ORIGIN OF THE LOW PRESSURE – HIGH TEMPERATURE CHARACTER OF PREDOMINANT THOLEIITIC COMPOSITIONS

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The tholeiitic rock series represents the most common igneous rock series in the Earths crust. This characteristic together with the four phase proximity of olivine-quartz normative tholeiitic compositions at 1 bar suggests some general control of magma generation. The control originates in a slow and constant velocity of the convection currents in the mantle, the constant convection velocity causing a constant rate of partial melting and a constant eruption frequency, resulting in a constant and small flow rate of ascending magmas, and a constant thickness of the litosphere. The low ascent rate causes four phase proximity at low pressures and the tendency towards a constant lithosphere thickness prevents the extrusion of low temperature – low pressure related compositions.

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The low-pressure differentiated character of tholeiitic magmas was demonstrated by Yoder and Tilley (1962), who pointed out that tholeiitic compositions have a low-pressure, four phase proximity and a small melting interval at one bar. The low pressure control of tholeiitic magmas was later demonstrated by other methods by O'Hara (1965) and Maaløe (1973).

Another important characteristic of the tholeiitic rocks is their position as the most common igneous rock type in the crust. Tholeiitic rock types are the most common basalt types within the great basalt plateaus (Walker & Poldervaart, 1949). Sampling from the oceanic bottoms suggests that a specific low-K theoleiite constitutes the mainpart of the oceanic crust (Engel & Engel, 1964 and Cann 1971). Two fundamental characteristics are consequently displayed by the tholeiitic rock series i.e., a low pressure character and a position as the most dominant igneous rock type. This coincidence must be of fundamental significance.

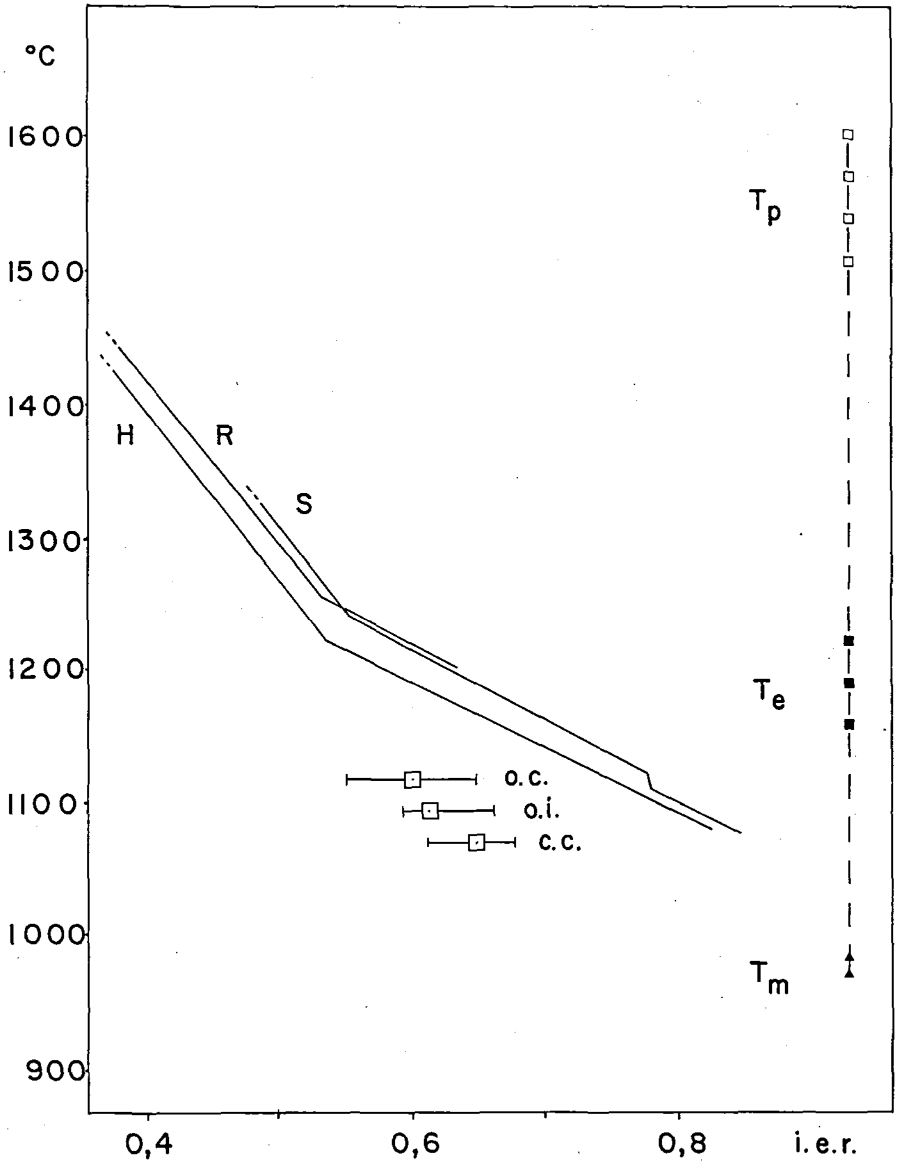

Fig. 1. The variation in liquidus temperature of tholeiitic compositions as a function of their iron-enrichment ratios, ($FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO$). The variation is shown for three *different* series; H: Hawaiian series; S: Snake River Plain series and R: Reunion series (Tilley &Thompson 1970, Thompson 1971). Abreviations; o.c.: oceanic crust average, o.a.: oceanic island average and c.c.: continental crust average (Cann 1971, Manson 1967). T_p: temperature range of primary magma generation, T_e: temperatures of eruption and T_m: lowest temperature possible for magmas of tholeiitic origin.

Temperature relations on the tholeiitic rock series

The temperature of eruption and the experimentally determined liquidus temperatures of tholeiitic lavas are rather similar (Yoder & Tilley 1962). Approximate temperatures of eruption may therefore be estimated from liquidus temperatures. Experimental determinations of the liquidus temperatures indicate, as shown in fig. 1, a systematic relationship between the iron-enrichment ratio and the liquidus temperatures within a given rock suite. The difference in the liquidus curves for the different suites shows that only approximate liquidus temperatures may be obtained from known ratios. The differences are partly due to different experimental techniques. The systematic increase in liquidus temperature with decreasing ratio is common to all the suites, and the iron-enrichment ratio is here considered a convenient indication of the liquidus temperatures.

Statistical studies for tholeiitic rock compositions have been made by Manson 1967, Engel & Engel 1964, Cann 1971. The iron-enrichment ratios estimated from their data are listed in table 1 and plotted in fig. 1. The oceanic crust average is lower than the continental average, but their distributions overlap. However, the lower iron-enrichment ratio of tholeiites from the oceanic crust indicate a slightly higher average liquidus temperature for these compositions than continental ones. A representative liquidus temperature for all the averages is 1190 ± 30°C.

A solidus temperature of 1060°C has been estimated for both a quartz and an olivine normative tholeiite (Yoder & Tilley 1962), in accordance with the experimental results of Humphries (1972). By the largest possible degree of differentiation the composition of tholeiitic magmas is changed towards the ternary minimum in the granite-system, having the temperature of 960°C at 1 bar, (Tuttle & Bowen 1958).

Table 1. Iron-enrichment ratios determined from the average compositions estimated by Manson (1967), (1–12) and Cann (1971), (13).

1	Pacific ocean islands	0.593	195
2	Atlantic ocean islands	0.661	60
3	Indian ocean islands	0.617	27
4	Africa	0.613	138
5	Antarctica	0.611	24
6	Asia	0.677	340
7	Australia	0.622	112
8	Europe	0.655	93
9	Indonesia	0.659	66
10	North America	0.635	173
11	Continents, average	0.645	946
12	Oceanis islands, average	0.613	282
13	Oceanic bottoms, average	0.600	94

Both the composition of the mantle material, from which the tholeiitic magma originates, and the degree of partial melting necessary to generate these magmas are unknown in detail. Therefore an exact temperature estimate of a primary magma is not possible; but a minimum temperature may be estimated from the liquidus temperatures of tholeiitic melts at high pressures.

From seismic evidence Eaton & Murata (1960) estimated the depth of generation to be approximately 60 km. This depth may be considered a minimum depth and a depth of 100 km, which corresponds to the upper part of the low-velocity layer, will be suggested here for the depth of generation of a primary tholeiitic magma, in accordance with Bowen 1956, O'Hara 1968, Jackson & Wright 1970.

For a primary magma to extrude as a tholeiite, the magma must not at any depth have a temperature below the experimentally determined liquidus temperature of tholeiitic compositions. The following experimentally determined liquidus and solidus temperatures at 30 Kbar can be used for an estimate of the temperature of a primary magma at this pressure:

liquidus temperatures	
olivine tholeiite, NM5, (Cohen et al., 1967)	1500°C
olivine tholeiite, (Green & Ringwood, 1967)	1528°C
olivine tholeiite, B3P1, (Ito & Kennedy, 1968)	1590°C
garnet peridotite, KA64–16, (Ito & Kennedy, 1967)	1980°C
solidus temperatures	
garnet peridotite, KA64–16, (Ito & Kennedy, 1967)	1465°C
pyrolite III, (Green & Ringwood, 1967)	1520°C
ternary minimum in the system diopside forsterite-pyrope, (Davis et al., 1965)	1670°C
garnet peridotite, A. 3/10596, (O'Hara & Yoder, 1967)	1415°C

The average of the first three temperatures is 1539°C, therefore the temperature of the primary tholeiitic magmas may be assumed higher than this temperature, but not higher than the liquidus temperature of the garnet peridotite. The temperature 1600°C may not be too high an estimated for the primary magma at 30 Kbar, as the ternary minimum temperature of the system diopside-forsterite-pyrope is 1670°C. The estimated average liquidus temperature of 1190°C at 1 bar, has three important properties:

1. It appears to be coincidental with the temperatures of eruption (Yoder and Tilley, 1962)
2. With an initial temperature of 1600°C at 30 Kbar and a lowest possible temperature of 960°C at 1 bar, the theoretical range of possible temperatures is 640°C. The temperature interval between the liquidus

temperature at 1 bar and 30 Kbar is 410°C, thus the eruption temperature is within the lower part of the possible range. This relation suggests a process which tends to prevent the extrusion of primitive magmas.

3. The average liquidus temperature of 1190°C is well above the lowest possible temperature range (fig. 1). The composition of predominant tholeiitic magmas is therefore not only dictated by low pressure, but also by a relatively high temperature. The low pressure – high temperature character suggests a control which tends to prevent the ultimate differentiation of ascending magmas.

Four phase proximity control

The generation of magmas depends on the thermal processes in the Earths interior. These processes are governed by the heat generation, which mainly is due to radioactive decay and occurs at a constant rate (Bott, 1971). The spreading of the oceanic bottoms and the high heat flow at the mid-oceanic ridge axes suggest the operation of convective currents in the mantle (Hess 1962, Oxburgh & Turcotte 1968). As the heat generation is constant the convection velocity will tend to be constant. The spreading rates of the Pacific and Atlantic oceanic bottoms have been rather constant since Mesozoic, although the average spreading rates are different, being 4.4 and 1.5 cm/year respectively (Vine 1966, Heirtzler et al. 1968).

The constant velocity of the convection currents results in a constant temperature-depth distribution within the mantle. The partial melting therefore occurs at a contsant rate at a given depth within the mantle, depending on the ascent velocity of the convection current and the composition of the mantle (Turcotte & Oxburgh 1969, Bottinga & Allegre, 1973). The convection velocity is unknown and might not be equal to the spreading rate, but the low heat flow in the main part of oceanic areas and the high viscosity of the upper mantle suggest that the velocity is of the same order of magnitude as the spreading rate (Lee & Uyeda, 1965, Bott 1971). The rate of generation of primary magma is consequently low, and the ascent rate of the primary magma is also low, probably of the same order of magnitude as the spreading rate, i.e. a few centimeters per year.

Estimated temperature-depth distributions indicate an essentially lower temperature for the mantle than for the ascending magmas (Turcotte & Oxburgh 1968, Green & Ringwood 1970). The sinking velocity of crystals in a basaltic magma is about 10^4 cm/year (Wager & Brown 1968), and probably at least two orders of magnitude higher than the ascent rate. Ascending primary magmas will therefore undergo differentiation as soon as they ascend from their generation site. The composition of the magmas

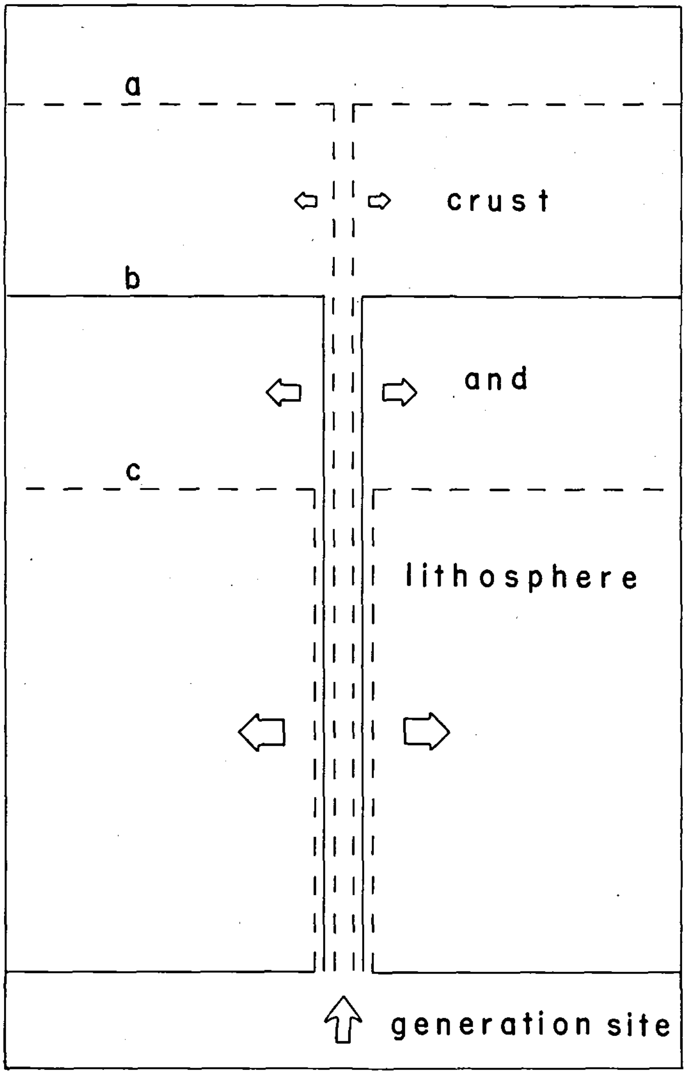

Fig. 2. Relation between spreading rate and thickness of the lithosphere. In case a the spreading rate is relatively low in relation to the generation rate of primary magma, in case b and c progressively higher. The degree of differentiation of erupted magmas will decrease from a to c.

at a given depth will correspond to the prevailing pressure and degree of differentiation during ascend, and they will display four phase proximity throughout most of their ascend. When the ascending magmas reach a high level their composition will display a low pressure four phase proximity. Continuous differentiation during ascent has also been suggested from geochemical considerations and phase relationships by O'Hara (1968).

Temperature and composition control

The total amount of magma solidified above the generation site of primary magma in a given time must always be equal to the amount generated within the same period. The spreading of the two lithosphere plates along the mid-oceanic ridge axes results in an average dilatation of 5–10 cm/year between the plates. The thickness of the lithosphere is determined by the relation, that the average volume of primary magma generated in a given time must be exactly equal to the dilatational volume developed in the same time between the two diverging lithosphere plates. By a given generation rate of primary magma, a fast spreading results in a relatively thin lithosphere, while a slow spreading results in a relatively thick lithosphere (fig. 2). The thickness of the lithosphere is consequently restricted to a specific value, and the composition of the erupted magmas is also restricted. This follows from the relation that an especially high or low degree of differentiation is prevented by the tendency towards a constant thickness of the lithosphere. A relatively thick lithosphere will cause a large degree of differentiation, as the ascending primary magmas undergo a relatively large degree of cooling during a long period of ascent. A thin lithosphere will result in relatively basic erupted magmas. The degree of differentiation of the erupted magmas is therefore related to the thickness of the lithosphere.

The progressive increase in the iron-enrichment ratios of tholeiitic rocks from oceanic bottoms, oceanic islands to the continents may be caused by an increasing ascent distance (O'Hara 1973).

The limited range of compositions of tholeiitic magmas is therefore governed by a constant generation rate of primary magmas and a constant spreading velocity, which in turn results in constant thickness of the lithosphere, and a constant degree of differentiation of the ascending primary magmas.

By an increase in the convection velocity the amount of ascending mantle material brought into the melting region below the lithosphere will increase. The dilatational volume between the two diverging lithosphere plates will also increase, as their spreading velocity is increased by a larger convection velocity. An increase in the convection velocity will therefore result in both a higher rate of partial melting and a larger spreading rate. Provided the relation between the partial melting rate and the dilatation rate is kept constant, the thickness of the lithosphere and the composition of the erupted magmas will remain the same as by a smaller convection velocity. The simultaneous increase in both the generation rate of primary magma and the spreading rate may thus explain why the Atlantic and Pacific oceanic crusts have a similar thickness (Talvani 1965), even although the average spreading rates are different, and why they have apparantly similar average compositions (Cann 1971).

The discussed model may afford an indication of the geophysical relations governing the low pressure – high temperature character of the most frequently erupted magmas. It does not account for the actual composition of the tholeiitic magmas and the thickness of the lithosphere and crust. These features depend on the composition of the mantle, the degree of partial melting and the degree of differentiation of the ascending primary magmas (O'Hara 1968, Cann 1970, Green 1971, O'Hara 1971, Kushiro 1972).

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Dansk sammendrag

Den tholeiitiske bjergartsserie repræsenterer den mest almindelige bjergartsserie i jordens skorpe. Dette forhold sammenholdt med den invariante karakter af olivin til kvarts normative tholeiitiske bjergarter tyder på en generel kontrol af magmadannelse. Kontrollen skyldes dels konvektionsstrømningernes konstante og langsomme bevægelse, og dels en ret konstant kappesammensætning. Kappens konstante konvektionsstrømninger forårsager en konstant spredningshastighed af lithosfæren og en konstant dannelse af primære magmaer. Den konstante spredning af lithosfæren og dannelse af magmaer bevirker at de dannede primitive magmaer stiger op med en konstant hastighed. Magmaerne afkøles og differentieres under deres opstigning, og da deres opstigningshastighed er konstant vil de undergå en konstant grad af differentiation, samtidig med at deres sammensætning bliver invariant. På grund af den konstante grad af differentiation får de extruderede tholeiitiske magmaer en ret konstant sammensætning, samtidigt med at de er fasemæssigt invariante.

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