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Chemical mineralogy of the aureole of the Nahant Gabbro at East Point, Nahant, Mass., USA

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SUMMARY. The Lower Cambrian Weymouth Formation at Nahant, Massachusetts, consisting of interbedded pelitic and calcareous rocks, was intruded by the Nahant Gabbro. The predominant metapelitic mineral assemblage of the contact aureole is quartz–muscovite–chlorite–magnetite–ilmenite. The calcareous hornfelses exhibit a varied mineral assemblage, and in some cases the variation can be spatially related to the intrusive. A number of cross-cutting thin mineral veins, many containing prehnite, are characteristically associated with these calc-silicate rocks.

The minerals have been analysed by electron microprobe and this work indicates the presence of a possible solvus in the Fe^{3+}-Al epidote solid solution series. At the physicochemical conditions of the formation of the Nahant hornfelses, the ferric mole fractions of coexisting epidotes are 0.49 and 0.98.

Comparison with experimental work shows that the conditions of the contact metamorphism were $T \simeq 500$ °C, $P_{total} \simeq 2$ kb, and $X_{CO_2} \simeq 0.2$. However, the present assemblages are the result of a later low-grade regional metamorphism, the ultimate product of which was prehnite.

NAHANT, a former island, is situated in the Boston Bay region, about 12 miles north-east of Boston. East Point, the easternmost part of Nahant, consists of the metasedimentary rocks of the Weymouth Formation (Lower Cambrian) and the Nahant Gabbro (Ordovician) with associated sills. A number of dykes are also present (fig. 1); Lane (1888) interpreted the structure of Nahant as a syncline with a NE–SW axis. The Nahant Gabbro occupies the centre of the syncline. The intrusion of the igneous rocks in the area was accompanied by the contact metamorphism of the sedimentary rocks to form hornfelses.

Previous workers (Lane, 1888; Clapp, 1921; LaForge, 1932; Bell, 1948; Kaye, 1965) concentrated their studies on the igneous rocks of the area claiming their contact effects as minor or inconsequential. The detailed work by the author, however, has indicated that the effects of the metamorphism are extensive. While the calc-silicate mineral assemblages include calcite–quartz–garnet–plagioclase assemblages indicating a medium-grade contact metamorphism, the predominant pelitic assemblage is quartz–muscovite–chlorite–magnetite ± (ilmenite) which, perhaps, is a similar assemblage to the pre-contact metamorphism assemblage.

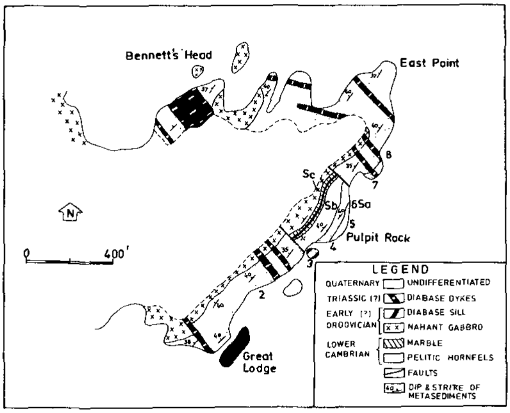

FIG. 1. Geological map of the East Point, Nahant, Massachusetts, after Verma (1973). Location of samples analysed (Tables I and II) are indicated.

Analytical methods

Many calc-silicate grains were sufficiently coarse (up to 1 mm across) to enable a number of optical measurements to be made, but in general an X-ray diffractometer was used for the identification of minerals present. The compositions of the phases were determined using an electron microprobe of the Applied Research Laboratories (EMX) at Hoffman Laboratory of Harvard University. The accelerating potential was 15 kV and the sample current was 0.015 μA (measured on brass). Data were taken with a focused electron beam (= 1 μm diameter), with the exception of biotite for which a slightly defocused beam (3–5 μm diameter) was used in order to minimize loss of alkalies through evaporation.

The calculation of ferric iron in cationic proportion was based on distribution of the total iron algebraically between ferric and ferrous iron so as to balance the charge between cations and anions. Since, for the minerals of the present study, iron is the only element capable of existing in two valence stages, the proportions thus arrived at are assumed to be correct.

Nahant Gabbro

Almost the whole island of Nahant is occupied by rocks of gabbroic composition for which Lane (1888) proposed the term the Nahant Gabbro. Radiometric age determination (Zartman and Martin, 1971) indicate that the intrusion of the Nahant Gabbro took place between 461 ± 23 Ma and 493 ± 21 Ma ago.

The diabase sills at East Point resemble closely the Nahant Gabbro in texture and mineralogy and it is likely that these sills are related to the Nahant Gabbro. Dykes at East Point and elsewhere are different from the sills and the gabbro in both texture and mineralogy. The dykes are fine-grained and mainly consist of fresh plagioclase and augite. Because the Nahant Gabbro and the sills show evidences of having undergone a low-grade regional metamorphism (Verma, 1973), whereas dyke rocks are comparatively fresh, it is thought that the intrusion of the dykes post-dated the low-grade metamorphic episode.

Although variations in texture and mineralogy can be found, the gabbro has a uniformly even, medium-grained hypidiomorphic texture. There are only four essential primary minerals: augite, pigeonite, and orthopyroxene, and a calcic plagioclase. Opaque minerals commonly fill interstices in the pyroxene–plagioclase assemblage. Some of the outcrops show a crude layering or segregation of dark- and light-coloured constituents into thick layers. Other accessory minerals are biotite, apatite, and zircon. Secondary minerals are abundant and chlorite, actinolite, epidote, and some secondary magnetite are common.

Weymouth Formation

The Weymouth Formation at Nahant, with an exposed thickness of about 750 ft, consists of well-bedded buff and maroon pelitic hornfelses that dip 40° NW. Calcareous nodules are concentrated in some of these beds. Marbles and calc-silicate rocks are interbedded with the hornfelses.

Pelitic hornfelses. There are two varieties of the pelitic hornfelses. The dominant variety is a fine-grained dark-brown to black rock. Interbedded with this is a light-coloured pelitic hornfels, which due to its very fine-grained nature (grain size less than 50 μm) exhibits a smooth chert-like surface.

Under the microscope, the most common texture is decussate, composed of granoblastic polygonal aggregates of quartz with randomly oriented flakes of muscovite and chlorite. At places, quartz, chlorite, and muscovite form a mosaic or web texture. Beside quartz, muscovite, and chlorite, albite, potassium feldspar, and biotite are found in some layers. At Bennett's Head, towards the contact with the overlying gabbro, the pelitic hornfels contains aggregates of chlorite laths in a manner suggestive of a pseudomorphic growth after cordierite. Magnetite is more abundant than limonite but both are distributed throughout the rock. In some cases they are concentrated in selective beds. Accessory minerals are zircon, tourmaline, and rutile.

The *calcareous nodules* occurring within the pelitic hornfelses are, as a rule, ellipsoidal. They are several cm long parallel to the bedding and around 1 cm thick normal to the bedding. Commonly they are 2 or 3 cm apart but some coalesce along the bedding. The nodules exhibit concentric zoning by various coloured minerals, such as epidote, garnet, diopside, calcic hornblende, and chlorite. The zones may be monomineralic, though commonly more than one mineral is present. Two kinds of nodules occur: one type containing garnet in the core and the other chlorite. Quite commonly the zones are repeated. In such cases epidotes occurring in the different zones may differ in their chemical composition.

Marbles and calc-silicate rocks. Pure marbles show granoblastic texture in which calcite occurs as a mosaic of equant grains. Commonly the marbles are interlayered with calc-silicate hornfelses. Some calc-silicate layers consist exclusively of garnet with a few calcite grains present, while in others the pale-brown garnet is joined by calcite, quartz, and epidote. Other layers are characterized by calcite, diopside, and epidote without garnet. Calcite and quartz are associated with calcic garnet in nearly all occurrences. Calcic plagioclase (An_{55-60}) is also present with garnet in some assemblages but most of these assemblages lack quartz. Clinozoisite and less commonly epidote are other associated minerals. Both garnet and plagioclase grains show alteration to epidote.

Mineral chemistry

Chemical analyses of several minerals were carried out with the electron microprobe. The minerals analysed are epidote, garnet, prehnite, diopside, calcic hornblende, chlorite, and biotite. The composition of the plagioclase was estimated optically by means of the universal stage. While many epidote and garnet grains exhibited compositional zoning with respect to certain elements, other minerals yielded practically uniform chemical composition. Determinations were also made at the phase boundary between unzoned epidote and garnet grains in order to estimate the distribution coefficient of ferric iron between the mineral pair.

Epidotes in the calcareous hornfelses of Nahant belong to clinozoisite–epidote series. Following Deer, Howie, and Zussmann (1962) the optically positive variety has been called clinozoisite and the optically negative variety epidote. As is evident from Table I, the epidotes fall into two distinct ranges with respect to content of ferric iron: one group, essentially clinozoisite, has an iron content in the octahedral sites between 0.35 and 0.47; the other group includes the true epidotes with ferric iron values between 0.97 and 0.99. The ferrous iron ranges from 0.02 to 0.20 whereas manganese is 0.01–0.02. Two end-members of the epidotes denoted by Cz($Ca_2Al_3Si_3O_{12}(OH)$) and Ps ($Ca_2Fe_3Si_3O_{12}(OH)$) are also calculated. For this purpose any ferrous iron or manganese assigned to the eightfold sites is ignored. Ps ranges from 11.65 to 15.65 in the clinozoisite and 32.30 to 32.94 in the epidotes.

TABLE I. *Electron-microprobe analyses of epidotes from Nahant*

Wt%	1	2	3	4	5	6	7
SiO_2	36.13	36.75	38.68	36.90	35.30	33.59	36.24
TiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al_2O_3	26.41	22.75	28.23	29.15	28.25	21.64	21.41
FeO	7.29	8.01	6.74	6.54	10.02	15.90	16.27
MgO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	0.14	0.28	0.30	0.30	1.05	0.13	0.29
CaO	22.55	22.97	23.01	22.93	21.29	22.79	22.05
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Na_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	92.54	95.76	97.28	95.83	95.91	94.05	96.26
Si	2.94	2.86	3.01	2.85	2.72	2.94	2.89
Al	2.50	2.54	2.60	2.65	2.56	2.03	2.01
Fe^{3+}	0.47	0.46	0.40	0.35	0.44	0.97	0.99
Fe^{2+}	0.02	0.06	0.02	0.18	0.20	0.04	0.09
Mn	0.01	0.02	0.02	0.02	0.01	0.02	0.02
Ca	1.96	1.91	1.91	1.89	1.75	1.93	1.88
Ps	15.65	15.31	13.32	11.65	14.65	32.30	32.94
Cz	84.35	84.69	86.68	88.35	85.35	67.70	67.04

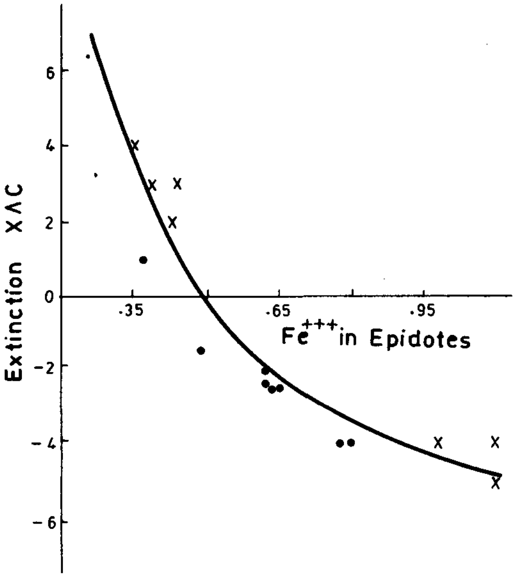

FIG. 2. Variation of the ferric iron in epidotes corresponding to the extinction angles. Data are from Myer (1966) as dots and from the present study as crosses.

With increasing iron content the birefringence of the epidotes increases. Fig. 2 shows a plot of extinction angle and optic sign against ferric iron content of the epidotes from Nahant as well as from Myer's (1966) paper. The data plotted do not show a linear correlation and apparently the optical properties do not bear a simple relation to the substitution of ferric iron for aluminium. The change in the optic sign appears at $Al_{2.53}Fe^{+3}_{0.47}$.

Garnet. The analyses of the garnets from Nahant presented in Table II have also been recalculated to yield the ratios of idealized garnet end-members. It has been assumed that all the tetrahedral sites are occupied by silicon atoms. It was observed that for most of the analyses the number of silicon atoms falls short of the required number of three. The remaining tetrahedral sites have been assumed to be (O_4H_4) groups representing a hydrogarnet component.

Table II shows four prominent garnet components. Amongst these four, Gr (grossular) is the largest component ranging from 49.80 to 73.35%, And (andradite) ranges from 5.0% to 37.50%, while Tg (titangarnet) and Gh (hydrogrossular) range from 7% to 20% and 0% to 10.54% respectively; Sp (spessartine), Alm (almandine), and Pyr (pyrope) are generally less than 5% and rarely exceed 1%. It is interesting to note that, in general, garnets from the marbles have a smaller And content to that of the garnets from the calcareous nodules but the Tg component in the garnets is quite small in this case.

Other calc-silicate minerals. In addition to the epidote and garnet, *prehnite* is one of the characteristic minerals of the calc-silicate assemblages. The prehnite shows a nearly constant composition (Table III) and this is also reflected in the optical properties, which show little variation.

TABLE II. *Electron-probe analyses of garnets from Nahant*

Wt%	1	2	3	4	5	6	7
SiO_2	37.71	36.42	35.47	37.96	34.14	38.09	37.23
TiO_2	3.56	0.33	0.34	0.87	2.83	0.69	0.35
Al_2O_3	16.96	17.15	16.80	18.87	15.41	13.57	14.1
FeO	5.25	11.47	12.08	7.14	9.88	12.60	3.46
MgO	n.d.	0.25	0.34	0.27	0.25	0.09	0.18
MnO	0.31	0.31	0.30	0.67	0.83	1.23	1.23
CaO	36.19	33.98	34.41	33.59	34.15	35.19	34.10
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Na_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.88	99.81	101.70	99.33	97.59	101.46	100.75
Si	2.85	2.70	2.70	2.84	2.56	2.89	2.89
Al	1.50	1.42	1.50	1.66	1.36	1.31	1.23
Ti	0.20	0.02	0.02	0.05	0.16	0.04	0.02
Fe^{3+}	0.20	0.02	0.02	0.05	0.16	0.04	0.02
Fe^{3+}	0.10	0.54	0.46	0.24	0.32	0.71	0.75
Mg	—	0.03	0.04	0.03	0.03	0.01	0.01
Fe^{2+}	0.03	0.25	0.10	0.22	0.14	0.05	0.07
Mn	0.02	0.02	0.12	0.05	0.06	0.08	0.07
Ca	2.34	2.72	2.72	2.69	2.76	2.86	2.85
K	—	—	—	—	—	—	—
Na	—	—	—	—	—	—	—
Gr	73.35	56.08	61.74	73.36	49.80	55.85	55.51
Gh	—	5.61	5.61	—	10.54	—	—
And	5.00	27.00	23.00	12.00	16.00	35.5	37.50
Tg	20.00	2.00	2.00	5.00	16.00	4.00	2.00
Sp	0.66	0.99	0.33	1.44	1.99	2.66	2.33
Alm	0.99	8.32	7.32	7.32	4.66	1.66	2.33
Pyr	—	0.66	0.33	0.66	0.99	0.33	0.33

TABLE III. *Electron-probe analyses of prehnite, diopside, and calcic hornblende from Nahant*

Wt%	Prehnite		Diopside		Calcic hornblende		
	1	2	1	2	1	2	3
SiO_2	45.08	44.84	54.85	55.04	44.86	43.96	50.37
TiO_2	n.d.	1.75	0.51	0.36	0.29	0.12	0.08
Al_2O_3	23.47	22.29	3.61	2.79	8.23	6.53	1.53
FeO	1.75	n.d.	0.64	0.64	20.52	20.32	10.09
MgO	n.d.	n.d.	15.98	17.16	10.19	9.98	16.58
MnO	n.d.	n.d.	n.d.	n.d.	0.53	0.43	0.07
CaO	25.89	26.69	24.02	23.62	11.50	12.05	11.94
K_2O	n.d.	n.d.	n.d.	n.d.	0.43	0.38	n.d.
Na_2O	n.d.	n.d.	n.d.	n.d.	1.25	1.32	1.14
Si	3.08	3.10	1.85	1.83	6.75	6.82	7.69
Al	0.92	0.82	0.16	0.12	1.25	1.18	0.27
Al	0.97	1.00	0.01	—	0.20	0.01	—
Ti	—	0.08	0.01	0.01	0.04	—	0.01
Fe^{3+}	0.05	—	—	—	0.64	0.66	1.21
Fe^{2+}	0.04	—	0.02	0.02	1.93	1.96	0.04
Mg	—	—	0.87	—	2.28	2.30	3.79
Mg	—	—	—	—	0.06	0.06	0.01
Ca	1.89	1.97	0.94	—	1.85	1.99	1.95
K	—	—	—	—	0.68	0.08	—
Na	—	—	—	—	0.36	0.43	0.29

Diopside from Nahant is very nearly iron-free (Table III) although the amount of aluminium is slightly more than would normally be expected. Optically the amphibole in the calc-silicate rocks resembles actinolite but because of its high aluminium content (Table III) it is described as *calcic hornblende*. Most of the aluminium is present in the octahedral sites. 100 Mg/(Mg+Fe) ranges from 46.34 to 75.24. The A-site in these hornblendes is partly filled by Na and K atoms to a total between 0.29 and 0.75. This degree of A-site occupancy is fairly typical of metamorphic hornblendes (Stout, 1972).

Chlorite from the calcareous nodules exhibits blue anomalous interference colours. It is high in silicon and low in iron (Table IV) compared with normal chlorite. Table IV also includes the chemical compositions of the analysed *biotites*. The Mg:Fe ratio varies from 0.83 to 1.56. There appears to be a deficiency in the cations in the A-site. This, probably, has been caused by the volatilization of alkalies under the electron beam. Titanium is either present in very small quantity or is absent.

Distribution of aluminium and ferric iron in garnets and epidotes

Wherever calcic-garnet and epidote coexist, the distribution of ferric iron and aluminium in them can be related by a distribution coefficient K_D. For the garnet and epidote studied here, the partinent relation can be expressed as follows.

$$(N_{1GR})(1-N_{1EP})/(1-N_{1GR})(N_{1Ep}) = K_D^{GR\text{-}Ep} \quad (1)$$

where $N_{1GR} = Fe^{3+}/(Fe^{3+}+Al)$ in garnet and $N_{1Ep} = Fe^{3+}/(Fe^{3+}+Al)$ in epidote. Whereas the calcic garnet has only one kind of octahedral site there are three distinct kinds of these in the epidote structure (Burns and Strens, 1967). Two of these octahedra are in the form of chains of AlO_2 and $AlO_4(OH)_2$ octahedra running parallel to the *b*-axis whereas the third octahedral site occupies a position between these chains (Ito, 1959). These sites are respectively referred to as AlO, Al(OH) and Al sites (Strens, 1965). Burns and Strens (1967) on the basis of crystal field, X-ray, Mossbaüer, and optical studies concluded that the preference for Fe^{3+} in the octahedral sites is Al > AlO > Al(OH). The maximum ferric iron content is about 1.2 Fe^{3+} per formula unit. Since the maximum Fe^{3+} content of the Nahant epidotes is only 0.99, it is assumed that the substitution for Al of Fe^{3+} is restricted in the present case to one site alone, presumably the Al site.

TABLE IV. *Electron-probe analyses of chlorite and biotite from Nahant*

Wt%	Chlorite						Biotite		
	1	2	3	4	5	6	1	2	3
SiO_2	28.18	28.32	28.06	38.92	32.74	37.70	38.06	38.64	39.01
TiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.18	0.07
Al_2O_3	16.30	15.73	15.08	14.88	18.34	15.38	17.06	17.49	15.45
FeO	32.01	33.48	30.66	24.15	28.90	25.60	17.42	17.90	15.82
MgO	13.17	11.66	11.15	9.39	9.79	9.41	13.70	14.58	13.82
MnO	1.28	1.78	1.47	0.86	1.27	0.86	0.15	0.15	0.07
CaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.12	0.12	0.53
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	6.28	7.37	6.36
Na_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.19	0.21	0.09
Total	90.94	90.91	86.42	88.20	91.07	88.95	92.98	96.64	91.82
Si	5.98	5.93	5.93	7.12	6.94	7.50	5.33	5.47	5.83
Al	2.02	2.07	2.07	0.88	1.04	1.00	2.67	2.53	2.17
Al	2.04	1.89	1.91	2.95	3.55	2.94	0.49	0.48	0.72
Ti	—	—	—	—	—	—	—	0.02	0.01
Fe^{3+}	—	0.54	0.14	0.29	0.12	0.28	0.88	0.41	0.28
Fe^{2+}	5.64	5.43	5.60	4.36	5.01	4.37	1.34	1.85	1.82
Mg	4.14	3.71	3.71	3.06	3.10	3.05	3.21	9.24	3.27
Mn	0.23	0.32	0.28	0.11	0.23	0.11	0.02	0.02	0.01
Ca	—	—	—	—	—	—	0.02	0.02	0.09
K	—	—	—	—	—	—	1.26	1.38	1.41
Na	—	—	—	—	—	—	0.06	0.05	0.03

Fig. 3A shows a plot of values of N_{1GR} and N_{1Ep}, which are listed in Table V. It is apparent that no straight line or simple hyperbola passing through the origin could be a best-fit line for these points. The distribution of points suggests that one or both members of the mineral pair epidote-garnet do not have a simple complete solid solutions. The K_D, a function of pressure and temperature, controls the composition of coexisting garnet and epidote.

TABLE V. N_{1GR}, N_{1Ep}, *and* $K_{D(Fe^{3+})}^{GR-Ep}$ *in coexisting garnets and epidotes*

No.	N_{1GR}	N_{1Ep}	$K_{D(Fe^{3+})}^{GR-Ep}$
1	0.250	0.47	0.375
2	0.270	0.46	0.434
3	0.230	0.40	0.448
4	0.335	0.37	0.017
5	0.375	0.99	0.006

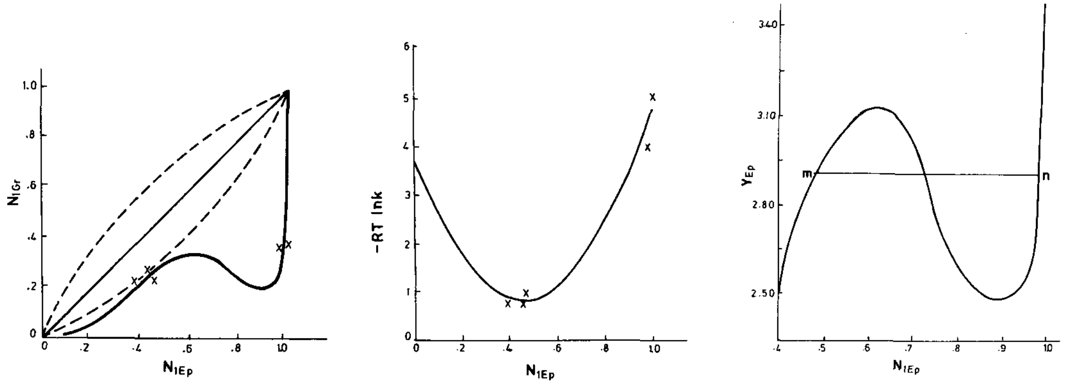

FIG. 3. A (*left*), N_{1Ep} and N_{1GR} values of the five epidote–garnet coexisting pairs. The thin line indicates possible ideal solutions of both epidote and garnet, whereas dotted curves denote non-ideal simple solutions. The thick curve represents a theoretical curve based on equation 4. B (*middle*), graph of equation 3 representing a two-parameter Margules model for the epidote solution. C (*right*), method for determining the composition of the coexisting epidote solution phases as given by *m* and *n*. The Y_{Ep} includes excess Gibbs function $G_{ex,Ep}$.

Obviously, the thermodynamic solution properties of these two phases affect the nature of the K_D.

It is generally recognized that the solid solution in calcic garnets is complete (Deer *et al.*, 1962). Of late, some theoretical and experimental work has been carried out to investigate the nature of two component and multi-component garnet solid solutions (Saxena, 1968; Novak and Gibbs, 1971; Ganguly and Kennedy, 1974; Ganguly, 1976). These works have also justified the implicit contention in the literature (e.g. Coleman *et al.*, 1965) that grossular and andradite mix almost ideally. Hence the garnets from Nahant, which are essentially of grossular-andradite composition, can be assumed to represent an ideal solid solution. This solution refers only to a substitution of Al by Fe^{3+} in the octahedral site alone.

Since the calcium garnet solid solution is ideal, an attempt is made here to investigate the nature of the unmixing properties of epidote. A non-linear correlation between many chemical and optical properties, such as the one depicted in fig. 2, indicates that the epidote solutions may be complex and Strens (1965) has proposed a solvus in the Fe^{3+}-Al epidotes. In order to investigate the nature of this solvus let us assume that the epidote solution may be approximated by a two-parameter Margules relation between $\ln K_D$ and N_{1Ep}. The following second order equation is used:

$$\ln K^{GR\text{-}Ep}_{D(Fe^{3+})} = a_0 + a_1(N_{1Ep}) + a_2(N_{1Ep})^2 \quad (2)$$

where a_0, a_1, and a_2 are constants. The constants were determined by least-square analysis and the equation (2) thus becomes:

$$\ln K^{GR\text{-}Ep}_{D(Fe^{3+})} = -3.8050 + 12.8468(N_{1Ep}) - 13.9445(N_{1Ep})^2 \quad (3)$$

(cf. Thompson, 1967; Thompson and Waldbaum, 1968). Fig. 3B shows diagrammatically equation (3). This enables us to eliminate $K^{GR\text{-}Ep}_{D(Fe^{3+})}$ between equations (1) and (2) and hence

$$N_{1GR} = A/(1+A) \quad (4)$$

where $A = \{N_{1Ep}/(1\text{-}N_{1Ep})\} \exp \{a_0 + a_1(N_{1Ep}) + a_2(N_{1Ep})^2\}$. The curve represented by equation (4) is plotted in fig. 3A. The shape of this curve resembles fig. 2 of Thompson and Waldbaum (1968), and following them we may write for $G_{ex,Ep}$, excess Gibbs function:

$$G_{ex,Ep} = N_{1Ep}N_{1GR} - (W_{GEp}N_{1Ep} + W_{GGR}N_{1GR}).$$

This yields: $(G_{EP}/RT)/N_{1Ep} = \ln\{N_{1Ep}/(1\text{-}N_{1Ep})\} + a_1N_{1Ep} + (N_{1Ep})^2 + \text{Constant.}$ (5)

The left-hand side of equation (5) is computed for several values of N_{1Ep}, and the curve between the left-hand side, designated as Y_{Ep}, and N_{1Ep} is plotted as fig. 3C. It is obvious from this that a miscibility gap in the Fe^{3+}-Al epidote solid solution exists. However, it should be noted that no two epidote grains with compositions lying across the solvus have been found at Nahant, but the compositions of coexisting epidotes can be obtained, with the help of the curve of fig. 3C by equal-area method (Waldbaum, 1966). In the present case, i.e. the physicochemical conditions of the formation of the Nahant hornfelses, the N_{1Ep} values for the coexisting epidotes are 0.49 and 0.98.

Metamorphism

The major metamorphic event was associated with the intrusion of the Nahant Gabbro and the emplacement of the sills imprinted an additional contact effect. That a period of low-grade regional metamorphism followed the contact metamorphism is evident in the metamorphism of the intrusives themselves with the presence of prehnite-bearing veins attesting to the presence of this low-grade regional metamorphism.

Paragenesis in the pelitic hornfels. The essential minerals of the pelitic hornfels are quartz, muscovite, chlorite, plagioclase, biotite, and magnetite, with zircon, tourmaline, rutile, and ilmenite as accessories. These mineral assemblages are shown in fig. 4A (*b*) on an AFM projection (Thompson, 1957). Potassium feldspar is shown but plagioclase, magnetite, and other minor phases are omitted. Quartz and muscovite are also necessarily present in all assemblages for which this projection is appropriate.

As mentioned earlier, some samples close to the contact between sediments and the intrusives contain chlorite that appears to be pseudomorphous after cordierite. Therefore, it is likely that the prograde metamorphic assemblage included biotite and cordierite. This is shown in fig. 4A (*a*). The breakdown of cordierite during the retrograde metamorphism can be presented by the following equation (see Thompson, 1972, table 2, equations 21 and 26, and Schreyer, 1965):

$$13\text{Cdt} + 10\text{Bio} + 48H_2O \rightarrow 8\text{Chl} + 10\text{Mus} + 7\text{Qtz}. \quad (6)$$

The reaction (6) is probably a reversal of the original prograde reaction.

Mineral paragenesis in calc-silicate rocks. The minerals present in the calc-silicate rocks are calcite, quartz, plagioclase, epidote (or clinozoisite), diopside, serpentine, calcic-hornblende, prehnite, and chlorite. Textural evidence suggests that chlorite, serpentine, and prehnite are the product of a later period of low-grade regional metamorphism, whereas garnet, epidote, calcic hornblende, diopside, and plagioclase were formed by the main-

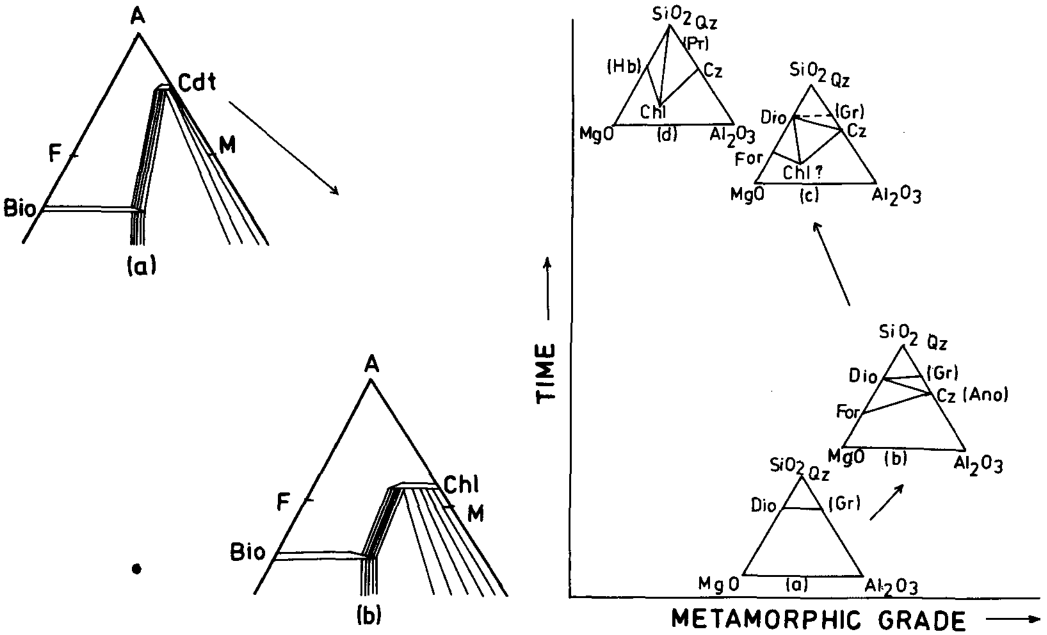

FIG. 4. A (*left*), Thompson diagrams for the possible metamorphic reactions in the pelitic hornfelses at Nahant. B (*right*), various stages during the metamorphism of the Calcareous hornfelses at Nahant. It shows one period of progressive metamorphism followed by two possible periods of retrogression.

contact metamorphism. Clinozoisite grains are also associated with plagioclase as secondary minerals. Therefore, some of the epidote (clinozoisite) present appears to be a product of retrogression. The present mineral assemblages are shown in fig. 4B (*b* and *c*).

The graphical analyses of mineral assemblages in calcareous rocks is complicated by the role of carbon dioxide. Considering the CaO-MgO-Al_2O_3-SiO_2-H_2O-CO_2 system we should expect no more than four minerals to coexist, in general, if temperature, total pressure, and the chemical potentials of CO_2 and H_2O are externally controlled. The assemblages as noted are consistent with this assumption (cf. Korzkinskii, 1959; Thompson, 1959). Calcite is present in all assemblages and, therefore, all assemblages are projected through $CaCO_3$ on the MgO-SiO_2-Al_2O_3 plane.

The prograde changes involved the disappearance of clinozoisite, the appearance of calcic garnet, and finally the appearance of calcic plagioclase. The first two of these changes can be interpreted in terms of reaction (7) and the second in terms of reaction (8).

$$2Cz + 5Cal + 3Qtz \rightarrow 3Gr + 5CO_2 + H_2O. \quad (7)$$

$$2Gr + 2CO_2 \rightarrow An + Qtz + Cal. \quad (8)$$

Equation (8) involves recarbonation of the assemblage at a higher temperature, whereas reaction (7) involves dehydration and decarbonation. The production of the anorthite component of the plagioclase could also have been partially at the expense of clinozoisite according to the following reaction, which involves dehydration:

$$2Cz + CO_2 \rightarrow 3An + Cal + H_2O. \quad (9)$$

The stability of grossular has been investigated by Yoder (1950) and later important works in the CaO-Al_2O_3-SiO_2 and related systems involving the appearance of grossular are by Hays (1966), Newton (1966), Boettcher (1970), Gordon and Greenwood (1971), and Lious (1973). Gordon and Greenwood (1971) synthesized grossular and associated calc-silicates in the presence of fluids having various ratios of H_2O to CO_2. Their study (fig. 5, p. 168) shows that at a total pressure of 2 kb reactions (7), (8), and (9) involving grossular take place between 450 °C and 550 °C at a maximum X_{CO_2} of 0.2. These figures are consistent with the assumption made earlier regarding the presence of a miscibility gap in the Al-Fe^{3+} epidotes. Strens (1965) had proposed that this solvus closes at 550 °C at a total pressure of 5 kb in the presence of quartz and in the field of hematite. However, absence of hematite and the presence of clinozoisite (cf. Holdaway, 1966, 1972) indicate that f_{O_2} values were perhaps in the neighbourhood of those defined by the QFM buffer curve. Addition of other species in the volatiles or any increase in the total pressure will result in the expansion of the grossular field to lower temperatures.

The effects of retrograde metamorphism, which were drastic in the metapelitic assemblages, are also obvious in the case of calc-silicate rocks. Conversion of garnet and plagioclase grains to epidote and of olivine to serpentine are indicative of a low-grade metamorphism. From this it appears that the process of hydration rather than recarbonation predominated during this metamorphic phase. Since the ratio of chemical potentials of H_2O and CO_2 differed from that of the prograde metamorphism (see also Agrell, 1965) the prograde reactions could not be reversed. Instead, new mineral assemblages came into being. The prograde calcic-hornblende epidote assemblage in the calcareous nodules reacted to give chlorite, calcite, and quartz. An ideal reaction can be written as (see Deer *et al.*, p. 259, vol. 2)

$$3\mathrm{Act} + 2\mathrm{Ep} + 10CO_2 + 5H_2O \rightarrow 10\mathrm{Cal} + 3\mathrm{Chl} + 21\mathrm{Qt}_3. \quad (10)$$

This is shown in fig. 4B (*b*). The formula of the chlorite used in the equation (10) is similar to the chlorite formulae given in Table V. This formula, however, differs from the one used in equation (6) which is more representative of chlorites from pelitic schist.

The presence of secondary mineral veins also indicates a still later period of metamorphism. Their growth is controlled by fractures that cross minerals of different composition. Calcite veins predominate but the most interesting are prehnite veins. Prehnite, as Harker (1939) pointed out, has been formed in many instances during a low-grade regional metamorphism. This is consistent with a later low-grade regional metamorphism described above. The production of prehnite perhaps took place through a reaction such as (11):

$$\mathrm{Gr} + H_2O + CO_2 \rightarrow \mathrm{Pre} + \mathrm{Cal}. \quad (11)$$

Conclusion

The sedimentary rocks of the Weymouth Formation were metamorphosed by the intrusion of the Nahant Gabbro and associated sills. The mineral assemblage representing the highest grade in the pelitic hornfels was quartz-muscovite-biotite-cordierite-Fe-Ti-oxide-Ab-plagioclase, and that in calc-silicate assemblage was calcite-Al-Fe^{3+} garnet-An_{55-68} plagioclase. Comparison of the assemblages and compositions of the phases with phase equilibrium studies indicate that the metamorphism was accomplished under $T = 500$ °C, $P_{\text{total}} \simeq 2$ kb, and $X_{CO_2} \simeq 0.2$.

A low-grade regional metamorphism followed the contact metamorphism. The reactions in the metapelite were reversed but those in calc-silicate rocks produced a different set of minerals amongst which prehnite is most noteworthy.

The mineral assemblages in the marbles, related to the contact metamorphism, are better preserved compared with those found in the pelitic hornfels. This would be expected as the metamorphic reactions in pelitic rocks involve only dehydration (or hydration) whereas the metamorphism of calcareous rocks involve essentially both dehydration (or hydration) and decarbonation (or recarbonation). The availability of CO_2, once a calcareous rock is metamorphosed, is less compared with the availability of H_2O. Hence, the pelitic hornfelses give the appearance of being comparatively less metamorphosed.

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