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THERMAL REGIMES IN PROTEROZOIC ISLAND ARCS — AN HYPOTHESIS

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Estimates of thermal regimes in the Proterozoic have an important bearing on the evolution of island arcs inasmuch as they provide models to account for the nature of magmatism at that time. With this aim in mind, a model is presented based on the geology and geochemistry of basaltic rocks from the Early Proterozoic greenstone belt of the northern Guiana Shield. In most of the Precambrian areas of South America, volcanism during the Archean and Proterozoic was essentially confined to ensialic enviroments. In addition, older sialic crust and preserved Archaean nuclei in Brazil, whose constitution and history vary from place to place, appear to have served as the basement for greenstone belts. On the other hand, structural, stratigraphic and geochemical evidence show that the Early Proterozoic greenstone belts of the Guiana Shield, occurring as a narrow extensive belt from Venezuela across the Guianas, were formed in tectonic settings similar to present-day island arcs. That is to say, at a time when ensialic conditions prevailed in Precambrian terrains in the rest of the continent, the Guiana belt evolved by island arc magmatism. Geochemical characteristics of volcanics were employed to draw inferences regarding mantle composition and thermal regimes which existed in this early period. As a working hypothesis, the island arc features of the Guiana belt are examined in the light of known models of partial melting of four-phase peridotite and available data relating to magma generation. The results suggest that the interaction of primitive warm crust and warm mantle and the resulting elevation of isotherms into the mantle wedge might account for the extensive volcanic belt and copious magma production.

As estimativas de regimes térmicos do Proterozóico têm uma relação importante com a evolução de arcos de ilhas uma vez que estes últimos fornecem modelos que explicam a natureza do magmatismo daquela época.* apresentado um modelo baseado na geologia e geoquímica de rochas basálticas do cinturão de rochas-verdes do Proterozóico Inferior da parte norte do Escudo Guiano. Na maior parte das áreas Precambrianas da América do Sul, o vulcanismo durante o Arqueano e o Proterozóico estava confinado principalmente em ambientes ensiálicos. Ainda mais, a crosta siálica mais antiga e núcleos arqueanos no Brasil, cuja constituição e história variam de local para local, parecem ter servido de embasamento para os cinturões de rochas-verdes. Por outro lado, evidências estruturais, estratigráficas e geoquímicas mostram que os cinturões de rochas-verdes do Proterozóico Inferior no Escudo Guiano, que ocorrem como estreito e extensivo cinturão desde a Venezuela e através das Guianas, foram formados em ambientes tectônicos similares aos arcos de ilhas do presente. Ou seja, no tempo em que condições ensiálicas prevaleciam em terrenos Precambrianos no resto do continente, o cinturão Guiano evoluiu através de um magmatismo de arco de ilha. As características geoquímicas das vulcânicas foram empregadas para obter inferências sobre a composição e regimes térmicos do manto que existiram naquele período. Como hipótese de trabalho, as feições de arcos de ilha do cinturão Guiano são examinados sob a luz dos modelos conhecidos de fusão parcial de peridotita de quatro fases e dados disponíveis relacionados com a geração de magmas. Os resultados sugerem que a interação entre a crosta primitiva aquecida e o manto aquecido e a consequente elevação das isotermas em direção do manto, poderiam explicar o cinturão vulcânico e a produção abundante de magma.

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INTRODUCTION

It is generally agreed that the Archean was a time of higher geothermal gradients and higher heat production, as a consequence of which tectonic processes and magma production were somewhat different from those of to-day. Increased heat production would bring with it a higher hot spot activity, according to Abbott & Hoffman (1986), as a result of which there would be a difference in the relative importance of types of plate movement which contribute to tectonic processes. A more rapid turnover and subduction in ocean crustal areas would be linked to such movements, assuming of course that some sort of plate movement was already taking place at that time. In continental areas, however, the Archean crust and lithosphere had acquired thicknesses comparable to present day crust so that melting of lower continental crust was prevented by the existence of thick root zones (Davies, 1979) or tectosphere (Jordan, 1978). By the Proterozoic, continental crust was stabilized by cooling through time and lowering of thermal gradients. In Brazil, the crust had become stable in the late Archean (Iyer et al., 1984) and in several places formed the basement for greenstone belts. On the other hand the Lower Proterozoic in the Guiana Shield witnessed the formation of greenstone belt by island arc magmatism without the involvement of continental crust and without a recognizable sialic basement (Gibbs & Barron, 1982). In its size and extension, its variety of volcanic rocks varying from Mg-rich basalts, komatiites, tholeiites and cal-alkaline lavas, the Guiana greenstone belt is unique for the Early Proterozoic. Here we examine some of its characteristic features in terms of geochemistry and suggest a thermal model for the setting.

GEOLOGICAL BACKGROUND

The major part of Precambrian terrain in South America occurs in the Brazilian and Guiana Shields with minor exposures in Colombia, Bolivia and Paraguay (Almeida et al., 1981). In Brazil, the Precambrian is characterized by stable old cratonic areas of Archean age bordered by younger fold belts which developed during the Trans-Amazonian (2.1-1.9), Uruaçuano (Ca. 1.2 Ga) and Brasiliano (0.5-0.6 Ga) tectono-thermal cycles (Almeida et al., op. cit.). Although rocks of Archean age belonging to the Imataca Group occur in Venezuela, most of the Guiana Shield is of Early to Middle Proterozoic age. The geology of this region has recently been reviewed by Gibbs & Barron (1983). In common with Precambrian areas in other continents, many areas in the Brazilian and Guiana Shield are marked by volcanism since Archean times. The extent or volume of volcanic rocks diminished with time as the shield areas were consolidated and cratonized. For example in the Guiana Shield magmatism, including various types of volcanic and intrusive activity, peaked in the Early and Middle Proterozoic, and was much less extensive in later periods (Gibbs, 1986). A similar evolution can be traced in Brazil since the Archean (see e.g. Schobbenhaus et al., 1984).

If we now consider the nature of mafic-ultramafic volcanism in the Precambrian we find that in Brazil volcanic sequences were deposited in ensialic environments corresponding to already stabilized cratons (i.e. most of the Amazon craton as well as the entire Guaporé and São Francisco cratons), whereas the volcanic rocks which belong to the Proterozoic greenstone belt along the northern part of the Guiana Shield formed in an ensimatic setting (Choudhuri, 1980; Gibbs, 1980; Bosma et al., 1983). Gibbs et al. (1984) have shown by stratigraphic, structural and geochemical studies that the Guiana belt formed in an island arc environment being similar to Archean greenstone terrain in Canada and lithologically and geochemically similar to present-day island arcs.

TECTONIC SETTING OF GREENSTONE BELTS

Brazilian greenstone belts occur scattered over the country in Archean basement as the Amazon craton in Pará State, in the São Francisco craton in Minas Gerais and Bahia States in the Central Goiás massif (Schobbenhaus et al., 1984). Tassinari and Montalvão (1980) dated the granitic rocks of the Crixás greenstone belt at 2.9 Ga, and a similar age was found by Wernick et al. (1981) for the migmatite basement of the Fortaleza de Minas greenstone belt in southern Minas Gerais. Their occurence in stable shield areas consolidated since the Archean, where crustal thickness had already attained present-day proportions (Iyer et al., 1984) suggest that these greenstone belts may have formed in a rifting environment. In support of this idea there are several similar thermal models (Burke & Kidd, 1978; Davies, 1979) according to which Archean cratons were underlain by thick, cool root zones, and the thermal gradients were not much higher than those of today. Further evidence for a thick lithosphere at this time comes from the Archean age recently obtained for diamonds from southern Africa and their restriction to cratonic areas (Boyd et al., 1985). That is to say that continental litosphere was stabilized to depths within the diamond stability field during the Archean. Also, Takahashi and Scarfe (1985) have shown that the magmas for komatiites of greenstone belts must have been generated by small amounts of partial melting of mantle peridotite at depths of 150-200km below Archean cratonic areas. An extensional environment for an Archean bimodal lava suite in the Serra dos Carajás, Amazon craton, has been suggested by Olszewski et al. (1986). On the basis of heat flow data, Drury (1986) suggests that sialic continental crust probably underlies Brazilian greenstone belts. In other words, although some of these ideas border strongly on speculation, what evidence is available points to rifts in old continental crust as a possible tectonic setting for these greenstone belts.

Independent of whether some Archean greenstone belts formed in island-arc-like situations (Windley, 1977; Card, 1986), we turn our attention to the Early Proterozoic greenstone belts of Guiana. The belts extend, with interruptions, from Venezuela through Guyana, Suriname and Frenchl Guiana, with a total length of about 1500 km and a breadth of approximately 200 km (Fig. 1). The belts typically have arcuate and branching forms with interspersed tonalitic intrusives similar to the characteristic patterns met with in Archean greenstone belts. Stratigraphic sequences established by Gibbs (1980) and Renner & Gibbs (1985) as well as geochemical studies by these authors show strong affinities to island-arc volcanics. Lower mafic rocks and pillowed basalts to tholeiite and Mg-tholeiite compositions give way to upper felsic units; mafic, intermediate and felsic units of both tholeiite and calc-alkaline series are overlain by volcaniclastic greywackes and chemical sediments. Whereas ultramafic bodies and Mg-basalts are reported from Guyana (Gibbs, op. cit.), komatiites have been recorded by Gruau et al. (1985) from French Guiana.

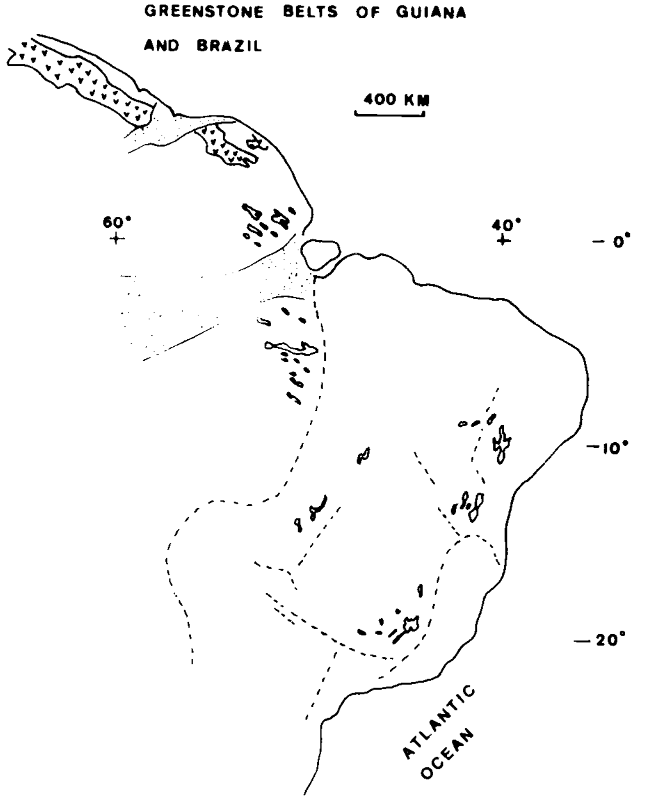

Figure 1 — Greenstone belts in the northern Guiana Shield (v's) and in Brazil shown schematically after Gibbs & Barron (1983) and Shobbenhaus et al. (1984); dashed lines are gravimetric lineaments after Haralyi & Hasui (1982), while dashed line along the middle is the eastern limit of the Amazon craton.

Although the Guiana greenstone belts are very similar to Canadian greenstone belts of Archean age (Gibbs, 1980), U-Pb determination in zircons have yielded Early Proterozoic ages of 2.1 Ga from Guiana (Gibbs & Olszewski, 1982). Sm-Nd analyses of metavolcanics from French Guiana yield an isochron age of 2.11 ±0.09 Ga (Gruau et al., 1985). Low Sr isotope ratios of intrusive granitic rocks point to mafic precursors for the magmas, and there is no evidence of a sialic basement for the greenstone belts (Gibbs et al., 1984).

From the brief outline given above it can be seen that the tectonic environment for the Guiana belts and those in Brazil are distinct. Stratigraphic and geochemical evidence indicate the formation of the former in Early Proterozoic island arcs, while geophysical evidence documented by Haralyi & Hasui (1982) and Hamza (1982), in addition to other evidence mentioned earlier on favour ensialic rifting for the latter. (Fig. 1). Much remains to be done, however, to explain the exact nature of tectonic processes which were responsible for the latter belts some of which are Late Archean and some Early Proterozoic (Schobbenhaus et al., 1984).

Some of the characteristic geochemical features of the Guiana greenstone belt volcanics are examined in the next section and compared with present-day island arcs.

NATURE OF ISLAND ARC VOLCANICS

Island arcs form where oceanic lithospheric plates converge with one of the plates subducting as a slab below the other. The subduction is recognisable by a dipping zone, the Benioff zone, along which seismic activity is registered at increasing depths away from the site of plate convergence. Island arcs are complementary to mid-ocean ridges inasmuch as the latter represent divergent plate margins marked by upwelling of magma and creation of new ocean floor. In a simplified model island arcs may thus be regarded as sites of shortening of crust and mantle, being made up of successive tectonic elements in the arc-trench system such as fore-arc, main arc basin and remnant arc (Hawkins et al., 1984).

Compositionally island arc tholeiites (IAT) are distinct from basalts generated at mid-ocean ridges (MORB), although basalts from a back-arc environment may be similar to the latter. Besides these magma types there are also the boninites (high-Mg andesites) and fore-arc tholeiites (Jakes & Miyake, 1984). A general comparison of characteristic chemical features of IAT, MORB and high-Mg basalts from Guyana are shown in TABLE 1.

Abreviations: MORB = Mid-ocean ridge basalts
IAT = Island arc tholeiites
GMB = Magnesian basalts from the Guiana Shield

N.B. In addition, the GMB have high CaO/Al_2O_3, i.e. greater than or approximately equal to 1, as well as higher Ni, Cr, Co and V than island arc tholeiites (GIBBS, 1980; BOSMA et al., 1983).

Table 1 – Comparison of tholeiites from different tectonic settings

	MORB	IAT	GMB
K_2O	low $<<$ 0.8%	mod. ~ 0.8%	mod. ~ 0.8%
TiO_2	moderate $>$ 1%	low $<$ 1%	low $<$ 1%
Zr	moderate 80 ppm or higher	low ~ 60 ppm	low ~ 60 ppm
LREE	flat to depleted	enriched	enriched

Abreviations: MORB = Mid-ocean ridge basalts
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In addition to the high-Mg basalts, the greenstone volcanic sequences of the Guiana Shield contain rocks of tholeiitic as well as calc-alkaline series. Fig. 2 illustrates that only some of these have affinity with their present-day equivalents. Middle Proterozoic continental tholeiite dykes which cut the northern Guiana Shield are also plotted in Fig. 2; however, not all of them have affinities with continental basalts. Gruau et al. (1985) have reported komatiites from French Guiana, and although no undoubted komatiites have yet been found in Guyana, their compositions are very similar. This is clearly brought out in Fig. 3 which shows the fields for Archean komatiites as well as the Mg-basalts, tholeiites and calc-alkaline volcanics from Gibbs (1986); here again we find ample similarity with the Archean greenstone belts of Abitibi, for example. It is noteworthy that the extent and profusion of the Guyana volcanics is not matched elsewhere in the Lower Proterozoic.

Taken together, all the above chemical characteristics point to a distinct geochemical fingerprint for the mafic to intermediate volcanics of the Guiana greenstone belts, and this led Bosma et al. (1983) to stress the primitive nature of the Lower Proterozoic Guiana island arc (Reference may be made to Renner & Gibbs, 1985, and Gibbs, 1986 for chemistry of associated acid volcanic rocks). One of the important features which stands out in their chemistry and which is worth emphasizing is the high Ni and Cr content of the Guyana tholeiites as well as basalts and andesites of the calc-alkaline series. In order to assess the significance of this fact we must turn to the work of Mysen & Kushiro (1979) on the partitioning of Ni in mafic magmas. Generally speaking, mafic magmas fractionate olivine as they evolve from melts derived from melting of four-phase peridotite at mantle depths. According to these authors, the partition coefficient for Ni between olivine and melt decreases with increasing pressure (depth); conversely partial melts formed at shallow levels with compositions ranging from olivine tholeiite to andesite will have low Ni contents. This is compatible with compositions of present-day mafic magmas, but for the Guyana rocks might it not imply a more primitive mantle and support the idea of Bosma et al. (1983) of a primitive island arc?

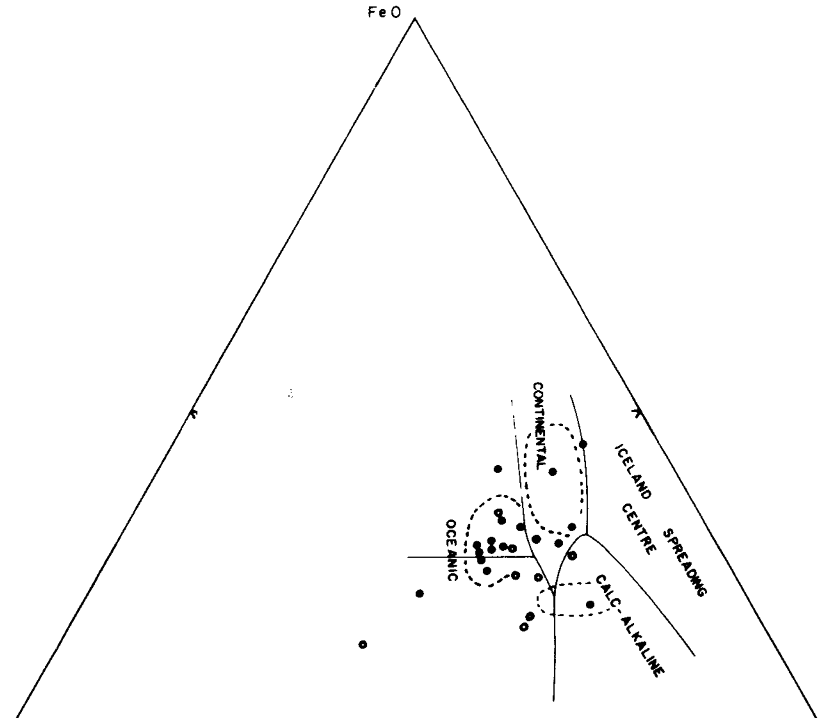

Figure 2 — AFM diagram showing distribution of Guiana greenstone volcanics (dotted fields), middle Proterozoic tholeiite dykes of Guiana (filled circles) and fore-arc tholeiites (open circles) — the latter after Jakes & Miyake (1984), in relation to specific tectonic settings.

To account for such a mantle three similar models for mantle constitution come to mind. These are the models proposed by Tatsumoto (1978), Morris & Hart (1983) and Ringwood (1985). According to the first, in a mantle convection cell the outer portions are depleted whereas the central part remains undepleted in trace elements thus providing a relatively enriched mantle magma source. The arguments of Morris & Hart (1983) are similar in principle though different in structure inasmuch as they propose enriched (or undepleted) local mantle regions scattered in a depleted mantle matrix, much like plums in a plum pudding (comparison of these authors!). These regions would tend to mix with their surrounding during partial melting necessary for volcanic events at island arcs. Stretching the analogy, the Lower Proterozoic mantle beneath Guiana should have had a greater quantity of such undepleted regions or mega-blobs to account for the primitive nature of the volcanic products of partial melting of mantle. Ringwood's (1985) model suggests magma generation from a harzburgite of lherzolite megalith embedded with ocean crustal blocks at a depth of 600 km and resulting from subduction of oceanic lithosphere slabs. Here, enrichment of magmas comes from partial melting of ocean crust blocks which are scattered in the megalith. With a definite bias toward the model of Morris & Hart (1983), we appeal to a more primitive mantle for our model of the Lower Proterozoic island arc.

THERMAL REGIMES

If the geochemistry of the Guiana island arc appears difficult to acount for adequately, then any suggestions as to the thermal regime are even more shaky and hazardous. However, as an exercise and as a working hypothesis it is worthwhile examining this aspect on the basis of what has been established, also in no less speculitive terms, for present-day island arcs. It must be borne in mind that two essential factors which constrain any model one wishes to set up are the highly magnesian nature of the magmas represented by the mafic-ultramafic lavas and secondly the tectonic setting in which they were produced. As mentioned before, the Brazilian greenstone belts occur in stable cratonic regions in contrast to the ensimatic Guiana belts. Moreover, the very nature of the magmas requires their derivation from dry melting of mantle peridotite as otherwise in the case of wet melting (in the presence of a good amount of water or even water-saturated) the group of rocks known as boninites are produced (Cameron et al., 1979) which are characteristic of some modern western Pacific island arcs.

Davies (1979) has modelled geotherms for the Archean oceanic and continental environment and compared these with their present-day counterparts. He has shown, that the continental crust had already thickened considerably in the Archean with geotherms not very different from those in shield areas today, as otherwise the lower crust would have been subjected to widespread melting in these areas. On the other hand, according to him, much of the higher Archean heat flow was dissipated in the oceanic areas (where geotherms were high) possibly by a rapid convective turnover. Burke & Kidd (1978) come to a similar conclusion regarding the thickness of Archean continental crust in the Superior Province of Canada (35 Km thick) based on the absence of minimum-melt granites in this province. In other words continental geothermal gradients were not much steeper then than today. The preservation of thick cratonic areas in Brazil is probably due in part to this factor as well as to the refractory nature of the crust in these areas (Iyer et al., 1986). Archean and present-day geotherms after Davies (1979) are shown in Fig. 4. The point to be made is that we assume that the geothermal gradient in an Early Proterozoic island arc, such as that of Guiana, was probably nearer the Archean oceanic geotherm since it has to do with an ensimatic environment quite different from the cratonic areas of Brazil. The higher geotherms

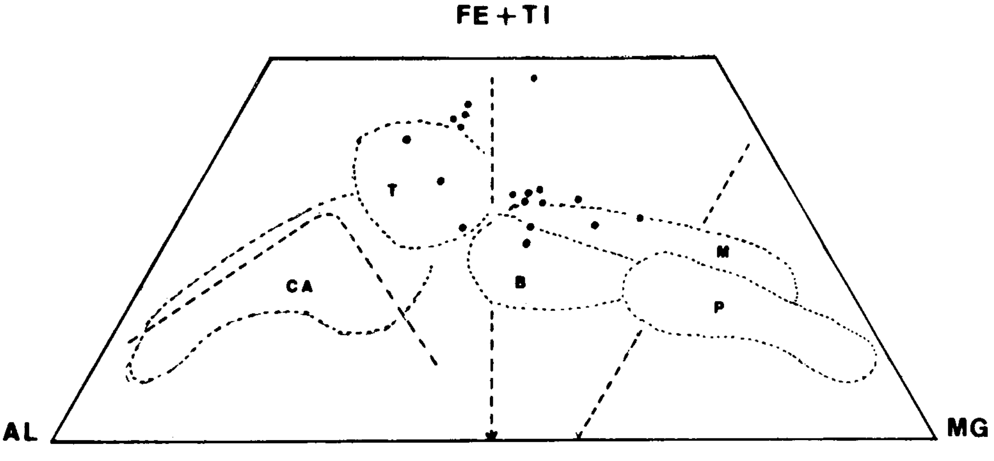

Figure 3 — Fe + Ti — Mg — Al plot for Guiana volcanics — dotted fields marked M, T and CA for high-Mg basalts, tholeiites and calc-alkaline series respectively; midle Proterozoic tholeiite dykes (filled circles); P and B mark fields of peridotitic and basaltic komatiites from literature.

of such early primitive arcs together with a much thinner oceanic lithosphere (Davies estimates about half present-day thickness for Archean oceanic lithosphere) could be responsible for the profusion and extent of volcanism recorded in the Guiana belt.

In several possible models for the distribution of isotherms in a subduction environment and the production of magma Wyllie (1984) bases his ideas on present-day island arcs for which oceanic lithosphere is much thicker and so is the continental crust — the latter with a thickness of 50 km could easily be a continental margin. Referring to magma generation, for instance, a warm subducting crust and a warm mantle are shown to trigger melting in the former, in the mantle and at the base of the continental crust, and for all purpose Wyllie (1984) illustrates these possibilities for the case of wet melting of mantle peridotite. According to Tatsumi et al. (1983) thermal structures proposed for the mantle wedge above the subducting slab, to which Wyllie adheres, are inadequate for magma generation; he suggests instead a region in the mantle wedge where the temperatures should be of the order of 1400°C and not as in low isotherms proposed by several previous workers. One of the possible models of Wyllie is depicted in Fig. 5a. Considering the higher heat flow in the Early Precambrian, isotherms in island arcs must have been quite different.

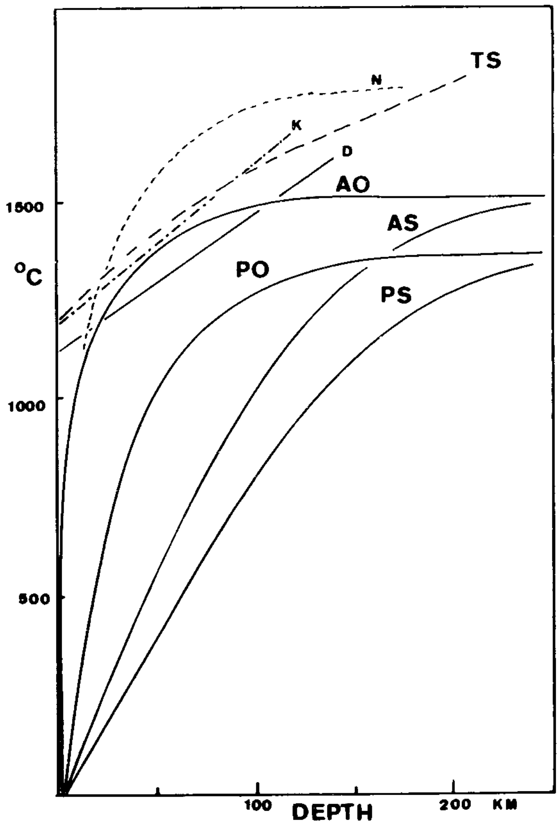

Figure 4 — Relation of various geothermal gradients to mantle peridotite solidus: AO, AS, PO and PS are Archean oceanic, Archean shield, present oceanic and present shield geotherms, and D is dry solidus for peridotite solidus from Davies (1979). N is Archaean geotherm from Nisbet (1984) and K and TS are dry solidus for mantle peridotite according to Kushiro (1973 — indicated in Wyllie (1984) and Takahashi & Scarfe (1985). Note that DAVIES A.O. intersects D which represents older values for dry solidus, whereas it should be slightly higher to intersect TS and K as does geotherm N.

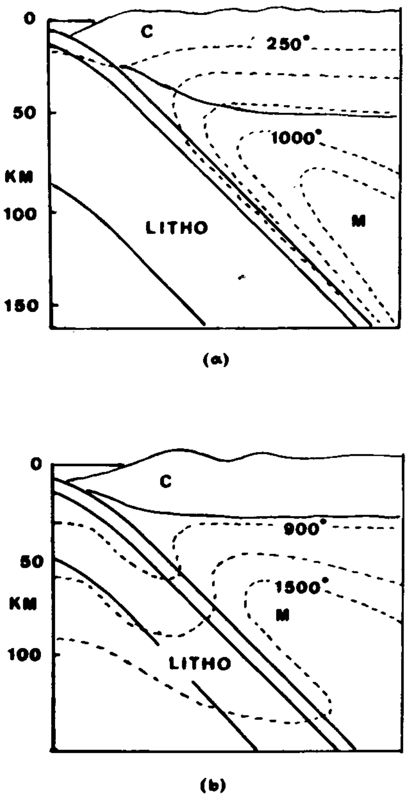

Figure 5 — a) Isotherms in a subduction environment after Wyllie (1984). Litho = oceanic lithosphere, C = continental crust, M = mantle.
b) Possible isotherms necessary in mantle wedge below an early Proterozoic island arc to permit dry melting of peridotite at relatively shallow depths (see e.g. intersection of N & TS in Fig. 4) and to produce komatiites and high-Mg basalts; thickness of crust (C) and oceanic lithosphere (LITHO) according to estimates of Davies (1979).

With the recent investigations of Ohtani (1974) and Takahashi and Scarfe (1985), the problem of komatiite generation has taken a new turn. Ohtani has shown that basic liquids in the deep upper mantle are denser than olivine and pyroxene and that komatiites are probably produced by ascending partially molten diapirs from depths around 200 km. This is corroborated by the melting experiments of Takahashi and Scarfe (1985) who have demonstrated that peridotite melts give komatiite liquids at depths of 150 to 200 km, at shallower depths partial melts give rise to picritic and basaltic liquids. This implies that komatiites were indeed generated at great depths below Archean continental lithosphere where the thermal base with temperatures around 1200°C was perhaps around 150 km. Possibly, the situation in old cratonic areas of Brazil where greenstone belts occur was similar to this model, since in continental areas the thermal gradient was not much steeper than today. However, in oceanic areas and at island arcs with much higher thermal gradients high temperatures were attained to permit generation of komatiite and high-Mg basalts at shallow depths.

To illustrate this point, Fig. 4 shows some of the relevant geotherms and the melting curve for peridotite (solidus of Takahashi & Scarfe (1985). Davies' (1979) geotherms were modelled for a somewhat lower solidus and need be only slightly higher to cross the solidus determined by them.

A hypothetical situation for isotherms in a Proterozoic island arc is shown in Fig. 5b while Fig. 5a is from Wyllie (1984), and it is suggested that thermal gradients must have crossed the dry peridotite solidus, TS, in Fig. 4, to generate the most basic and ultrabasic magmas in the northern Guiana Shield. The still warm mantle in a lower Proterozoic oceanic plate and island arc environment would cause the elevation of isotherms into the mantle wedge above the subducting plate and cause melting in this regions without necessarily invoking the kind of situation in Fig. 5a.

There is good reason to believe, therefore, that dry melting of mantle peridotite produced these high magnesian magmas at Proterozoic island arcs, whereas in Phanerozoic island arcs boninites were formed by wet melting. Continued magmatism would be later caused by melting in the subducting plate as well as at the base of the newly formed crust, as for example the tonalitic orthogneisses which later intruded the greenstone belts and which according to Gruau et al. (1985) probably formed by melting of basic precursors.

To have a universal applicability, such an hypothesis requires to be tested in specific cases. Whereas models established for magma generation, whether in the Archean or Proterozoic, are based on broad theoretical considerations, the model presented here is for the concrete example of the Guiana greenstone belts whose tectonic setting is that of a Lower Proterozoic island arc, firmly based on geological and geochemical evidence. Some of the Canadian Archean greenstones most probably also formed in an island arc-like situation. It remains to be shown whether other Proterozoic volcanic sequences formed in similar environments in which magmatism was governed by the prevailing high geothermal gradients as in the present model. No doubt, further refinements, such as isotopic signatures of the volcanic rocks, are necessary to complete the picture in which the uncertainties can be resolved more satisfactorily. In summary, for other possible ancient island arcs an understanding of their formation requires a knowledge of their tectonic setting, the geochemistry of the rocks and adequate thermal regimes necessary to generate the magmas which gave rise to the specific volcanic sequences.

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