

Autometasomatic alteration of gabbro, Kap Edvard Holm intrusive complex, East Greenland

R. ELSDON

Department of Geology, University College, Dublin 4, Ireland

ABSTRACT. A local area of the Kap Edvard Holm Upper Layered Series gabbro has been converted into a quartz-albite-epidote-ilmenite rock by leaching of iron and with a net mass loss. Among the textural changes is the dissolution of the magnetite matrix of magnetite-ilmenite lamellar intergrowths. This is an extreme example of a series of low-temperature changes occurring throughout the intrusion due to the reaction of the gabbro with a volatile-rich phase which separated during the magmatic stage and remained trapped within the walls of the intrusion. The Fe-rich fluid formed by this autometasomatic process is similar to those responsible for the genesis of Cornwall-type magnetite deposits. The probable temperature range for the process is 400–550 °C.

THE Kap Edvard Holm complex is one of the Tertiary igneous intrusive centres around Kangerdlugssuaq Fjord on the East Greenland coast (fig. 1). It contains three units of layered gabbros (Elsdon, 1969a), mainly plagioclase-augite-olivine-magnetite orthocumulates. Cutting all the gabbros, but themselves cut by later syenites (Lwin, 1960), are numerous dolerite dykes of the East Greenland coastal dyke swarm (Wager and Deer, 1939).

In the Upper Layered Series (Elsdon, 1969a) there is evidence that the magma had a high water content, based mainly on observations on the Fe-Ti oxide assemblage (Elsdon, 1972). A notable feature of the Upper Layered Series is the widespread hydrothermal alteration of the primary minerals, and evidence to be presented in this paper suggests that the source of the alteration was a hydrous phase emanating from the crystallizing water-rich magma itself.

Near the southern end of the Upper Layered Series the highest part of the sequence is exposed, as deduced from the geometry of the rhythmic layering (Abbott, 1962; Elsdon, 1969b). In one locality here (fig. 1) the gabbro is extensively altered to a vivid green, porous rock consisting mainly of quartz, albite, epidote, and ilmenite. Pseudomorphs after primary plagioclase and augite can

sometimes be seen. Other gabbros only 50 m away show no more alteration than elsewhere, so that this intense alteration is a local phenomenon at the present erosion level. The rock is peculiar in its texture and in the *extent* of development of the secondary minerals; it appears to represent a sporadic transformative alteration of gabbro in which the original nature of the rock has been almost totally obliterated.

Petrography. EG7097 (Table III), collected some 50 m from the transformed rock, is typical of the whole Upper Layered Series in its overall mineralogy. It is a plagioclase-augite-magnetite orthocumulate, with intercumulate crystallization of large augite crystals locally imparting a mesocumulate texture.

Core compositions of the plagioclase crystals average An₆₀; some crystals show normal zoning with rims of composition An₄₆, while a few show well-developed oscillatory zoning. The augite is pale brown and contains occasional small inclusions of brown hornblende. Magnetite, containing {111} lamellae of ilmenite, forms euhedral crystals which sometimes show secondary enlargement. It is also present in the intercumulate generation where it commonly encloses small volumes of pale-green chlorite, and is usually intergrown with pale-green acicular actinolite.

TABLE I. *Electron-probe analyses of epidotes*

	1	2	Unit cell contents (O = 25)		
SiO ₂	38.05	38.19	Si ⁴⁺	6.06	6.03
Al ₂ O ₃	22.57	23.80	Al ³⁺	4.23	4.43
Fe ₂ O ₃	13.85	12.96	Fe ³⁺	1.66	1.54
CaO	23.70	23.48	Ca ²⁺	4.04	3.97
Total	98.17	98.43	Comp.	Cz ₇₂ Ps ₂₈	Cz ₇₄ Ps ₂₆

1. Mean of two rim compositions.

2. Mean of two core compositions (same crystals as 1).

Alteration of the primary minerals is patchy; plagioclase takes on a heavily clouded aspect, with patchy zoning and clusters of small, pale-yellow epidote crystals. Augite is relatively fresh, but in a few places the proximity of pockets of chlorite is associated with marginal alteration to a pale-green or pale-brown pleochroic amphibole.

Two specimens of the intensely altered gabbro were collected. In thin section EG7098 is seen to consist almost entirely of quartz, albite, epidote, and ilmenite, with small amounts of actinolite. Quartz occurs in clusters of several equigranular crystals up to 0.5 mm in size, showing irregular cracks.

The albite occurs firstly as clusters of laths pseudomorphous after igneous plagioclase, up to 2 mm long and often containing small ragged

grains of epidote. Universal-stage measurements on twinned crystals give compositions with less than 3% An, and a low-temperature structural state. The second mode of occurrence is as a new generation of smaller crystals up to 0.1 mm in size and intergrown with epidote.

Epidote is the most common mineral. It forms numerous stubby prisms up to 0.5 mm long. There appear to be two types, of which the first is the most abundant; it consists of colour-zoned crystals in which the cores are pale yellowish-green and pleochroic, while the rims are almost colourless. These crystals typically contain large numbers of minute opaque inclusions. They occur in massive aggregates intergrown with quartz, and also in smaller masses within original igneous plagioclase crystals. The second type occurs only within the

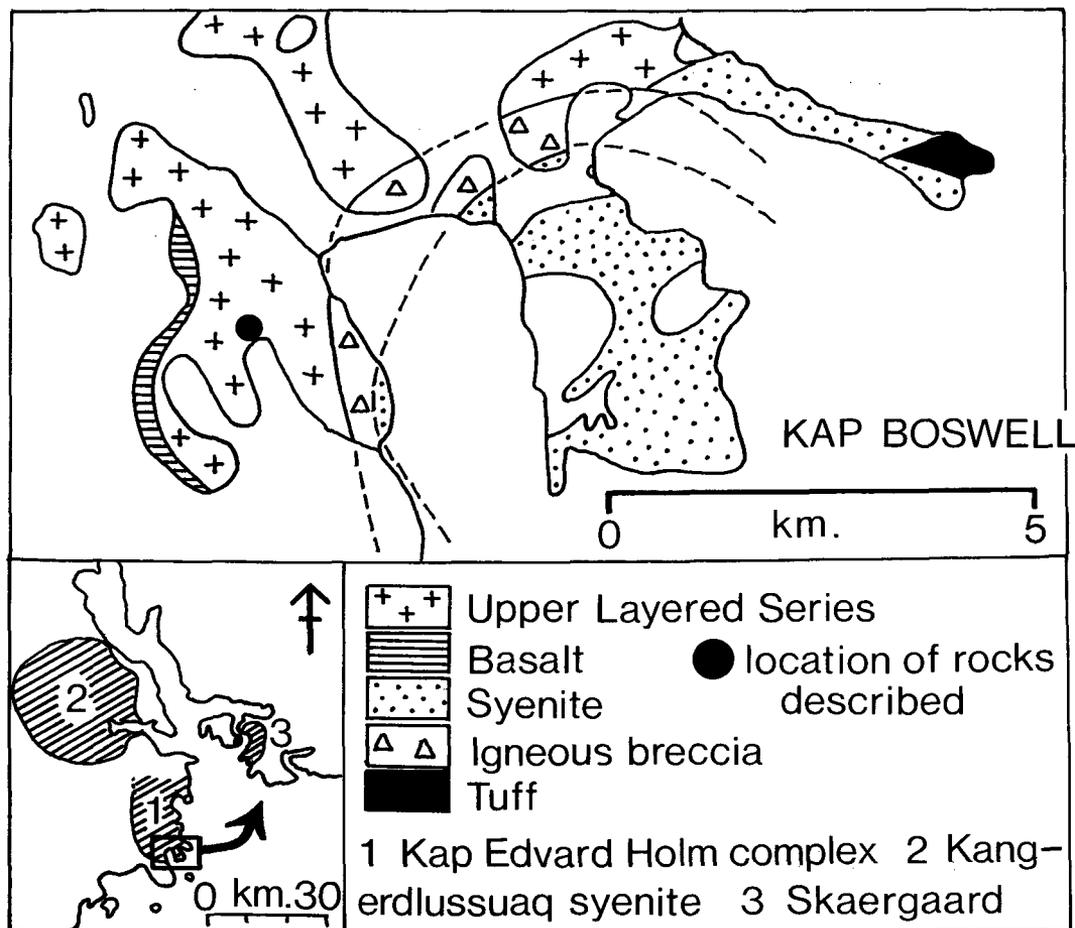


FIG. 1. Geological map of part of the Kap Edvard Holm igneous complex. Inset map indicates location of area in relation to other intrusive centres around Kangerdlugssuaq Fjord.

TABLE II. *Electron-probe analyses of actinolites*

	1	2	3	4
SiO ₂	52.31	52.77	53.07	53.12
Al ₂ O ₃	2.31	1.73	1.66	1.16
FeO	15.15	18.54	17.51	14.28
MnO	0.36	0.27	0.35	0.20
MgO	14.22	11.52	12.36	13.75
CaO	11.99	12.35	12.51	12.49
Total	96.34	97.18	97.46	95.00
Si ⁴⁺	7.73	7.84	7.83	7.92
Al ³⁺	0.40	0.30	0.43	0.31
Fe ²⁺	1.87	2.30	2.16	1.78
Mn ²⁺	0.05	0.03	0.04	0.03
Mg ²⁺	3.13	2.55	2.72	3.05
Ca ²⁺	1.90	1.97	1.98	1.99
Y	5.05	5.04	5.19	5.09

1. Mean of two rim compositions, new generation of acicular crystals included in quartz.
2. Mean of two core compositions, same crystals as 1.
3. Core of actinolite pseudomorph after augite.
4. Rim of same crystal.

former mode; here the crystals are very pale yellow, non-pleochroic, slightly larger in mean grain size than the zoned crystals, and they occur exclusively within irregularly shaped monomineralic aggregates usually within intergrowths of quartz with the other epidote type. Although they differ slightly in colour, and in lack of zoning, this second type of epidote has the same relief, 2V, optic sign (-ve), and birefringence, and appears therefore to be chemically similar to the first type.

Table I presents electron-probe analyses of cores and rims of two colour-zoned epidote crystals; the mean rim composition is slightly more Fe-rich than the core (difference is 2% pistacite) and the data indicate that the colour of epidote in thin section is not related in a simple way to the Fe content, for two reasons: (1) the coloured cores are relatively Fe-poor; and (2) the rims and cores have only slightly different Fe contents yet the colour zoning is often quite pronounced.

Ilmenite forms scattered networks of skeletal crystals, similar in appearance to those described from the Pennsylvania diabases (Davidson and Wyllie, 1968). Chemical data presented elsewhere (Elsdon, 1972) show that these trellis-like networks are the remains of oxidation-exsolution intergrowths of magnetite and ilmenite, where the former phase has subsequently been removed. The volume formerly occupied by the magnetite is now largely occupied by epidote, which is sometimes

rendered semi-opaque by the presence of an extremely fine-grained brown substance, probably a hydrated Fe-oxide, which also occurs elsewhere in the rock in small quantities.

Augite is pseudomorphed by a pale-green fibrous actinolite (Table II, anal. 3 and 4). These crystals show an unusual type of zoning, in which the cores have a higher Fe:Mg ratio than the rims; this pattern may be related to the high mobility of Fe indicated by the nature of the Fe-Ti oxides, and of other major elements (see next section). There is also a second generation of actinolite (Table II, anal. 1 and 2), as small acicular crystals, bluish-green in colour and enclosed in quartz. These crystals are also zoned, and in this case the rims have higher Fe:Mg ratios than the cores.

The main accessory minerals are rutile, which forms small amounts of reddish-brown ragged flakes, and apatite, which is present as elongated euhedral prisms.

The other rock (EG7099) is broadly similar but shows more evidence of igneous origin. There are more pseudomorphs after plagioclase and augite, less epidote and quartz. This rock is taken to represent a transitional stage in the alteration of relatively unaffected gabbro to the profoundly transformed assemblage of EG7098.

Bulk rock chemistry. Chemical analyses of EG7097-9 are presented in Table III, and in fig. 2 major element contents of EG7098 and 7099 are

TABLE III. *Major element chemistry*

	1	2	3	4
SiO ₂	50.19	41.01	43.76	36.52
TiO ₂	1.19	3.02	3.46	0.00
Al ₂ O ₃	15.36	14.46	12.45	20.97
Fe ₂ O ₃	9.74	6.15	6.23	17.22
FeO	1.25	3.90	10.26	0.45
MnO	trace	0.16	0.23	0.00
MgO	1.57	6.34	7.53	0.00
CaO	19.47	22.68	12.05	23.05
Na ₂ O	0.25	0.18	2.13	n.a.
K ₂ O	0.14	0.03	0.76	n.a.
H ₂ O ⁺	1.25	1.08	1.44	1.98
H ₂ O ⁻	0.20	0.34	0.18	n.a.
P ₂ O ₅	0.25	0.10	0.15	n.a.
Total	100.86	99.45	100.63	100.19

1. EG7098
2. EG7099 } quartz - albite - epidote - actinolite - ilmenite rocks.
3. EG7097; plagioclase-augite-magnetite orthocumulate.
4. Epidote; vein in diabase, Westfield, Massachusetts (Palache, 1936).

plotted along with those of relatively unaltered gabbros of the Upper Layered Series (Elsdon, 1969b). CaO and Fe_2O_3 show appreciable increases; SiO_2 changes erratically while Al_2O_3 increases slightly. There are sharp decreases in TiO_2 , MnO, FeO, MgO, and alkalis. The porous nature of the resulting altered rocks indicates that a significant loss of mass occurred. None of the other

rocks of the Upper Layered Series possesses this porous nature, so that the porosity is considered to be a result of the alteration rather than being a cause of it.

Since these rocks occur only over a limited area at the present erosion level, it is not possible to evaluate the extent of redistribution of the elements involved. Mg was obviously removed from the

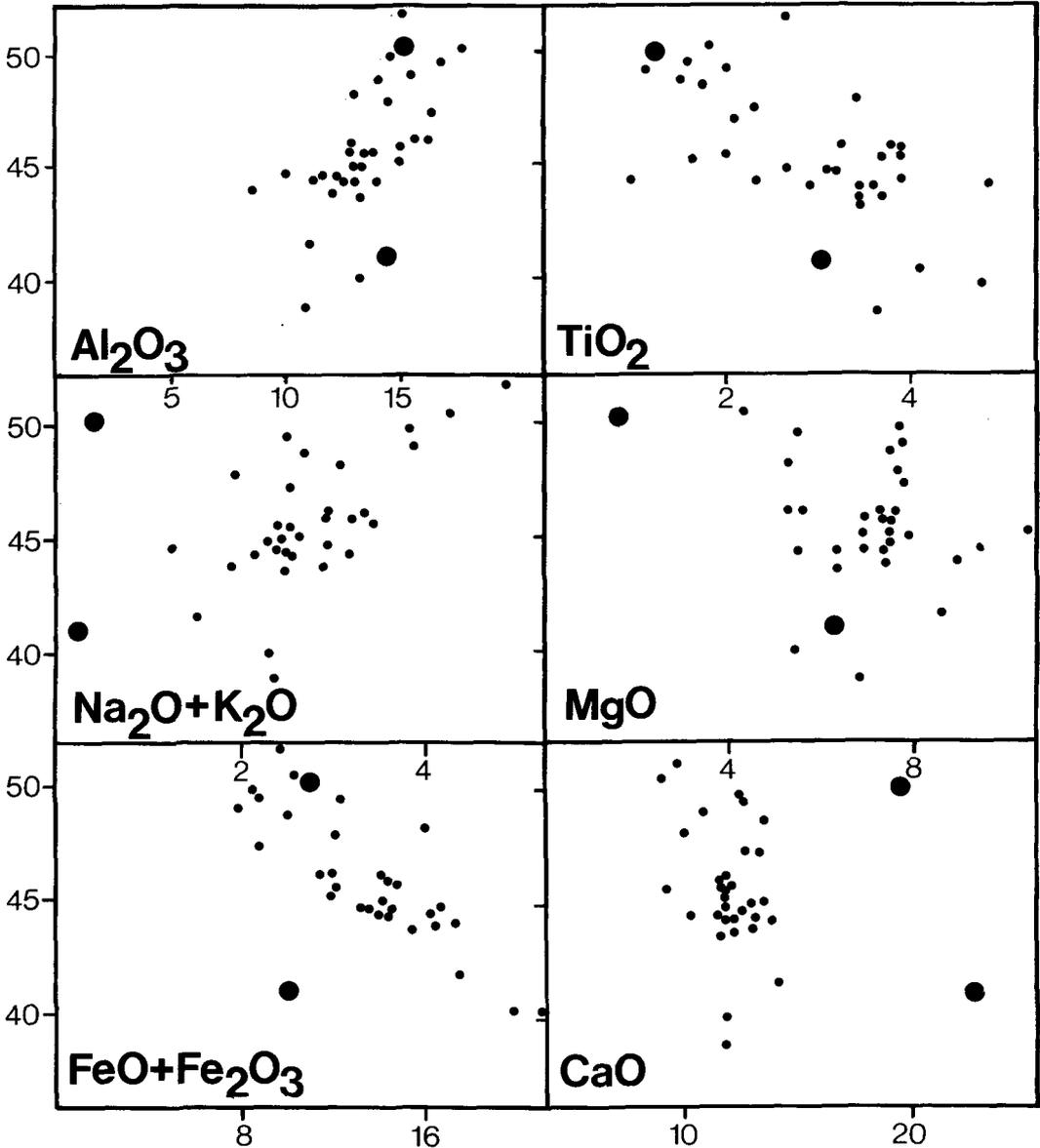


FIG. 2. Major-element chemistry of quartz-epidote-albite-ilmenite rocks compared with data from relatively unaltered members of the Upper Layered Series. Individual major oxides plotted against % SiO_2 . Large circles—EG7098 and 7099; small circles—Upper Layered Series gabbros.

vicinity of EG7098 but it is not possible to say how far or in what direction it was transported before being involved in some other mineral-forming reaction. Field evidence does not indicate that this liberated Mg remained at the present erosion level. Similarly, the spatial extent of redistribution of other elements, though probably related, is unknown.

The increase in Fe_2O_3 is probably due to oxidation of FeO, but the sharp decrease in MnO suggests a net total loss of Fe from the rock. The erratic variation in SiO_2 is probably a question of scale; EG7098 and 7099 are both extremely heterogeneous in hand specimen, with sporadic clusters of large quartz crystals, and antipathetic variation in the distribution of the epidote. Thus, while Table III shows that EG7098 is enriched in SiO_2 , EG7099 is depleted, so that there may be little overall change during the transformation process.

Harrigan and MacLean (1976) have described a similar kind of alteration process in gabbro dykes and volcanic rocks at Matagami, Quebec. Here the alteration is patchy and gives rise to an assemblage consisting mainly of epidote, quartz, and hornblende, with minor albite, chlorite, apatite, and sphene. The alteration is accompanied by enrichment in CaO, SiO_2 , and P_2O_5 and by depletion in total Fe, MgO, and alkalis. The alteration is here ascribed to autometamorphic/deuteric fluids channelled through permeable zones as the rocks cooled. These fluids could have been of magmatic origin, but Harrigan and MacLean consider them to have probably been meteoric, moving by convective circulation; this is indicated by the large volume of affected rocks.

Nature and timing of alteration. It has already been stated that the water content of the Upper Layered Series magma was high, and an obvious possibility is, therefore, that the alteration of gabbro to a quartz-albite-ilmenite-epidote assemblage was autometamorphic. However, the later intrusion event of the East Greenland dolerite dyke swarm could have provided a further supply of magmatic water and heat to effect the alteration. A third possibility is that the metasomatizing fluids were derived from the nearby Kap Boswell syenite (fig. 1), which was intruded after the dyke swarm event. Meteoric water could also have been responsible, during any of the three intrusion events mentioned above; in which case the thermal gradients introduced could have driven hydrothermal convection systems which were then responsible for the alteration.

It is considered most likely that the fluids were derived from the Upper Layered Series magma and that the alteration is therefore autometamorphic,

since the widespread development, in rather smaller quantities, of albite, epidote, actinolite, quartz, and the dissolution of magnetite in the gabbros must be contrasted with the fairly fresh nature of the country plateau basalts and dolerites, and with the comparative lack of these minerals in the gabbros of the nearby Skaergaard intrusion (Wager and Deer, 1939; Wager and Brown, 1968). Further, the margin of the Upper Layered Series consists of a band of hornfelsed gabbro and peridotite which represents a slightly earlier ring-dyke (Elsdon, 1969a). These rocks are completely unaltered and are considered to have acted as a barrier to the lateral movement of hydrothermal fluids.

The ability of fine-grained basic rocks to act as a barrier in this way has been further demonstrated by oxygen isotope studies on the Lilloise intrusion of the East Greenland coastal province (Sheppard *et al.*, 1977) which have shown that dolerite dykes had this role during the post-intrusion history of Lilloise. This is to be contrasted with the oxygen isotope evidence which, for the Skaergaard intrusion, reveals extensive interaction of gabbros with a hydrothermal convective system over a wide temperature range, even though primary mineral alteration is much less extensive than at Kap Edvard Holm (Taylor and Forester, 1980; Norton and Taylor, 1980).

Temperature of autometamorphic changes. Various lines of evidence converge to give a qualitative idea of the temperatures at which the gabbros were transformed:

1. Compositions of coexisting magnetite and ilmenite in relatively unaltered gabbros throughout the Upper Layered Series give equilibration temperatures in the range 580–720 °C and it seems likely that dissolution of magnetite from magnetite-ilmenite intergrowths commenced at temperatures lower than 580 °C.

2. A number of experimental studies have given information on the dissolution of magnetite and the movement of iron in hydrothermal systems. Martin and Pivinskii (1969) reported dissolution and transport of iron in hydrothermal laboratory runs in the temperature range 450–580 °C, with precipitation of hematite at the lower temperature end of the pressure vessels. Sweeton and Baes (1970) showed that magnetite solubility changes little in the temperature range 50–300 °C for any given fluid composition but that, at any given temperature, it increases rapidly as pH falls from slightly above 7 to slightly below 7. A study at higher temperatures (500–650 °C) has been performed by Chou and Eugster (1977), whose results confirm those of Sweeton and Baes with respect to pH. They also found that dissolution of magnetite was extensive

at 525 °C but decreased markedly as temperatures rose above these values.

3. Textural evidence already presented demonstrates that the alteration of plagioclase to albite-epidote could not have been complete before magnetite dissolution occurred. Thus they were probably broadly contemporaneous, with the dissolution of magnetite providing the Fe necessary for the crystallization of epidote. It is highly unlikely that the two events were unrelated. Magnetite dissolution studies already discussed have indicated a likely temperature range of approximately 450–550 °C, and epidote stability studies indicate a broadly similar range.

4. Various studies have given information on epidote-bearing assemblages (e.g. Liou, 1973; Bird and Helgeson, 1981). In summary, they show that epidote is stable over a wide range of temperatures, depending on the bulk composition of the system and that of the coexisting hydrothermal fluid. Upper limits are usually in the range 500–600 °C, and it is considered that conditions in the Kap Edvard Holm quartz-albite-epidote-ilmenite-actinolite assemblage reflect temperatures nearer to this than to the lower limits reported (100–200 °C) since actinolite is present rather than minerals such as laumontite (Bird and Helgeson, 1981).

5. Much more speculative is the possibility that the colour zoning in the epidote might be caused by variations in Al-Fe ordering between the different types of octahedral sites in the structure. It has already been shown that the colour is not related in a simple way to the Fe content, and electron-probe investigations have not revealed any significant concentrations of any minor element (e.g. Mn, Mg, V, Ti, Cr). Within the Al-Fe epidotes, while refractive indices vary with composition, graphs of composition against α , β , γ , and Δ show appreciable scatter (Deer *et al.*, 1962; Strens, 1966), and more detailed work has shown that these optical parameters are markedly affected by changes in Al-Fe ordering (Wood and Strens, unpublished data). It is therefore possible that colour could also be affected by octahedral site ordering.

If this is a correct interpretation, then the epidote described here may well have grown through a temperature range where ordering became gradually more difficult. Mössbauer spectral data (Liou, 1973; Dollase, 1973) indicate that high-temperature synthetic epidotes are substantially more disordered than natural epidotes forming below 500 °C; this temperature is consistent with a thermodynamic treatment of epidote ordering (Bird and Helgeson, 1980). The conclusion of this line of reasoning is that the colour variations in

the Kap Edvard Holm epidotes was due to growth over a temperature range centred around 500 °C.

Conclusion. Data are presented which describe the profound metasomatic transformation of gabbro to a quartz-albite-epidote-ilmenite-actinolite assemblage. The main chemical changes were addition of Ca, loss of Fe, Mg, Ti, and alkalis, and the oxidation of ferrous iron.

There are various possible sources for the fluids which caused the transformation, but the hydrous nature of the Upper Layered Series magma and the distribution of alteration products throughout the basic rocks of Kap Edvard Holm strongly suggest an autometasomatic process, and accompanied the cooling of the intrusion from magmatic temperatures.

Various semi-quantitative lines of reasoning, based on the observed mobility of iron, the mineral assemblage, and possibly the colour zoning of the epidote, suggest temperatures within the range 400–550 °C.

The loss of iron from the transformed rocks must have led to the precipitation of Fe-bearing minerals elsewhere. None have been found in the area elsewhere, and this is probably not surprising since these transformed rocks were collected on some of the highest ground in the area. If the Fe-bearing fluids were moving upwards, the products of reprecipitation have now been removed by erosion.

Such a process as described here has been postulated as the source of iron in Cornwall-type magnetite deposits in limestones in the vicinity of diabase dykes (Lapham, 1968; Davidson and Wyllie, 1968; Martin and Piwinski, 1969; Lapham and Gray, 1972; Chou and Eugster, 1977). Lindgren (1933) postulated that metasomatic iron deposits form in the range 400–600 °C while Lapham and Gray (1972) have suggested, for the Pennsylvania deposits, a temperature of 500 °C or possibly lower. Qingtong *et al.* (1980) have described a similar deposit from eastern Guangdong, China, and have estimated from isotopic data that iron was transported and precipitated as magnetite in the range 310–560 °C. Similar phenomena, including particularly growth of epidote, have been documented from geothermal boreholes; White and Sigvaldson (1961) found epidote at depths corresponding to a wide temperature range, with the minimum temperature of appearance for this mineral of 225–40 °C.

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