

The significance of tridymite in igneous and metamorphic petrogenesis.

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1. INTRODUCTION.

PHYSICO-CHEMICAL data clearly show that the presence of tridymite in a rock indicates the prevalence not only of high temperatures, but also of relatively low pressures during the formation of that rock. Whereas many authors (e.g. Shand, 1927; Larsen, 1936) have used tridymite as an indicator of temperature, the importance of tridymite as an indicator of pressure has been largely overlooked.

Although the presence of tridymite is by itself sufficient to enable the pressure, and hence the depth, at which a rock formed to be estimated within certain limits, the presence of tridymite in association with some other pressure- or temperature-indicating mineral allows much closer limits to be set.

2. THE PHYSICO-CHEMICAL DATA.

a. The stability field of tridymite.

Recent and accurate work by Mosesman and Pitzer (1941) permits the calculation, within definite limits of error, of the rates of variation of the inversion temperatures with pressure for the various forms of silica. This calculation is based on the Clausius equation

$$dT/dP = T(\Delta V)/q,$$

where dT/dP is the rate of change of the inversion temperature with pressure; T is the transition temperature on the absolute scale ($^{\circ}\text{K}.$); ΔV is the change in volume during the transition; and q is the heat change involved in the inversion. For the inversion of 1 mole of silica from quartz to tridymite Mosesman and Pitzer found the following values: $T = 867^{\circ}\text{C.} = 1140^{\circ}\text{K.}$; $V = 3.75$ c.c. and $q = 120 \pm 50$ calories; corresponding to which dT/dP lies between the limits 1.476°C. and 0.608°C. per atmosphere increase in pressure, the most probable value being 0.861°C. per atmosphere.

Mosesman and Pitzer's values relating to the transition of tridymite to cristobalite are: $T = 1470^{\circ}\text{C.} = 1743^{\circ}\text{K.}$; $V = \sim -0.1$ c.c.; and

$q = 50 \pm 50$ calories. For this inversion dT/dP lies between the limits $-\infty$ ° C. and -0.0421 ° C. per atmosphere increase in pressure, the most probable value being -0.0842 ° C. per atmosphere; Mosesman and Pitzer state that dT/dP is definitely negative.

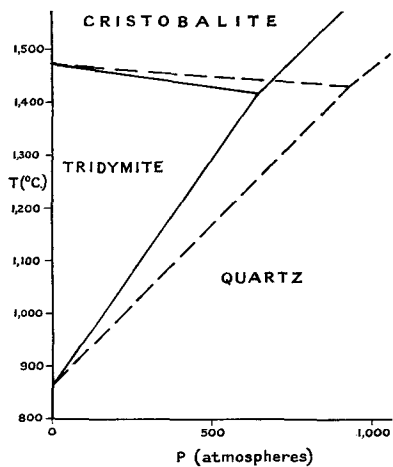


FIG. 1.

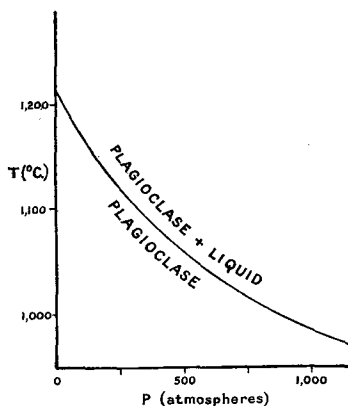


FIG. 2.

FIG. 1. The stability field of tridymite. The phase boundaries shown in unbroken lines are those derived from the most probable values of dT/dP ; those shown in broken lines have been derived from values of dT/dP selected so that the tridymite field reaches its greatest possible extent.

FIG. 2. Curve showing the probable variation in the temperature of incipient fusion of An_{35} with pressure.

Bridgeman's researches (1949) have shown that the values for dT/dP do not vary significantly with considerable increase of pressure; the above data are therefore sufficient to determine the stability field of tridymite. If the most probable values of dT/dP are selected, the quartz-tridymite boundary is the straight line $0.861P - T = -867$ and the tridymite-cristobalite boundary is the straight line

$$0.0842P + T = 1470$$

where P is the pressure and T the temperature.¹ The triple point quartz-tridymite-cristobalite lies at the intersection of these two lines; its co-ordinates are therefore 640 atmospheres and 1415° C. (fig. 1). Below

¹ These equations relate pressure in atmospheres with temperature in degrees Centigrade.

this pressure tridymite can form quartz, above it quartz inverts directly to cristobalite.

If values for dT/dP are selected from the limits given above so that the stability field of tridymite reaches its greatest possible extent, the quartz-tridymite and tridymite-cristobalite boundaries are the lines $0.608P - T = -867$ and $0.0421P + T = 1470$ respectively; the triple point now occurs at 930 atmospheres and 1430°C . A pressure of 930 atmospheres is consequently the greatest possible pressure at which tridymite can form.

b. The variation in the fusion-point of plagioclase in the presence of water vapour with pressure.

The fusion point of albite decreases markedly with increasing pressure in the presence of water vapour (Goranson, 1938). The fusion point curve, at least for pressures greater than 500 atmospheres, has affinities with the curve of the adiabatic expansion of a perfect gas, $PV^\gamma = k$, where P is the pressure, V the volume, γ is the ratio of the two specific heats of the gas, and k is a constant. For pressures less than 500 atmospheres, however, the curve approximates closely to a straight line, $0.310P + T = 1115$.

It is reasonable to assume that the temperature at which the sodic plagioclases commence to fuse in the presence of water vapour will also decrease with increasing pressure. A measure of this decrease can be obtained by comparison of the fusion temperature of albite with the temperature of incipient fusion of the plagioclase, both at a pressure of one atmosphere. For example, at this pressure, plagioclase of composition An_{35} begins to fuse at 1210°C . (Bowen, 1913), that is, 95°C . above the fusion point of albite. It is probable that the curve of the variation of the temperature of incipient fusion of An_{35} with pressure would, at least for relatively low pressures, parallel the fusion-point curve of albite but would, at any particular pressure, be at a temperature approximately 95°C . higher. The curve of the incipient fusion of An_{35} , for pressures less than 500 atmospheres, would therefore be expected to approximate to the straight line $0.310P + T = 1210$ (fig. 2). This curve intersects the quartz-tridymite phase boundary at a pressure which cannot exceed 375 atmospheres and is probably not more than 295 atmospheres (fig. 3).

3. GEOLOGICAL APPLICATION OF THE DATA.

The greatest pressure under which tridymite can possibly form from quartz is less than 930 atmospheres and is probably not more than 640

atmospheres. These pressures would be reached under covers of 3850 and 2650 metres, respectively, of rock of specific gravity 2.5.

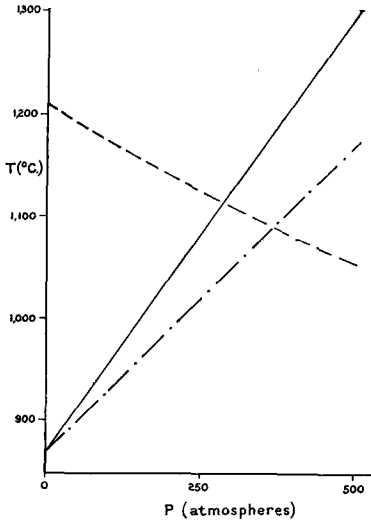


FIG. 3.

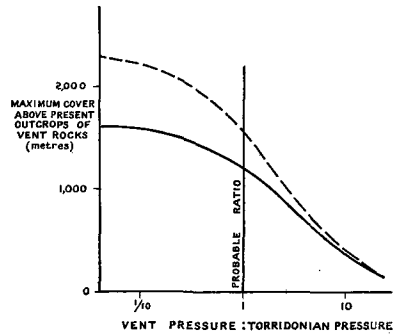


FIG. 4.

FIG. 3. Diagram showing the application of figs. 1 and 2 to the determination of the depth of formation of the present outcrops of the Tertiary vent in eastern Rhum. The solid line represents the most probable quartz-tridymite phase boundary and the dotted and dashed line the limiting position of this boundary (fig. 1). The dashed line is the variation of the incipient fusion point of An_{35} with pressure (fig. 2). If the pressure in the vent equalled that in the surrounding rocks, as appears probable, the pressure-temperature conditions in the vent and its neighbourhood must have fallen within the tridymite field (i.e. to the left of the quartz-tridymite phase boundary) very slightly above the incipient fusion curve of An_{35} . In consequence the maximum pressure cannot have exceeded 385 atmospheres and was probably less than 305 atmospheres, pressures which would be reached under covers of 1600 and 1250 metres of rock of specific gravity 2.5.

FIG. 4. Relation of maximum cover above present outcrops of the vent rocks and the ratio of vent pressure to Torridonian pressure. The solid line has been derived from the most probable tridymite field and the broken line from the greatest possible tridymite field.

Several occurrences of tridymite have been reported from the Tertiary complexes of Scotland. Harker (1950) has described tridymite-bearing hornfelsed sandstones from the aureole of the Rhum complex; Wager (1953b) has reported the existence of a tridymite-bearing granophyre in

the Skye complex; and Wells (1951) has described hypersthene-gabbro containing tridymite-bearing xenoliths from part of the Ardnamurchan complex. The tridymite now exposed in these rock masses must have crystallized at depths which certainly did not exceed 3850 metres and which were probably less than 2650 metres below the then existing surface.

The present author (Black, 1953) has described the occurrence in the east of Rhum of a small area of 'hybrid rocks', resembling marscoite, between Tertiary gabbro and Torridonian sandstone. The Torridonian adjoining the 'hybrid rocks' has been intensely metamorphosed, with the production of abundant tridymite, while the 'hybrid rocks' themselves, interpreted by the author as the metasomatized infilling of a small vent, contain crystals of plagioclase (An_{35}) which have been very slightly fused; from petrological evidence the partial fusion appears to have occurred in the presence of water vapour. The outcrops of rock bearing partly fused plagioclase occur some 10 yards from the nearest outcrops of tridymite-bearing sandstone. The plagioclase crystals could not have been partly fused at a higher level in the vent and then introduced into their present position as this would imply that the vent temperature decreased rapidly with depth; on the other hand, if the fusion were effected at a lower level and the crystals then introduced from below, the estimates of the maximum depth at which the present outcrops of the 'hybrid rocks' formed would have to be correspondingly reduced.

The temperature and pressure in the vent and the adjoining rocks were such as to fall within the tridymite stability field very slightly above the curve of incipient fusion of An_{35} . If the pressures in the vent and in the surrounding Torridonian were equal, as appears to be probable, this curve lies within the tridymite field (fig. 3) only up to pressures which do not exceed 375 atmospheres and are probably no more than about 295 atmospheres pressures which would be reached under covers of 1550 and 1200 metres, respectively, of rock of average specific gravity 2.5. If, however, the pressure in the vent differed from the pressure in the surrounding Torridonian these estimates of the maximum thickness of cover would have to be amended accordingly. The probable and possible maximum thicknesses of cover corresponding to a wide variation in the ratio of the vent pressure to the pressure in the Torridonian are shown graphically in fig. 4. The author considers it probable that the two pressures were approximately equal or that the vent pressure may have been slightly the higher.

The temperature in the vent was slightly greater than that required to produce incipient fusion in An_{35} , and, in consequence, the maximum possible pressure in the vent slightly exceeded the values quoted above, but, owing to the very small extent to which the plagioclase has been fused, the vent pressure, and hence the depth of formation of the now exposed vent rocks, could not have been significantly in excess of these values. The depth at which the presently exposed vent rocks were emplaced cannot therefore have exceeded 1600 metres and was probably less than 1250.

4. CONCLUSIONS.

Important integral members of the Tertiary complexes of Rhum, Skye, and Ardnamurchan were emplaced under covers whose tops were no more than 3850 metres and were probably less than 2650 metres above the present levels of erosion. A small Tertiary vent in the east of Rhum pierced a cover whose top was no more than 1600 metres and was probably less than 1250 metres above the vent rocks seen on the surface today.

The highest rocks preserved of the Rhum complex outcrop a short distance away from, and some 550 metres above, the tridymite-bearing Torridonian. These highest rocks and the gabbro responsible for the metamorphism of the Torridonian and the resultant tridymite form parts of the same rock mass and were presumably emplaced at the same time. The highest rocks now preserved on Rhum were therefore emplaced under a cover which cannot have exceeded 3300 metres and was probably less than 2100 metres. The vent exposures also lie 550 metres below the highest rocks now preserved on Rhum; the highest rocks were therefore not more than 1050 metres and probably less than 700 metres below the surface when the vent was active.

In a diagram accompanying a recent paper, Wager (1953a) shows the highest rocks at present preserved in the Rhum complex to have been at a depth of 8500 metres, this depth being necessitated by the hypothetical differentiation mechanism assumed to account for the rocks. The limiting thicknesses of cover consistent with the physico-chemical data are very much less than those envisaged by Wager.

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