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PALEO-UPLIFT AND COOLING RATES FROM VARIOUS OROGENIC BELTS OF INDIA AS REVEALED BY RADIOMETRIC DATA: DISCUSSION

by

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The wide spectrum of geochronological methods now available (see Faure, 1977) enables one to decipher some of the important steps in the postcrystallisation cooling history of geological rock systems. In particular, it is possible to take advantage of the different closure (or retention) temperatures of various mineral phases for the different geochronological systems, to follow the cooling history of geological units down to ∿100 C and derive uplift rates from the relationship,

Uplift rate = (cooling rate)/(geothermal gradient) (I)

This equation is an equation of state, i.e. it gives only an overview of the bulk change in depth of the analysed samples while cooling, independently of the actual path followed. The correct application of this equation requires that several conditions be satisfied and these are listed below†.

1. The closure (retention) temperatures of the mineral phases dated must be known for the geochronological system in use.
2. The cooling rate calculated from age differences between two or more phases having different closure temperatures must be attributable to uplift.
3. All the data must refer to the same system, i.e. be obtained from the same hand specimen or nearby samples belonging to the same structural unit.
4. The geothermal gradient for the time interval and geological areas considered, must be guessed or calculated fairly accurately.

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† A prerequisite to such treatment of data is obviously that all the "dates" used can be considered to be geologically reliable "ages" (Armstrong, 1966).

Moreover, (i) in order to compare age data obtained from the different dating techniques, all the ages must be calculated according to a set of recommended decay constants (i.e. as per Steiger and Jager, 1977, for K-Ar, Rb-Sr and U-Th-Pb dating), or careful geological calibrations where some age equation parameters are not accurately known (e.g. Poupeau 1980, 1981a,b, for fission track (FT) dating; Faure, 1977 for ^{40}Ar - ^{39}Ar dating), (ii) the evaluation of cooling/uplift rates must take into account the precision of the various age determinations.

Recently, Sharma, et al (1980) have attempted to derive from their own FT measurements as well as from data from the literature, the cooling/uplift rates of a large part of the Indian sub-continent. We believe that some of their conclusions are erroneous due to incorrect application of the relationships outlined above. These points are considered in detail below.

1. Closure temperature of geochronological systems.

Following the pioneering work of Hart (1964) and Hanson and Gast (1967) it was clearly understood that the various mineral phases in a rock reacted differently to thermal events. In the ensuing years, the closure temperature of various mineral phases for dating system such as K-Ar, Rb-Sr, U-Pb, were evaluated from experimentally determined metamorphic reaction temperatures (e.g. Purdy and Jager, 1976). However, it was realised quite early that such temperatures were subject to wide variations, depending on such factors as (amongst others): - (a) size of crystals involved (for K-Ar, Rb-Sr, U-Pb dating),

(b) presence of fluids, (c) chemical composition of the mineral sample and (d) differences in conditions of formation and subsequent history. Using Dodson's (1973) model for determination of closure temperatures, it has recently been shown from $^{40}Ar-^{39}Ar$ incremental heating studies, that depending on various factors, the argon retention temperature (Tc) of some important mineral phases may vary widely. Based on work carried out on metamorphosed rocks, Tc was seen to vary from $\sim 450^0C$ to $\sim 750^0C$ for hornblendes, from $\sim 200^0C$ to $\sim 420^0C$ for biotites and from $\sim 200^0C$ to $\sim 250^0C$ for plagioclases (Berger et al, 1979, Berger and York, 1979, 1981a, b, Baksi and Wilson, 1980, Baksi et al, 1981, Baksi, 1981).

For the FT dating system, closure temperatures are calculated from the extrapolation of laboratory annealing experimental data (Fleischer et al, 1975). Recently, it has been shown (Naeser, 1980), that the FT closure temperature of apatite obtained by the above method can be confirmed from geological calibrations, giving some support to model calculations. However, here also, there are suggestions from laboratory data that chemical variations within a given mineral phase (for garnets, see Haack and Potts, 1972, Lal et al, 1977 for phlogopites and apatites see Poupeau 1981b) might result in significant variations of geological closure temperatures. Also the eventual effect of metamictisation-which is known to affect the etching rates of certain mineral phases like zircon (Poupeau, 1970) and sphene (Gleadow, 1978)-on their FT closure temperatures, has yet to be evaluated.

Finally, the closure temperature for both argon and track retention varies slightly for metamorphic rocks, depending on the cooling rate (see Dodson, 1973, 1979). Thus, we believe that adopting the same retention temperature for all samples of a given mineral species, as has been done by Sharma et al (1980), can lead to significant errors in calculating cooling/ uplift rates. In particular, it may be noted that while "garnet" is referred to as one single mineral phase for the calculation of closure temperature by Sharma et al (1980, Table 1), it was shown by the same group of workers (Lal et al, 1977, see also Haack and Potts, 1972) that the thermal track retention temperature of garnets varied quite signicantly depending upon their mineral chemistry and that "before using the garnet of various varieties for fission track dating, their annealing characteristics should be determined separately" (Lal et al, 1977, p. 131).

2. "Dates" and "Ages" in Geochronological Systems.

As noted earlier, a prerequisite to any use of equation (1) is that the "date" obtained by radiometric analysis, must be shown to be an "age" (see Armstrong, 1966, for definition of these terms). Examination of this point is particularly critical for the K-Ar and FT dating systems. In the K-Ar method of dating, one should first confirm that volume diffusion (of argon) is the controlling factor in determining the age of closure of the sample. The work of Chopin and Maluski (1980) illustrates that this is not always so. In this respect, the great advantage of the ^{40}Ar-^{39}Ar incremental heating technique is that, in addition to obtaining a plateau age, one can veri fy wether volume diffusion of argon controls the age of closure and only then determine the argon retention temperature to be used with the age, all from one set of experimental data (Berger and York, 1981b). Conventional K-Ar dates must not be assumed to be same as ^{40}Ar-^{39}Ar plateau ages. We stress here that K-Ar dates, unsupported by other data, should not be used for calculating cooling rates in metamorphic terrains and orogenic belts.

Similarly, in FT dating, apparent ages (i.e. ages derived from the canonical age equation) in rocks from metamorphic basements are often meaningless due to partial track fading. Instead, model ages taking into account this effect, should be utilised. The plateau method of dating (Poupeau et al 1980, Poupeau, 1981b) appears most useful in this respect as in addition to the above, it provides FT ages with a high degree of precision† (Poupeau, 1981b). Sharma et al's (1980) use of FT apparent ages has led them to derive incorrect cooling/uplift rates (see below).

It should be stressed here that guessing retention temperatures for different mineral and whole-rock systems for the various geochronological methods, for purposes of calculating cooling/uplift rates, poses dangers, even for the U-Th-Pb and Rb-Sr dating methods. Thus, though, in general, the Rb-Sr whole-rock and U-Pb zircon systems are expected to show quite high resistance to disturbance by postcrystallisation thermal

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†The ^{40}Ar-^{39}Ar incremental heating method also yields high precision plateau ages due to the "error contraction effect" (Berger and York, 1981b).

events, (i.e. have quite high retention temperatures, see Dalrymple and Lanphere, 1969, p. 163, Faure, 1977, Sharma et al, 1980, p. 138), such is not always the case. Thus, it has been shown that the U-Pb systems in zircons can be disturbed by thermal events at $\lesssim 300^{\circ}C$ (Gebauer and Grunenfelder, 1977, 1978). Similarly, the Rb-Sr whole-rock system may be disturbed without affecting the Pb-Pb (zircon) and even perhaps the ^{40}Ar-^{39}Ar (hornblende) systems in the same rock. This is best illustrated by the recent work of Dallmeyer et al (1981) on the Switf Current Granite, Canada. The ages obtained in this study are: - Pb-Pb (zircon) - 580 ± 20 Ma, ^{40}Ar-^{39}Ar (hornblende) plateau age - 560 ± 15 Ma, Rb-Sr (whole-rock) - 548 ± 11 Ma (all errors at 2σ level). It is evident that the Rb-Sr age is significantly younger than the Pb-Pb age. Dallmeyer et al (1981) point out that in rocks that lack good Sr-acceptors, it is possible to partially reset the Rb-Sr whole-rock age by thermal events which do not affect other geochronological systems that normally possess lower retention temperatures (see also Faure, 1977, Faure and Powell, 1972).

For these reasons, we stress that for the present, quantitative attempts at calculating cooling/uplift rates should be based only on data obtained by the thermochronometric techniques (^{40}Ar-^{39}Ar method - Berger and York, 1979, Berger and York, 1981b, FT plateau method - Poupeau et al, 1980). A "date" must first be shown to be an "age" (Armstrong, 1966), and only then should the retention temperature for the individual sample under study be calculated from laboratory heating data. As yet, this is not possible for the U-Th-Pb and Rb-Sr dating systems.

3. Cooling Rates and Uplift Rates.

Sharma et al (1980) have assumed that all discordances in age data obtained on rocks from a single area are due to a single orogenic cycle and slow cooling. This is certainly not true in all areas, where such discordances may be due to later reheating events (nearby intrusions, later orogenic cycles) or even in the case of conventional K-Ar ages (unsupported by $^{40}Ar-^{39}Ar$ incremental heating data) to the presence of excess argon, partial loss of argon from some of the phase (minerals) in the rocks due to alteration or later reheating. Cooling rates should not always be equated with uplift rates through the use of the appropriate geothermal gradient. The possibility of intrusive bodies causing reheating seems to have been discounted altogether by Sharma et al (1980) in all the orogenic belts of India studied by them. Yet, the effects of intrusion on radiometric dating systems are well known (Hart, 1964, Hanson and Gast, 1967, Berger, 1975, Hanson et al, 1975, Harrison and McDougall 1980a, b, Calk and Naeser, 1973, Naeser et al, 1979). The scarcity of geochronological data available in the literature for rocks from India may have prevented a proper evaluation of such postorogenic intrusion effects.

4. Selection of Geochronological Data for the Calculation of Uplift Rates.

It has been stressed above, that all radiometric age data to be used in calculating cooling rates should be obtained preferably on the same hand specimen, or at least from one rock unit. Taking bits and pieces of age data obtained by various dating techniques on rocks units (from one area) separated by ∿100 km can lead to gross errors. The cooling history within a small section of the Grenville Province has been shown to vary widely over a lateral extent of ∿50 km. Data obtained from thermochronometric work on three sets of intrusive bodies in the Madoc-Bancroft area are summarised in Fig. 1 and the meaning is self-evident. If (for example), use is made of (a) the hornblende data from the Tudor Gabbro (∿590°C at 1110 Ma - Bakši, 1981), (b) biotite from the Thanet Gabbro (∿350°C at 1080 Ma - Berger and York, 1981a) and (c) plagioclase from the Haliburton Instrusions (∿200°C at 700 Ma - Berger et al, 1979), a totally incorrect (average) cooling curve for the whole area results (see dotted line in Fig. 1). In fact, Berger and York, (1981a, Fig. 5), postulate a reheating event around 1150 Ma for the Thanet Gabbro (also see Fig. 1). This could well be due to the emplacement of the nearby Tudor and Umfraville Gabbros at around 1150 Ma (Bakši, 1981). Only the careful thermochronometric work of Berger and York (1981a), combined with detailed field mapping delineating metamorphic zones, has managed to detect the possibility of a reheating event after emplacement of the Thanet Gabbro at ∿1210 Ma.

Similar variations were observed in the Hercynian metamorphic basement in France from the detailed investigations of Duthou (1977). Therefore, using whatever geochronological age data is available within a given area, without their proper evaluation as has been done by Sharma et al (1980), has probably led them to draw incorrect cooling curves.

5. Geological Control

Internal consistencies between various geochronometers gives some support to cooling rates obtained by different geochronological systems (Berger and York, 1981b, Fig. 13). Geological controls, though often scarce, are extremely useful to the interpretation of isotopic data and subsequent cooling/uplift rates especially when only a few isotopic ages are available.

This is illustrated by an example taken from the Grenville Province (see Fig. 1). $^{40}Ar-^{39}Ar$ thermochronometric work suggests an uplift rate of ∿30m/Ma for the area near the Tudor Gabbro for the period ∿1100 - 700 Ma (Baksi, 1981). An average uplift rate for this area can also be calculated from the fact that the area to the south of the Tudor Gabbro is covered by Ordovician sediments; this yields a value of ∿40 m/Ma for the period ∿700 - 500 Ma. Finally for the contiguous northern Adirondack region, Selleck (1980), suggests an average denudation rate (based on unroofing calculations) of ∿ 40 m/Ma for the period ∿1100 - 700 Ma. The close agreement in values obtained by these three very different methods, leads to confidence in the calculated average uplift rates for the period ∿1100 - 500 Ma.

6. Incorrect use of published age data by Sharma et al (1980).

There are numerous examples of the fact that Sharma et al have made incorrect and unwarranted use of published age data and some of these are enumerated below. Four general crit icisms are listed first however. Firstly, Tables II-V in Sharma et al's paper should carry an extra column, listing the source from which the age data is taken. We believe that many of the ages are average of various values and are untenable for use in calculating cooling rates for reasons mentioned above. Secondly, Sharma et al have apparently made no attempt to reduce published U-Pb, Rb-Sr, K-Ar data to the values that would result if use is made of the revised decay constants as given by Steiger and Jager (1977). Such an exercise could well alter some of the ages by ∿5%, thus negating many of the calculated cooling rates presented by Sharma et al.

Third, these authors use their FT data in an unwarranted manner. Systematically, they make use of <u>apparent</u> FT ages, even when in earlier papers, they determined <u>model</u> FT ages allowing them to take into account the effect of partial fossil track fading. As stated earlier, in this paper and elsewhere (Poupeau 1981b, 1982), apparent ages in basement rocks have geochronological significance in <u>specific contexts only</u>. Fourth, cooling rates are calculated regardless of whether the data being used are <u>(statistically) significantly different or not.</u>

Specific criticisms of the Sharma et al (1980) paper on these grounds are listed below; -

<u>Table II</u>:- (Dharwar Orogenic Belt) Serial Nos. 1 and 2:-

Rb-Sr whole -rock age of 1600 Ma and a U-Pb age (on a detrital monazite) of 1570 Ma are obviously indistiguishable from one another at any proper level of statistical confidence. Yet Sharma et al see fit to use these two data points to calculate a cooling rate to two significant figures for the Eastern Ghats Cycle.

Serial No. 3:- The sphene FT age of 1210 Ma has been corrected for partial fading of tracks to 1330 ± 40 Ma (Nagpaul and Mehta, 1975). Obviously this age cannot be used in conjunction with the zircon FT age of 1330 ± 40 Ma to calculate a cooling rate in the Arcot region of Tamil Nadu for the period 1330 - 1210 Ma. Serial No. 5:- The FT age of the sphene (1280 Ma) has been corrected for partial fading of tracks to 1410 Ma (Nagpaul and Mehta, 1975). This latter age, which agrees with the zircon FT age of 1406 Ma can obviously not be used for any attempt to calculate cooling rates; yet Sharma et al overlook their own data and present a cooling rate for the period 1406 - 1280 Ma for the Salem area. Serial No. 6:- The zircon and apatite FT ages are listed as 570 ± 20 and 520 ± 40 Ma respectively (Nagpaul and Mehta, 1975). These data points cannot be used for calculating cooling rates. Further, the same apatite age has been corrected for partial fading of tracks to 570 ± 40 Ma (Nagpaul and Mehta, 1975); once again Sharma et al prefer to bypass some of their own published data to present totally dubious cooling rates for the Khammam area. Serial nos. 7 and 8:- The apatite FT ages have been corrected for partial fading of tracks from 430 to 470 Ma (no. 7), and 450 to 510 Ma (no. 8) (Nagpaul, 1975). This negates any possibility of calculating cooling rates for the Kanyakumari and Madurai areas respectively. It is also worth noting that U-Pb dates on four monazites from Satbhays to Salem (covering a distance of over 1000 km) are listed as being identical (1570 Ma), a most unlikely situation. In summary, it is evident that almost all the cooling rates arrived at in Table II, for the Dharwar Orogenic Cycle, are totally untenable when the proper ages are used in conjuction with their associated analytical arrors.

Table III:- (Satpura Orogenic Belt). Serial No. 1:- A U-Pb age of 970 Ma is evidently statistically indistinguishable from a K-Ar age of 920 Ma. The FT garnet and apatite ages are stated to be the average values for various bodies; dangers in using "average" data from an area in this fashion have been pointed out above. Thus three of the cooling rates tabulated herein are of very dubious value.

Table IV. (Aravalli Orogenic Belt). Serial No. 1:- A whole-rock Rb-Sr age of 1500 Ma is certainly not significantly different from a garnet FT age of 1370 ± 130 Ma (Sharma et al, 1980, p. 146). Serial no. 2:- This is an especially bad case of misuse of published data. The listed muscovite K-Ar age of 1024 Ma is actually the average of two determinations (1042 ± 42 and 1006 ± 40 Ma, Mahta and Rex, 1976). The garnet FT age is actually 990 ± 110 Ma (1σ error) as quoted by Lal et al (1976). Further comment on using two such data points to calculate a cooling rate to two significant figures would be superfluous. Serial No. 3:- A whole-rock Rb-Sr age of 955 Ma and a Rb-Sr biotite age of 900 Ma are used to calculate the cooling rate of the Godra granite. The whole-rock age is actually 955 ± 20 Ma (Gopalan et al, 1978); these authors add, "All the biotites are concordant within experimental error *at about 900 Ma. This is not significantly different from the whole-rock age .....*" (our italics), (ibid, p.150). Sharma et al see fit to calculate a cooling rate from these two data points, neglecting the assertion of the authors (Gopalan et al, 1978) on the significance to be attached to these ages. At least three of the cooling rates listed in Table IV are of extremely questionable quality.

In their Figure 4, Sharma et al have presented detailed cooling/uplift curves for the various orogenic cycles in India, based on the data summarised in their Table VI. We feel each of these curves, should be based on at least five points to define their shape and extent. Yet, most of these are based on only two or three cooling rate determinations (see their Table VI), and most of these have also been shown (above) to be totally unwarranted in view of incorrect application of published age data and/or misconceptions regarding use of guessed values of retention temperatures for the various dating schemes. It may also be noted that all the curves, with the exception of the one for the Himalayan Orogenic Cycle, bear the same shape, namely a slow cooling rate at first, followed by more rapid cooling for the ensuing ∿150 Ma and very slow final cooling. This is certainly not the type of cooling curve seen in the Grenville Province as based on careful thermochronometric work (see Fig.1.). In this context, it may be borne in mind that the Grenville Orogeny probably resulted from a "Himalayan-type" collision between two plates (Dewey and Burke, 1973).

In relatively young orogenic belts, such as the Himalayas, the approach used by Sharma et al of relying almost totally on FT data to calculate uplift rates, may have some merit, provided (a) that one can assume a constant geothermal gradient in all areas, (b) that partial fading of tracks is taken into account. In such areas with relatively fast uplift rates, high precision plateau FT ages (Poupeau, 1981b) would be required. Careful work on rocks from the Hercynian basement reveal concordant Rb-Sr whole-rock, K-Ar and FT ages, at around 290 Ma. This indicates very rapid cooling in the temperature range $\sim$600 - 100°C. It would appear that both uplift and erosion in this area were extremely rapid. In such areas, one may not be able to obtain quantitative cooling rates even from very careful thermochronometric work†. In Proterozoic terrains, a ± 3% analytical uncertainty in the various ages would mean that "events" spaced together at less than 40 Ma (at 600 Ma) to 150 Ma (at 2500 Ma) could not be resolved at all. Unless cooling rates are quite slow (such as in the Grenville Province) only the thermochronometric techniques making use of high precision $^{40}Ar-^{39}Ar$ and FT incremental heating age data would enable one two to separate various events in time, leave alone calculate quantitatives values for cooling/uplift rates.

It is in light of the points raised above that we suggest that only very careful analytical work taking the utmost care in interpretation of the results so obtained (as also published ages in the literature) can serve a useful purpose in calculating paleo-uplift and cooling rates. It is felt that Sharma et al's (1980) paper leaves a great deal to be besired in this respect and their evaluation of the uplift and cooling rates for the various orogenic cycles in India, should be regarded with the utmost caution.

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†Similar situations were found in the French Hercynian platform (Poupeau, 1982) and Alpine Corsica (Mailhe et al, 1980).

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FIGURE CAPTIONS.

Fig. 1. Cooling curves for three sets of intrusive bodies in the Madoc-Bancroft region of the Grenville Province, Ontario, Canada, as derived from thermochronometric results (modified from Berger and York, 1981a, Dunlop, 1981). Inset shows simplified geological map of the region. Data taken from Berger et al (1979), Berger and York (1981a) and Baksi (1981).

Symbols Hb, Th, Tu, Co, and Um it the inset, identify the Haliburtion Intrusions and the Thanet, Tudor, Cordova and Umfraville Gabbros reapectively. Dotted line represent erroneous "average" cooling curve making use of data obtained form (a) Tudor Gabbro, (b) Thanet Gabbro and (c) Haliburton Intrusions (see text).

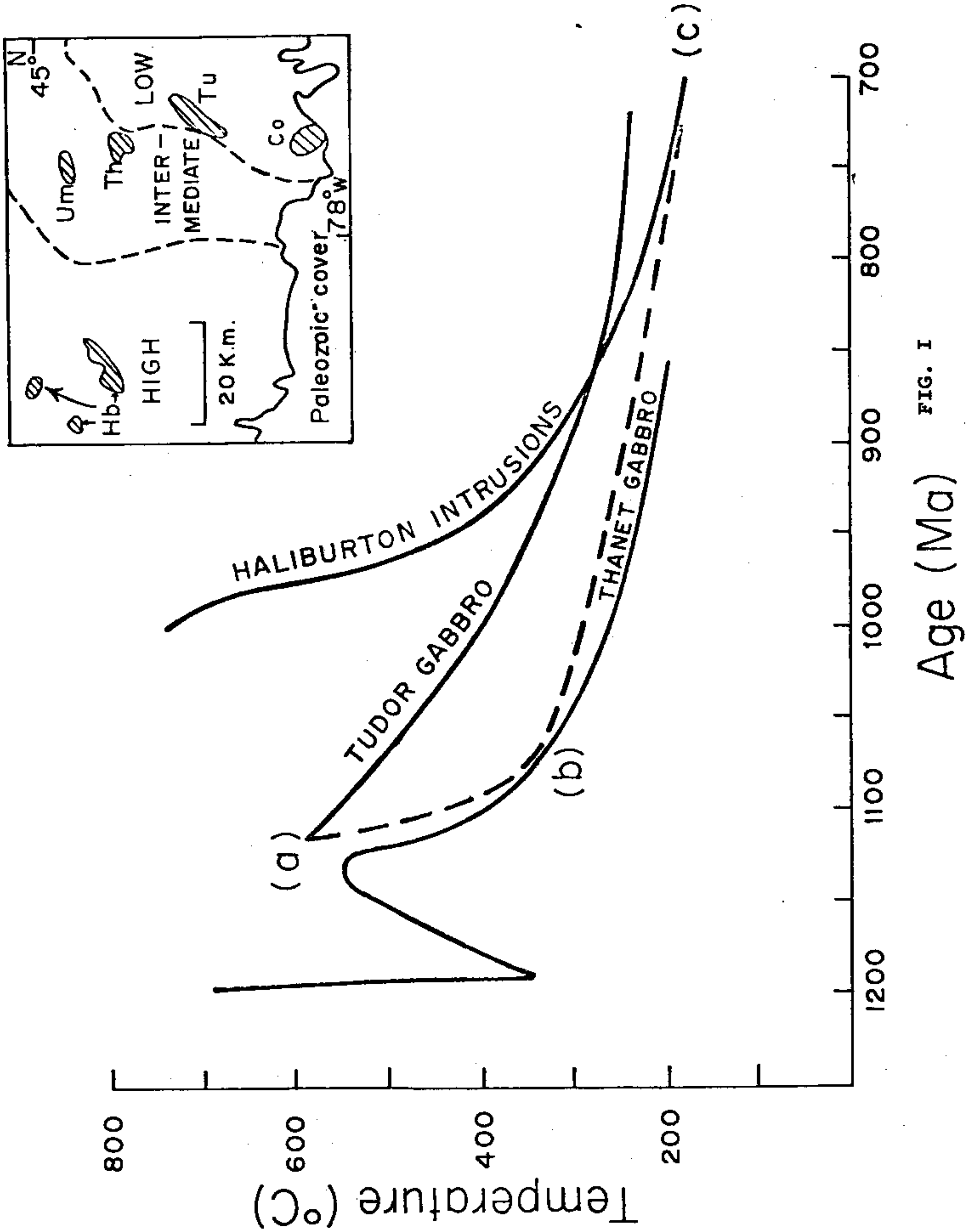
HALIBURTON INTRUSIONS
TUDOR GABBRO
THANET GABBRO
(a)
(b)
(c)
Temperature (°C)
800
600
400
200
Age (Ma)
1200
1100
1000
900
800
700
Hb
HIGH
20 K.m.
Paleozoic cover
Um
Th
INTER-
MEDIATE
LOW
Tu
Co
N
45°
78°W

FIG. I