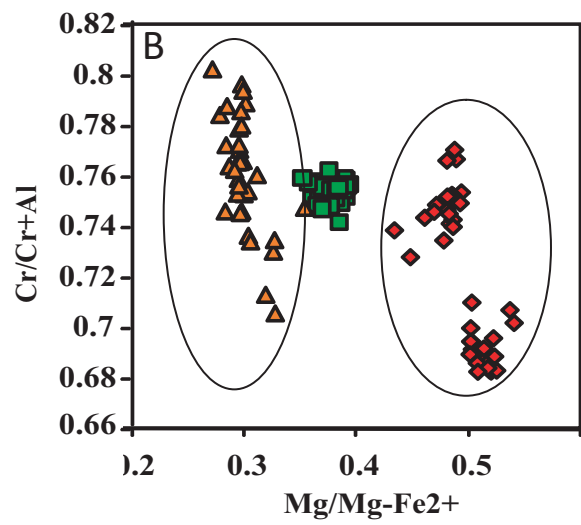
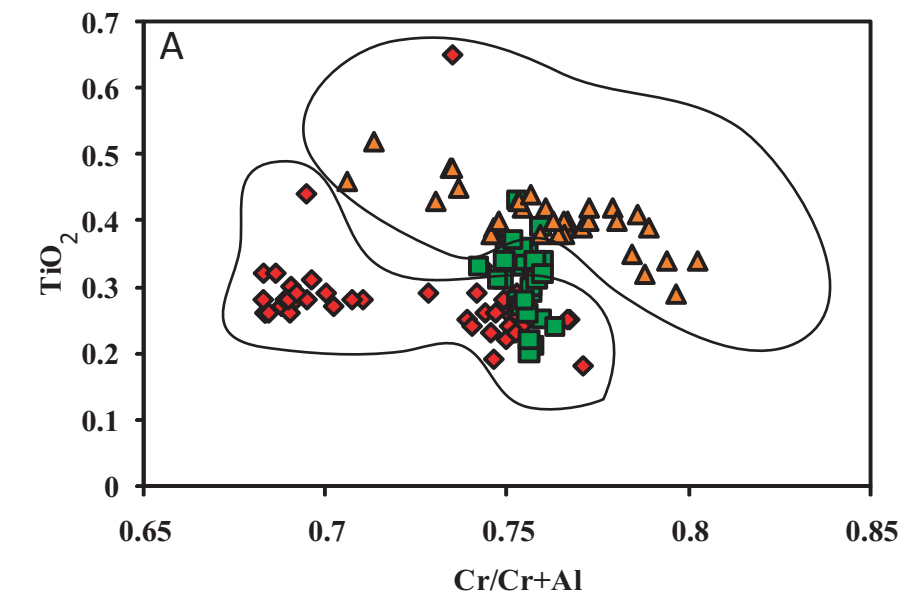


Fig. 7

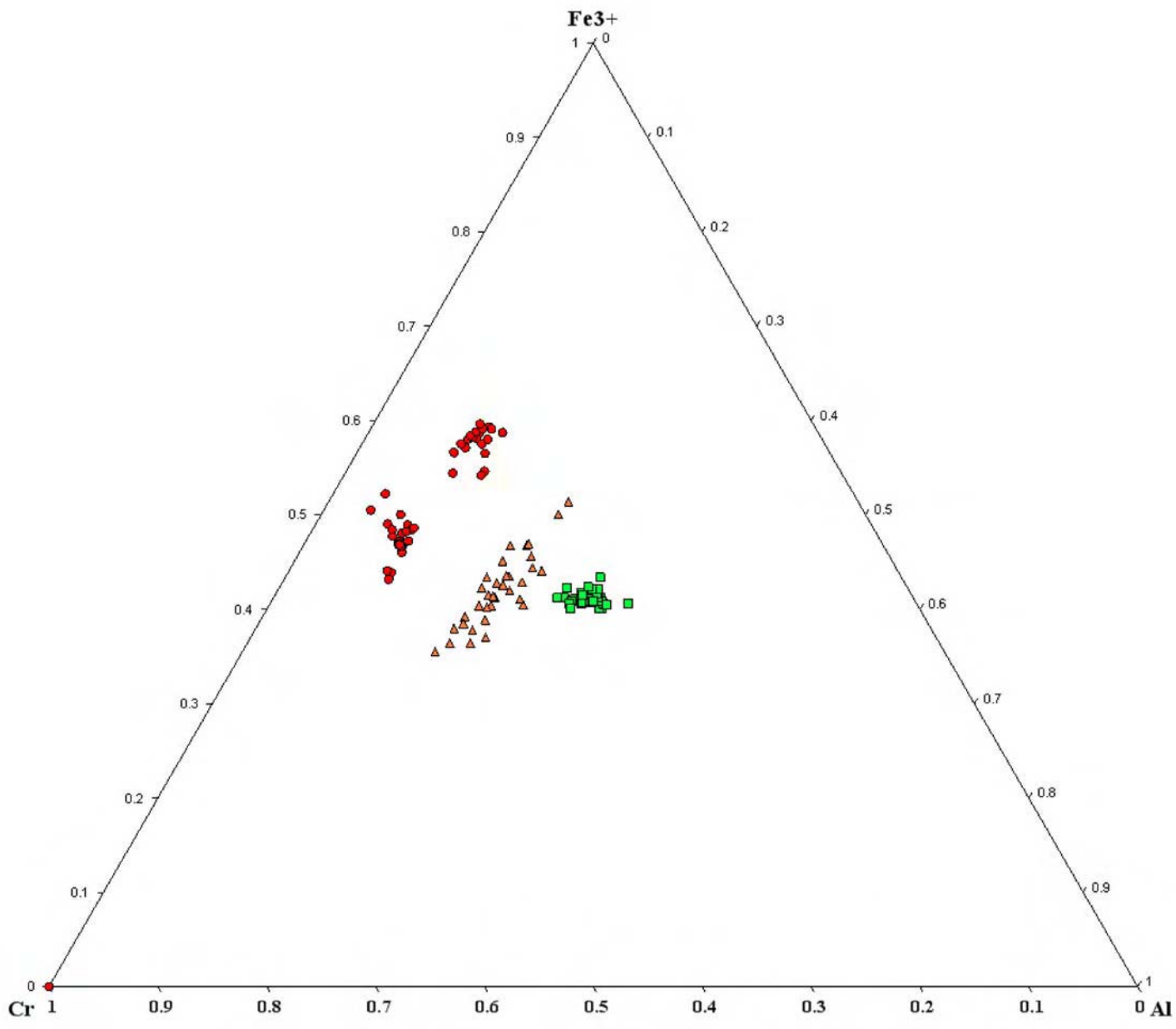


Fig.8