Nickel anomalies in ultramafic profiles of Jayachamarajapura schist belt, Western Dharwar Craton

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Jayachamarajapura schist belt consists predominantly of ultramafic rocks (mainly komatiite) with minor metasediments of the Sargur group in the Western Dharwar Craton. Sampling of plant species and soil over high magnesia komatiite-bearing areas of this belt has been carried out. Out of the seven plant species analysed, one species, i.e. *Vicoa indica* has indicated higher Ni values (540–896 ppm), and its potential as a local indicator for Ni has been recognized. The soil samples have yielded distinct signatures of Ni (3126–12,406 ppm) and Co (382–1071 ppm). The high Mg content of the soil samples indicates that the soil profile is mostly derived from undifferentiated komatiitic bed rocks, and the observed anomalies of Ni and Co warrant a detailed study of this belt for possible Ni–Co mineralization.

Keywords: J. C. Pura schist belt, komatiites, lateritic Ni ores, nickel–cobalt mineralization, primary Ni sulphides.

NICKEL is a hard, malleable and ductile, silvery-white metal mainly used for making stainless steel and other corrosion-resistant alloys. Its other important uses include coinage, plating, colouring glass, manufacture of nickel–cadmium and nickel–metal-hydride batteries and armour plates (war hardware), besides several other uses in metal and chemical industries. Not surprisingly, the world demand for nickel continues to grow[1] at an average of 4.4% per year. It is an important strategic metal in India and a considerable amount of foreign exchange is spent on its import (45,000–50,000 tonnes per year), as there is no indigenous production of nickel.

Ultramafic rocks are the chief source of nickel. Either as primary Ni–sulphide-enriched rocks (e.g. Norilsk in Russia, Sudbury in Canada, Jinchuan in China and Kambalda in western Australia) or as their lateritized products (e.g. Kumiambo in New Caledonia, Mindoro in Philippines and Sulawesi in Indonesia), ultramafic rocks continue to be the most productive suites for Ni and serve as the hotspots for its exploration. It is estimated that >64% of the world's Ni reserves and resources are in the laterite deposits and 36% in sulphides. Both 'types' have their advantages and challenges. Nickel sulphide deposits have the advantage of by-product values from Cu, Co and PGEs, whereas the laterite Ni reserves are large and could be worked by lower operating costs using high-pressure acid leach and hydrometallurgical techniques.

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Although India has several reserves of Ni, indigenous production has not been possible yet. The known occurrences at the Sukinda chromite belt and Simplipal basin in Mayurbhanj District and adjacent areas of Orissa, and the Andaman Island region, and other prospects in the country are essentially in mafic–ultramafic terrains and warrant intensive exploration owing to the strategic importance of Ni. Several areas in the Dharwar Craton, especially the Western Dharwar Craton contain ultramafic rocks and are associated with Ni anomalies as in Doddkanya, Sindhuvalli, Nagamangala, Shankaraghatta, Dandeli and Kaiga areas. As part of an interdisciplinary study of the mineralized areas of southern Karnataka, the Jayachamarajapura (J. C. Pura) schist belt was selected for detection of Ni–Cu–Co and Cr mineralization through geobotanical and soil-sampling studies and their possible implications on the exploration of Ni and associated metals. This communication presents the results of these studies.

The J. C. Pura belt is a small schist belt (~12 km^2 area) situated in the southern part of the Dharwar Craton (Figure 1) and forms part of the Sargur Group; the detailed geology of this belt has been given by Venkatadasu *et al.*[2]. It is predominantly made up of ultramafic rocks with less abundant amphibolite, cherty quartzites and iron formations. Normally, mafic–ultramafic sequences show gradational contacts and mafic flows invariably overlie ultramafics. Metasediments are intercalated with mafic flows. Among the ultramafics, peridotitic komatiites are dominant and show excellent pillow structures and quench textures. Extensive serpentinization and carbonization have altered the original mineralogy of these rocks (Figure 2 *a*). At many places, especially south of Rampura, thin bands and veins of chromite and magnesite are hosted within the serpentinized ultramafics (Figure 2 *b*). The chromite veins are primary and occur as thin layers formed during the early crystallization of the magma. However, structural disposition of the magnesite veins indicates that they have been formed at later stages when CO_2 (which was mostly released during extrusion of lavas) reacted with the ultramafic rocks. This belt is overlain by the Kibbanahalli arm of the Chitradurga schist belt in the north and north-eastern parts.

Geomorphologically, this belt forms a residual hill range (Figure 3) at an average elevation of 650 m and receives average rainfall of 600 mm. The soil profile is moderate with 3–10 m depth and is residual in nature. Due to variable gradient of the belt, the soil is poor to well-developed. In slopy areas, the topsoil is thin, which normally grades down to partially weathered bedrocks. In plateau and less-slopy areas, the soil profile is mature with recognizable A, B and C zones. In the sampled locations, soil thickness varied from 1.5 to 3 m. Here the top-

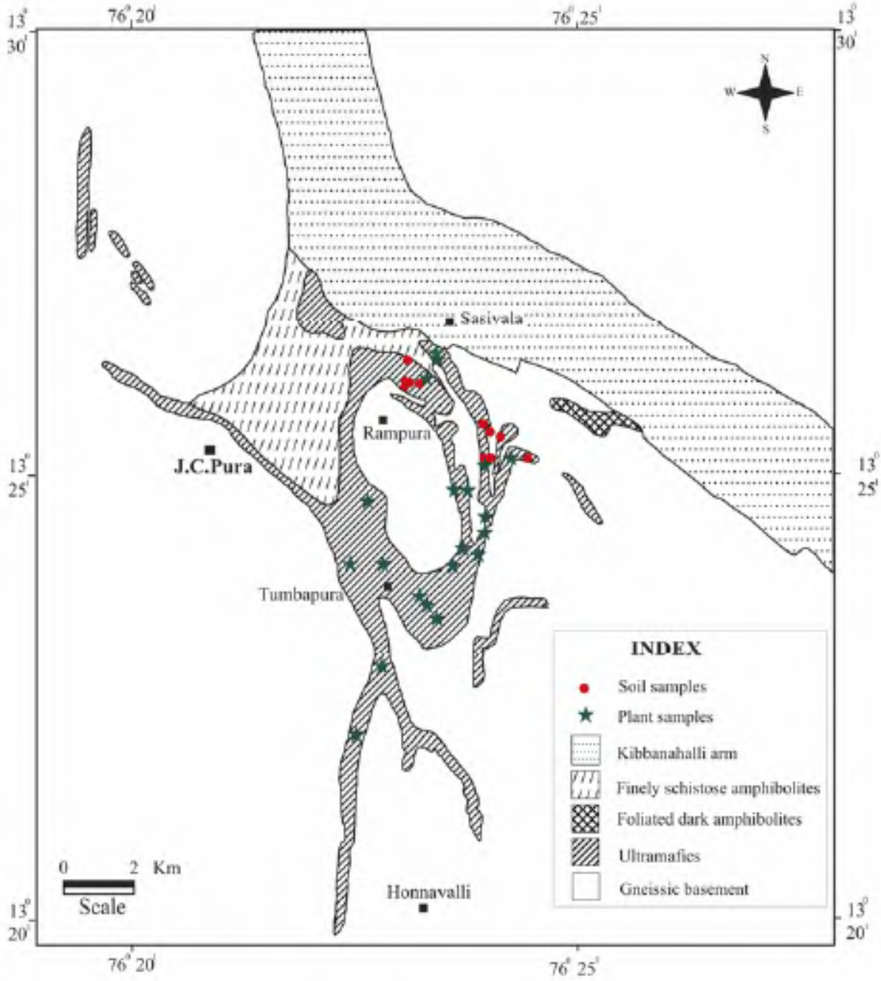

Figure 1. Geological sketch map of J. C. Pura schist belt (after Venkatadasu *et al.*[2]) showing soil and plant sample locations.

Figure 2. Spinifex textured komatite outcrop showing intense alteration (***a***), and veins and stringers of magnesite developed in altered peridotite (***b***) about 2 km south of Rampura.

soil is medium-to-coarse textured, brownish-grey coloured and silty-to-loamy in composition. The profile beneath this is normally yellowish-brown in colour and medium-textured. The pH of the soil varied from 5.1 to 6.91, indicating its slightly acidic nature. Altered komatiitic ultramafics underlie the soil profiles in the sampled areas. The hill ranges are covered by dry deciduous to scrubby forest with poor to moderate biodiversity. This vegetation pattern further reflect at the serpentinized ultramafic substratum, because such substratum does not support luxuriant growth of vegetation due to its high contents of Ni, Cr, Co and deficiencies of K and other essential elements[3]. Localized lateritic profiles are observed over ultramafic rocks at some places, which indicate the conspicuous *in situ* chemical weathering. However, due to vegetation (gross and scrubby shrubs) cover, the extent of lateritization in the entire belt could not be ascertained in the present study.

Locations of soil and plant samples are shown in Figure 1. Plant sampling was carried out in almost the entire belt on a wide spacing, whereas soil sampling was restricted to the northeastern part of the belt in the first phase. Herb species of *Leucas ciliata*, *Vicoa indica* and *Vernonia conyzoides* with fairly good density and distribution were sampled. In the absence of the herbal species, shrubs like *Dodonea visocosa*, *Pavetta indica*, *Maytenus emerginata* and *Cassia* species common in the belt were sampled. The sampling procedures followed are as enumerated in Brooks[4]. Mature and healthy leaves and tender twigs of the species were collected. Care was taken to avoid diseased and damaged plants. A representative sample of each species was collected and preserved as herbarium. The precise locations were recorded using a hand-held GPS and subsequently transferred to a map. The sampled plant materials were packed in muslin bags and shifted to the laboratory. They were dried under shade at room temperature of 25–28°C for two weeks. Before pulverizing, they were dried in a hot-air oven at 50°C for 5–8 min to remove surface moisture. Grinding and pulverizing was done using stainless-steel jars to reduce their size (<1 mm). To 0.5 g of this powder, 2.5 ml conc. HNO_3 and 0.5 ml H_2O_2 were added in a tefflon digestion vessel and digested in a microwave digester for 20 min. As the radiation energy is applied directly to the sample and digestion mixture, extremely rapid heating is possible and the sample material is digested by acid oxidation. On sufficient cooling, the contents from the tefflon vessel were transferred to a 100 ml volumetric flask.

Figure 3. Topographic expression of J. C. Pura belt, looking north.

The vessel was thoroughly rinsed using double-distilled water and the rinsed water was also transferred to the flask, and the contents diluted to 100 ml.

The soil samples were collected from a depth of 30–60 cm, from 'B' horizons of the soil profile developed over ultramafic lithologies. Sampling was carried out at close spacing to test the mineralization indicators. About 2.0 kg of soil from each location was collected and sieved to eliminate organic litter and coarse pebbles. The samples were dried under shade in the base camp, packed in the polythene bags and shifted to the laboratory. They were pulverized in a steel pestle and mortar and fine-ground in agate mortar to –200 mesh size. Thorough coning and quartering was done before representative samples were taken up for analysis. These soil samples were decomposed in a microwave digester as detailed above. To 0.25 g of sample, 2.5 ml of conc. HNO_3 and 2.5 ml HF were added in a tefflon vessel and digested for 25 min and the digested contents were made up to 100 ml.

Both soil and plant samples were analysed using atomic absorption spectrometer (AAS). Merck AAS standards were used for calibration. Repeat analyses were carried out at a five-sample interval to ensure precision.

In all, 44 plant samples representing eight species, viz. *Cassia auriculata* (11 samples), *D. viscosa* (14 samples), *V. indica* (7 samples), *L. ciliata* (3 samples), *Legas mollis* (1 sample), *P. indica* (2 samples), grass (5 samples) and *V. conyzoides* (1 sample) have been analysed for Ni, Co, Cr, Cu, Zn and Mg, and the results are presented in Table 1. Amongst the plant species, all samples of *V. indica*, one sample of *Cassia*, 3 samples of *D. viscosa*, 1 sample of *P. indica* and 1 sample of *L. ciliata* indicated Ni values. However, only *V. indica* (Figure 4) exhibited anomalous Ni in the range 540–896 ppm, much higher than the normal background distribution of 65 ppm in plant ash[4]. Amongst the seven samples of *V. indica* analysed, one sample did not show any Ni content, one sample shows 88 ppm and the rest over 500 ppm. Relatively higher (than background) and slightly anomalous values of Cu and Cr were also noticed in *V. indica*. However, none of the *V. indica* samples showed Co content. This herb has a tap root system with shallow penetration (less than 1 ft). The tolerance limit of this species for different metals still needs to be ascertained through experiments. However, when compared to mean Ni concentration in plants[4], the observed higher values in *V. indica* probably indicate that either this species has high tolerance for Ni or could selectively absorb it (Ni) for its nourishment. Thus, high Ni values only in *V. indica* in J. C. Pura belt has enabled to identify it as a local indicator for Ni. Most of the other plant species have shown slightly anomalous concentration of Cu and Cr, but all of them showed poor values of Zn. The distribution of these values possibly points to the Mg–Cr–Ni-rich substratum.

Table 1. Trace element analysis (in ppm) of plant samples

	Cu	Cr	Zn	Ni	Co	Mg
Vicoa indica						
JCP2	165.4	73.82	–	595.8	–	73.82
JCP5	298.4	219.58	–	540.16	–	219.58
JCP11	111.2	194.28	21.48	896.68	–	194.28
JCP14	289.4	191.06	38.34	648.26	–	191.06
JCP33	276.6	74.4	53.24	88.66	–	74.4
JCP40	282.6	42.96	60.06	–	–	42.96
JCP43	513.6	100.88	29.64	–	–	100.88
Cassia auriculata						
JCP1	199.4	86.94	56.62	–	–	86.94
JCP6	405.4	71.74	–	–	–	71.74
JCP7	141.8	52.22	16.36	–	–	52.22
JCP8	229.2	108.92	73.62	–	–	108.92
JCP9	225	86.42	11.12	20.8	–	86.42
JCP13	214.6	68.06	–	–	–	68.06
JCP17	299	75.34	–	–	–	75.34
JCP28	374	63.14	–	–	–	63.14
JCP32	314.6	64.32	–	–	–	64.32
JCP42	350.4	63.7	22.42	–	–	63.7
JCP44	176.4	50.88	–	–	–	50.88
Leucas ciliata						
JCP29	401.6	173.26	136.52	–	–	173.26
JCP36	333.4	71.88	25.18	–	–	71.88
JCP37	377.6	100.56	67.18	69.06	–	100.56
Vernionia conyzoides						
JCP3	235.4	90.76	146.2	–	–	90.76
Legas mollis						
JCP 39	6.9	103.64	206.18	–	–	103.64
Pavetta indica						
JCP24	118.6	39.22	–	22.56	–	39.22
JCP26	274.6	41.98	–	–	–	41.98
Grass						
JCP19	294.2	48.26	5.18	–	–	48.26
JCP22	90.8	98.7	–	–	–	98.7
JCP27	173.4	56.04	–	–	–	56.04
JCP30	275.6	49.64	–	–	–	49.64
JCP35	106.4	45.32	–	–	–	45.32
Dodonea viscos						
JCP4	290.4	58.3	45	–	–	58.3
JCP10	–	73.96	65.46	–	–	73.96
JCP12	282	71.72	123.46	–	–	71.72
JCP15	166	57.9	84.96	25.64	–	57.9
JCP16	437.8	52.9	87.92	–	–	52.9
JCP18	230.2	66.36	108.42	–	–	66.36
JCP20	214.2	55.7	5.32	55.32	–	55.7
JCP21	303.8	53.7	17.9	66.14	–	53.7
JCP23	366.4	30.66	40.08	–	–	30.66
JCP25	282.8	34.4	92.62	–	–	34.4
JCP 31	375.2	35.54	35.96	–	–	35.54
JCP34	162.2	35.76	56.02	–	–	35.76
JCP38	290.8	128.52	79.8	–	–	128.52
JCP41	373	26.66	104.86	–	–	26.66

–, Not detected.

High Ni concentration has been indicated in the soil samples (Table 2) of the J. C. Pura belt, with concentration ranging from 3126 to 12,406 ppm. Majority of the samples showed >5000 ppm concentration, which is much higher compared to the normal concentration in the soil (40 ppm)[4]. Ni is a relatively immobile element and

Table 2. Trace element analysis (in ppm, except for Mg) for soils

Soil sample no.	Cu	Cr	Zn	Ni	Co	Mg%
JCPS1	39.6	24751.08	7.6	10727	789.84	16.47
JCPS2	–	10869.8	379.32	5840.48	565.24	12.30
JCPS3	54	6405.36	–	4321.88	386.48	3.91
JCPS4	45.2	13014.4	118.16	10518.24	699.8	16.18
JCPS5	–	14528.2	–	10132.6	800.72	16.61
JCPS6	91.6	16272.68	240.64	12406.72	1071.04	39.54
JCPS7	53.6	7535.48	220.16	7608.44	626.56	17.31
JCPS8	42	6038.76	201.72	3441.8	382.24	23.29
JCPS9	32	7484.92	100.88	3126.16	366.92	24.73
JCPS10	88.4	12684.5	96	5596.6	644.88	43.35
JCPS11	40.4	22085.88	–	8227.72	740	4.89
JCPS12	88	9975.24	205.96	4589.08	429.92	13.02
JCPS13	77.2	14953.44	415.44	5009.04	506.88	8.35

–, Not detected.

Figure 4. *Vicoa indica* species from the northeastern part of J. C. Pura belt.

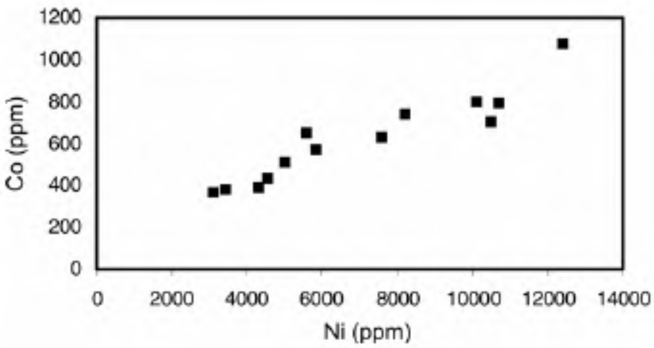

Figure 5. Positive correlation of Co with Ni in soil samples.

tends to be well preserved in residual soils. This could serve as a good indicator of nickel deposits[3]. The high Ni values in the study area clearly suggest that the komatiitic bed rocks contain significant Ni. Besides Ni, the soil samples have also yielded higher Co values (382–1071 ppm). Thus, higher concentration of Co could also be possible in the bed rocks. A positive correlation of Co is observed when plotted against Ni (Figure 5). However, Cu values in all the samples were low (32–91 ppm). Though these values are relatively higher than their normal concentration in the soil (15 ppm), they do not indicate any specific trend with Ni. However, the possibility of Cu being leached from the top horizon could have also affected its concentration, as it is a relatively more mobile element. Zn shows a broad range of concentrations (7.6–415 ppm). Majority of the Zn values were in the range of >200 ppm, but like Cu, Zn does not show any correlation with Ni values.

The higher concentrations of Cr, Ni, Co and Mg clearly reflect the high Mg-bearing komatiitic substratum in the sampled locations of the J. C. Pura schist belt. A geochemical study by Jayananda *et al.*[5] also indicates higher values of these metals in the bed rocks. Thus it is likely that komatiitic ultramafics, either in their magmatic or metamorphic state, structurally affected[6] or not, could be the primary source of Ni in this area. Several Ni prospects with proved reserves in western Australia have been shown to be high Mg-bearing komatiites[7] and constitute about 13.6% of the world's total inventory of mineable nickel. Residual weathering also enhances the value of the Ni-bearing rocks. This has been recently demonstrated from the Mindoro Ni prospect from the Philippines, where 0.9% Ni and 0.074% Co have been obtained from a thick lateritic profile over ultramafic sequences which is considered suitable for surface mining[8].

In the background of these aspects and the observed anomalous Ni and Co values in the komatiite-bearing areas, a detailed geochemical sampling, besides critical stratigraphic evaluation, including volcanic stratigrapy in the J. C. Pura schist belt is called for.

Magnesia-rich high-temperature komatiite sequences in the J. C. Pura schist belt appear to be enriched in Ni–Co metals. Hence, it is worthwhile to make a detailed study of the geochemical signatures of komatiite rocks, their metamorphism and structural deformation and their role in the possible Ni–Co sulphide ore mineralization, as adopted for many new prospects near Kambalda in Western Australia and Raglan in Quebec, Canada to explore potential zones. It may also be necessary to investigate the geomorphological evolution of the belt to ascertain the possible spatial extent and degree of *in situ* weathering, which are important for Ni and Co concentration by lateritic processes. Though Ni prices have indicated fluctuations (US$ 24/pound in 2007 to US$ 8.2/pound at present) in the international market, they are unlikely to fall below US$ 5/pound[8]. This can still afford profitable mining of ore with ~0.9% Ni and 0.074% Co, as has been shown for the Mindoro deposit in the Philippines. With no productive deposits in India, and in view of the strategic importance of Ni and Co, it is necessary to make an inventory of the Ni–Co prospects in the J. C. Pura schist belt.

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Evidence of a late-medieval mega flood event in the upper reaches of the Mahi River basin, Gujarat

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Palaeoflood records are of great significance in revealing the magnitude and frequency of large floods and thus the past monsoon conditions. The Mahi River, one of the major west-flowing rivers of India controlled by the southwest monsoon has preserved deposits of past floods dating back to 5 ka. A flood deposit emplaced by a mega flood event with discharge ~7300 $m^3 s^{-1}$ has been found at Diapattan in the upper reaches of the Mahi River basin. Based on the pottery available at the site, the event can be said to belong to late-medieval time. The timing of this mega flood event recorded at Diapattan in the Mahi River basin and records of the adjacent river basins suggest that this event represents the strengthened monsoon during the Medieval Warm Period (900–1400 AD). There exists a correlation between the extreme hydrological events in the Mahi, Narmada and Tapi river basins and this can be attributed to a regional monsoon domain.

Keywords: Mega flood event, monsoon, palaeofloods, pottery.

THE southwest (SW) monsoon controls the rainfall supply to the west-flowing rivers in India. As the flow of these rivers changes only as a consequence of rainfall variation, the flood records provide information about the SW monsoon conditions. Historical and palaeoflood data are an important source of information for establishing the magnitude and frequency of extreme floods that have occurred prior to the instrumental period[1]. The magnitude and frequency of large floods are precisely known for the period of gauge and historical records, but information on earlier floods is lacking. The sediment records of the large-magnitude floods are selectively preserved, whereas deposits from smaller floods are more likely to be removed by subsequent erosion due to their proximity to the active channel[2]. The availability of any palaeoflood record is therefore of significance in revealing the past monsoon conditions. The Narmada, Tapi and Mahi are the three major west-flowing rivers with a long palaeoflood history. Whereas the Narmada and Tapi are considered to be tropical rivers, the Mahi is a sub-humid to semi-arid river. However, the flood history of these rivers appears to be comparable and the extraordinary peak flood events dating back to late Pleistocene have been inferred in the

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