

Table 1. Magnetic properties and palaeomagnetic data of calc-granulites compared with those of Visakhapatnam charnockites

Rock type	$J_r \times 10^3$ A/m	$K \times 10^3$ (SI)	Q_n	D_m	I_m	k	α_{95}	λ_p	ϕ_p
Calc-granulite	1.3-350	0.5-35.7	0.24-8.6	278°	+38°	16.4	13°	24°N	12°N
Visakhapatnam charnockites (A) ⁶	—	—	—	280°	+35°	—	—	15°N	9°E

process. There are very few palaeomagnetic results reported from the Eastern Ghats belt of northern Andhra Pradesh. Though the geologic history of Eastern Ghats is known on a broader scale, there is need for palaeomagnetic investigations to bring out any local variations in metamorphic or tectonic activity.

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Discovery of Proterozoic boninite from Jagannathpur volcanic suite, Singhbhum craton, Eastern India

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Jagannathpur volcanic suite occurs as faulted out-liers within the Noamundi-Koira sequence of banded iron formation of the Singhbhum craton. Recent chemical studies have delineated some quartz normative samples from this suite which, similar to boninites, have high MgO, Ni and Cr content at an intermediate SiO_2 . These are differentiated along a calc-alkaline trend and their low $\text{CaO}/\text{Al}_2\text{O}_3$, Ti/Zr , Ti/Y and high Zr/Y ratios along with the high LILE and Zr are comparable with those of modern boninites. We infer that they are derived from MORB-type mantle source and represent an early phase of arc volcanism.

ALTHOUGH Proterozoic volcanism has a significant position in the geologic record of the Singhbhum craton¹ various volcanic suites have not received adequate attention. Their chemical affinity and/or tectonic setting has not yet been interpreted in terms of plate tectonics. Recently, in course of a geochemical study on Jagannathpur volcanic suite², samples containing low TiO_2 attracted much attention because of their possible tectonic significance in relation to the origin of ophiolites³ and because of their recognition as

distinctive, if not a diagnostic feature of boninitic lavas⁴⁻⁶. This prompted us to identify some boninite samples from this suite. Here we report the boninite discovery and discuss its significance.

On the western side of Singhbhum Granite, Jagannathpur volcanic suite occurs as faulted out-liers within the Noamundi-Koira sequence of banded iron formation⁷. It has been dated to be 1629 ± 30 Mys (million years) by K-Ar method⁸. Unlike the other Proterozoic suites of the region, viz. Dalma, Ongarbira, Dhanjori, Simlipal and Bonai volcanic suites, it does not have any sedimentary rock association and is free from regional metamorphism. It appears to be made up of a large number of block lava flows, individual flow sets have a plan width of 100 to 200 m. Banerjee⁷ identified the number of flows between 25 and 30. Less abundance of vesicles in the flows and lack of pyroclastics suggest that volcanism was predominantly nonviolent and had low volatile content.

Cameron *et al.*⁹ used mineralogical and petrographical features to identify boninites. As these features mainly reflect the modes of eruption and consolidation of a volcanic rock, they vary widely in any magma type and hence they may not be considered reliable^{4,10}. The chemical characteristics more consistently reflect the genetic differences between boninite and other magma types^{4,5,10-12}.

The most striking features of the samples (Table 1) are the high concentrations of refractory elements such as MgO, Ni and Cr combined with silica saturation and high values of large ion lithophile elements. Al_2O_3

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Table 1. Chemical analysis of boninitic samples from Jagannathpur volcanic suite

Sample No.	A1	C7	C17	E5
SiO ₂	55.99	54.94	56.50	56.59
TiO ₂	0.63	0.62	0.40	0.67
Al ₂ O ₃	12.78	9.66	12.60	11.28
Fe ₂ O ₃	3.95	4.87	4.03	2.49
FeO	7.36	5.56	5.20	7.40
MgO	8.39	13.19	10.15	8.45
CaO	5.80	7.31	4.97	6.15
Na ₂ O	2.71	0.97	2.91	2.85
K ₂ O	1.46	1.40	0.73	1.12
MnO	0.16	0.14	0.14	0.17
P ₂ O ₅	0.05	0.06	0.27	0.05
LOI	1.78	1.70	2.32	2.32
Total	100.06	100.40	100.22	99.54
Ni	172	269	104	191
Cr	531	730	216	541
V	283	282	268	288
Rb	91	24	61	46
Sr	385	246	270	190
Ba	416	389	627	370
Zr	219	153	232	137
Y	22	41	16	38
<i>Element ratios</i>				
Mg. No.	62.94	79.00	75.61	64.46
Ti/V	13	12	9	13
CaO/Al ₂ O ₃	0.45	0.75	0.39	0.54
Ti/Zr	17.24	23.50	10.33	29.32
Ti/Y	171.67	87.73	149.87	105.71
Zr/Y	9.95	3.73	14.50	3.60
Al ₂ O ₃ /TiO ₂	20.28	16.10	31.50	16.83
CaO/TiO ₂	9.20	12.18	12.42	9.17

and TiO₂ contents, similar to komatiites and boninites, are notably lower than the other basaltic lavas at similar MgO (ref. 13). Moreover, all the samples are quartz-normative and none of the sample is found to obey the criteria set by Arndt and Nisbet¹⁴ for the identification of komatiite.

These samples contain more normative hypersthene than the diopside content, which is a characteristic feature of calc-alkaline extrusive rocks¹⁵. Statistical discrimination analysis of major element compositions as suggested by Pearce¹⁶, low Ti/V ratios (< 20) as reported by Shervais¹⁷, and the decoupled behaviour of various major and trace elements are also suggestive of their subduction-related tectonic setting.

In comparison to arc volcanics¹³ these samples have low CaO/Al₂O₃, and Ti/Zr ratios while Mg numbers (100 MgO/MgO + FeO' mole% with Fe₂O₃/FeO ratio = 0.15) and Ni, Cr abundance are indicative of their primary nature with minor crystal fractionation. Their SiO₂ contents are also higher than those found at particular Mg number in MORB and arc volcanics¹³. Although their high LILE/HFS ratios are similar to those found in arc volcanics, the lower Ti/Y and higher Zr/Y ratios than the chondrite ratios are indicative of a

complex HFS distribution pattern. All such features are the characteristics of boninites^{4,5,10,11,18,19}.

Boninites are generally considered to be a product of subduction zone-related melting, though there is disagreement as to whether they are linked to a back arc basin volcanism²⁰, represent early phases of arc volcanism^{5,10} or follow arc tholeiitic volcanism^{4,5}. The field characteristics⁷ and clear cut volcanic arc trend of Jagannathpur volcanics² preclude the possibility of a back arc basin volcanism. As the Al₂O₃/TiO₂ and CaO/TiO₂ in primitive basalts tend to increase along with the degree of partial melting up to the ratio in chondrite, i.e. 20 and 17 respectively, Sun and Nesbitt³ concluded that MORBs are derived from a nondepleted mantle source while modern boninites with higher Al₂O₃/TiO₂ and CaO/TiO₂ are formed by the melting of a depleted source which had experienced a previous episode of magma extraction. Since Al₂O₃/TiO₂ and CaO/TiO₂ ratios in studied samples are much lower than those in modern boninites and are similar to those found in MORB, it is inferred that they are derived from MORB type mantle materials which probably had not melted previously. In this way they appear to represent an early phase of arc volcanism.

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Sulphur enrichment in a sediment core from the central western continental margin of India

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Anomalous sulphur values in relation to organic carbon have been found in the sediments of a core collected from the central western continental margin of India. The relationship between organic carbon and sulphur is similar to that of the sediments deposited in anoxic environment. Our study indicate that the excess sulphur is mainly due to the addition of sulphides from the shallow regions by mass sedimentation processes rather than water column sulphide formation as observed in anoxic environment.

MARINE sediments rich in organic carbon are also usually rich in sulphur content and much of the sulphur is in the form of pyrite¹. Pyrite is formed owing to interaction of reactive iron with H_2S , which is produced by the reduction of interstitial dissolved sulphate by bacteria using sedimentary organic matter as energy source and reducing agent². In normal marine sediments (sediments overlain by oxygenated bottom water), a linear relationship is expected between organic carbon and sulphide sulphur, as 1 g carbon is oxidized for each $4/3$ g H_2S sulphur produced³. If a constant proportion of total deposited organic matter is reduced to form pyrite, the remaining organic matter should correlate positively with pyrite sulphur, and the regression line pass through the origin and the average S/C ratio is 0.36 (refs. 2,3).

The occurrence of pyrite has been reported from the Arabian Sea sediments⁴. We discuss here the relationship between organic carbon and sulphur in a 12-m-long sediment core collected from the central western continental margin of India (latitude $16^{\circ}26'N$, longitude $69^{\circ}57'E$, water depth 3627 m, Figure 1). Subsamples collected at 5-cm and occasionally at 10-cm interval were washed with distilled water and rendered salt- and pore-water free. Organic carbon content was determined with CHN analyser (Perkin-Elmer model 200B). Reduced sulphur content was determined gravimetrically

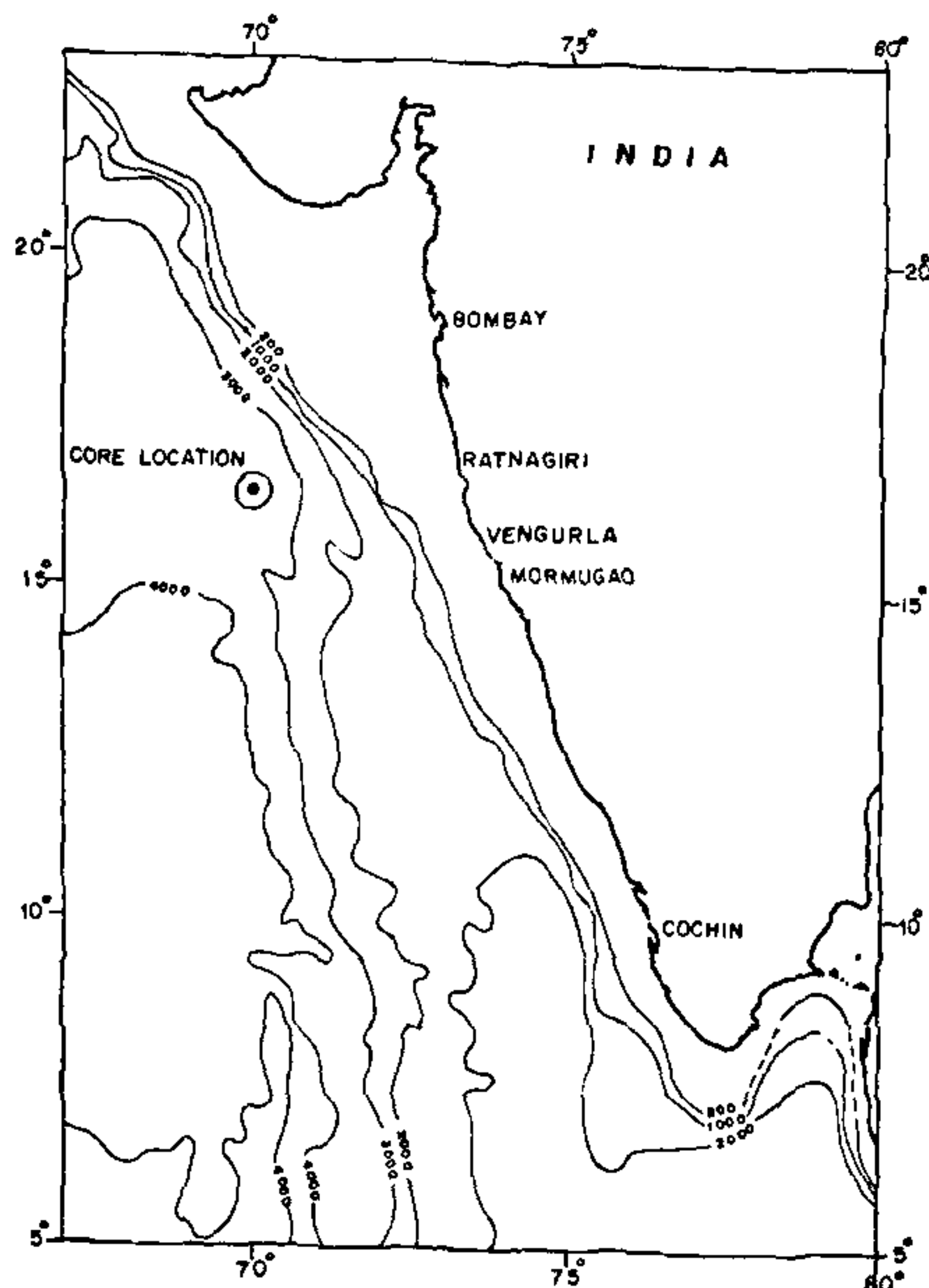


Figure 1. Location of the core. Simplified bathymetry of the western continental margin of India. Depth contours in meters.

according to the method of Vogel⁵. To avoid dilution effects of carbonate, the sulphur values were recalculated on a carbonate-free basis. Organic carbon varied from 0.5 to 5.9 wt% and sulphur from 0.28 to 3.65 wt%. The S/C ratios changed from 0.263 to 2.764. Figure 2 is a plot between organic carbon and sulphur. The regression line (line 1) intersects S-axis positively at 0.908 with a slope of 0.291. The correlation between organic carbon and sulphur is 0.416. Also shown in Figure 2 are the regression lines for normal marine sediments³ (dashed line) and surficial sediments of the Black Sea⁶ (line 2). The similarity between line (1) and line (2) and the distribution of points in the C-S plot indicate that the sediments are enriched in sulphur compared to normal marine sediments, as most of the points fall above the dashed line. The Black Sea is a different oceanographic environment from other seas, as it has a layer of H_2S laden water in its water column⁷. The positive S-axis intercept in the C-S plot of the Black Sea sediments (line 2) results from the addition of sulphides at the sediment water interface, that formed due to reaction of water column produced H_2S with iron⁸.

The Arabian Sea experiences a well-developed