Fluid of magnesitization: Diagenetic origin of Bauri magnesite, Kumaun Lesser Himalaya

Rajesh Sharma and M. N. Joshi*

Wadia Institute of Himalayan Geology, Dehra Dun 248 001, India
*Department of Geology, D.B.S. College, Dehra Dun 248 001, India

The primary fluid inclusions in Proterozoic magnesite and associated marine dolomite of Bauri area in Kumaun Lesser Himalaya are studied to understand the origin of magnesite. The data obtained from both the carbonate phases closely match and their T_h vs T_m plots show a correlation between salinity and temperature. A magnesite formation temperature of about 90°–160°C and a diagenetic replacement origin for these magnesites is suggested.

THE Lesser Himalayan magnesite deposits extending in Western Himalaya from Pithoragarh district of Uttar Pradesh to near Jammu in Jammu and Kashmir are the Indian representatives of the 'Veitsch' type magnesite deposits, as the lenses and pockets of these coarsely crystalline magnesites occur within the marine platform sediments. Diverse views about their origin are in vogue[1] ranging from direct chemical precipitation[2,3], penecontemporaneous diagenetic replacement[1,4,5] and epigenetic hydrothermal metasomatism by Mg and/or CO_2-rich solutions[6]. The origin inferred from field, petrographic and chemical evidences has remained inconclusive. Considering this dispute, present fluid inclusion data as new aspect in understanding magnesite genesis is significant.

The Bauri magnesite deposit (29°44'N: 79°47'E) located about 5 km south-east of Kathpuria Chhina, 50 km north of Almora on Almora–Takula–Bageshwar road is hosted by the dolostone of the middle to Late Proterozoic Gangolihat Formation. Magnesite is found as lenses, pockets and bands associated with dolomite. The dark grey to blue dolostone occurs in micro-crystalline, massive as well as in stromatolitic form, whereas the magnesite is pinkish and very coarse and stellate. The contact between these two is both concordant, sharp, abrupt as well as exhibiting interdigitation and sutured. Relics of cryptocrystalline silica in the form of chert fillings and veins are observed both in dolostones and magnesites. Talc occurs as relics within magnesite as well as the product of later magnesite–quartz reactions[7]. Occasionally galena also occurs associated with both the carbonate facies. There is a gradual increase in MgO and FeO with a corresponding decrease in CaO and a striking depletion in Sr from dolostone to magnesite. However, no distinct variation in other major or minor elements and in insoluble contents has been noted. Both dolostones and magnesites are characterized by the same

range of oxygen isotope ratios but a marked enrichment in lighter carbon isotopes in magnesites is found[5].

The fluid inclusions with nearly similar characters are observed both in magnesite and associated dolomite, as described below:

(i) Primary monophase aqueous inclusions are common both in magnesite and dolomite. They are usually regular and equant (geometric) in shape, < 10 μm in size and found scattered in the grains. They also occur in small groups associated with the biphase inclusions.

(ii) Biphase aqueous inclusions contain 80 to 95 vol% liquid and 5–20 vol% gas. They are commonly about 10 μm in size with a variation from < 5 μm to rarely about 20 μm. They are mostly equant to subequant in shape, some of them are elongated and rounded. In rare cases movement of their gas is noticed. The distribution pattern and the shape of the mono and biphase inclusions in magnesite and dolomite (Figure 1 a and 1 b) suggest that they are primary in nature[8], and hence these are taken to represent the fluid that participated in magnesitization process.

(iii) Although uncommon, inclusions with about 20 vol% CO_2 and a major proportion of aqueous liquid are also observed. These inclusions are semicircular in shape, nearly 10 ± 5 μm in size and occur in planar arrays, trails or in groups (Figure 1 c). Careful observation showed a liquid–liquid meniscus in two inclusions. Due to their secondary nature in magnesite, they appear to be unrelated with the magnesite formation process.

The microthermometry on double-polished wafers containing magnesite and dolomite is carried out, using gas flow SGE and Linkam THMSG 600 fluid inclusion systems. The observation of the low temperature phase behaviour in many inclusions was poor because of optical limitations. The accuracy of the heating runs was found to be ± 5°C whereas on freezing it was ± 0.4°C. Thermometric runs were repeated on many inclusions to check leakage and/or stretching in the inclusion cavities[9].

On freezing, the monophase inclusions did not nucleate any vapour bubble indicating that they are not metastable stretched water solution. This also suggests that they were trapped at a lower temperature than biphase inclusions. The temperature of eutectic melting in many frozen inclusions could not be observed. However, the first phase separation in some biphase inclusions was noticed at a temperature range of −28.8° to −24.5°C. This is lower than the eutectic temperature of $H_2O + NaCl + KCl$ solution (cf. −22.9°C)[10]. It is known that the presence of divalent cations like Mg and Ca may cause lowering in eutectic temperature of $NaCl + KCl$-bearing solution[8]. Hence from the estimated temperature of first phase separation, presence of other cations like Mg and Ca in the trapped $NaCl–KCl–H_2O$ fluid is

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indicated. Such inference also supports the host composition and suggests that this fluid participated in the magnesite formation. The salinity is estimated in terms of eq. wt.% NaCl considering final ice melting temperatures[11]. The reported values indicate the amount of NaCl which would produce equivalent lowering in melting temperature. The recorded T_m ice in magnesite is –6.3 to –13.8°C and in dolomite it is –7.1 to –13.2°C, which corresponds to a salinity of 9.6 to 17.6 eq. wt%
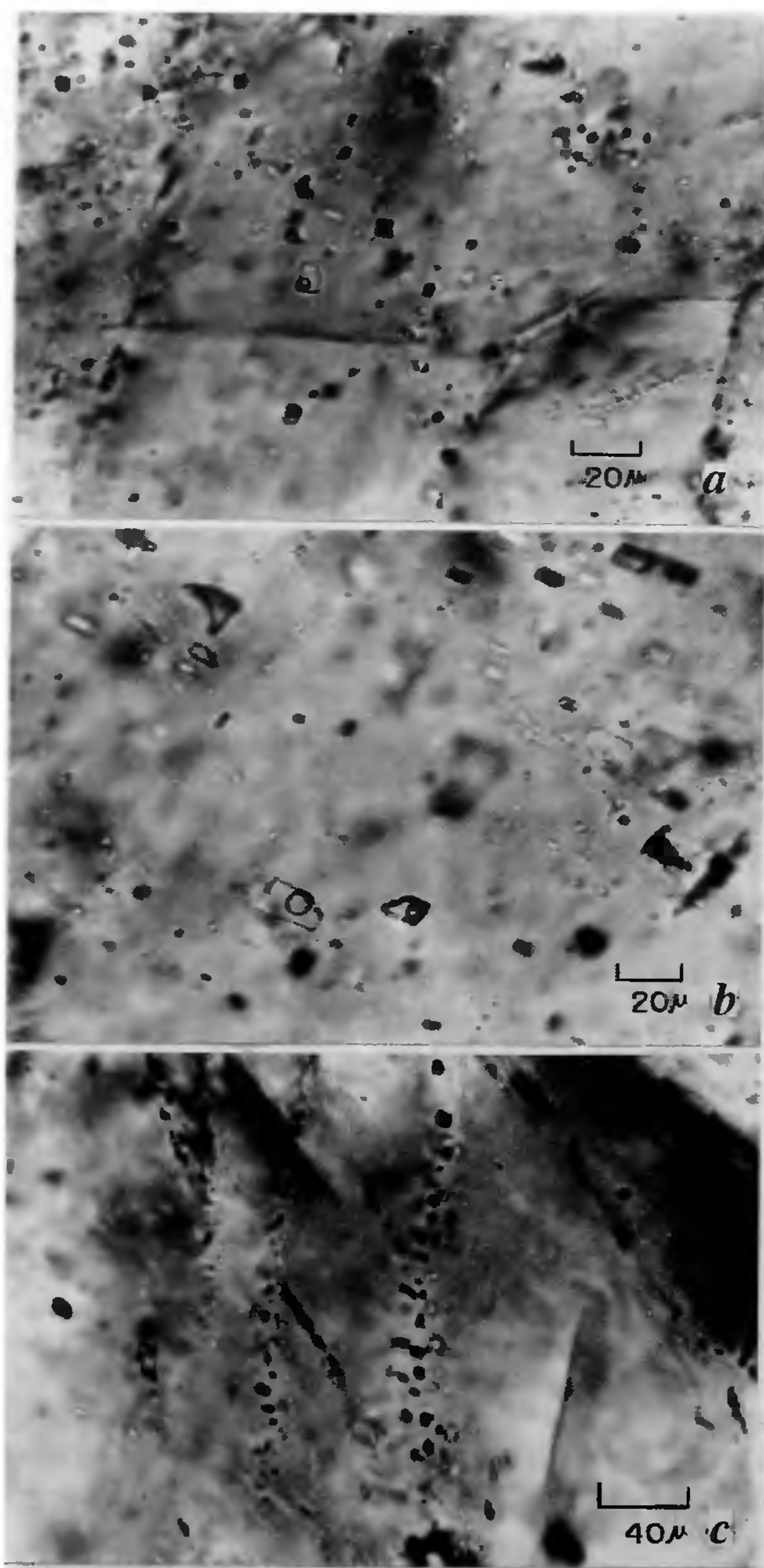

Figure 1. Photomicrograph of biphase and monophase aqueous inclusions (a) in magnesite and (b) in dolomite. (c) shows H_2O-CO_2 inclusions in magnesite.

NaCl and 10.6 to 17.1 eq. wt% NaCl respectively. The homogenization of these biphase aqueous inclusions in dolomite ranges from 84° to 162°C with a peak at 100–110°C, whereas the biphase inclusions in magnesite were homogenized at temperature range of 92° to 176°C with a histogram peak at around 120°–130°C (Figure 2). The average estimated density of aqueous fluid in magnesite is about 1.04 ± 0.02 g/cm^3. As the monophase inclusions were trapped after the thermal peak, they indicate a lower temperature than the biphase inclusions, although by the usual petrographic observations their chronology is unpredictable. The samples having galena in addition to magnesite and dolomite generally do not show inclusions with lower temperature range (< 100°C) and no other distinct difference was noticed.

The microthermometry on a few $H_2O + CO_2$ inclusions suggests the presence of CO_2 with a low density (about 0.78 g/cm^3). The occurrence of talc shreds in magnesite together with the secondary CO_2-bearing inclusions in magnesite implies that the trapped CO_2 was produced by $MgCO_3 + SiO_2$ reaction forming talc and releasing CO_2. As these secondary inclusions are not representative of magnesitization process, therefore they are not discussed here.

The T_h vs T_m plots (Figure 3) of Bauri magnesite show that the salinity of the fluid decreased along with the lowering in temperature, hence fluid was diluted at reduced temperature. This indicates mixing of two fluids, one being low saline, low temperature probably a meteoric water and the other diagenetic in nature as has been suggested by the salinity and temperature records[12]. Such dilution by meteoric water would favour the magnesite formation because the carbonate solubility
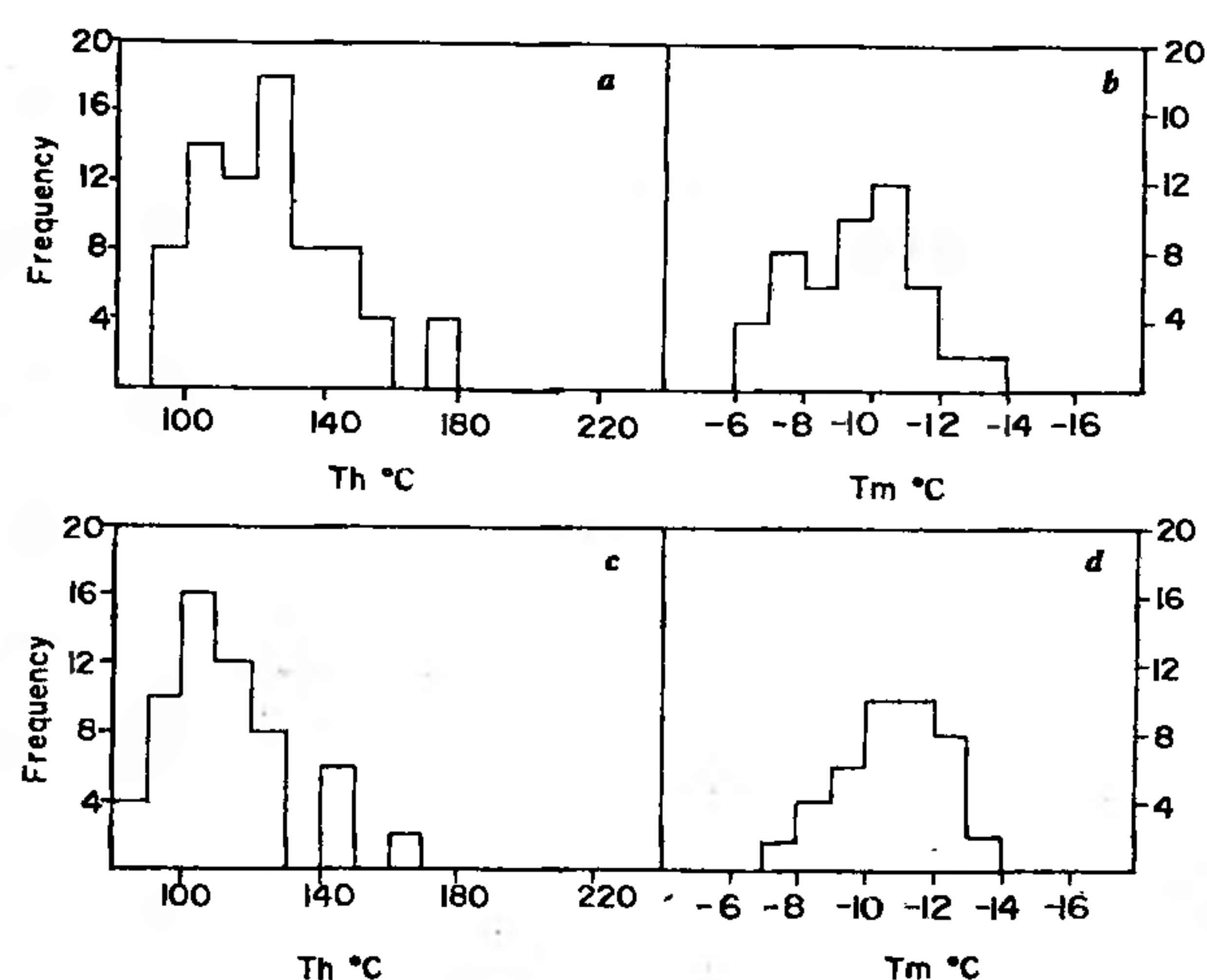

Figure 2. Histogram of biphase aqueous inclusions. a, For homogenization temperatures in magnesite; b, For final ice melting temperatures in magnesite; c, For homogenization temperatures in dolomite; d, For final ice melting temperatures in dolomite.
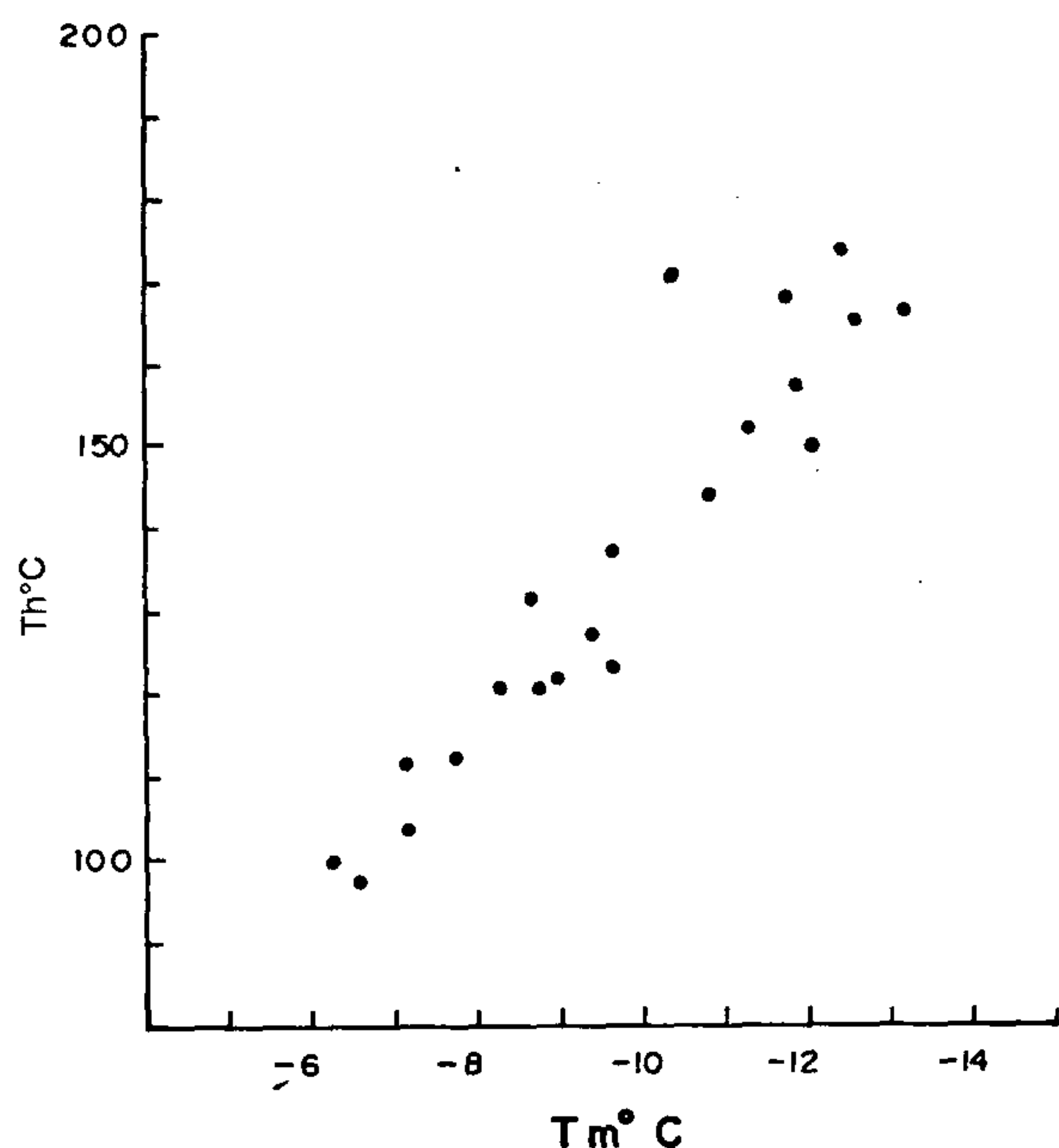
Figure 3. Melting vs homogenization temperature diagram for Bauri magnesite.

increases at lower temperature[13] and therefore the removal of Ca by Mg is easier at lower temperature. It is difficult to ascertain the advent of meteoric water mixing, however the near-horizontal distribution of higher homogenization temperatures over the plots suggests that the mixing was introduced soon after the attainment of maximum temperature. Further, the recorded temperature reflects near-formation temperature without applying pressure correction because these Proterozoic carbonates are effected by increased overburden pressure.

The compatibility of inclusion data with the genetic models of Lesser Himalayan magnesite is discussed. This can place constraints on the process involved in magnesite origin. It is evident that the transformation of dolomite to magnesite by the Mg-rich emanations of basic magmatic origin is not possible because fluids of such origin have high temperature with rich CO_2 contents, which in present case is lacking. These evidences also do not support hydrothermal replacement by Mg- and CO_2-rich fluids, forming magnesite. For the hydrothermal deposits it is well demonstrated that they result from much larger volumes of ore fluid which must successively pass through the sites of the ore body, thus leaving its remnants[8]. Whereas this study shows that since the characters of inclusions and estimated micro-thermometry of magnesite and dolomite closely match therefore, they do not qualify for the origin from hydrothermal fluid flux.

The chemical precipitation of magnesite/syngenetic

model suggests that it was formed in high-saline media and high-Mg/Ca ratio. This has also been proved by the experimental precipitation of magnesite wherein high saline fluid was used[2]. Present day evidences of carbonate crystallization in sabkhas also indicate that hypersaline brine richer in Mg than ordinary sea water are required for the precipitation of primary magnesite. The recorded salinity of 18 wt% NaCl eq. are much lower than the hypersaline fluid required for chemically precipitated magnesite. Also in the chemical precipitation, the grains are usually fine and the trapping of suitable inclusions is a major problem. The coarse crystalline magnesites are considered as product of diagenesis[14] and the crystal size of carbonates has been used to distinguish early and late diagenetic origin[15,16]. In the present case the magnesite is coarser than dolomite and occurs in pockets and in lenses in the latter. The change in crystallinity, sharp contacts and form of magnesite suggests a post-dolomitization replacement event responsible for magnesite formation. These inferences indicate that dolomite is formed earlier and magnesite formed later. In the absence of a foreign fluid trapped in magnesite, its formation by syndiagenetic replacement is suggested. This is supported by the similar nature of fluids, identical inclusion cavities, their distribution pattern and minor difference in their temperature and salinity in magnesite and dolomite. The salinity and histogram peak of homogenization temperature in magnesite (120°–130°C) is marginally higher than that in dolomite (100°–110°C). These conditions suggest an increased overburden during compaction and diagenesis and favourable environment during magnesite formation. The occurrence of algal structures indicates that Mg might have derived from original algal limestone which may contain as much as 24% $MgCO_3$. A diagenetic event following primary sedimentary precipitation of magnesite also cannot be invoked as formation process. This is because no remnant of early stage fluid is found, the temperature is too low to completely eliminate the early trapped fluid if any, the trend of T_h vs T_m is similar to diagenetic origin deposits[12,17] and also because of the mode of occurrence of magnesite and dolomite. Hence, it is attributed that magnesite was formed by the diagenetic replacement of dolomite.

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A new sapphirine occurrence from Kambam valley, Tamil Nadu and its possible relation to the Pan-African tectonothermal event

K. Francis Anto, A. S. Janardhan and P. Sivasubramanian*

Department of Geology, University of Mysore, Manasagangotri, Mysore 570 006, India
*Department of Geology, VOC College, Tuticorin 628 008, India

Petrography and metamorphic conditions of a new sapphirine-bearing assemblage from Kambam valley are described. Temperature of formation of sapphirine-bearing assemblages is high, around 850°C, and pressures range from 7.5 to 5 kbars, suggesting that sapphirine formation took place during decompression events.

The sapphirine occurrence of the Kambam valley is the southern most, reported so far in the southern granulite terrain (SGT). Here we report the sapphirine occurrences of the eastern Kodaikanal ranges cluster around the Kambam fault, which hosts carbonatite. In addition, numerous syenite bodies and alkaline granites are common to the Kodaikanal ranges. The age of garnet separates (Sm–Nd garnet/whole rock) of Kambam valley and Kodaikanal ranges is around 550 to 520 Ma. This indirectly gives the age of sapphirine formation, as sapphirine develops after garnet. The age of the carbonatite, syenite bodies and alkali granites which occur along these intra-cratonic lineaments ranges between 790 and 550 Ma. The close

spatial association of the high temperature sapphirine-bearing assemblages with the Kambam fault strongly suggest that their formation is closely linked to Pan-African tectonothermal event.

In this paper, we report sapphrine-bearing assemblage from a new locality, south of the Kodaikanal ranges. This locality lies in the Kambam valley and is the southernmost sapphirine occurrence so far recorded from southern India. However, this sapphirine assemblage can be tied up with the numerous sapphirine occurrences from the eastern Kodaikanal ranges. Stress is laid on the tectonic significance of these sapphirine occurrences restricted to a rather narrow zone; the timing of sapphirine formation and the possible heat source.

The South Indian granulite terrain can be broadly subdivided into a late Proterozoic (Pan-African) southern granulite terrain (SGT) and late Archaean northern granulite terrain (NGT) with the fundamental Palghat–Cauvery break, now a graben, separating the two. The SGT is dominated by granulite grade supracrustal units, in addition to the normal charnockite and two pyroxene granulites. These litho units contain critical mineral assemblages which are excellent tools in constraining the metamorphic conditions and P–T–t paths. High temperature (900°C) silica-deficient sapphirine granulites have been reported from several localities in SGT, viz. Ganguvarpatti[1–3], Panrimalai[4], Perumalmalai[5–7] and Usilampatti[8].

The wedge-shaped Kambam valley is bordered by the Cardamom hills to the west and the Varushanad hills to the east (Figure 1). This valley, the resultant of a deep fault (the Kambam fault) trends in a NNE to NE direction. As can be seen from the map, the Kambam fault cuts across the eastern Kodaikanal ranges and extends further northward across the Kadavur massif anorthosite body of Proterozoic age.

The dominant rock types of the area include granulite grade pelitic and calc-silicate lithologies, interbedded with pyroxene granulite bodies amidst quartzofeldspathic charnockites. The terrain as a whole is punctured by several granite bodies. Presence of syenite and late carbonatite intrusives is significant.

Pelitic lithologies include both silica saturated (grt–cord–bt–sil) and silica undersaturated (spr–crd–opx–bt–spl–plag) varieties. Calc-silicate lithologies are intimately intermixed with pyroxene granulite bodies on a decimeter scale and contain wollastonite–scapolite–garnet–clinopyroxene associations. Charnockite is normally devoid of garnet. The present study focuses on the silica-deficient sapphirine-bearing assemblages.

Silica-deficient pelitic granulites occur as *in situ* outcrops of a few meters amidst charnockite. Pelitic and calc-silicate bands can be seen in the vicinity. Two distinct mineral assemblages, viz. spr–crd–opx–bt–spl (sapphirine present) and crd–opx–bt–plag (sapphirine