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ARCHAEAN GEOLOGY INVESTIGATIONS IN SOUTHERN INDIA

C. S. PICHAMUTHU

Abstract

A brief review is made of the investigations conducted on the Archaean rocks of southern India from the time of Newbold (1838) to the present. Problems connected with Dharwar stratigraphy and the relationship of Peninsular Gneiss to Dharwar schists and charnockites have given rise to considerable differences of opinion and the main features of these controversies are summarised. Much of the confusion is due to the fact that terms like 'Dharwar' and 'Peninsular Gneiss' have been used in very different senses by individual workers. Geochemical and geochronological investigations are of recent origin and have yielded some interesting results. An account is given at the end of some of the problems in Precambrian geology that are still awaiting solution in southern India.

INTRODUCTION

Research on the Archaean rocks of southern India commenced with the work of Newbold who, in a series of papers published between 1838 and 1844, described the geology of some regions which fall within the present-day boundary of the State of Karnataka. He was the first to separate the schists from the gneisses and record instances of intrusion of gneisses into schists. Foote (1886, 1888, 1895) coined the term 'Dharwar System' to designate all crystalline schists (of volcano-sedimentary origin) as opposed to felsic gneisses, and considered the Dharwar as younger. Holland (1900, 1902, 1909) was, however, of the opinion that all the Dharwar rocks were not younger than the Archaean gneisses. Almost all the early geologists (Hatch, 1902; Walker, 1902; Maclaren, 1906; Middlemiss, 1917; Jones, 1922; Heron, 1935; Crookshank, 1948) found the gneisses intruding the schists, but explained it away as due to local re-fusion, or plastic deformation and penetration, because at that time it was believed that the crust of the earth was granitic in composition, and that the schists had a sialic basement.

DHARWAR SCHIST-PENINSULAR GNEISS RELATIONSHIP

In the former princely State of Mysore (now Karnataka), the geologists of the Survey headed by Smeeth (1901, 1916) and Sampat Iyengar (1920), found numerous evidences of gneissic intrusion into schists and, therefore, considered the Dharwar formations as older, a view that was accepted by Fermor (1909, 1936), Rama Rao (1936a), and Pascoe (1950). More recently some have expressed a diametrically opposite view that the gneisses *nowhere* intrude the schists, and that they are all older, and form a basement to the schists (Nautiyal, 1966; Radhakrishna, 1967; Swaminath *et al.*, 1974). There has, however, been a gradual withdrawal from this extreme position, and it is now conceded that the gneisses intrude the high grade schists but form a basement to the younger schist belts (Radhakrishna, 1974; Swaminath *et al.*, 1976), that the Kolar belt has suffered a subsequent thermal event (Ramakrishnan *et al.*, 1976), and that the mantled gneiss domes in the younger belts are 'rejuvenated basement' and not just 'basement highs'.

NOMENCLATURE

Considerable confusion has recently been caused by several interpretations given to the term 'Dharwar'. The main cause for this is the attempt made to sub-divide

Foote's Dharwar System into 'Dharwar' and 'Pre-Dharwar'. If a sequence with a particular name is divided, separate names should be given to the parts; a name designating the whole sequence should not be used for a part of it (Hedberg, 1976). That is how confusion arose in charnockite nomenclature because Holland gave the same name 'charnockite' to the whole series as well as to its acid member. Some schists cannot, therefore, be 'Dharwar' and others 'Pre-Dharwar'; the sub-divisions should have distinct names. Even among those who are using these terms there is no agreement at present as to where Dharwar ends and Pre-Dharwar commences. The prevailing confusion has been aggravated by some geosynclines being called 'Dharwar type' (Ramakrishnan *et al.*, 1976). Normally, Pre-Dharwar rocks should lie below the oldest schist formation (say, Sargur, if it is proved to be the oldest). But now, it is Sargur to some, Kolar and Hutti belts to others, and even Sandur belt to some others. 'Dharwar basement' has, therefore, many different meanings; this is a very unsatisfactory state of affairs.

It is necessary also to use the term 'Peninsular Gneiss', which was coined by Smeeth in 1916, in its original meaning. According to Smeeth, it is a complex of various granites that 'give evidence of successive intrusion, and the fact that the earlier forms contain their own pegmatites which are truncated by subsequent forms, points to a long continued period of plutonic activity. Frequently, the various members mingle either by repeated injection or absorption or crushing and shearing, and we get zones or areas which are highly banded or with complex flow structure. Other portions are more homogeneous and appear as granite masses. Amongst these latter are some which may be definitely later in age than the gneiss as a whole' (Smeeth, 1916).

Terms like Dharwar and Peninsular Gneiss are fundamental in Indian geology; they have become international terms, and gone into the very fabric of Precambrian nomenclature. Great caution should, therefore, be taken before attempting to change their significance and scope.

Peninsular Gneiss is a migmatitic complex which probably includes basement and intrusive components. This implies that there could be pre- and post-Dharwar gneisses. Both Dharwar schists and Peninsular Gneisses cover a vast span of geological time during which sedimentation and intrusion were taking place. Field and laboratory studies should be undertaken to identify these different episodes. Tonalite pebbles in the Dharwar Kaldurga conglomerates have given very old dates—3250±150 m.y. (Venkatasubramanian and Narayanaswamy, 1974). Peninsular Gneisses are younger (2950-2600 m.y.), and are mainly granodioritic.

PRIMORDIAL CRUST

Suggestions regarding the nature of the primordial crust vary from granitic gneiss (Radhakrishna, 1967), migmatites (Swaminath *et al.*, 1974), oceanic tholeiites, and basaltic komatiites (Viswanathan, 1974 a, b) to partly oceanic and partly reworked continental crust (Ramakrishnan *et al.*, 1976); also, that segments of the Indian proto-crust may be anorthosites, or basic and ultrabasic charnockites of komatiitic chemistry (Viswanathan, 1975). Geochemical investigation by the N.G. R.I. group has led to the conclusion that the primitive crust was basaltic—a thin unstable oceanic type; that the Archaean mantle beneath southern India was peridotitic; that the period from late Archaean to lower Proterozoic was transitional from simatic to sialic crustal development; and that cratonisation was over by mid-Proterozoic (Naqvi and Hussain, 1972, 1973; Satyanarayana *et al.*, 1973, 1974; Naqvi *et al.*, 1974, 1976; Divakara Rao *et al.*, 1975; Naqvi, 1976).

STRATIGRAPHY

For some decades it has been known that the younger Dharwar chloritic schists prevail in northern Karnataka, and the older hornblendic schists in the south as well as bordering some schist belts, especially the Chitradurga belt (M.G.D. geological map, 1915). It was then believed that both schists and gneisses were igneous in origin. The sedimentary origin for some Dharwar rocks was finally established only in 1935-1936 (Pichamuthu, 1935 a, b, c; Rama Rao, 1936 a, b). This was a major break-through in Archaean geology research in southern India.

In 1901, Smeeth suspected that the Kolar belt was older than the Shimoga and Chiknayakanhalli belts. In 1905, Sampat Iyengar classified the Chitradurga Schist Belt into three divisions based on unconformities. The first comprehensive classification of the Dharwar System was attempted by Rama Rao (1936 a) when he divided it into Lower (basic and acid flows and intrusives), Middle, and Upper, separated by unconformities. He considered that all of them were intruded by Peninsular Gneiss. Like Smeeth, he was of the opinion that the original basement was not recognisable.

The geosynclinal development of Dharwar was envisaged by Pichamuthu in 1946; he then postulated two cycles of sedimentation in the Shimoga and Chitaldrug belts each with its attendant igneous phenomena, and stated that the Dharwar sequence started with an igneous complex of basic volcanic flows and intrusives followed by sedimentary successions interrupted by batholiths and stocks of acid rocks.

In 1968, Srinivasan and Sreenivas recorded a geosynclinal history in the Chitradurga belt starting with shelf passing through flysch, and finally to molasse facies of sedimentation. In 1972, they classified the Dharwar System into a four-fold division based on tectonomagmatic and atmospheric evolution.

In 1972, Naqvi and Hussain proposed two sequences in the Dharwar Supergroup, one older than 2600 m.y. and another younger. Later, Naqvi *et al.* (1974) considered the older as 'true greenstone belts' and the younger as 'geosynclinal piles'. According to their latest thinking (Naqvi, 1976; Naqvi *et al.*, 1976) the Kolar, Holenarsipur, Nuggihalli, and Sargur schists are 'true greenstone belts' (3500-3200 m.y.), and the Shimoga, Bababudan, and Chitradurga belts are 'greenstone-like geosynclinal piles' (3000-2500 m.y.). Somewhat similar suggestions have also been made by Radhakrishna (1974), and Ramakrishnan *et al.* (1976).

Till about 10 years ago all crystalline rocks in southern India were considered to be of Archaean age. Nautiyal (1966) was the first to suggest, without any supporting evidence, that the Dharwar schists were Proterozoic, and that the gneisses, amphibolites, and charnockites were Archaean. In 1972, Srinivasan and Sreenivas stated that the Dharwar rocks were Proterozoic and overlaid the Archaean charnockites. According to Radhakrishna (1975), the Archaean greenstone belts are Nuggihalli, Kolar, Ramagiri, and Hutti, whereas the Shimoga and Chitradurga belts are Proterozoic. Similar distinctions are made by Ramakrishnan *et al.* (1976) who consider that, apart from high-grade schists, there are two types of greenstone belts– one, Archaean (Sandur, Kolar, Hutti, Ramagiri), and another, Proterozoic (Bababudan, Shimoga, Chitradurga).

These speculative exercises are still continuing, but cannot be conclusive unless backed by geochemical and geochronological data. Correlation should be based on lithology and stratigraphy but there is very little evidence as yet of this type of detailed field work. In many of these classifications, the Chitradurga belt is considered to be Proterozoic, but this has been invaded by a granite which is at least 2535 m.y. old. The Kurubarmaradikere trap has given Rb-Sr ages of 3690 m.y. and 3205 m.y., and the Ingladhal trap 2595 m.y. (Crawford, 1969 a). The galenas in this belt are 3000 m.y. old (Venkatasubramanian *et al.*, 1977). It is now generally agreed that the age of 2500 m.y. limits the Proterozoic-Archaean boundary, and on this basis some of the traps in the Chitradurga belt are not Proterozoic but Archaean in age.

Since the term 'Dharwar' is now being used with several meanings, there are differences of opinion as to which is the lowermost member of the Dharwar Supergroup. According to Foote (1895), in the Bellary district of Karnataka, it is in some places a trap flow, in others a micaceous quartzite, and in the Copper mountain ridge a bed of hematite quartzite. To some it is an orthoquartzite-carbonate bed (Srinivasan and Sreenivas, 1968), to others it is a current bedded quartzite, and to some others it is an oligomictic quartz-pebble conglomerate (Ramakrishnan *et al.*, 1976). The occurrence of conglomerates, and instances of schists 'resting' on gneiss, no doubt indicate unconformities, but not necessarily that they represent the very base of the Dharwar Supergroup (Pichamuthu, 1974). According to Naqvi (1976), the Holenarasipur-Nuggihalli belt is the oldest sequence in the Dharwar protocontinent, and that nowhere is there proof that it is underlain by a sialic crust.

Owing to a northerly tilt of the Dharwar craton, the older and more-metamorphosed rocks occur in southern Karnataka as narrow belts, small strips, and islands, representing not only some of the formations exposed at deeper levels, but also older sequences. Except for slices of high-grade rocks at the borders of some schist belts, the main mass of rocks in Karnataka generally show a progressive increase in metamorphism from north to south (Rama Rao, 1936a; Pichamuthu, 1953; Radhakrishna, 1956; Narayanaswami, 1970). This prograde metamorphism in southern Karnataka has been confirmed by the recent geochemical work of Anantha Iyer and Narayanan Kutty (1973, 1974, 1976) done on potash feldspars, garnets, and amphiboles.

The Dharwar craton is partly surrounded by the Eastern Ghats mobile belt formed penecontemporaneously with it and characterised by high-grade metamorphic rocks such as charnockites and khondalites. The N-S Dharwarian strike in southern Karnataka is deflected westwards by the ENE-WSW Eastern Ghats trend, the disturbed zone being marked by sheared gneisses and mylonites. There is no abrupt break between the lower grade schist-gneiss region and the high grade charnockites as suggested by Nautiyal (1966) and Iyengar (1976); the change from one to another is transitional (Pichamuthu, 1974). This granulitic belt is polymetamorphic and could represent reactivated segments of the basement.

In 1936, Rama Rao stated that the Sargur rocks resembled Fermor's Eastern Ghat facies, and raised the question whether they could not be the more intensely metamorphosed rocks of the Shimoga schist belt, or a zone of still older Dharwar rocks not found elsewhere in the Shimoga area.

High grade schists and gneisses may represent exposed co-eval roots of lower grade volcano-sedimentary-granite suites. If this is the case, it would result in crustal zonation—vertical metamorphic, as well as age variations. The transition between low and high grade terrains would then be continuous, as noticed in the Dharwar craton.

The available dates for Eastern Ghats rocks indicate that they are younger than the Dharwar schists. The belief that the charnockites are all older than Dharwar is not supported by present geochronological data. There are charnockites formed during different episodes of metamorphism with as wide a spacing of ages as 2740-2650 m.y., 2130 m.y., 1500-1300 m.y., and 600-500 m.y.

Some charnockites are products of regional thermal metamorphism of gneisses and schists (Pichamuthu, 1965). In southern Karnataka, charnockites are interbedded with runs of quartzites and banded ironstones. In Tamil Nadu, the association of pyroxene granulite-magnetite quartzite-pyritiferous quartzite in the granulite facies is considered to be the metamorphic equivalent of the basalt-ferruginous chert-sulphide association in greenstone belts; the Satyamangalam complex of schistose rocks exhibiting amphibolite facies grade of metamorphism has been correlated with the Wynaad complex of Kerala and the Sargur complex of Karnataka (N. G. K. Murthy, personal communication).

GEOCHEMISTRY

Early attempts at geochemical investigation were made by Karunakaran and Neelakantan (1947; 1948) in the Nellore district; by Howie (1955) and Subramaniam (1959, 1962, 1967) in the charnockite region of Tamil Nadu; and by Leelanandam (1967 a, b; 1969 a, b, c) in the Kondapalli area, Andhra Pradesh. More recently, Sisir Sen, Sobhen Ray and others in I.I.T., Kharagpur have been doing detailed geochemical work on minerals and rocks in the type area for charnockite near Madras (1970, 1971, 1974).

Since 1964, workers in the National Geophysical Research Institute, Hyderabad, have been continuously engaged in geochemical research on several fundamental problems in Archaean geology, such as the nature of the primordial crust, protocontinental growth, evolution of greenstone belts, recognition of continental nuclei, etc. Viswanathan (1974, a, b; 1975) has introduced several modern geochemical concepts, and was responsible for the recognition of komatiites. Anantha Iyer and Kutty (1973, 1974, 1976) are actively engaged in the geochemical investigations of minerals in the Dharwar craton.

GEOCHRONOLOGY

Holmes (1955) was the first to date Indian rocks. Aswathanarayana (1956; 1962; 1964) did pioneering work in this field. Sarkar and his associates (1964; 1968) have contributed considerably in dating Indian rocks. Vinogradov and Tugarinov (1964); Crawford (1969 a, b), and Venkatasubramanian and his associates (1974, 1977), are responsible for a number of dates. The Geological Survey of India, the Atomic Minerals Division, and the National Geophysical Research Institute are prominent among the institutions actively engaged in geochemical and geochronological investigations.

FUTURE WORK

In this brief account of Archaean geology investigations in southern India certain problems for further investigation have at appropriate places been pointed out. The tempo of research has appreciably quickened during the last 10 or 12 years giving rise to several questions still to be answered. Among the many problems awaiting solution, the following may be mentioned:

1) Correlation and reconciliation of several proposals made regarding Precambrian stratigraphy;
2) Identification of the different episodes in Peninsular Gneiss and Charnockite formation;
3) Mineralisation episodes;
4) Nature and extent of migmatites:
5) Mantled gneiss domes;

6) Distribution and nature of mafic and felsic dykes;
7) Relationship of charnockites and khondalites;
8) In Tamil Nadu, whether the gneisses and migmatites represent the Peninsular Gneisses of Karnataka, whether the granulites are metamorphosed greenstone belts, and if so, whether they have a recognisable basement.

Basic work like geological and structural mapping should have priority. The major thrust will, however, have to be in the fields of geochemistry and geochronology. Sophisticated instruments like mass spectrometer, electron microprobe, XRF, XRD, etc. are required, but these facilities are either negligible or absent at present. It is very necessary that steps should be taken for the early setting up of at least one Central Laboratory equipped with advanced instruments necessary for this type of work which can be utilised by interested workers in government organisations and universities.

Geochemical and geochronological investigations would help in throwing light on some specific problems in the Archaean geology of southern India, such as: (1) Recognition of vestiges of the primordial crust; (2) Age and varieties of granites, gneisses, and charnockites; (3) Age and nature of pebbles in Dharwar conglomerates; (4) Age and variety of xenoliths in granites and gneisses; and (5) Classification and composition of dykes.

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Address of the author

C. S. PICHAMUTHU, President, Geological Society of India, 1, De Souza Road, Bangalore 560025.

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RADIUM CONTENT OF SOME RIVER WATERS OF INDIA

S. D. CHATTERJEE AND PARTHA BANERJI

Abstract

The radium content of river waters collected from eighteen different Indian rivers has been measured. The river water can usually be classified into two categories: limpid and turbid. The radium content of limpid waters has been found to be lower ($\sim 10^{-16}$g/ml) than that of its turbid partner ($\sim 10^{-15}$g/ml). In the latter case, the radium contents both of the filtered component and the sediment have been separately measured. The sediment invariably exhibits a higher value.

INTRODUCTION

The natural radioactivity of water is derived primarily from the radioactive rocks and minerals with which the water has been in contact. In certain areas, radioactive gases emitted from magmas may impart some radioactivity to natural waters emanating from thermal springs. Heretofore, very little information has been published in our country regarding the radium contents of normal surface and river waters. This is probably because the radium content of these waters is usually relatively small and there is no advertising incentive comparable to spring waters that are used at spas and health resorts. Moreover, the radioactivity of river water is subject to wide variation according to the character of the gathering ground, the land over which the river flows, the discharges of its tributaries, sewages, industrial wastes, the season of the year and climatic conditions. The magnitude of the seasonal change will vary, of course, depending on the particular stream of river in question. Accordingly, it is necessary to record the natural radioactivity of the running water of some selected rivers at suitable sites and to check the trend of its variation with time. A second important consideration is that the assessment of radium content of a river at selected sites along its route may furnish valuable information about geographical distribution and location of radioactive minerals in the river valley. This has been typified in the case of the Ganges.

With the advent of the nuclear age, another important factor has become evident, viz., the selection of river sites for the installation of water-cooled reactors. As the river water flows through the reactor, certain elements present as dissolved salts become radioactive from the neutron bombardment, and other radio-isotopes present as corrosion products are washed from the heat-exchange surfaces. The reactor effluent thus contains a complex mixture of radio-isotopes, each contributing to the total activity. It should be noted, however, that the radio-isotopes present in the effluent are emitters of β and γ-radiation only. The concentration of α-emitters, such as radium and uranium, below the plants, is not substantially different from that which occurs in the river stream. The various radio-isotopes discharged with reactor effluent into the river accumulate in aquatic organisms. It would therefore be worthwhile to make periodical ecological studies on the abundance of river organisms together with quantitative estimation of radio-elements at suitable sites along the line of shore of particular rivers.

The present paper deals with preliminary measurements of the radium content of the water of some Indian rivers.

EXPERIMENTAL METHOD

It is well-known that Ra^{226} the familiar radium isotope with a half-life of 1,620 years decays to the noble gas radon by α -emission.

Thus, $_{88}Ra^{226} \xrightarrow{\alpha} {}_{86}Rn^{222}$. Radon itself is radioactive, decaying with a 3.82 days half-life by α -emission. Since radon can easily be isolated from the parent material and introduced directly into the ionisation chamber, the measurement of the radioactivity of radon gives a quantitative estimation of radium present in the mother material. This particular technique is well established and has been successfully utilised in many radiological laboratories all over the world.

The experimental investigation can be divided into three sections as follows:

a) Chemical treatment of the sample: Twenty litres of river water are collected in a polythene container. If the water happens to be turbid, the insoluble material is allowed to settle down at the bottom of the vessel. The clear water at the top is treated separately from the sediment for the measurement of radium content.

The clear water is treated with pure calcium chloride (2.0 gm/litre of water) and sodium potassium carbonate, so that radium, if present, could be co-precipitated with calcium carbonate. The possibility of such a separation was envisaged by Otto Hahn (1936). Finally, the acid soluble carbonate is dissolved in dilute HCl and transferred to a bubbler for the estimation of radon as described in the next section.

One gramme of the sediment is powdered and mixed with 0.2 gm of pure $BaCl_2.2H_2O$, in an agate mortar. Next it is incorporated in 10 gm of fused $NaHSO_4$. The mixture is heated to bright redness at 600°C for 20 minutes. It is then taken up by distilled water and filtered. The residue is treated by dilute HF for eliminating silica and rare acids. The filtrate is dried and the residue is fused with fusion mixture. The mass is washed with water and then redissolved in dilute HCl. The HCl solution contains practically the total amount of radium, which is then estimated by the radon method as described below.

b) Estimation of radium: The method of estimation of radium is based on the evaluation of the qnantity of radium emanation which a given amount of material disengages in a given time. The form in which this method is largely utilised consists in measuring the radioactivity of the emanation given out by a known volume of a solution containing dissolved radium. This method was first advocated by Curie. It is very practical and gives very precise results.

The solution is placed in a bubbler, having a volume of about 100 cc and provided with two stop-cocks. However, only a cc of the solution is necessary. The solution is purged of the emanation by bubbling argon through the solution for 10 minutes; for this purpose one end of the bubbler is connected to a water pump while the other end is attached to a gas cylinder via a regulator. It is advisable to filter the gas through cotton wool to arrest unwanted dust particles. After purging, the stop-cocks at the two ends of the bubbler are closed and the hour is noted. Fresh emanation is now allowed to accumulate within the bubbler. The best results are obtained with a time of accumulation between one and two days, when the radium content is appreciable. For measurement of low radium content, it is advisable to wait for 12 days for equilibrium to be attained. The emanation is then introduced into a cylindrical ionisation chamber, which serves to measure its activity.

The ionisation chamber is initially evacuated and connected to the bubbler via a gas transference device, operated by the manipulation of a mercury column. The carrier gas argon from a cylinder chases the accumulated radon in the bubbler into the ionisation chamber. When the transfer is completed, the atmospheric pressure is not yet reestablished in the ionization chamber. The latter is kept at a reduced pressure for avoiding loss of emanation by leakage. It is advisable to wait for some time so that following the development of active deposit, the ionization current attains its maximum value. The maximum is steady between 3-4 hours after the aspiration of the emanation. It is during this time that the measurements are to be made, taking care that the atmospheric pressure in the chamber has been established a few minutes before the measurement.

Calculation

Let $X =$ no. of gms of Ra contained in the solution.
$t =$ time of accumulation of radon.
$N =$ number of divisions traversed by the electrometer needle in unit time (here chosen 1 min.).
$n =$ number of division-minute of leakage.

The ionozation-current, expressed in division-minute is

$$i_t^{\text{div-min}} = N - n \qquad \ldots\ldots (1)$$

If one has waited for a time long enough to attain the equilibrium between radium and its emanation, the quantity of emanation would be

$$q_\infty = \frac{q^t}{1 - e^{-\lambda t}} \qquad \ldots\ldots (2)$$

where $\lambda =$ probability that any particular atom will disintegrate in unit time, the radioactive disintegration constant.

The corresponding ionization current would be

$$i_\infty^{\text{div-min}} = \frac{N-n}{1 - e^{-\lambda t}} \qquad \ldots\ldots (3)$$

If one knows the number C of gms of Ra, which at equilibrium furnishes a current of one division per minute in the same apparatus, one would have evidently

$$X = \frac{(N-n)\,C}{1 - e^{-\lambda t}} \qquad \ldots\ldots (4)$$

For determining C, it is necessary to operate with a solution containing a known quantity of Ra, known as the standardisation of the apparatus, C being called the constant of the apparatus.

c) Measurement of radioactivity: The most common method for determining radon quantitatively in amount between 10^{-9} and 10^{-13} curie is to measure the ion current in a gas when the radon mixed with the gas is introduced in an ionization chamber. Our experimental arrangement for the measurement of minute quantities of radon closely resembles the experimental set up described by Kropf (1939). In order to reduce the contribution of background ionization caused by local contamination or cosmic rays, the measurements were carried out using the differential ion-chamber technique. In this arrangement, equal voltages ($\sim$500 volts) of opposite sign were applied to the outer cylinders of two identical ion-chambers, (2-3 litres) placed in juxtaposition. One of the chambers, called balancing chamber was kept constantly filled with pure argon at atmospheric pressure, while the measuring chamber was filled with argon laden with radium emanation from the bubbler at the same pressure. To collect electrons, a negative potential was applied to the measuring chamber, while the balancing chamber, collected positive ions only. The collecting electrodes of both the chambers were connected to the terminal of the deflecting needle of a Lindemann electrometer with a sensitivity of 100 divisions per

TABLE I. Radium content of Indian river waters

Collection time	Name of the river	Nearest locality	Approximate distance from origin (miles)	Nature of water	Radium-content ($\times 10^{-15}$ g/ml)	Remarks
Mar., 1965	Ajoy	Mihijam	60	Limpid	0.20	In all cases of turbid waters, clear water was separated from insoluble sediments. The radium content in such cases refers to the clear component only. The radium-content of the insoluble sediment of some river waters is given in Table II.
Nov., 1965	Brahmaputra	Gauhati	1200	Turbid	1.10	
Jan., 1967	Cauvery	Seringapatanam	200	Limpid	0.95	
,, ,,	,,	Krishnarajsagar	220	,,	1.19	
Mar., 1965	Damodar	Ramgarh	50	,,	0.80	
Jan., 1966	Falgu	Gaya	100	,,	1.14	
Mar., 1965	Ganges	Hardwar	100	,,	0.55	
Apr., 1965	,,	Varanasi	875	,,	0.67	
June, 1965	,,	Patna	1000	,,	0.61	
Mar., 1965	,,	Calcutta	1450	Turbid	1.15	
June, 1965	,,	Diamond Harbour	1500	,,	1.30	
Jan., 1966	,,	Kakdwip	1550	,,	0.46	
June, 1966	Godavari	Rajamundry	750	Limpid	0.76	
Mar., 1965	Jamuna	Delhi	200	Turbid	1.14	
Nov., 1965	Jhelum	Srinagar	100	Limpid	1.80	
June, 1966	Krishna	Vijayawada	700	,,	1.17	
Jan., 1966	Mahanadi	Cuttack	500	,,	0.65	
Oct., 1966	Mahananda	Siliguri	30	Turbid	0.64	
Jan., 1967	Narmada	Jubbalpur	100	Limpid	0.77	
,, ,,	Rangeet	Teestabazar	100	,,	0.81	
Oct., 1966	Rapti	Gorakhpur	250	Turbid	0.58	
May, 1965	Rupnarayan	Kolaghat	175	,,	0.64	
Sept., 1965	Subarnarekha	Ranchi	50	,,	0.76	
Oct., 1966	Teesta	Sevoke Road	100	,,	1.35	

TABLE II. Radium content of sediments of turbid river waters

Collection time	Name of the river	Nearest locality	Radium content ($\times 10^{-15}$ g/ml)	Remarks
Mar., 1965	Ganges	Calcutta	1.89	
June, 1965	,,	Diamond Harbour	2.54	
Mar., 1965	Jamuna	Delhi	3.00	
May, 1965	Rupnarayan	Kolaghat	5.30	

volt. The constant of the apparatus C, was determined with the help of a Hönigschmid radium substandard obtained from the Radium Institute, Vienna.

RESULTS AND DISCUSSION

Two or more analyses were made of each water sample, the average value being listed in Table I. The individual determinations are mostly within 10 per cent of average values, with greater variation as the samples approached lower levels. It may be emphasized, however, that although the results on the majority of the water samples are estimated to be accurate within 10 per cent, it may by no means be inferred that the average value of the radium content of the individual raw water has been established within this range. Water chemists are well aware of the seasonal, as well as the day-to-day variations in the concentration of dissolved salts in streams and rivers. The discharge of a stream is dependent upon precipitation. As run-off water characteristically has a relatively low concentration of dissolved salts, the usual finding is that salt concentration is lower at times of high water.

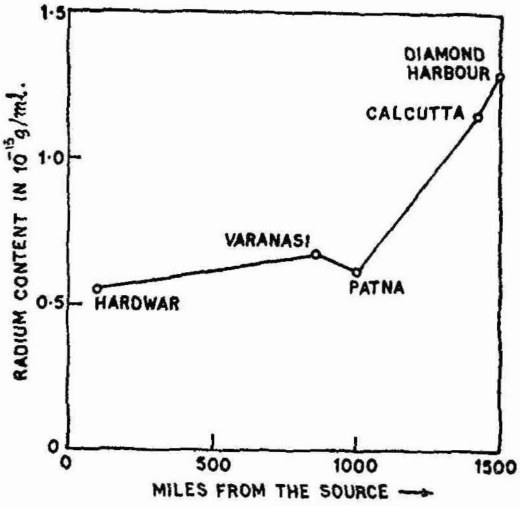

Figure 1. Variation of radium content of Ganges water with distance from the source.

Thus, a seasonal variation in the concentration of radium may be inferred. This effect will be most noticeable in river supplies and will probably be less significant in supplies derived from large lakes or deep wells.

Table I gives the radium content values of the clear component of the river waters. In the case of turbid waters, the clear component was separated from the insoluble sediment and treated as test sample. The radium content of the sediments is shown separately in Table II.

Despite the uncertainty produced by single-spot sampling procedure, it is noteworthy that the data meet several tests of internal consistency, for example, the radium content of Ganges water at Hardwar is 0.55×10^{-15} g/ml. If it is assumed that raw waters very low in dissolved salts contain a high portion of run-off water or are collected from areas underlain by comparatively insoluble rocks, a low radium concentration is expected. Taylor (1958) reports approximately the same value for the radium content of Thames water in England. The Ganges water shows a 20% higher value of radium content at Varanasi. This may be partly due to the confluence of the Jamuna with the Ganges at Allahabad. Incidentally, the radium content of the Jamuna water was found to be higher in the vicinity of Delhi. It is probable that the natural radioactivity of Jamuna water is high because Jamuna originates from a number of thermal springs at Jamunotri. The slight diminution of radium content in the Ganges water at Patna may be due to the discharge of many tributaries like Gogra, Sone, Gandak etc., into it above Patna, thereby diluting its radium content. The radium content further downstream shows a rapid rise between Patna and Calcutta. The existence of several radioactive thermal springs in this region suggests that the Ganges drains through a terrain containing radioactive minerals. The radium content of the Ganges water shows its maximum value at Diamond Harbour. Further down, it declines sharply at Kakdwip, located in the Gangetic estuary, probably because of a large admixture of sea-water from the Bay of Bengal. Fig. 1 gives a diagrammatic representation of the radium content of the Ganges water as it meanders through various localities into the sea. Hursh (1954) has traced a similar course of the rivers Mississipi and Missouri in the United States of America.

The highest radium content among Indian river waters tested by us was found in the sample collected from Jhelum at Srinagar. Since the water was limpid, it is most likely that the river drains through some radioactive mineral belt. Alternatively, this high value may be due in part to the discharge of some thermal spring water or connate water from insidious oil wells in its neighbourhood. Botset (1934) found radium concentration in connate waters from oil wells as high as 1.7×10^{-15} g/ml. It may be noted that while the radium content of most of the Indian river waters ranges between 2×10^{-16} g/ml and 8×10^{-16} g/ml, some rivers like Brahmaputra, Cauvery, Falgu, Ganges, Jamuna, Jhelum, Krishna and Teesta show substantially higher values at selected places.

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Address of the Authors

S. D. CHATTERJEE and PARTHA BANERJI, Indian Association for the Cultivation of Science, Jadavpur, Calcutta-32.

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EXPLORATION PLANNING FOR SANDUR MANGANESE ORES

R. N. MISHRA

Abstract

Three prevailing ore types viz., stratiform, podiform and tabular deposits occur at the incidence ratio of 75 : 6 : 19. The stratiform orebodies can be designated as plenemensurate and regular; the podiform types as partimensurate and complicated; and the tabular ones as extramensurate and irregular.

Based on the study presented here, a stratiform body may be explored on 100 m × 100 m square grid by core-drilling for the results to remain within the confidence level of ±20%; while podiform bodies may be explored with jack hammer-cum-diamond drilling at 50 m × 50 m square grid and the tabular deposits at 20 m × 20 m square grid with deep pits-cum-drilling for the results to remain at the same level of assurance.

INTRODUCTION

The low-grade bimetallic ores from Sandur (Bellary district) and North Kanara in Karnataka State, as well as Goa, are important on account of relative abundance and good export market. Their low silica and phosphorus content add to their importance because of the suitability of these ores as blendable additions to the high-grade but high phosphorus ores produced from the gondite and kodurite rocks of Madhya Pradesh and Andhra Pradesh respectively. Low-grade ores (around 30% Mn) are increasingly being used in the Blast Furnace charge at about 50 kg per tonne of hot metal for deoxidising and desulphurising.

The *Sandur Ores are by far the best known from a mining-geological point* of view and the Indian Bureau of Mines has categorised the following reserves for these ores in Bellary district as on 1. 1. 1971:

Measured	290,000 tonnes
Indicated	2,670,000 tonnes
Inferred	11,660,000 tonnes
Total	*14,620,000 tonnes*

Though more reliance could be placed on these estimates than the only earlier published estimate of 2.7 million tonnes of ore (Venkataram & Dutt, 1974), the fact is that the figures are not based on any systematic subsurface exploration and hence, the bulk of the total has been rightly classed under 'Inferred Reserves' with questionable degree of assurance. The usefulness of this estimate could at best be with reference to an indexing of the potential resources of the region. Any major investment decision would naturally call for an appropriate scale of ore proving exercise in this area for ascribing a high level of confidence to these findings.

As a prelude to planning for a detailed exploration of these deposits, the geology, available types of ore bodies and parameters of exploration, are briefly presented in this paper, to enable making a realistic appraisal of the scale of operations called for.

GEOLOGY

Manganese ore bodies are stratigraphically restricted to the manganiferous lower formation of the Sandur Basin, comprising (a) bottom-most barren slaty/sericitic phyllites (500 m), overlain by (b) argillites (350 m) containing cavity fills and pods of some manganese ore, and finally topped by (c) mangan-phyllites (150 m), constituting the real protore of the Sandur manganese deposits. Laterite caps these formations and shows concentration of manganese ores as segregated tabular sheets.

Ore which is more defined with respect to visible minerals rather than any specific cut-off grade, is an aggregate of cryptomelane/psilomelane, pyrolusite and manganite for the greater part and a host of other oxides and hydroxides in minor proportions, with total absence of silicates and carbonates. Gangue is constituted of magnetite and pyrite grains, some hematite-limonite admixtures, secondary quartz, calcite and allophane. Normative averages of the major ore minerals with their range of variation shown by means of statistical variance are:

TABLE I. Major Ore Mineral Composition*

Name of Minerals	Proportion (%)	Variance
Cryptomelane/psilomelane	20 - 28	7.11
Pyrolusite	12 - 16	2.45
Manganite	9 - 10	8.93

* Generalisation based on study of 117 specimens at random.

Physical properties, being largely a function of ore mineralogy, tend to average out with reference to weighted proportions of the mineral components. A few characters like grain sphericity, permeability and porosity are however, more dependent on the packing up of the constituents, than the constituents themselves. A few important metallurgical porperties of the ore are generalised in Table II.

TABLE II. Metallurgical Properties

Nature of the Property	Quantitative Index
Scratching Hardness (Moh's scale)	2 to 4
Abrasion Hardness (by Lapping Test)	4.5 to 5.0
Indentation Hardness (by Knopf's indentor)	475 to 500
Toughness of Rock (Brinell's scale)	300 to 600
Tumbler Index (Resistance of breakage by impact)	20% to 25%
Abrasion Index (Measure of degradation by abrasion)	35% to 45%
Tensility of rock	About 250 to 300 kg/sq cm
Porosity of rock	3% to 10%
Permeability	Low
Specific gravity	3.7 to 4.3
Bulk density	About 3.0 to 3.3 tonnes/cu.m.
Grain sphericity	Medium

While manganese content of ore varies between 20% and 52% and Mn: Fe ratio is $1\frac{1}{2}:1$ to $3:1$, Mn+Fe is around 54% to 56%. Rice ratio or Fe/($SiO_2+Al_2O_3$) is between 1 and 2. Oxidation ratio or 100 Fe‴/(Fe″ Fe‴) is over 80%. Silica: Alumina is around 1 : 2 and their sum within 10%. Moisture is about 1.0%;

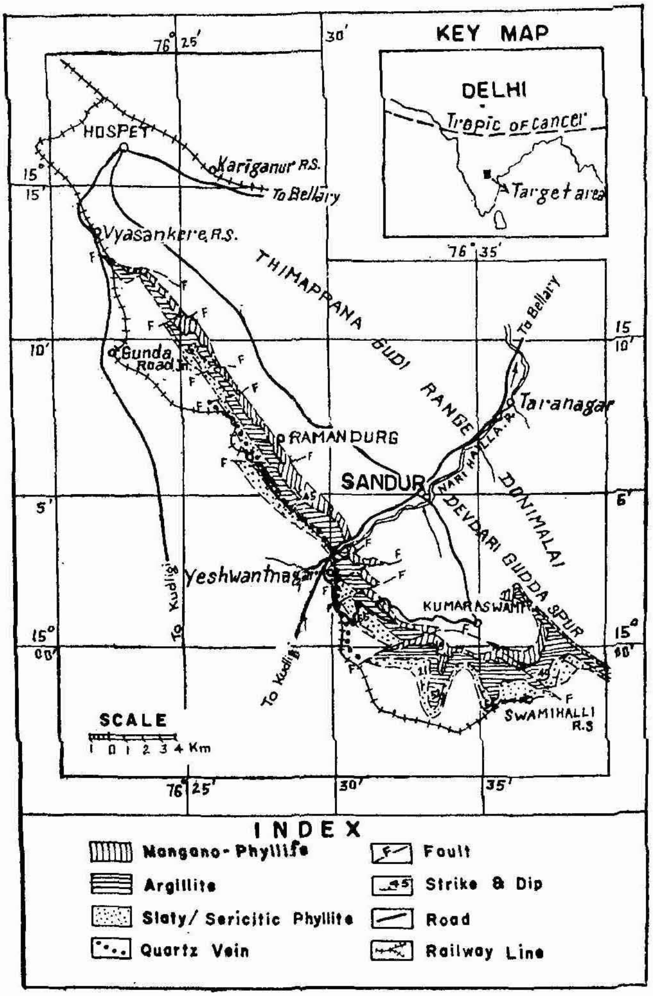

Figure 1. Geological map of manganiferous stage of rocks in the Sandur schist belt.

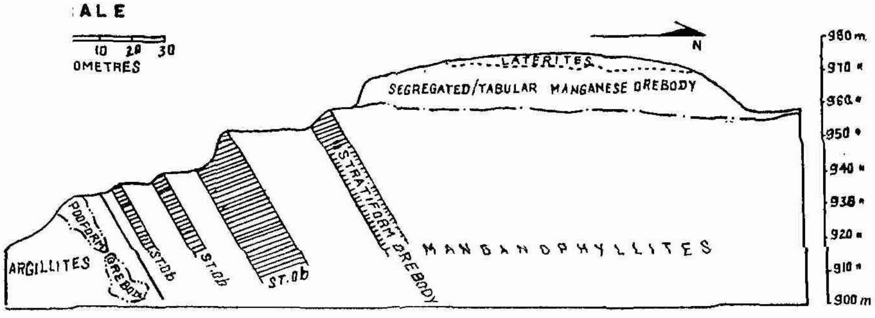

Figure 2. A diagrammatic cross-section through Jogannanadithakolla-mine of M/s. Sandur Manganese and Iron Ores Limited, exhibiting different types of 'Sandur' Manganese Orebodies.

sulphur is in traces; titania is up to 2%; and phosphorus is within the range of 0.02% to 0.05%. Deleterious ions like Cu and Pb are low, generally in ppm level, while radicals like As, Bi and Sn are not detected at all. Total of CaO and MgO are within about 2% and BaO/SrO only in ppm levels. SiO_2 and CO_2 make up the balance of the chemical composition of the ores, as other radicals are in extremely minor quantities.

CLASSIFICATION OF ORE

Classification systems for the ore are naturally based upon the physico-chemical characteristics, as these properties alone make the pertinent criteria for trade in manganese ore at home and abroad. The Indian Standards Institution has formulated the following classification for the purpose of sampling in the stacks (IS: 1449-1969) after the ore is mined.

1.	Uniform Ore:	Where the sizes of lumps are less than 50 mm and the tenor is more than 43% Mn.
2.	Ore of average uniformity:	Where sizes of lumps are—50 mm but has upto 43% Mn
3.	R. O. M. ore:	All sizes irrespective of Mn%

However, classification standards for the ore in connection with production of ferromanganese (IS:4763-1968) is more exhaustive and is in four grades and the last one, viz., Gd 4, envisages 40-44% Mn, 12% Fe, 12% SiO_2 (max) and 1.05% P (max). The ores of Sandur area are marketed under trade brands like:

Sandur 'A' grade:	Mn 38–40%, Fe 16–18%, $SiO_2 + Al_2O_3$ permissible 8% (max) and P 0.05% (max).
Sandur 'B' grade:	Mn 32–34%, Fe 20–22%, $SiO_2 + Al_2O_3$ 10% (max). and P 0.05% (max).
Sandur 'C' grade:	Mn 30%, Fe 22–24%, P 0.05% (max).

In addition to the above, two other marketable grades like 36-38% Mn and high silica ores have also been introduced from the area.

From beneficiation point of view alone, the NML have categorised the Sandur manganese ores as 'ferruginous ores' which require magnetising, reduction-roasting, and magnetic separation for upgradation.

ORE TYPES

The following classification based on geology, however, takes into account the general morphometrics of the deposit as the guiding principle, though the same finds general agreement in respect of ideas regarding the origin of the different ore types.

Based on studies of shape, size and field association, as well as conformability in respect of the conceptual evolution of ore genesis, the ore deposits of Sandur area may be classified threefold (Mishra & Pitre, 1973 and Mishra, 1975) and their relative abundance worked out in terms of level of actual incidence of occurrence. They are:

TABLE III. Ore types and their incidence

Name of the ore type (deposit-wise)	Incidence (%)
Stratiform - Primary	75
Podiform - Secondary	6
Tabular - Lateritoid	19

The 'stratiform' types are conformably bedded within the country rock of mangan-phyllite with partings of low-grade iron ore, or barren lithological interbands. Dimensions of the outcrops are up to 500 m × 5 m while depth extensions may go up to 50 m; greater extensions are also expected. Ore is usually hard, massive and lumpy with tenor fairly consistent throughout the length and breadth of the deposit. A syngenetic precipitation model is evident.

Podiform types, on the other hand, are of the nature of cavity fillings within the argillite member, stratigraphically lower to the protore horizon, formed due to downward migration of the metal dissolved by the connate waters and precipitated at lower level locales in a process akin to secondary supergene enrichment. The bigger of these deposists seldom measures over 50–60 m^3 *in situ*. Though hard, these ores display botryoidal and nodular/stalactitic structures, which are often seen to form around non-ore nucleus.

Tabular bodies within the laterites at the top are generally soft with the tenor highly varying from point to point. Bodies of this kind may go up to sizes of around 25 m × 15 m × 5 m and their recovery is even lower than 30% in a working face, due to their occurrence in the form of pockets and highly gradational character into the waste laterite. These deposits seem to have formed due to lateritic weathering with the metal moving upwards with the help of recirculating meteoric waters and released at the oxygen interface.

EXPLORATION PARAMETERS

The extent to which a deposit can be explored depends on (a) the geological form in three dimensions, (b) inherent complexity due to structural set-up vis-a-vis non ore inclusions and boundary embayments, (c) cost/time envisaged and (d) the risk involved to reach a planned rate of production. However, depending on the "explorability", i.e., the ease with which the deposits could be currently explored (fully or in part) the Sandur manganese ore types fit into the threefold specifiaction of explorability proposed by McLaughlin (1939).

TABLE IV. Exploration Specifications of Sandur Ore Types

Type of Ore Body		Examples at Sandur
Plenemensurate	Those capable of being fully explored at an early stage of the work	Stratiform – Primary
Partimensurate	Those in which additional potential remains as a substantial quantity, until later stages of mining	Podiform – Secondary
Extramensurate	Those which are difficult to gauge much in advance of mining and the estimated tonnage remains always less than the actual reserves supporting the mine work	Tabular – Lateritoid

Based on the natural complications in comparing the deposit as a whole to a measurable and known auxilary geometrical solid figure, the intensity of exploration will be varied, the complex ore bodies necessitating a greater intensity of exploration and *vice versa* to yield similar assurance on the estimated tonnage or grade. Where the complexity remains similar, greater intensity of exploration naturally results in greater degree of reliability for the findings. This uncertain natural factor i.e., complexity of a deposit, may result from the following characterstics of the ore body.

1. Irregularity of the ore/non-ore boundary, quantified as an expression of the Modulus of boundary irregularity.

$$= \frac{\text{Largest fitting elliptical perimeter}}{\text{Actual peripheral length of deposit}}$$

2. Inclusions of non-ore patches within the ore zone in all the dimensions, better termed as 'Mineralisation Factor' (Kreiter, 1968) expressed as

$$= \frac{\text{Net Ore (area/volume/drilled metres)}}{\text{Gross Ore (area/volume/drilled metres)}}$$

3. Coefficient of variation of any attribute, like thickness, grade, etc., or 'variability' expressed as percentage:

$$= \frac{\textit{Standard deviation of the variable}}{\text{Arithmetic/weighted average of it}}$$

The inter-relationship of these discretely separate characters have been expressed by the Russian formula practised in calculating iron ore in the captive mines of the Bhilai Steel Plant (Ref: Unpublished brochure by the Division of Ore, Mines & Quarries, 1972).

$C = V/FM$ When $C =$ Coefficient of complexity
$V =$ Variability of any character
$F =$ Mineralisation Factor
and $M =$ Modulus of contact irregularity

Depending on the value of 'C' thus obtained, deposits could be classed as Regular (C = less than 50%), Complicated (C = 50 to 100%) and Irregular (C = more than 100%). The Sandur manganese ore deposits have been studied with reference to the above characters in respect of explorability and the three types have been grouped as follows:

TABLE V. Parameters of Exploration for Sandur Manganese Ores

Ore Type	V	F	M	C	Class	Number*
Stratiform	28	0.84	0.75	45	Regular	5
Podiform	36	0.60	0.62	97	Complicated	7
Tabular	105	0.51	0.70	298	Irregular	11

* Indicates the number of deposits considered.

INTENSITY OF SAMPLING

Having ascertained the degree of complexity of the manganese ore deposits in terms of their coefficients of complexity 'C', the next logical step is to deliberate on the predictable intensity of collection of samples by diamond core drilling, jack hammer drilling, pitting or any other form of exploratory openings/points of inspection to arrive at the desired degree of accuracy or reliability to compute the overall tonnage and/or average grade. This would yield the grid density of exploration, most economically capable of producing the required results within stipulated confidence levels, as may be seen from the mathematical expression (Russian equation on geostation applicable to normal/lognormal distributions):

$$N = \left(\frac{C}{P}\right)^2 \times t$$

When $N =$ Number of exploratory openings
$P =$ Accuracy limit desired in percentage
$t =$ Student's t, for various confidence levels like
$t = 1$ at 68.3% con. level
$t = 2$ at 95.0% con. level
$t = 3$ at 99.7% con. level

For exploration programming, t is customarily taken at $t = 2$, i.e., at 95% confidence level to decide the desired confidence level of accuracy like ±20%, ±10%, ±5%, etc., for the equations to be rewritten for $P = 0.20$, $P = 10.$ or $P = 0.05$ respectively and thus the only unknown N, is to be determined. Judging by the surface area available for exploration, the borehole density in terms of number per sq km or metre grid interval is computed for the purpose. In view of the total lack of any subsurface data for the Sandur manganese ore deposits, square grid exploration scheme is proposed as a safe programme. Based on the number of deposits mentioned in Table V, the following square grid density of exploration has been worked out for different confidence levels of accuracy in computation of reserves:

TABLE VI. Norms of Exploration

Ore Types	Square Grid Density		
	Accuracy +20%	Accuracy +10%	Accuracy +5%
Stratiform	100 m × 100 m	75 m × 75 m	25 m × 25 m
Podiform	50 m × 50 m	15 m × 15 m	—
Tabular	20 m × 20 m	—	—

It may be mentioned here that the exact densities worked out like 11,087.57 m^2 etc., have been rounded off to 10,000 m^2 and resolved into 100 m × 100 m square grid for working convenience. All figures are thus rounded off to the nearest multiples of 5 m.

TYPE OF EXPLORATION

The purpose would be defeated unless the most suitable tool of exploration is prescribed for various types of deposits, so that an agency may straightaway scheme out the exploration strategy for the Sandur manganese ores. The 'drillability' (Sievers, 1952) for any rock is a function of resistence to abrasion and lack of brittleness. Based on the physical nature of the rock as in Table II, the core recovery in the case of drilling exploration in the harder ores of the stratiform and podiform types of deposits may be as high as the Drill Index (100 to 150). So the conventional method of diamond drilling may be considered for the stratiform type of ore where the core recovery must be kept near cent per cent, if need be, by resorting to dry drilling as is being practised in the soft iron ore deposits today. Even a cross-sectional method of exploration and proving can be practised and the tonnage/grade worked out on integration of the cross-sectional averages weighted against cross-sectional tonnages.

Podiform and tabular ore bodies pose greater problems with increased non-uniformities. Since conventional core drilling is a costly practice involving a larger quantum of drill meterages, jack-hammer drilling with extension rods (where cuttings are examined and analysed) is proposed as a cheaper alternative to economically demarcate and eliminate the barren zones between patches of ore. Ore zones thus delineated by drilling may however, have to be carefully sampled through reliable exploratory openings. Podiform bodies may be sampled by diamond core or jack-hammer drill holes, but the tabular types necessarily have to be tackled by 2 m × 2 m size deep pitting down to 12 or 15 m depth (depending on the thickness of the laterite blanket *in situ*) as the recovery of this type of ore is a great problem and the ore tonnage estimated largely rests on a successful estimation of the recovery factor of the R.O.M. ore.

Even in the case of the stratiform deposits explored by drilling, exploratory mining in the form of deep pits and adits is necessary for suitably blocking out the proved ore with a high degree of reliability especially in places where the deposits have remained virgin without any quarry openings. This would be the penultimate stage of exploration for arriving at the blocked out and proved reserves, equivalent to the Russian A & B, categories.

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Address of the author

R. N. MISHRA, Geologist (Sr) Geological Survey of India, 78, Diagonal Road, Jayanagar III Block, Bangalore-560011.

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THERALITE-MELTEIGITE-CARBONATITE ASSOCIATION IN MER RING OF MUNDWARA SUITE, SIROHI DISTRICT, RAJASTHAN

MANAS K. CHAKRABORTI AND MIHIR K. BOSE

Abstract

The theralite-melteigite-carbonatite association is being reported from Mundwara alkaline suite in the Sirohi district, Rajasthan. The assemblage occurs in an arcuate ring around the central plug of Mer. Theralite (composed mainly of plagioclase, pyroxene, and nepheline) and melteigite (composed mainly of pyroxene and nepheline) are feldspathoid bearing basic and ultrabasic rocks, having high colour index and are closely associated with fine to coarse grained carbonatites in the south eastern part of the ring.

INTRODUCTION

The theralite-melteigite-carbonatite association is developed along an arcuate ring around the central Mer hill (584 m) near Mundwara, Sirohi district, Rajasthan. The ring is formed of a few hills aligned in arcuate form around the Mer Plug which is intermediate in position between Tua (436 m) to the NW and Musala (509 m) to the east. The mer plug (Fig. 1) covers an area of about 6.4 sq km. Erinpura granite, the country rock, extends on the flanks of Mer ring up to a considerable height (Chakraborti, unpublished thesis). The deserted village of Mer, is situated within the ring. The arcuate ring is the expression of homophanous theralitic rocks which at the southeastern part of the Mer hill form an intimate association with melteigite, carbonatite and pyroxenite (Fig. 1). The arcuate ring does not extend at

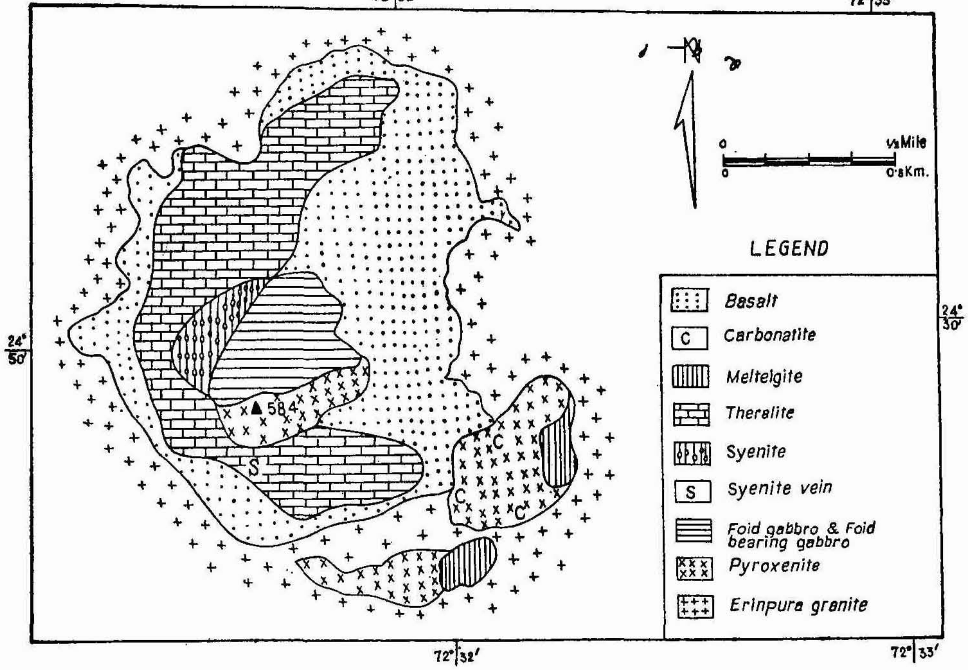

Figure 1. Distribution of the magmatic units in Mer Complex near Mundwara, Sirohi district, Rajasthan. (Mapped by M. K. Chakraborti).

the NE and eastern portion of the central Mer complex. The central Mer reveals an assemblage of basic and ultrabasic rocks with subordinate syenites. This interesting association has not so far been found in the other two adjacent complexes (viz. Tua and Musala) or in any other part of this country.

Coulson (1933) first described briefly the Mundwara igneous suite. Lately Sharma (1969) studied the petrology of the suite in some detail. The alkali syenites of the Mundwara suite have been described by Bose and Dasgupta (1973) and the carbonatites of the Mer complex has been studied recently by Subrahmanyam and Rao (1977).

PETROGRAPHY

Theralite

Megascopically the theralites are homophanous, feebly inequigranular, coarse to medium grained, mesocratic to melanocratic rocks. Grains of greasy, pale brown nepheline are evenly distributed within haphazardly arranged plagioclase laths. Under the microscope the rocks can be divided into two groups on the basis of the foid percentage (modal data in Table I, Nos. 1 to 4):

TABLE I. Modal data of theralite-melteigite-pyroxenite-carbonatite from Mer Ring

Serial No.	1	2	3	4	5	6	7	8	9	10	11	12
Specimen No.	M/3B	M/P9	M/K12	M/S12	M/5A	M/5AL	M/5AN	M/6C	M/10E	M/6B	M/7	M/P6
Plagioclase	32.9	41.7	28.0	20.3	—	—	—	—	—	—	—	—
Pyroxene	34.5	24.6	40.0	42.3	52.6	55.7	52.5	52.6	80.5	78.0	1.4	10.3
Brown amphibole	—	4.0	—	1.4	—	2.1	3.6	—	3.2	2.9	—	—
Biotite	7.5	6.8	3.1	0.9	8.5	10.4	8.0	12.9	5.4	4.6	6.8	5.4
Olivine	4.5	3.8	3.6	1.3	0.9	2.7	8.7	—	—	2.6	—	—
Nepheline	2.0	4.5	9.1	13.8	16.2	15.0	13.9	15.3	—	—	—	—
Sodalite	0.8	—	1.1	5.6	3.8	1.9	—	2.2	—	—	—	—
Apatite	3.7	4.6	1.2	1.1	5.0	4.5	1.5	3.4	—	3.5	—	—
Chlorite	—	—	—	2.7	2.5	—	—	—	—	—	—	—
Sphene	—	—	—	0.6	—	—	0.2	—	—	—	—	—
Opaques	14.2	9.9	14.2	10.2	9.9	7.7	11.5	14.0	11.0	8.6	0.8	15.3
Carbonate	—	—	—	—	—	—	—	—	—	—	91.8	69.2

1 - 2 Foid bearing olivine gabbro.
3 - 4 Foid olivine gabbro (i.e. Theralite).
5 - 8 Melteigite.
9 - 10 Pyroxenite.
11 Carbonatite, coarse grained.
12 Carbonatite, fine grained.

(i) Foid olivine gabbro and dolerite (theralite) which fall in field No. 14 in F-P-A diagram (IUGS recommendations, 1973).

(ii) Foid bearing olivine gabbro which fall in field No. 10 in F-P-A diagram (IUGS recommendations, 1973).

In both the groups, the major constituents are plagioclase, clino-pyroxene, feldspathoids, brown amphibole, biotite and olivine whereas apatite, chlorite and opaques are accessory minerals. Divergent orientation of long plagioclase laths gives rise to common doleritic appearance. Pyroxene develops zoned equant grains or (Fig. 2a) occurs within the interspaces between plagioclase and develops intergranular, ophitic to subophitic textures. In some cases interstices of plagioclase framework are filled by granular aggregates of pyroxene and nepheline which is compositionally equivalent to the melteigite occurring as a distinct rock unit in association with theralite.

Figure 2a. Photomicrograph of theralite, showing zoned pyroxene (Px), plagioclase (P) and interstitial nepheline (N). Cross polars (×25).

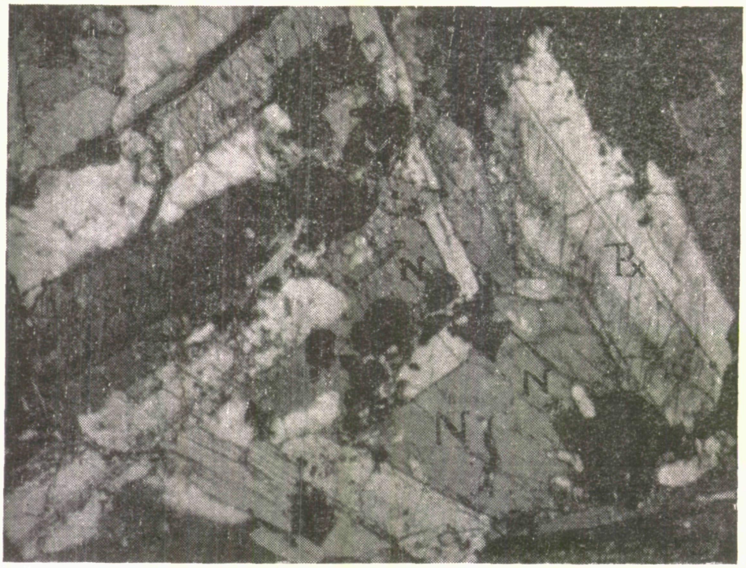

Figure 2b. Photomicrograph of melteigite showing nepheline (N) coexisting with tabular clinopyroxene (Px). Cross polars (×25).

Melteigites and Pyroxenites

Melteigites and pyroxenites are closely associated. Both are coarse grained, slightly inequigranular, melanocratic and with moderately high specific gravity. Only the frequent presence of nepheline in melteigite distinguishes it from pyroxenite (Williams, Turner and Gilbert, 1965). The feldspathoidal rock was designated as melteigite considering the following characters (IUGS. 1973):

(i) Colour index, within the range of 70 to 90.
(ii) Feldspathoid content, 60 to 100 per cent of leucocratic minerals.
(iii) Amount of sodic minerals greater than potassic minerals.
(iv) Feldspar usually completely absent.

Under the microscope the melteigite is found to be constituted dominantly of pyroxene, nepheline, biotite, amphibole and olivine, while apatite, chlorite, sodalite, sphene and opaques are common accessory minerals. Large rounded to subrounded crystals of pyroxene, showing zoning and occasionally repeated twinning, are closely associated with tabular crystals of pyroxene and interstitial nepheline (Fig. 2b). Brown amphibole occurs at the periphery of pyroxene grains.

In thin section the pyroxenite exhibits almost the same characters as that of melteigite except the absence of feldspathoid. Pyroxene crystals are large in size and anhedral in shape. The open spaces between the large anhedral pyroxene grains are occupied by smaller pyroxene tablets, biotite and other accessory minerals e.g. amphibole, apatite, olivine and opaques of variable shapes and sizes.

Modal compositions (Table I) of the investigated ultrabasics fall in the fields of melteigite and jacupirangite in N-M-A diagram (Sorensen, 1974, p. 17).

Carbonatites

These rocks are designated as carbonatite on the basis of their composition and intrusive relation to other rocks. Lenticular veins of carbonatite, varying in length from 6 to 70 m and in width from 2 to 6 m, are located within the Erinpura granite and closely associated with melteigite pyroxenite. Fine grained buff coloured rocks and coloured rocks and coarser grained varieties mottled with reddish brown and milky white patches are encountered. The rocks effervesce with cold dilute hydrochloric acid. The carbonatites of Mer complex have been described in more detail by Subrahmanyam and Rao (1977).

Under the microscope the chief variety is found to be composed almost wholly of colourless carbonate (Table I, Nos. 11, 12) with three sets of cleavage. Twinkling effect is conspicuous with characteristic high order interference colour. Staining with Alizarine red solution identifies the mineral to the calcite. Biotite, pyroxene and opaques are found as accessory minerals in sovite. The anhedral shape and the interlocking nature develop allotriomorphic granular texture. Zoned calcite crystals are developed in adjoining granitic rocks which seem to be introduced from the carbonatitic liquid.

MINERALOGY

Plagioclase: Occurs only in theralites as slender laths, showing typical lamellar twinning with distinctly sharp lamellae of variable width. Most lamella are continuous but in some cases they are discontinuous. Refractive indices of plagioclase is invariably higher than that of canada balsam. From the $2V_X$ and $x' \wedge 010$ values, the composition of plagioclase is found to range from

$$An_{35}\ (2V_X = 86°,\ x' \wedge 010 = 22°) \text{ to } An_{55}\ (2V_Z = 77°,\ x' \wedge 010 = 32°).$$

Pyroxene: It is the chief mafic constituent in basic and ultrabasic member of the assemblage and occurs as euhedral to subhedral tablets with conspicuous pleochroism. Optical properties are given in Table II. Optical data suggest that the pyroxene in all the rock types is augite with appreciable enrichment in titanium in melteigite and pyroxenite and less so in theralite. It may be mentioned that titaniferous salite is a diagnostic constituent of alkaline basic and ultrabasic rocks.

TABLE II. Optical data for pyroxene

Rock type	Theralite	Melteigite	Pyroxenite
Scheme of Pleochroism	X=deep pink Y=grey Z=pinkish brown $X=Z>Y$	X=pink Y=brownish yellow Z=pale pink $X\geqslant Z>Y$	X=pink Y=greyish pink Z=pale pink $X\simeq Z>Y$
$\alpha=$	1.721	1.707	1.708
$\gamma=$	1.747	1.732	1.731
$\gamma-\alpha=$	0.026	0.025	0.023
$2V_z$	53°	56°	66°
$Z\wedge c$	49°	48°	49°

Amphibole: Occurs mostly in theralites as irregular patches and also as anhedral ains with $2V_X=78°$, $Z\wedge c=17°$ and $\alpha-\gamma=0.030$. The amphibole shows strong pleochroism with the following scheme:

X = brown.
Y = slightly pale brown. $Z>X>Y$.
Z = reddish brown.

Optical data suggest that the amphibole is possibly a member of barkevikite-kaersutite series.

Biotite: Found in all the rock types as a late mafic phase, strongly pleochroic ($Z>Y=X$) with $\beta=1.653$. The optical data suggest the mineral to be highly enriched in iron.

Olivine: Occurs as nodular crystals, intimately associated with opaques. Granular opaques are seen along irregular fractures. Grains show high birefringence. From the 2V value ($2V_X=74°$) from a theralite sample, the composition of olivine is estimated to be about $Fo_{50}\ Fy_{40}$. The olivine is appreciably rich in iron.

Feldspathoids: Both nepheline and sodalite occur in theralite and melteigite as small anhedra or as distinct euhedral tablets. The minerals occur in close spatial association with pyroxene filling the interstices of plagioclase framework in theralite.

CHEMICAL PETROLOGY

Major elements

Chemical analysis of the alkaline ultrabasic rock from Mer was carried out to know its chemical status and to compare the same with average melteigite (Nockolds, 1954) and also with alkaline ultrabasic rock from Kunavaram - Vinyakapuram alkalic pluton, Khammam district, A.P. (Table III). The chemical composition of melteigite of Mer ring assemblage shows extreme silica deficiency as in the case of Morotu assemblage. That the rocks are strongly undersaturated is indicated by the presence of a number of normative undersaturated minerals viz., nepheline, leucite, kaliophyllite and olivine. The values of differentiation index (D.I. $\simeq$ 15.6) and solidification index (S.I. = 22.7) suggest that the rock crystallised at a relatively early stage of evolution of the complex. The modal nepheline is more or less equal to that of normative nepheline denoting the high degree of alkalinity. This is supported by the Na_2O and K_2O percentages and the calc-alkali index of the rock. Further, Na_2O content is greater than K_2O which is a characteristic feature of the ijolite-melteigite group of rocks according to the classification and nomenclature of plutonic rocks recommended by IUGS subcommission (1973). High CaO, MgO and FeO + Fe_2O_3 percentages in the analysis may be attributed to high mafic index which suggests the rock to be an early member in the suite. These chemical characters are also confirmed by partial chemical analysis of another sample (M/6C) from the same ring assemblage which gave the following results: $Na_2O = 2.56\%$, $K_2O = 2.01\%$, $MgO \simeq 7.92\%$ and $CaO = 12.87\%$.

The alkaline mafic magma was appreciably rich in titanium as revealed from the analysis. The element entered into both silicate minerals and opaque oxides.

Trace elements

Trace element analyses of investigated malteigites are presented in Table IV along with other comparable data. Ba contents of these alkaline ultrabasics are significantly higher than that of average ultramafics. High Ba and Rb contents of the investigated rocks are apparently due to their alkaline enrichment relative to *average ultrabasics (Table IV, No. 8) or those developed through crystal accumulation* in calc-alkaline assemblage (Table IV, Nos. 5 & 6). Ba/Rb is maintained almost at the same level in average ultramafics and crustal rocks (Table IV, Nos. 7 & 8) but a higher Ba enrichment relative to Rb is noticed in the investigated rocks. K/Rb in the ultrabasics is slightly higher than average ($R \simeq 230 \pm 50$) for crustal magmatic rocks. The investigated rocks and their analogues (Table IV, Nos. 1-4), because of their very high Sr level relative to average value may be designated as high Sr ultrabasics. Ca/Sr in these rocks is correspondingly very low. The alkaline ultrabasics may be discriminated from peridotite (Table IV, No. 6) in having significantly low Ni relative to Mg. So that Mg/Ni in the investigated type of rocks are relatively high. Co/Ni ratio in the alkaline ultrabasics is not much different from average magmatic rocks. Average ultramafics and those developed through crystal accumulation (Table IV, Nos. 5, 6 & 8) are remarkably chromiferous than the alkaline ultrabasics. On the other hand Ti enrichment is noticed in alkaline types.

It is significant that the contents of most of the analysed trace elements in the investigated rocks are comparable to those of alkaline ultramafics of Kola peninsula and they together form a distinct group from average ultramafic rocks (Goles, 1967) and rocks developed through crystal accumulation in calc-alkaline assemblage.

DISCUSSION

The theralite-melteigite-carbonatite association of Mer hill near Mundwara, Rajasthan, is a unique example in India. In Mer ring these melteigite-pyroxenites are associated with large volume of theralite. Such melteigite-pyroxenite rocks are closely associated with carbonatites in many alkaline provinces in the world. Theralite-melteigite-pyroxenite-carbonatite assemblage of Aldan Shield area in Siberia

TABLE III. Chemical analyses of melteigites.

Oxides	1.	2.	3.
SiO_2	39.98.	40.90.	37.62.
TiO_2	4.53.	3.99.	2.35.
Al_2O_3	16.04.	13.65.	18.37.
Fe_2O_3	3.19.	6.67.	4.04.
FeO	9.23.	7.14.	9.36.
MnO	0.09.	—	0.03.
MgO	5.44.	8.35.	4.14.
CaO	12.90.	13.28.	11.19.
Na_2O	3.43.	3.06.	4.95.
K_2O	2.72.	1.65.	3.08.
P_2O_5	0.84.	0.84.	1.03.
H_2O (Total)	1.40.	0.50.	1.46.
CO_2	—	—	2.26.
Total	99.79.	100.03.	99.88.
CIPW NORM			
Or	—	9.4	8.50
Ab	—	1.6	—
An	20.29	18.6	20.01
Lc	11.34	—	7.28
Ne	15.62	13.1	21.58
Kp	0.95	—	—
Di	30.42	33.0	12.62
Ol	4.47	4.5	10.44
Mt	4.64	9.7	5.80
Il	8.66	7.6	4.40
Ap	2.02	1.9	2.35
Ct	—	—	5.10
D.I.	15.62	24.10	30.08
Agpaicity Index	38.30	34.50	42.62
S.I.	22.70	31.75	16.45
Calc-alkali Index	67.70	73.82	58.83

1. Melteigite of Mundwara alkaline Suite - (Sp. No. M/5A). Analyst: M. K. Chakraborti.
2. Average melteigite (Nockolds, 1954) Analyst: D. K. Bailey.
3. Alkaline ultrabasic rock from Kunavaram-Vinayakapuram alkalic pluton, Khammam Dist. A.P. Analyst: B. P. Gupta.

D.I. Differentiation Index after Thronton and Tuttle, 1960.

S.I. Solidification Index after Kuno, 1968.

Agpaicity Index. $\frac{(Na_2O+K_2O)\%}{Al_2O_3\%} \times 100.$

TABLE IV. Trace element data (in ppm)

Elements	1	2	3	4	5	6	7	8
Ba	950	715	260	850	173	45	650	4
Rb	67	61	102	80	—	3	150	1
Sr	1040	910	785	1300	60	13	340	20
Li	8	7	—	2	< 100	2	32	—
Cu	100	70	14	34	59	23	47	30
Pb	20	20	—	13	—	—	16	—
Zn	225	215	—	50	—	—	83	—
Ni	80	140	129	36	450	2617	58	1500
Co	30	30	13	15	47	173	18	110
Mo	5	5	2	—	—	—	1	—
V	300	350	156	440	167	74	90	—
Cr	30	100	10	30	1467	6100	83	2400
Ga	—	—	17	26	7	< 5	19	∼5
La	—	—	—	—	—	—	—	—
Nb	—	—	186	300	—	—	20	—
Y	—	—	29	—	—	< 20	—	5
K/Rb	337	274	251	—	—	327	—	—
K/Ba	24	23	98	—	—	22	—	—
Ca/Sr	89	101	62	—	—	1300	—	—
Mg/Ni	410	341	194	—	—	80	—	—
Co/Ni	0.38	0.21	0.10	0.42	0.10	0.06	0.31	0.07
Cr/V	0.10	1.29	0.06	0.07	0.78	82.43	0.92	—
Sr/Ba	1.09	1.27	3.02	1.53	0.35	0.29	0.52	5.0
Ba/Rb	14.18	11.72	2.55	10.63	—	15.0	4.33	4.0

1. Melteigite from Mer Ring, near Mundwara, Sirohi district, Rajasthan (Sample No. M/5A)
2. Melteigite from Mer Ring, near Mundwara, Sirohi district, Rajasthan (Sample No. M/6C)
3. Ultrabasic alkaline rock from Kunavaram-Vinayakapuram alkalic pluton, Khammam district, A.P. (Sample No. Km/70)
4. Alkaline ultramafic rocks from Kola peninsula (Kukharenko *et. al.*, 1965) in 'The Alkaline Rocks' (Sorensen, 1974; p. 407)
5. Pyroxenites from the layered complex of Kondapalli, Andhra Pradesh. (unpublished data, M. K. Bose).
6. Poikilitic harzburgite of Keshargaria, Singhbhum (Saha *et. al.*, 1972). Average of three analyses.
7. Average composition of magmatic rocks of the Earth's crust, Vinogradov, 1962 in 'The Alkaline Rocks' (Sorensen, 1974; p. 403).
8. Average trace element content of ultramafic rocks (Goles, 1967)

(Sorensen 1974, p. 175) is comparable to that of the present area. If any particular group of rocks may be considered especially characteristic of carbonatitic ring complexes, the urtite-ijolite-melteigite series certainly qualifies (Heinrich 1966, p. 45). Thus there are definite indications for the Mer assemblage to be a subvolcanic ring complex.

For the melteigite-theralite association, there must be a link in the crystallisation history of theralite and the melteigite pyroxenite. In theralites petrographic characters indicate plagioclase to be earlier than interstitial pyroxene and nepheline. It is possible that separation of a strongly alkaline iron-enriched carbonated liquid separated from the alkaline basic magma, resulted in the melteigite and segregation of mafics at places caused the local development of pyroxenite. Carbonatites formed from late carbonatitic liquid left after the crystallisation of the silicates. So, in the ring assemblage the crystallisation was initiated by plagioclase (as seen in theralite) followed by pyroxene (pyroxenite) which was later accompanied by nepheline (melteigite). It is noted that in theralites the composition of interstitial material (pyroxene and nepheline) is same as that of melteigite. Thus melteigite has a composition comparable to later interstitial liquid derived from theralite dolerite which indicate a possible genetic connection between alkaline basic and ultrabasic rocks of Mer ring assemblage. Another important feature in the assemblage is the absence of alkali feldspar which suggests that crystallisation of pyroxene was immediately followed or accompanied by crystallisation of nepheline without entering the field of alkali feldspar, where as, in foid syenite and related rocks of central Mer, nepheline is invariably accompanied by alkali feldspar. There is no field or petrographic evidence of meltiegite being formed through nephelinisation of pyroxenite.

Investigations by the authors (Chakraborti, 1974; Dasgupta, Chakraborti and Bose, *in preparation*) clearly bring out a fractionation history of alkali olivine basalt magma, manifested in rock assemblages of Tua, Mer and Musala. The early stages of fractionation are recorded in rocks of Tua whereas the ultimate fractionation products are revealed in Musala assemblage. Absence of felsic alkalic minerals in Tua assemblage (chiefly picrite, olivine melagabbro, banded gabbro etc.) may conceal the alkaline character of the parent magma and Tua assemblage poses to be a calc-alkaline suite (Sharma, 1969). But meneralogical characters of Tua rocks distinctly put an alkaline stamp on the assemblage. The distinctive characters among others are the presence of modal titaniferous salite, ubiquitous presence of olivine and development of normative nepheline in the major members. Thin stringers of alkali syenites are also found in Tua plug. These alkaline characters are further accumulated in central Mer and Musala assemblages. A comparable trend of differentiation has been established for the Girnar Complex of Gujarat (Bose 1973) which is also a manifestation of Deccan volcanism as the presently discussed suite.

The presently investigated Mer ring assemblage (theralite, melteigite, pyroxenite and carbonatite) does, however, shows some deviation from the major fractionation trend successively developed in Tua, central Mer and Musala, while in the central Mer nepheline occurs in constant association with alkali feldspar in theralite of Mer ring such association is lacking—suggesting an independent trend of differentiation for the Mer ring. So the Mer ring assemblage (theralite-melteigite-pyroxenite-carbonatite), a subvolcanic to hypabyssal association, shows no direct link with the major trend of differentiation from Tua to Musala including the central Mer at the present level.

Subrahmanyam and Rao (1977) in a recent contribution have treated together the rocks of central plug and ring complex. Although they present a map after Sharma (1969) the rock names used in the index have been changed and petrographic descriptions of the newly named rocks have not been furnished. The essexite of Subrahmanyam and Rao (1977) as indicated in the reproduced map and Table I corresponds to alkali dolerite of Sharma (1969) which in fact is theralitic dolerite (foid dolerite and gabbro), described in this paper. It is significant to observe that this rock analysis (Subrahmanyam and Rao 1977, Table I, No. 6 and Figs. 15, 17 and 18) invariably plots away from the fractionation trends drawn by Subrahmanyam and Rao (1977). The data thus available seem to indicate that theralite-melteigite assemblage does not evolve directly from the main fractionation trend manifested in the Mundwara plugs as mentioned above. A carbonated, strongly undersaturated alkaline basic magma resulted independently or, as an offshoot from the fractionating Mundwara magma and was emplaced in arcuate fashion (controlled by ring fractures) around the Mer plug. It is significant that the volcanism in the eastern part of Mer was associated with paroxysmal activity, as suggested by abundance of tuffaceous rocks.

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Address of the authors

MANAS K. CHAKRABORTI and MIHIR K. BOSE, Department of Geology, Presidency College, Calcutta.

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PETROLOGY AND GEOCHEMISTRY OF A RECENTLY DISCOVERED NICKELIFEROUS SERPENTINITE IN SRI LANKA

C. B. DISSANAYAKE AND B. J. VAN RIEL

Abstract

Geological and geochemical investigations of a serpentinized ultramafic body in the south of Sri Lanka have revealed the presence of nickel in the range 0.8 - 1.9%. Nickel is present in silicate form in the serpentine minerals. The typical tropical climate prevailing has been responsible for the formation of a deep weathering profile conducive to the residual enrichment of nickel. Cobalt, chromium and zinc are also present, though in lesser quantities when compared to nickel. The opaque minerals consisted of magnetite, chromite/picotite and other spinels. The leaching of silica and magnesium had resulted in the formation of chert, agate, chalcedony and carbonate veins respectively.

INTRODUCTION

This study deals with the preliminary geological and geochemical investigations on a nickeliferous serpentine body recently discovered in Sri Lanka. Nickel bearing deposits have not so far been recorded in Sri Lanka. Even though serpentinites in Sri Lanka have been mapped and recorded, their nickel potential has never been evaluated. A reconnaissance survey of this body was conducted by the Department of Geology of the University of Sri Lanka in 1970. This study is a result of further geological and geochemical work carried out by the authors on the nickel potential of the serpentinite.

Oliver (1960) had observed the occurrence of a serpentine patch just east of the Walawe river and also some serpentine boulders near Kaltota ridge (north of the Uda Walawe reservoir). Vitanage (1973) related the discovery of some minor mineralizations tentatively to a possible metalliferous source in the serpentine rocks. Since up to now Sri Lanka's mineral wealth has been thought to be rather poor with only graphite, mica, beach sands and apatite being mined—a positive evaluation of the mineral potential of the Uda Walawe basin would prove to be worthwhile from an economic point of view. Even though the data presented in this paper are inadequate for the full evaluation of the nickel potential of the serpentine body, the authors feel that the information outlined here would provide a good basis for a much more thorough geological investigation of the body.

Serpentinites and other ultramafic bodies have been the target of a great deal of research recently. As reviewed by Eckstrand (1974) a large number of exploration programmes on nickeliferous ultramafic bodies are being carried out in Canada, Australia and Africa. Similar work has been carried out in Thailand and India, where the type and degree of weathering seems conducive to the formation of nickeliferous laterites.

LOCATION

The area as shown in Fig. 1 lies in the lowlands of Sri Lanka and is a part of the drainage basin of the Walawe river. The serpentine body covers an area of approximately 7 km² and is surrounded by migmatitic gneisses and marbles.

Tropical climate characterized by well marked wet and dry seasons and long periods of drought is prevalent in the area. The annual average temperature varies little from 80°F and the annual rainfall is 150 cm/yr. The alternations of the dry and wet seasons affect the groundwater table to a considerable degree. This and the prevailing high temperatures are highly conducive for weathering with resulting leaching and residual concentration of certain elements like nickel, iron and aluminium.

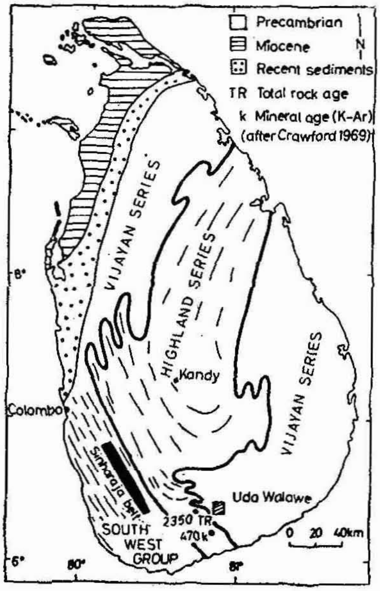

Figure 1. The main geological division of Sri Lanka (After Katz, *1972*). The inset near Uda Walawe shows the location of the area investigated.

The vegetation on the serpentine body differs from that around it. Only tall and bushy trees with deep roots grow on the deposit. Around it however, a variety of tall grass and cultivated crops grow very well.

GEOLOGY

The Precambrian of Sri Lanka is divided into 3 main units, based on the grade of metamorphism and lithology. (Fig. 1).

a) *Highland Series:* Charnockites, quartzites, marbles and calc gneisses, metamorphosed under granulite facies conditions.

b) *The Southwest Group:* mainly charnockites and pelitic gneisses, characterized by the presence of cordierite; marble is lacking.

c) *Vijayan Series:* migmatites and granitic gneisses metamorphosed under amphibolite facies conditions.

The Uda Walawe region shows characteristics of all the three units, charnockites, calc gneisses, migmatites and cordierite bearing rocks being present (Fig. 2). Most rocks still exhibit high grade metamorphic features, but the main part seems to have undergone retrograde metamorphism.

The serpentinite body forms a gently sloping hill and is marked by infertile soils. The serpentinized green rock is generally massive but inhomogeneous. Foliation is noticeably absent. An unserpentinized dike found only at one locality could perhaps be related to the serpentine. This basic dike is slightly discordant and is composed of tremolite and two pyroxenes.

PETROGRAPHY

The serpentinous rocks are completely serpentinized with some remnants of pyroxene and tremolite. Magnetite whenever present forms disseminated dust-like particles. The *mafic dike* is composed of tremolite/actinolite, diopside, enstatite and quartz.

As shown in Fig. 4 the serpentinite is composed of fibrous and platy serpentine minerals (chrysotile and antigorite) associated with various amounts of silica and carbonates. Brown picotite/chromite concentrations are disseminated and where present are cut by small carbonate veins. In many sections a pale green, vesicular micaceous mineral (fuchsite, delessite?) is present.

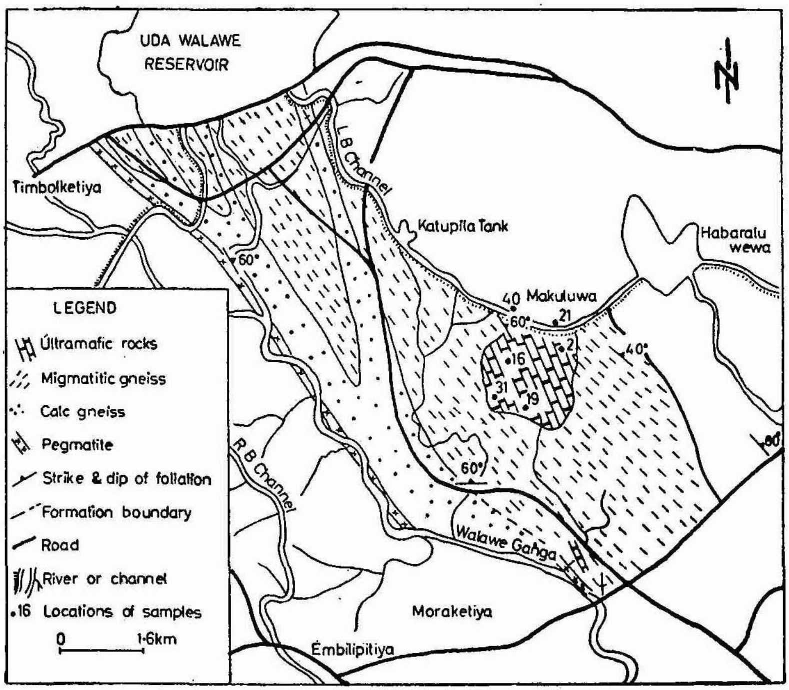

Figure 2. The geology of the area around the serpentinized ultramafic body of the Uda Walawe.

According to textures and mineral associations the following serpentinites can be distinguished:

a) oolitic serpentinite, with oolitic silica and the micaceous mineral mentioned above.

b) fibrous serpentinite. Compact vesicular antigorite and silica with or without dispersed carbonates.

c) mesh-like serpentinite (Fig. 5) with platy chrysotile and vesicular antigorite associated with carbonate and delessite (?); chromite/picotite may or may not be present. This texture points to an original peridotitic composition.

d) micaceous serpentinite, mainly composed of delessite (?).

GEOLOGIC HISTORY

Katz considered the Sinharaja forest (Fig. 1) ultramafic belt as an ancient Precambrain suture of two plates. The amphibolitic migmatites of the Uda Walawe region in which the serpentinite is situated might be the southward expression of this belt. The presence of another recently recorded serpentinite a few km north of the Uda Walawe occurrence and Oliver's (1960) discovery of serpentinite boulders further north (all of them approximately in the strike of the earlier mentioned belt) may support this hypothesis.

WEATHERING

The weathering profile on the serpentinite is that characterized by products developed from weathering as seen in a tropical terrain. The serpentinite varies from pale yellowish green to dull dark green depending on the degree of weathering among many other factors. The profile consists of residual products from the weathered rock and also of the minerals deposited by descending solutions, containing leached material. Fig. 3 shows a generalized wethering profile for the serpentinite body.

The upper part of the profile consists of a duricrust of lateritic iron ore, composed mainly of secondary iron oxides and hydroxides. Residual soil is lacking in most places on the serpentinite body and where present consists mainly of brown to black clayey soil with organic matter from decomposed vegetation. Below the iron oxide hard crust is the zone of weathered serpentinite, characterized by veinlets, box-works and cavity fillings of secondary silica in the form of agate, chert and chalcedony (Fig. 6). Just above the parent ultramafic rock is the partly weathered material containing in some instances, carbonates in the form of calcite and/or magnesite. The presence of these imparts a white appearance to the rock and pockets of such shining white carbonate aggregates are found.

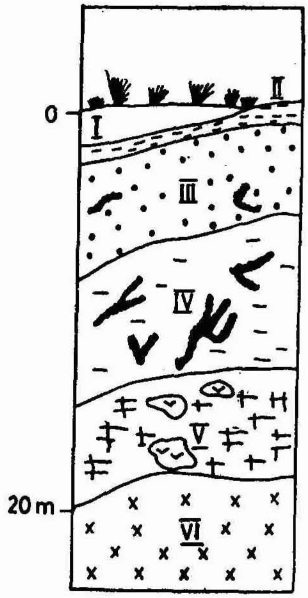

Figure 3. A generalised weathering profile of the serpentinite body.

I. Soil.
II. Ferruginous lateritic cap.
III. Zone of highly weathered serpentinite with disseminated grains of magnetite and chromite/chrome spinels.
IV. Zone of weathered serpentinite showing original reticulate banding and veinlets of secondary silica.
V. Weathered ultramafic zone containing pockets of carbonate minerals.
VI. Parent ultramafic body.

GEOCHEMICAL DISTRIBUTION OF ELEMENTS

The chemical analyses of the serpentine samples located as in Fig. 2 are shown in Table I. From Table I it can be seen that the nickel content of the serpentinite samples lies approximately in the range 0.8–1.9%. It is of interest to note the comparable nickel content of the Ramana-Loma Mulo altered serpentine of the Nicaro (Cuba) nickel deposit (column 9 of Table I). The mineralogy of this deposit as discussed by Fisher and Dressel (1959) bears strong resemblance to this deposit in Sri Lanka. In the present study, no nickel bearing minerals, sulphides or otherwise were observed. It was therefore assumed that most of the nickel present in the serpentinite is in the silicate form as garnierite. In this study, following the definition of

Springer (1974), garnierite is considered to be a nickel-magnesium hydrosilicate with or without alumina, having a structure typical for serpentine, talc, sepiolite, chlorite, vermiculite or mixtures of these.

TABLE I. Major and trace element analyses of serpentinite

Sample No.	MgO%	SiO_2%	Total Fe%	Al_2O_3%	Ni%	Co%	Cr%	Zn%	Cu ppm
D 40 d	22.76	38.14	15.5	0.79	1.92	0.12	0.17	0.04	350
D 2 P 6 S	22.70	38.78	14.5	0.83	0.80	0.06	0.07	0.06	60
D 31	23.21	36.50	15.0	1.01	0.92	0.10	0.07	0.09	60
D 21 a/s	22.79	38.00	13.5	0.80	0.76	0.09	0.06	0.05	55
D 40 b	22.70	37.90	14.0	0.81	1.64	0.10	0.15	0.05	300
D 40 a	22.97	37.50	13.5	0.90	0.98	0.07	0.06	0.05	40
D 16 S	21.55	39.00	15.0	0.55	1.40	0.09	0.12	0.03	290
D 19 a	22.38	32.40	18.5	0.62	1.36	0.09	0.10	0.03	250
Romona-Loma Mulo @ Serpentine (Cuba)	22.6	33.1	17.4	1.3	1.6	0.05	0.86	—	—

@ Data from Fisher and Dressel (1959)

D 40 d : Highly weathered serpentinite with very conspicuous grains of spinels imparting a bluish tinge.

D 2P 6s : Dull dark green serpentinite with very small veinlets of chert. Rather massive.

D 31 : Very pale green, fine grained serpentinite with minute grains of ore minerals. Rather massive.

D 21 a/s : Serpentinite xenoliths in garnet-rich migmatitic gneiss.

D 40 b : Massive, weathered serpentinite without any trace of secondary silica.

D 40 a ; Pale yellowish green serpentinite with stains of secondary iron oxides and hydroxides. Weathered.

D 16 s : Pale green serpentinite with bands of chert and a high percentage of ore minerals occurring as disseminated grains.

D 19 a : Very pale green serpentinite with conspicuously disseminated grains of ore minerals. Rather homogeneous. Contact of serpentinite and lateritic soil.

On the basis of ionic radii (Whittaker and Muntus, 1970) and charge alone Ni^{2+} (0.77 Å) can be expected to substitute for six-coordinate Mg^{2+} (0.80 Å) in hydrous nickel magnesium silicates. The substitution of Ni^{2+} for Mg^{2+} as shown by Deer, Howie and Zussman (1962), Faust (1966) and Burns (1970) has also been well established for other classes of silicate minerals. Faye (1974) in a study of the optical absorption spectrum of Ni^{2+} in garnierite confirmed that absorption of garnierite is due to Ni^{2+} replacing Mg^{2+} in six-coordinate sites in nickeloan chrysotile.

EXPLANATION OF FIGURES

Figure 4. Chromite/spinel grains intersected by carbonate veins.

Figure 5. Mesh-like serpentinite.

Figure 6. The association of cherty silica with serpentine forming a 'box-work' type of structure.

Fig. 4

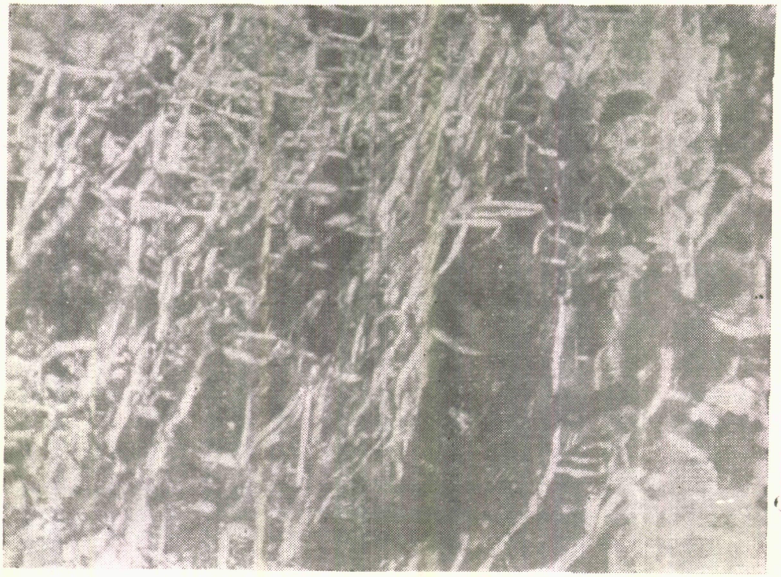

Fig. 5

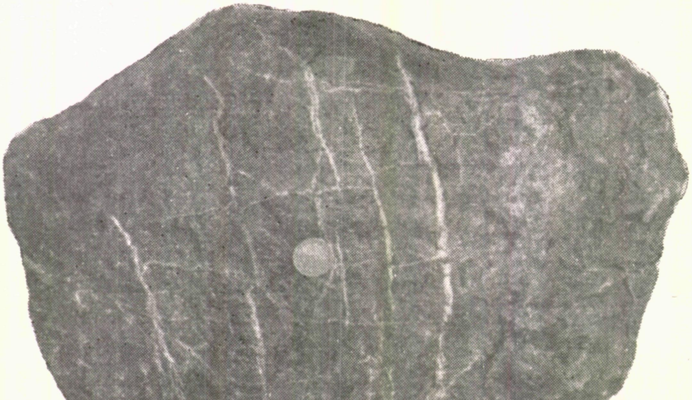

Fig. 6

Faust *et al*, (1969) have reported the nickel analogue of chrysotile (pecoraite) and a solution between the two end members Mg and Ni is expected. In the case of antigorite too, complete substitution by Ni^{2+} would be expected to be possible and Faust (1966) has indeed reported a specimen with a high nickel content.

It appears therefore, that the nickel enrichment can be attributed to one of the two following possibilities.

a) Either the nickel was introduced during serpentinization, or

b) it was present in the parent rock and was later enriched during the process of leaching and weathering.

As no nickel sulphides have been observed, it is very likely that nickel was in the silicate form. There is no evidence for the introduction of nickel bearing solutions from outside during the process of serpentinization. Since nickel is known to substitute for magnesium during the process of leaching and weathering, it can for the present be assumed that the nickel in serpentine was due to residual enrichment.

It has been shown that nickel becomes concentrated by movement of groundwater below the water table. Nickel is considered to be leached from the top layers and deposited at depth due probably to changes in pH of the solution. Groundwater rich in CO_2 is known to attack the silicates, with magnesium, iron and nickel going into solution while the silica forms a colloid. Iron and cobalt are readily oxidized and generally precipitated as hydroxides. Magnesium and nickel remain in solution and are carried down as long as conditions are acidic. On neutralization they precipitate as hydrous silicates such as nickel magnesium hydrous silicates. Magnesium being more soluble than nickel tends to get carried further while nickel takes the place of magnesium in silicate structures.

Cobalt and chromium occur in comparable amounts in the serpentinite with Cr represented by a sparsely distributed chrome spinel—possibly picotite. Zinc also occurs in approximately the same amounts as Co and Cr but Cu is found in much smaller quantities. Since Zn is known to enter the spinel structure very readily (Dissanayake and Vincent, 1972) the amount of Zn present in the serpentinite under study can be expected to reside in magnetite and chrome spinels.

Considering the major elements, the Mg contents of the samples show a highly constant value even though the Ni content varies. However, it is of interest to note that the average of 18 for the MgO/Ni ratio in this study compares well with the 14 for Nicaro (Cuba) ores which are of very similar mineralogy.

While the analysed samples contain significant concentrations of Ni, the available data are insufficient for the purpose of full evaluation of the Ni potential of the serpentinite body. Further detailed work particularly on the variation of nickel with depth is essential. However, judging by the nickel potential of other serpentinite bodies of similar mineralogy and nickel content of analysed laterite samples (eg: Nicaro ores) a complete geophysical, geochemical and drilling programme could be justified.

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Address of the authors

C. B. DISSANAYAKE, Department of Geology, University of Sri Lanka, Peradeniya, Sri Lanka.

B. J. VAN RIEL, Unesco House, 40-B, Lodi Estate, New Delhi, India.

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ACANTHOCERAS FROM THE UPPER CRETACEOUS ROCKS OF SOUTH INDIA

G. W. CHIPLONKAR AND V. G. PHANSALKAR

Abstract

Five species of *Acanthoceras* Neumayr are described here of which two species are new. *Acanthoceras rhotomagense* represented by two varieties—*sussexiense* (Mantell) and *confusum* (Gueranger), and *Acanthoceras sanctorum* Matsumoto are being reported for the first time.

INTRODUCTION

Stoliczka (1865) reported the occurrence of *Ammonites rhotomagensis* Defrance, the genotype of *Acanthoceras* Neumayr from the Upper Cretaceous Rocks of South India. While revising the ammonoid fauna of these rocks, Kossmat (1895–98) reported it as *Acanthoceras newboldi* since it did not conform to the definition of *A. rhotomagensis* Defrance. Since then these two names have been appearing in literature. No one, however, has looked at them critically.

Acanthoceras Neumayr is represented by five species. Of these, two are new. The well known species *rhotomagense* Defrance is represented by its two varieties *sussexiense* (Mantell) and *confusum* (Gueranger). *A. sanctorum* Matsumoto is being reported from South India for the first time.

The South Indian species assigned here to the genus *Acanthoceras* are in some respects very similar to *Calycoceras newboldi* (Kossmat) but they show characters, most of which permit of their being assigned to *Acanthoceras* Neumayr.

Acanthoceras population in our collection comes from the lower part of the Middle Utatur group which has been termed as *Acanthoceras rhotomagense* assemblage zone by Chiplonkar and Phansalkar (1976).

SYSTEMATIC DESCRIPTION

Super family: ACANTHOCERATACEAE Hyatt 1900
Family: ACANTHOCERATIDAE Hyatt 1900
Genus: *Acanthoceras* Neumayr 1875
Acanthoceras matsumotoi sp. nov.
Pl. I, figs. 1 and 2

Material: Several specimens, *Holotype* MACS. G. 519

Dimensions:

Diameter of shell	:	180.0 mm	(1)
Breadth of whorl section	:	89.0	(0.49)
Height of whorl section	:	85.9	(0.47)
Umbilical diameter	:	83.6	(0.46)
Breadth of whorl section at ½ whorl	:	71.4	(0.39)
Height of whorl section at ½ whorl	:	60.8	(0.33)

B/H 1.03 ; B/H at ½ whorl 1.1

Description: Shell moderately large, evolute with fairly deep, steep walled umbilicus; costal whorl section squarish though slightly broader than high; the intercostal section rounded, but is squarish with flat sides on the inner whorls; maximum breadth approximately at mid sides.

The early growth stages ornamented with strong tubercles and ribs, with ribs tending to be dominant over tubercles on later whorls; umbilical, inner and outer ventrolateral and siphonal tubercles on every rib; the siphonals and outer ventrolaterals clavate, the inner ventrolateral tubercles conical; the siphonal tubercles tend to disappear followed by the outer ventrolaterals, inner ventrolateral and umbilical tubercles persist on though much weakened.

The ribs with symmetrical slopes; about 20 on the last whorl, but more numerous and broader than the interspaces on the earlier whorls; interspaces on the last whorl tend to be much broader; the ribs rectiradiate but some at the beginning of the body whorl somewhat flexuous and anteriorly bent on the venter; ribs on the body chamber slightly raised appearing like collars.

Sutures simple, *Acanthoceras* type.

Remarks: The present species is very much similar to *Acanthoceras rhotomagense* var. *confusum* (Gueranger) with which it is associated in our collection, but differs in having much faster rate of growth, a more evolute and slightly stouter shell. Also its umbilicus is deeper and the intercostal section more rounded.

Occurrence: Light brown clayey limestone from *Acanthoceras rhotomagense* zone near Odium and Kunnam.

This species is named after Professor T. Matsumoto of Japan.

Acanthoceras intermediatum sp. nov.

Pl. I, fig. 4

Material: Several specimens; *Holotype* MACS. G. 520

Dimensions:

Diameter of the shell	:	160.0 mm	(1) approx.
Breadth of whorl section	:	69.4	(0.43)
Height of whorl section	:	65.0	(0.40)
Umbilical diameter	:	66.5	(0.41)

B/H 1.07

Description: Shell moderate in size, evolute with a squarish cross section; the intercostal section somewhat rounded and depressed; umbilicus large, deep with steep sides.

At early stages tubercles predominate over ribs; ribs few with broad interspaces, stronger on the flanks than on the venter and alternately long and short; the inner ventrolateral tubercles spinose, the outer ventrolateral conical with clavate bases, siphonal tubercles clavate and fairly elongated.

In the middle growth stages, the ribs become numerous prominent and remain alternating; interspaces become slightly narrower than in early stages. While the siphonal tubercles disappear, the umbilical tubercles become weak; so do the inner and outer ventrolaterals.

The late growth stage is characteristic; shell grows rapidly in cross section; depressed cross section of the middle growth stage becomes squarish by increase of whorl height; costal section almost unchanged; all tubercles disappear except feeble umbilical, which shift to the sides; ribs become strong particularly on the venter, and sharp, with disappearance of the short ones; five ribs on the last part of the whorl preserved.

Suture *Acanthoceras* type.

Remarks: This species is comparable to *Acanthoceras rhotomagense* var. *confusum* which is represented in our collection, but differs from it in having smaller number of ribs on the last whorl, a narrower and deep umbilicus and early disappearance of ventrolateral tubercles.

The rapid growth of the shell makes this species comparable to *Acanthoceras matsumotoi* (vide supra) in our collection, but differs in having a depressed intercostal whorl section in the middle growth stages and a smaller number of ribs on the last whorl.

By prominence of tubercles over ribs in early growth stages and reverse relation in later growth stages, the present species shows a peculiar combination of morphological characters of Mantelliceratinae and Acanthoceratinae and hence the name given to it.

Occurrence: Light brown clayey limestone from *Acanthoceras rhotomagense* zone near Odium.

Acanthoceras rhotomagense var. *sussexiense* (Mantell)

Pl. II, fig. 1

1822 *Ammonites sussexiense* Mantell : Mantell p. 114, pl. 20, fig. 1, pl. 21, fig. 10.

1963 *Acanthoceras mirialampiense* Wright : Wright, p. 606, pl. 84, fig. 3, pl. 85, fig. 1.

1970 *Acanthoceras rhotomagense* var. *sussexiense* (Mantell) : Kennedy and Hancock, p. 472, pl. 89, fig. 2, pl. 91, figs. 1, 2, pl. 92, figs. 1, 2; text figs. 3, 4, 5, 6a.

Material: One specimen : *Plesiotype* MACS. G. 521

Dimensions:			
	Diameter of shell	: 194.00 mm	(1)
	Breadth of whorl section	: 82.00	(0.42)
	Height of whrol section	: 80.00	(0.41)
	Umbilical diameter	: 56.00	(0.28)
	Breadth of whorl section at ½ whorl	: 68.00	(0.35)
	Height of whorl section at ½ whorl	: *58.00*	*(0.29)*

B/H = 1.02 ; B/H at ½ whorl = 1.17

Remarks: The solitary specimen at our disposal is a septate part of the shell with characters which allow us to place it in this well known species. It, however, shows some minor differences as compared to the English form, e.g., slightly smaller umbilicus at comparable diameter and somewhat better rounding of the ventrolateral shoulder.

Occurrence: Brown sandy limestone from *Acanthoceras rhotomagense* zone near Odium.

Distribution: This species has a wide geographic distribution in the Middle Cenomanian of England, France, Madagascar and Australia.

Acanthoceras rhotomagense var, *confusum* (Gueranger)

Pl. II, figs. 3 and 4

1867 *Ammonites confusus* Gueranger : Gueranger, p. 5, pl. 2, fig. 4, pl. 3, fig. 1, pl. 8, fig. 1.

1970 *Acanthoceras rhotomagense* var. *confusum* (Gueranger) : Kennedy and Hancock, p. 478, pl. 94, figs. 1-4.

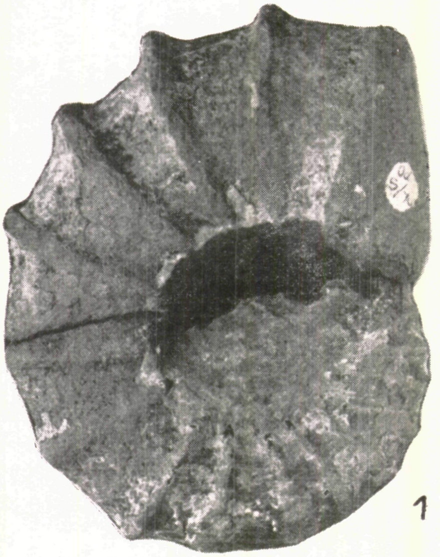
1972 *Guerangericeras confusum* (Gueranger) : Thomel, p. 119.

EXPLANATION OF PLATE I

1 & 2. *Acanthoceras matsumotoi* sp. nov. MACS G519 × 0.33

3. *Acanthoceras hunteri* Kossmat Od 63 × 0.33

4. *Acanthoceras intermediatum* sp. nov. MACS G 520 × 0.33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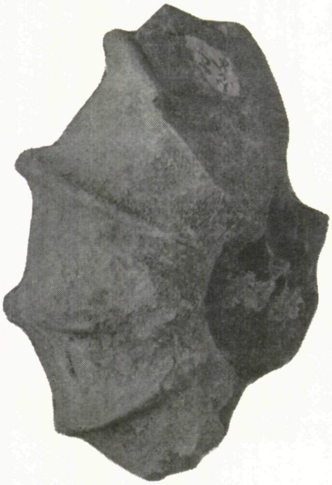
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CHIPLONKAR AND PHANSALKAR: *ACANTHOCERAS* FROM SOUTH INDIA

1

2

3

4

CHIPLONKAR AND PHANSALKAR: *ACANTHOCERAS* FROM SOUTH INDIA

Material: One specimen ; *Plesiotype* MACS. G. 521

Dimensions: Diameter of shell : 255.00 mm (1)
Breadth of whorl section : 88.6 (0.34)
Height of whorl section : 83.60 (0.32)
Umbilical diameter : 98.60 (0.38)
Breadth of whorl section at ½ whorl : 78.50 (0.30)
Height of whorl section at ½ whorl : 64.90 (0.25)
B/H = 1.06 : B/H at ½ whorl = 1.2

Remarks: Agreeing with Kennedy and Hancock (1970) we place our solitary specimen under *A. rhotomagense* var. *confusum* (Gueranger) rather than place it under *Guerangericeras confusum* as done by Thomel.

Occurrence: Whitish clays from *Acanthoceras rhotomagense* zone near Odium.

Distribution: This species is known from *rhotomagense* zone of Middle Cenomanian from England and France.

Acanthoceras sanctorum Matsumoto
Pl. II, Fig. 2

1966 *Acanthoceras sanctorum* Matsumoto : Matsumoto and Obata, p. 43, pl. 1-4.

Material: One specimen ; *Plesiotype* Od 3

Dimensions: Diameter of shell : 169.0 mm (1) approx.
Breadth of whorl section : 75.0 (0.44)
Height of whorl section : 70.0 (0.41)
Umbilical diameter : 55.0 (0.32)
Breadth of whorl section at ½ whorl : 44.0 (0.26)
Height of whorl section at ½ whorl : 44.0 (0.26)
B/H = 1.07 : B/H at ½ whorl = 1.00

Remarks: Though a solitary septate portion of the shell is available it is placed under Matsumoto's species because of its agreement in most of the characters.

Occurrence: Pale brown clays of *Acanthoceras rhotomagense* zone near Odium.

Distribution: This species is known from the Cenomanian of Japan.

Acanthoceras hunteri Kossmat
Pl. I, fig. 3

1897 *Acanthoceras hunteri* Kossmat : Kossmat, p. 9, pl. 3, fig. 4.

Material: One specimen : *Plesiotype* Od 63

Dimensions: Diameter of shell : 230.0 mm (1)
Breadth of whorl section : 91.0 (0.39)
Height of whorl section : 82.0 (0.35)
Umbilical diameter : 88.0 (0.38)
Breadth of whorl section at ½ whorl : 78.0 (0.33)
Height of whorl section at ½ whorl : 66.4 (0.28)
B/H = 1.1 : B/H at ½ whorl = 1.17

Remarks: The solitary specimen at our desposal agrees with Kossmat's type, but for a few ribs more per whorl. Inclusion of this species in *Acanthoceras* has

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EXPLANATION OF PLATE II

1. *Acanthoceras rhotomagense* var. *sussexiense* (Mantell) MACS G. 521 ×0.33
2. *Acanthoceras sanctorum* Matsumoto Od 3 ×0.33

3 & 4. *Acanthoceras rhotomagense* var. *confusum* (Gueranger) MACS G 521 ×0.33

been doubted by Matsumoto *et al*, (1969) but to us the present placement seems proper in the light of the diagnosis of *Acanthoceras* given by Kennedy and Hancock (1970).

Occurrence: Whitish clayey limestone from *Acanthoceras rhotomagense* zone near Odium.

Repository: Type specimens of *A. hunteri* and *A. sanctorum* of our collection are preserved in the Department of Geology, University of Poona, Poona 411007, while others are preserved in the type collection of the Maharashtra Association for Cultivation of Science, Poona 411 004.

ACKNOWLEDGEMENTS

We gratefully acknowledge the facilities given by Dr. G. B. Deodikar, Director, M.A.C.S. Research Institute, Poona, and Dr. B. G. Deshpande, Professor and Head of the Department of Geology, University of Poona, Poona for undertaking this work.

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Address of the authors

G. W. CHIPLONKAR, Maharashtra Association for Cultivation of Science, Poona 411 004.

V. G. PHANSALKAR, Department of Geology, University of Poona, Poona 411 007.

A comment on the paper:

An estimation of temperatures of intrusion of Indian carbonatites using calcite-dolomite geothermometry

by S. F. Sethna and S. G. Viladkar, Jour. Geol. Soc. India, Vol. 18, pp. 275-280

BY

J. GITTINS
Department of Geology, University of Toronto, Toronto, Canada M5S 1A1

In this paper the authors seek to determine the temperature of intrusion of several carbonatite magmas. Their work calls for some comment on the general principles involved.

First of all, at risk of being a trifle pedantic, the title is not accurate. What has been estimated is not the temperature of the magma at the time of intrusion, but the temperature at which carbonate minerals crystallized from the magma. As will be shown subsequently, this may be a very poor estimate because what is actually determined is the temperature at which diffusion rates between coexisting calcite and dolomite become negligible.

The method is, however, of dubious validity. It seeks to determine the amount of $MgCO_3$ in soild solution in calcite and to relate this to temperature by employing the solvus in the system $CaCO_3$–$MgCO_3$. The authors have employed the method described by Jennings and Mitchell (1969) which employs cold hydrochloric acid to dissolve calcite but not dolomite. The solution is then analysed to determine the composition of the calcite.

Unfortunately, the Jennings and Mitchell paper contained a misprint; the strength of the HCl was given as 6N instead of 6%. Sethna and Viladkar, by using 6N HCl will have dissolved any dolomite present, or at least enough of it seriously to affect the analyses.

However, there are several problems with the basic approach. First of all it cannot be assumed that the calcite in a carbonatite is saturated with $MgCO_3$ unless dolomite is present as a separate phase in the rock, or the calcite has exsolved dolomite. It appears from the sample descriptions that all but one of the samples were purely calcitic carbonatite. If the carbonatite does have calcite and dolomite in the same hand specimen, *and if the calcite has not exsolved dolomite,* the method will give the composition of the calcite. This composition can then be related to a temperature on one limb of the solvus. But what significance has this temperature? Jennings and Mitchell noted that the temperature obtained is a *minimum.* It is a minimum temperature for two reasons: (1) any mineral that exsolves a second phase on a solvus must have crystallized from a liquid at a higher temperature; (2) there is no way of determining how much further migration of Mg from calcite into exsolved dolomite may have continued after the initial exsolution occurred.

A second problem arises if the calcite contains exsolved dolomite. The method of Jennings and Mitchell, by failing to dissolve dolomite, produces the composition of calcite *after* it has exsolved dolomite. If the composition of the carbonate before exsolution can be determined (i.e., calcite plus its exsolved dolomite), then a temperature is obtained that, although it is still a *minimum* temperature of crystallization, is closer to the true temperature at which the carbonate crystallized from the magma. Unfortunately the Jennings and Mitchell method probably dissolves a small amount of the very thin dolomite exsolution lamellae and so produces a composition intermediate between the initial carbonate and the calcite after exsolution of dolomite.

As it happens, Sethna and Viladkar possibly have, albeit inadvertently, obtained the best minimum temperature for their Samalpatti specimen, which has calcite and exsolved dolomite, by mistakenly using 6N HCl instead of 6% HCl, for they will have taken both phases into solution and obtained the composition of the magmatic carbonate. If, however, the specimen contained primary dolomite, which is highly likely from their description given of the carbonatite complex, the result will be quite wrong.

Finally, it must be pointed out that the expression $T°C = \log MgCO_3$ (calcite) $+ 0.223/1.727 \times 10^{-3}$ is an extrapolation of the calcite-dolomite solvus to temperatures below 400°C, that the solvus was determined at a variety of pressures from 2 to 8 kbar and so it is not truly an isobaric solvus (although the pressure effect is probably minor), and that most carbonates in carbonatites contain several mol.% $FeCO_3$ and $MnCO_3$ in solid solution. This compositional effect has not adequately been studied experimentally but a thermodynamic analysis by Bickle and Powell (1977) suggests that the effect of $FeCO_3$ generally is to raise the temperature above that obtained by ignoring the $FeCO_3$ component. The method, therefore, has severe limitations, and it must be stressed again that it gives no more than minimum temperatures.

All of this can be illustrated by reference to a carbonate from the Goldray carbonatite complex in northern Ontario, Canada. One of the many types of carbonatite in this intrusion consists of calcite showing coarse and fine exsolution lamellae of dolomite. The calcite grains are of sufficient size that they can be hand picked in order to obtain a sample for classical wet chemical analysis. In this way, what is obtained is the composition of a formerly homogeneous carbonate which on cooling exsolved dolomite. Further cooling resulted in continued exsolution which is now represented by the very fine lamellae. The bulk composition of the originally homogeneous carbonate is (in mol.%):

$CaCO_3$	$MgCO_3$	$FeCO_3$	$MnCO_3$
73.8	21.7	4.1	0.5

which, through the Jenning and Mitchell equation gives a temperature of 903°C.

A series of electron microprobe analyses of the calcite host and the lamellae of exsolved dolomite of a single large (2 cm) carbonate grain gives (in mol.%.):

Dolomite				Calcite				
$CaCO_3$	$MgCO_3$	$FeCO_3$	$MnCO_3$	$CaCO_3$	$MgCO_3$	$FeCO_3$	$MnCO_3$	T°C
54.1	45.8	—	0.1	88.8	8.5	1.9	0.7	668°
51.0	43.1	5.4	0.4	89.3	7.8	2.6	0.4	645°
51.5	42.7	5.3	0.5	89.5	7.7	2.3	0.6	641°
53.6	40.8	5.2	0.3	90.7	6.5	2.4	0.4	600°
52.2	41.8	5.5	0.5	90.6	6.3	2.4	0.7	591°
52.3	41.8	5.4	0.5	92.6	4.8	2.1	0.5	522°
52.4	41.6	5.5	0.5	94.3	3.4	1.9	0.4	435°
53.6	40.5	5.3	0.5	96.8	1.3	1.5	0.3	201°

The temperatures indicated by calcite composition range from 668° to 210° within a single large grain. Even the highest temperature is 235° lower than the temperature indicated by the bulk composition and even that is only a minimum temperature for calcite crystallization from the magma. The example serves to illustrate how misleadingly low can be the temperature obtained from calcite alone if its exsolved dolomite is ignored.

Now consider the result of assuming the calcite to be saturated with $MgCO_3$ when the absence of dolomite as separate primary grains renders such an assumption unwarranted. The following compositions are of calcites from carbonatites, also in northern Ontario in which dolomite is not present either as separate grains or as exsolved lamella. The corresponding temperatures are hundreds of degrees lower than that obtained from the previous example (compositions in mol.%).

$CaCO_3$	$MgCO_3$	$FeCO_3$	$MnCO_3$	T°C
93.8	2.5	2.3	1.4	364°
92.6	3.3	2.8	1.4	431°
97.2	2.4	.2	.2	351°
95.8	3.6	.6	NIL	452°
98.4	1.0	.3	.2	134°

It is, of course, possible that these calcites are saturated with $MgCO_3$ despite the absence of dolomite, although it cannot be proved. It does, however, seem unlikely.

A point of interest is the high temperature obtained for the Goldray carbonatite, 903°C being the *minimum* temperature at which it crystallized. Even if the solvus is markedly affected by Fe and Mn, it is still a temperature much higher than petrologists are inclined to consider for carbonatites. Although much experimental work has shown that carbonatite magmas can exist to very low temperatures, it must not be assumed that carbonatite magmas do not also exist at temperatures more generally associated with silicate magmas.

The grave weakness in attempting to determine crystallization temperatures from calcite composition is the assumption that the composition is quenched at the time of crystallization. Clearly, it is not. Even when the temperature cools to the solvus and exsolution occurs, the process does not cease. Migration of Mg from magnesian calcite into already exsolved dolomite continues during the cooling of the carbonatite after the initial exsolution has occurred. This migration seems to occur to differing degrees within a single grain as shown by the compositions previously quoted for calcite and its exsolved dolomite, but also from one grain to another as indicated by the following compositions of separate grains within single thin sections, also from the Goldray carbonatite (analyses in mol.%).

	$CaCO_3$	$MgCO_3$	$FeCO_3$	$MnCO_3$	T°C	Δ°C
1516C	86.3	10.4	2.9	0.4	717°	126°
	87.9	8.8	2.9	0.4	675°	
	86.9	9.7	3.1	0.3	701°	
	88.1	8.6	2.9	0.4	670°	
	86.7	10.5	2.5	0.3	721°	
	81.1	14.2	4.3	0.4	796°	
1516A	85 1	10.3	4.2	0.4	715°	74°
	86.8	9.2	3.5	0.4	688°	
	88.6	7.6	3.3	0.4	641°	
G7-1-547A	83.1	10.8	5.7	0.5	767°	21°
	82.0	13.7	3.9	0.4	788°	
G7-1-860	86.7	9.7	3.2	0.4	701°	114°
	80.9	15.3	3.4	0.3	815°	

Even to obtain the minimum temperature of carbonate crystallization a large number of grains must be analysed, and the highest value taken. In view of all the factors that effect the result it is, however, doubtful if the method is worth pursuing.

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Authors' Reply:

We are grateful to Prof. Gittins for very clearly indicating the limitations of the use of calcite-dolomite geothermometry for estimation of temperatures of crystallization of carbonatite magmas.

We would like to clarify the basis of the method of preparation of solutions. Prof. Gittins has mentioned that we used 6N HCl which would dissolve a fairly large amount of dolomite. The 10 gms sample we took into solution was immersed in 100 ml distilled water and 6N HCl was then added drop by drop till effervescence ceased. We then added 1 ml of 6N HCl. The solution was filtered and residue was weighed to determine the amount of calcite taken into solution. Duplicate solutions were prepared and the results obtained were quite consistant. Thus we are certain that only calcite was dissolved and dolomite was not affected.

OBITUARY

SRI N. A. VEMBAN
(1921—1978)

The Geological Society of India records with sorrow the sudden demise of Sri N. A. Vemban, one of the founder members of the Society on the 13th May, 1978 at Madras at the age of 57.

Sri Nemam Appu Vemban was born on the 29th May, 1921 at Thanjavur district, Tamil Nadu, in a well-to-do family. He was the nephew of late M. S. Krishnan, one of the doyens of Indian Geology. He had his early education in Tiruchirapalli district and joined the Presidency College, in 1942 from where he obtained his M.Sc. degree in 1945. He joined the Geological Survey of India in 1946 and served the department for 32 years in various capacities. He was deputed in 1956 for advanced training in Economic Geology to Canada under the Colombo Plan. In the University of Alberta, Edmonton, Canada, he took courses in Sedimentology, Petrology, Structural geology and Geophysics. He carried out mapping and mineral investigation in the Uranium belt near Elliot point, Lake Athabasca, Saskatchewan. During this period, the Geographical Society named a lake in the Saskatchewan area where he carried out geological mapping as 'Vemban Lake'.

Sri Vemban was engaged on a study of the Petrography of the Cuddappah and Deccan Traps during the early part of his career. After joining the Geological Survey of India Sri Vemban was sent for regional geological mapping work in 1947 to Salem district in the Southern Region. Soon after, he was posted as Assistant Petrologist in the Central Petrological laboratories, Calcutta. He was posted to the Eastern Region in 1949 and assigned geological mapping of the Bihar mica belt. He was deputed to carry out detailed investigation of the manganese ores in the Sausar series of Madhya Pradesh and Maharashtra under the guidance of J. A. Straczec of the U. S. Geological Survey between 1951-54. He carried out investigation in the Panna area M.P. and in the Singhbhum copper belt, Bihar in 1955-56. After returning from Canada in 1957, Sri Vemban continued the investigation of the Bihar mica belt with emphasis on the study of the internal structure and morphological characters of the mica-pegmatites. He took up detailed investigations for base metals in the Ingaldhalu area of Chitradurga Schist (Karnataka) between 1957 to 1959. On his promotion as Superintending geologist Sri Vemban was posted to Mysore Circle in 1959. He was in charge of the Jammu and Kashmir Circle between 1960-65 when he organised the field trips in the Kashmir Valley for the 22nd International Geological Congress. He handled a difficult situation during the tours when 80 delegates were held up in snow-bound Kashmir and could not attend the main session of the Congress at New Delhi. He literally organised a parallel session of the Congress at Srinagar and kept them engaged. He was posted to the Gujarat Circle in 1965 where he contributed to the investigation for basemetals including the Amba Mata prospect. In April, 1967 Sri Vemban took charge of the Tamil Nadu Circle and worked till 1972. During this period he organised geological mapping in several districts with emphasis on deciphering the structure and tectonics. He also guided the assessment of the molybdenum prospect at Karadikuttam, Madurai district and set up a geological museum at Pondicherry.

Sri Vemban was transferred to Calcutta in 1972 as Director in the Field Techniques Research Unit. He took charge of the Eastern region in 1973, first as Director and as Deputy Director General in 1974. In the Eastern region he organised a group discussion on Quaternary Geology and a symposium on geochemical prospecting in 1975. In 1976 he was transferred to the A.M.S.E. Wing of the Geological Survey of India at Bangalore. In April, 1977, Sri Vemban was transferred to the Central Region, Nagpur. He could not take charge at Nagpur until the 13th February, 1978 owing to illness. In spite of the set back he had suffered due to illness he did not relax or decrease the tempo of work he was used to. He had spent only 3 months as Deputy Director General, Central Region before he passed away.

Sri Vemban was a member of several learned Societies. He was a member of Council of the Geological Society during 1968 to 70. He was very active and meticulous in his work and did a thorough job of whatever he took up. He had a high sense of duty and expected the same from his associates. In the death of Sri Vemban, the Geological Survey of India has lost one of its able geologists and the Society a distinguished fellow.

He leaves behind his wife, two sons and a daughter.

N. G. K. MURTHY.

B. VASUDEVA MURTHY

1917—1978

Sri B. Vasudeva Murthy, aged 61 years, passed away after a brief illness on 28th July, 1978. Vasudeva Murthy was the son of Sri J. Bhimasena Rao and was born at Mysore on 8th June, 1917. He had his early education in Mysore and took his M.Sc. degree in Geology from the Central College in 1940. After graduation, he joined the Police Department as a Sub-Inspector and served in that capacity for nine years till 1950. He felt a misfit in the Police Department and managed to get his services transferred to the Department of Mines and Geology. I was partly instrumental in securing this transfer and since then Vasudeva Murthy remained a close friend and associate. He served as an Assistant Geologist in the Board of Mineral Development and later came to occupy the post of Technical Assistant to the Director of Mines and Geology. He was a trusted assistant and made himself indispensable. He retired from service in 1972. Immediately after, the State Bank of India utilised his services as a Technical Officer for evaluating and advising the Bank on loan applications received for well sinking. He toured extensively in many parts of South India during the four years in the Bank.

Vasudeva Murthy was an extremely popular figure. He was helpful by nature and many people flocked to him for help. He was a loyal assistant. He leaves behind his wife, three sons, two daughters, and a large circle of friends to mourn his loss.

B.P.R.

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OBITUARY

Suryadevara Subba Rao (1936–1978)

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ADDRESS OF EDITOR

All papers intended for publication as also all correspondence in this connection should be addressed to Dr. B. P. Radhakrishna, 16/1, Ali Asker Road, Bangalore 560052.