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THE TEMPERATURES OF MAGMAS*

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INTRODUCTION

In the recent literature so much difference of opinion has been expressed as to the temperatures of magmas and even as to whether magmas of basaltic composition have higher or lower temperatures than do those of rhyolitic composition, that a connected attempt to reach as definite a conclusion as possible on the subject, seems highly desirable. Much good evidence, from field and laboratory petrology, from geophysics, and from physical chemistry is now available and some fairly definite conclusions seem possible. I have therefore selected as the subject of my address: *The Temperatures of Magmas.*

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RHYOLITIC MAGMAS HAVE LOWER TEMPERATURES THAN BASALTIC MAGMAS

Many economic geologists and some petrographers still adhere to the belief that rhyolitic magmas have higher temperatures than basaltic magmas. So far as I am aware, the only evidence for this is the fact that basaltic rocks on heating become fluid at lower temperatures than do rhyolitic rocks. However, a careful study of the evidence, mostly petrographic, shows conclusively that the opposite is true and we explain the apparent discrepancy as due to the water and other mineralizers which are in the rhyolitic magma but are not in the rhyolitic rock melted in an open crucible. It has long been known that an obsidian with considerable water becomes fluid before the blowpipe at a rather low temperature but on continued heating it loses its water and thereafter can be made liquid only at a much higher temperature.

Let us consider the crystallization on slow cooling of a magma intermediate in composition between a rhyolite and a basalt yielding a basalt porphyry, or a gabbro porphyry, containing more or less quartz and orthoclase. The study of thin sections of such rocks shows that, with few exceptions, the early crystals to form are calcic plagioclase and dark minerals and, as crystallization proceeds, the feldspar becomes progressively more sodic. The remaining liquid will become poorer and poorer in the material for calcic feldspar and dark minerals and richer in that for quartz, orthoclase, and sodic feldspar. It thus approaches a granodiorite in composition and at some stage reaches that composition. As cooling and crystallization continue plagioclase of intermediate composition and some dark mineral crystallize, finally leaving a liquid with a composition near that of a pegmatitic granite. There can be no doubt but that the original magma with the composition of basalt required a higher temperature to keep it liquid than did the material with the composition of a granodiorite and that the "granitic" material was liquid at a still lower temperature. A study of the whole series of rocks between rhyolite and basalt leads to the inevitable conclusion that rhyolite or granite crystallize at the lowest temperature of the group and that quartz latite or granodiorite, andesite or diorite, and basalt or gabbro crystallize at successively higher temperatures.

A study of the artificial systems similar to the igneous rocks leads to the same conclusion. In the system albite-anorthite-diopside,[1] mixtures rich in anorthite and diopside, which is approximately the composition of basalt, are liquid only at the higher temperatures and as the albite increases in amount and diopside and anorthite decrease, the temperatures of complete liquidity become lower. The mixture with the lowest temperature of liquidity, near 1090°, has approximately the composition; albite 97 per cent and diopside 3 per cent, which is near the composition of a soda syenite.

The theory of magmatic differentiation by crystallization, as advocated by Bowen requires the primary basalt to be the high temperature magma, and, as cooling progresses, crystallization proceeds, followed by separation of the liquid and crystal parts, the liquid part possessing a progressively lower temperature. Hence, the temperatures of magmas are progressively lower from basalt toward rhyolite. Following Bowen, magmas of the alkaline rocks would have still lower temperatures.

The evidence offered by the thermal metamorphism of included fragments or of the wall rock indicates that gabbros have higher temperatures than granites.[2] On the other hand, Lacroix[3] concluded from his classical studies of inclusions that the trachytic rocks, including the related alkaline rocks, had higher temperatures than the basaltic rocks.

SUPERHEAT

Bowen[4] has discussed the problem of superheat and concluded that magmas in general have little superheat. The field and laboratory study of igneous rocks shows that, at least for most lavas and most small intrusions at the time of eruption or intrusion with their intratelluric crystals, this must be true. For larger intrusions, at the time of final emplacement, it must also be true.

If the various rocks are formed through crystal differentiation, the primary basalts might have much superheat but not the later, derived rocks, and this would be true whether differentiation took place through crystallization or assimilation. Locally the magma in the throat of a volcano may be excessively hot due to gas reactions, surface oxidation, etc.

[1] Bowen, N. L.; *Am. J. Sc.*, **XI**, 161–185, 1915.
[2] Schwartz, G. M.; *Journ. Geol.*, **XXXII**, 89–138, 1924.
[3] Lacroix, A.; *Les Enclaves des Roches Volcaniques*, 594, 1893.
[4] Bowen, N. L.; *Jour. Geol.*, **XXX**, 520–3, 1922.
Daly, R. A.; *Igneous Rocks and Their Origin*, p. 210, 1914.

TEMPERATURES OF LAVAS

General Statement[5]

At first, only lavas and near surface magmas will be considered so as to avoid the complications due to pressure. In a later section the modifications required for deep seated magmas will be discussed.

The kind of evidence we can hope to get to determine the temperatures of magmas are:

Direct measurements of flowing lava or of lava lakes.

The melting or inversion temperatures of minerals crystallized from a magma.

The melting or inversion temperatures of minerals included in a magma.

The melting temperatures of mineral aggregates.

The temperature at which a mineral breaks down, a solid solution unmixes, or a reaction takes place.

The effect of the magma on the wall rock or on inclusions.

A study of gas and liquid inclusions.

The temperatures at which rocks melt in the laboratory.

The temperature at which a mixture of the composition of the magma, including mineralizers, melts in the laboratory.

Any point, such as a eutectic on a phase rule diagram.

Direct Measurements

A number of direct measurements of the temperatures of basaltic magmas have been made, chiefly in the lava lakes of active volcanoes, but no such measurements have been made on rhyolitic lavas, as no volcano of such lavas is known to maintain a lava lake or otherwise offer opportunity for measurement of the temperature of the lava. However, should eruptions take place, such as those that formed the broad, low rhyolitic domes of the San Juan Mountains of Colorado, with their wide-spread, thin flows, no doubt quietly erupted; temperature measurements might be made.

[5] Königsberger, J.; *N. Jb. f. Min., B.B.*, **32**, 101–103, 1911.
Bowen, N. L. In Fairbanks, E. E.; *The Laboratory Investigation of Ores*, 172–199, **1928.**
Harker, A.; *Natural History of Igneous Rocks*, 184–189, **1909.**
Daly, R. A.; *Loc cit.*, 375–6.
Von Wolff, F.; *Der Vulkanismus.* Band 1, 34–43, **1914.**
Shands, S. J.; *Eruptive Rocks*, 50–56, **1924.**
Erdmannsdörffer, O H ; *Grundlagen der Petrographie*, 6–8, **1924.**

Older measurements of the surface temperatures of Stromboli, Aetna, and Vesuvius lavas indicate temperatures of about 1000° to 1100° and those for Kilauea about 1200°. For the lavas of Vesuvius, Perret[6] records temperatures from 1000° to over 1200°. In 1911, Perret[7] found the temperature of the lava lake at Kilauea, 30 to 50 centimeters below the surface, to be 1050°. More recently, Jaggar, by forcing iron pipes containing Saeger cones into the lake, found the temperature of the lava to vary with depth. At the surface it was about 1000°, a meter below the surface the temperature decreased to 900°; it then increased to 1170° at the bottom of the lake which was 13 meters below the surface. He considered the high temperature at the surface to be due to surface reactions and that near the bottom to be due to oxidation caused by sinking blocks. He surmised that the temperature of the rising conduit lava was lower than that in the lower part of the lava lake. Individual measurements were as low as 750°.[8]

The temperature of the magma in the lava lake of Kilauea varies as much as 400° depending on depth, escape of gases, and surface reactions, and measurements at Vesuvius vary nearly as much. This is probably also true at other valcanoes and hence surface temperature measurements, as yet, give little data as to the temperature of the magma below the influence of surface agencies. Jaggar's observations show, however, that a basaltic magma may be relatively fluid at temperatures between 750° and 850°.

Melting Temperatures of Minerals

Only a few of the common rock-forming minerals melt within the range of magmatic temperatures and the data offered by melting phenomenon are otherwise indefinite. It can be stated with assurance, that when a mineral crystallizes from a solution the temperature must be below the melting point of the mineral. Thus orthoclase, which melts at about 1170° cannot form above that temperature. It may and probably commonly does crystallize much below that temperature. Likewise albite cannot crystallize above 1100°, nor aegirite above about 950°.

[6] Perret, R. A.; The Vesuvius Eruption of 1906, *Carnegie Inst.*, **1924**, pp. 19, 120, 132.

[7] Perret, R. A.; *Am. J. Sc.*, **36**, 480, 1913.

[8] Jaggar, T. A.; *Jour. Wash. Acad. Sc.*, **VII**, 397–405, 1917; *Am. J. Sc.*, **44**, 214, **1917**.

It must be remembered that most of the rock minerals are solid solutions and the melting phenomenon are somewhat complicated and the melting temperatures differ with the composition.

The melting of an inclusion of a mineral in a magma would, if it took place without reaction so that the resulting liquid had the same composition as the crystal, require a temperature at least as high as the melting temperature of the mineral. However, the melting of orthoclase, quartz, and other inclusions, described in the literature is no doubt mostly due to a reaction between adjacent minerals, between the mineral and a liquid phase, or between the mineral and mineralizers. Such melting can take place at a temperature much below the melting temperature of the mineral.

Melting Intervals of Rocks

On cooling, a rock crystallizes over a temperature interval as is well recognized by our statement of the order of crystallization. In general, the groundmass is the last part to crystallize, and it may and probably does crystallize at a temperature much below the melting temperature of any of the minerals that are in it. This would be true for a dry melt and the mineralizers in the rock no doubt lower the temperature of crystallization still more. Basalt melts at about 984° to 1260° and granite at about 1215° to 1260°.

Because of the mineralizers in the magma, the temperature interval over which it crystallizes will be lower than that over which the rock can be melted in an open crucible in the laboratory.

Inversion Temperatures of Minerals

The inversion temperatures of minerals offer some of the best points on a geologic thermometer, since, where the composition of the crystalline phase does not vary, as in the forms of silica, this temperature is independent of the composition of the liquid phase. Where the crystalline phase forms solid solutions with some of the other constituents, as happens with wollastonite and pseudowollastonite which carry more or less $MgSiO_3$ in solid solution, the temperature of inversion depends on the composition of the crystalline phase.

The various forms of silica give us the best evidence as to the temperatures of magmas. Silica is known in seven crystalline modifications. Three of these are unstable and form only at low temperatures, four have ranges of stability near or within the temperatures of magmas. Low quartz is stable up to 573°, high quartz from 573° to 870°, tridymite from 870° to 1470°, cristobalite from 1470° to 1720°, and glass at a higher temperature.[9]

The inversion from low to high quartz is instantaneous in either direction and all quartz is low quartz below 573° and high quartz above 573°. The quartz-tridymite inversion is also enantiotropic but the rate of inversion at or near the inversion temperature of 870° is very slow and even with a flux, above 870°, quartz first inverts to the unstable form, cristobalite.

Remembering that no case is known in which a form crystallizes from a melt or solution at a temperature above its range of stability but that commonly a form crystallizes at a temperature below its range of stability, we can gain much information as to temperature conditions in magmas from which silica has crystallized. Quartz can crystallize, at atmospheric pressure, only at temperatures under 870°. High quartz will form above 573° but will invert instantly to low quartz on cooling below 573°. Low quartz will form below 573°. Tridymite can form at any temperature below 1470°, and cristobalite can form at any temperature below its melting point at 1720°. In laboratory experiments cristobalite commonly forms before tridymite in the stability range of tridymite.

With a flux, below 870°, tridymite forms before quartz and is recrystallized as quartz slowly. Although for a time when quartz was crystallizing from a magma at atmospheric pressure, the temperature must have been below 870°, should quartz be found that had crystallized from the magma as tridymite or cristobalite and inverted to quartz in the solid state, the crystallization from the magma might have taken place either above or below 870°. Moreover, quartz inclusions in a magma may not be converted to tridymite or cristobalite even though heated for a long time at a temperature considerably above 870°.

On the other hand, the presence of tridymite or cristobalite in a rock gives no indication of the temperature of crystallization as these forms can, and commonly do, form below 870°. In nature, tridymite and cristobalite are common minerals and are formed

[9] Fenner, C. N.; *Am. J. Sc.*, **XXXVI**, 331–384, 1913.
Sosman, R. B.; *The Properties of Silica*, 782–6, **1927**.

chiefly in the gas cavities or groundmass of volcanic rocks and many rocks with these minerals carry quartz phenocrysts. The conclusion seems inevitable that the tridymite and cristobalite formed at temperatures below, and probably considerably below 870°.[10]

The application of these data to lavas leads to some important conclusions. Quartz phenocrysts are among the first constituents to crystallize from many rhyolites, quartz latites, and dacites and from some andesites and basalts. The conclusion seems justified that the rhyolites, quartz latites and dacites crystallize at temperatures below 870° and at least some andesites and basalts crystallize below that temperature also.

A magma of a given composition on cooling must crystallize according to a definite law. But the unknown quantity of mineralizers introduces an uncertainty as to the composition of the magma. For the basalts the variation in nature due to mineralizers is probably not very great and the temperature of crystallization does not vary much. The conclusion seems justified that some and probably most basaltic magmas remain almost completely liquid at temperature below 870°. Since the quartz phenocrysts are mostly intratelluric, they may have crystallized under considerable pressure and a correction—estimated as about 100° for 1000 atmosphere or 2 1/2 miles of cover,[11] must be added to 870°.

The inversion of low-high quartz at 573° gives another important point on the geological thermometer. This inversion takes place very rapidly and all the quartz we see is low quartz but some has been high quartz and has inverted on cooling below 573° to low quartz. Under favorable conditions, it is possible to tell with some assurance that the quartz of a particular occurrence crystallized as, or has at one time been, high quartz.[12]

A study of quartz from a large number of occurrences shows that the quartz phenocrysts of rhyolitic rocks and the quartz of granitic rocks crystallized as high quartz. In the pegmatites

[10] Emmons, W. H. and Larsen, E. S.; Geology and Ore Deposits of the Creede District, Colo., *U.S.G.S. Bull.* **718,** 47–49, 1923.
Rogers, A. H.; *Am. Min.*, **13,** 73–92, 1928.

[11] Bowen, N. L.; *Loc. cit.*, p. 181.

[12] Wright, F. E. and Larsen, E. S.; *Am. J. Sc.*, **27,** 421–447, 1909.
Mügge, O.; *Neues Jb., Festband*, 181–196, **1907.**
Cent. f. Min., 609–15, **1921.**

the quartz that crystallized directly from the magma as graphic granite crystallized as high quartz, while that deposited from hydrothermal solutions formed as low quartz.[13] Since the formation of the pegmatites is a continuous process it might be possible under favorable conditions, to determine at just what stage in the history of the pegmatites the temperature was about 573°.

Mügge[14] has shown that the prismatic quartz in a lava druse from Glade Creek, Wyoming, was formed above 573°.

The conclusion seems to be justified that rhyolitic and granitic magmas and pegmatites crystallize at temperatures above 573°, but that pegmatites do not form much above that temperature.

Temperatures at which Minerals Break Down or Solid Solutions Unmix

The temperature at which soda-potash-feldspar unmix to form microperthite might be helpful if we had sufficient data but this temperature would vary with the composition of the solid solution.

Kozu, Yoshiki, and Kani[15] found that common hornblende from six localities, on heating in nitrogen gas, changed to brown, basaltic hornblende at about 750°.

Kozu and Yoshiki[16] found that brown hornblende dissociated at about 1050° and concluded that the hornblende, in inclusions must not have been heated above 1050°. Such hornblende could not have crystallized from a magma above 1050°.

The Effect on Inclusions

The detailed studies of Lacroix and others[17] on inclusions in basaltic rocks have shown that shales and slates are commonly

[13] Bastin, E. S.; *Geology of the Pegmatites and Associated Rocks of Maine, U.S.G.S. Bull.*, **445**, 36–39, 1911.

[14] Mügge, O.; *Cent. f. Min.*, 593–4, **1922.**

[15] Kozu, S., Yoshiki, B., and Kani, K.; *Science Reports, Tohoku Imp. Univ.*, Ser. III, Vol. **III,** 143–159, 1927.

[16] Kozu, S. and Yoshiki, B.; *Sci. Reports, Tohoku Imp. Univ.*, Ser. III, Vol. **III,** 107–117, 1927.

[17] Lacroix, A.; *Les Enclaves des Roches Volcaniques*, **1893.**
Thomas, H.; *Quart. Jour. Geol. Soc.*, **78,** 230–254, 1922.
Erdmannsdörffer, O. H.; *Fort. der Min.*, **5,** 173–209, 1916.
Richarz, Stephen; *Jour. Geol.*, **32,** 685–9, 1924.
Brouwer, H. A.; *Cent. f Min.*, 41–46, **1918.**
Ramdohr, Paul; *Cent. f. Min.*, 33–36, **1920.**
Collins, W. H.; The Geology of the Gowganda Mining Division, *Canada Geol. Surv., Mem.* **33,** 78, 1913.

more or less melted, biotite is usually melted, orthoclase less commonly, and even quartz in some rocks. Granite or arkose inclusions may show some melting, especially at the contacts of the quartz and orthoclase, and Lacroix and Richarz have described granite melted to a vesicular glass.

Before applying these facts we must distinguish clearly between simple fusion, in which the liquid has the same composition as the crystals, and melting by reaction between adjacent minerals or between a mineral and a liquid or gas, in which case the liquid has a different composition from the crystals. For the partly melted quartz inclusions in basalt the liquid is in some cases reported as having minute crystals of sillimanite and other minerals showing clearly that it is not pure SiO_2. Furthermore, Fenner states, "finely ground quartz heated 108 hours at 1250°, showed only a small percentage of inversion (to cristobalite). After 90 hours at 1360° the product consisted of about two-thirds cristobalite and one-third unchanged quartz. At 1570° the reaction is nearly complete in an hour."[18] Silica glass inverts still more rapidly and at lower temperatures. It would seem certain that a fragment of quartz imbedded in a magma and protected from reaction at about 1600°, near its melting point, might be partly or completely fused but before cooling both the quartz and the glass would be converted to cristobalite or possibly further to tridymite. It is possible that below 870° quartz would again be formed but it should show clear indications of the inversion which would have taken place in the solid state and involves a large decrease in volume. I know of no well established case in which tridymite or cristobalite has formed at a high temperature and been inverted to quartz on cooling without a flux. Both minerals persist when once formed as the rates of inversion at temperatures near 870° without a flux are nearly zero.

It therefore seems certain that inclusions of quartz that are partly melted to glass, have melted by reaction and that the temperature must have been much below the melting temperature of quartz. Moreover, it seems probable that the magma should act as a flux on included quartz grains and that, if the temperature was much above 870°, the quartz would be either dissolved or inverted to tridymite.

[18] Fenner, C. N.; *Am. J. Sc.*, **36**, 359, 1913.

The melting of orthoclase and other minerals is probably also largely by reaction.

Biotite melts or decomposes within the range of the temperatures of magmas. Lacroix states that biotite is commonly melted, and melted or decomposed biotite has been described by Richarz, Ramdohr, Goldschmidt, and others. Unaltered biotite is also common in igneous rocks as an early mineral to crystallize and in inclusions. Biotite may, therefore, be expected to yield important data on the temperatures of magmas. Day and Allen[19] found that the biotite of a dense glassy andesite from Lassen Peak when heated in a neutral atmosphere, persisted fairly well at 850°, but with further rise in temperature it showed increasing decomposition. They concluded that "this lava could not have been heated above 850° at any time after it approached the surface."

Inclusions of granite and arkose in many cases show no fusion but in others they are more or less fused. Sosman and Merwin[20] found that an arkose inclusion in Palisade diabase showed no fusion. As this arkose was half fused after heating in the laboratory at 1150° they concluded that the temperature of the diabase was under 1150°. From the partial fusion of granite inclusion Knopf[21] concluded that a basalt in Inyo County, California, had a temperature of 1025° if no water was present but with water was much lower.

Rarely quartz inclusions are associated with tridymite or cristobalite. For inclusions in basalt Lacroix[22] found tridymite and cristobalite always associated with gas cavities and he concluded that they required mineralizers for their formation. Brouwer[23] has described similar associations from Sumatra, Ramdohr[24] from Germany, and Thomas[25] from the Isle of Mull. They resemble the tridymite and cristobalite in the gas cavities of lavas which were crystallized as unstable forms below 870°.

[19] Day, A. L. and Allen, E. T.; *The Volcanic Activity and Hot Springs of Lassen Peak*, p. 49, 1925.

[20] Sosman, R. W. and Merwin, H. E.; *J. Wash. Acad. Sc.*, **3**, 389–395, 1913.

[21] Knopf, Adolph; A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada, California, *U S.G.S.*, **75**, p. 110, 1918.

[22] *Loc. cit.*, pp. 520–1.

[23] *Loc. cit.*, p. 44.

[24] *Loc. cit.*

[25] *Loc. cit.*, pp. 239–240.

Lacroix[26] found quartz inclusions in trachytic rocks more often transformed to tridymite or cristobalite than in basaltic rocks and in one rock it was inverted to a mass of tridymite much like that produced artificially by heating quartz. For this inversion the temperature must have been above 870° and probably much above. In other rocks quartz remnants are surrounded by tridymite with some interstitial glass. Lacroix concluded that the temperatures of trachytic rocks were higher than those of basaltic rocks.

Lacroix[27] has shown that interstitial quartz in lavas may result from the inversion of original tridymite. Geijer[28] concluded that reticulated quartz is derived from the inversion of tridymite. Hawkes[29] has described quartz paramorphs after tridymite from Iceland; and Rogers[30] from California. Thomas[31] described tridymite in inclusions in basalt from the Isle of Mull that have reverted to quartz. Lacroix[32] described tridymite in cavities in an inclusion from Vesuvius that is partly inverted to quartz. In any of these cases the tridymite might have formed as an unstable form below 870°. The evidence for the inversion of tridymite to quartz without a flux must be very strong before we accept it, as the rate of inversion without a flux is near zero and it has not been possible to bring it about in the laboratory.

Wollastonite is stable at atmospheric pressure only below 1180° and above that pseudowollastonite is the stable form. The presence of MgO will raise this inversion temperature. Inclusions of limestone with wollastonite are rather common at igneous contacts, yet pseudowollastonite has never been found in nature. The conclusion seems justified that temperatures above 1180° are exceptional.

Goldschmidt[33] has constructed a temperature pressure diagram for the reaction $SiO_2+CaCO_3 \rightleftarrows CaSiO_3+CO_2$ but the accuracy

[26] *Loc. cit.*, p. 600.
[27] Lacroix, A.; *Le Montagne Pélee après sés Eruptions*, 52–58 **1908.**
[28] Geijer, Per; *Geol. Fören Förhandl.*, **XXXIV**, 1 pp. 51–80 1913.
[29] Hawkes, Leonard; *Geol. Mag.* **3**, 205–208, 1916.
[30] Rogers, A. F.; *Am. Mineral.*, **13**, 85, 1928.
[31] *Loc. cit.*, pp. 239–240.
[32] Lacroix, A.; *Bull. Soc. Min. France*, **31**, 334–8, 1908.
[33] Goldschmidt, V. M.; Die Gesetze der Gesteinsmetamorphose, *Vid. Skr. Math.-naturv. Klasse*, No. **22**, 1912.

of the curve has been questioned by Boydell[34] and Bowen[35]. Moreover, in the application of this curve to the metamorphism of a limestone, the effective pressure need have little relation to the weight of the load of rock as the carbon dioxide is able to escape and it seems probable that the rate of the reaction depends partly on the rate of escape of the CO_2.

Under a pressure of one atmosphere calcite breaks down to CaO and CO_2 at a temperature of 910°. The temperature of decomposition increases rapidly with pressure and is 1100° at a pressure of 20 atmosphere. This reaction may, for some inclusions, give a clue to the temperature of the magmas.

Fluid Inclusions

Estimations of the temperatures of magmas by measuring liquid and gaseous inclusions have as yet yielded no satisfactory data.[36]

TEMPERATURES OF DEEP SEATED MAGMAS

The deep seated magmas, which consolidated to form the great batholithic masses exposed to our view by erosion, at the time they reached their final position of consolidation, probably had about the same temperatures as the near surface magmas of the same composition. The effect of pressure should be to raise the temperature of crystallization but a greater content of mineralizers would tend to lower it. Some of the very deep magmas and in particular the primary basalt might have a much higher temperature. Indeed, the temperatures of plateau basalts may be much higher.

Most of the points on the geologic thermometer would have to be corrected for pressures. For the inversion low quartz–high quartz, the temperature of inversion is raised to 644° at a depth of ten kilometers.[37] For the inversion quartz-tridymite, Bowen calculated the increase in inversion temperature about 100° for a depth of four kilometers.

[34] Boydell, H. C.; Operative Causes in Ore Deposition, *Institution of Mining and Metallurgy, London*, 16–22, 1927.

[35] *Loc. cit.*, pp. 190–1.

[36] Sorby, H. C.; *Quart. Jour. Geol. Soc.*, **XIV**, 453–500, 1858.
Nacken, O.; *Cent. f. Min.*, 10–20 and 35–43, 1921.
Bowen, N. L.; *Loc. cit.*, pp. 192–3.

[37] Gibson, R. E.; *Jour, Phys. Chem.*, **32**, 1197–1205, 1928.

CONCLUSION

Let us assemble the evidence as to the temperatures of magmas.

1. Rhyolitic magmas have lower temperatures than basaltic magmas.
2. Direct measurements of temperatures at volcanoes give less satisfactory data than might be expected. Measurements of the basaltic magmas at Kilauea vary from 750° to over 1200°, those at Vesuvius vary nearly as much.
3. The melting temperatures of minerals that have crystallized from a magma yield only *maximum temperatures*. Some biotites must form below 850°.
4. The inversion temperatures of silica show that some basalts and most rhyolites and quartz latites are nearly completely liquid at temperatures below 870° and probably all magmas crystallize above 573°.
5. Common hornblende inverts to basaltic hornblende at a temperature of 750°. Hence most hornblende rhyolites and quartz latites, and many andesites crystallize below that temperature.
6. Since the inversion of quartz inclusions to tridymite or cristobalite is very rare, and this inversion takes place without a flux at an appreciable rate at 1250°, very few magmas have so high a temperature.
7. The lack of fusion of most granitic and arkose inclusions indicates a temperature below about 1150° but partial or complete fusion might take place at a much lower temperature in the presence of mineralizers—even the mineralizers in the crystallized granite or arkose.

The conclusions seem to be justified that some basaltic magmas have temperatures below 870°, many are below 1000°, very few are as high as 1260°, and probably most are not far from 800° to 900°. Rhyolitic magmas have lower temperatures. All are above 573° and below 870°. Nearly all are below the temperature of decomposition of biotite, about 850°, and that of common hornblende, about 750°. Probably most rhyolitic magmas have temperatures in the neighborhood of 600° to 700°.