EVIDENCE ON THE INTRUSION-TEMPERATURE OF PERIDOTITES.

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ABSTRACT.

Experiments in heating a coke inclusion from a peridotite dike in Fayette County, Pennsylvania, and chemical analyses of the same inclusion for hydrogen, oxygen, and nitrogen, agree in indicating that the maximum temperature reached by the coke was between 440 and 520° C. The intrusion-temperature of the peridotite could hardly have exceeded 600°. How a rock of peridotitic composition could have been intruded at so low a temperature remains to be determined by laboratory experiment.

INCLUSIONS AS A SOURCE OF EVIDENCE.

An igneous dike or sill is sometimes found intersecting a sedimentary rock in such a way as completely to inclose small fragments of the sedimentary. Such an occurrence offers an opportunity to obtain information on the temperature of the igneous rock at the time of its intrusion, as can be shown by the following reasoning. If the included fragment is small compared with the width of the dike, and particularly if there is no evidence of a chilled border phase surrounding the inclusion, it is reasonable to assume that the fragment soon attained, completely or very nearly, the temperature of the igneous rock itself. This is not true of the wall rock bordering the dike, because there is a continuous flow of heat across the boundary into an indefinitely large volume of rock at a lower temperature, resulting in the setting up of a temperature gradient, as can be readily recognized by inspection of such an occurrence. The heat that flows into the inclusion, on the contrary, all goes to raise the temperature of the inclusion nearer and nearer to the temperature of its surroundings, since there is no "sink" into which the heat can flow. To obtain information on the temperature, then, it is necessary only that the included sedimentary material be of such character that the results of heating it at various temperatures can be later recognized and differentiated.

Using this principle, Sosman and Merwin[1] investigated arkose and shale inclusions in the Triassic diabase of the

[1] Sosman, R. B., and Merwin, H. E.: Data on the intrusion temperature of the Palisade diabase, J. Wash. Acad. Sci., 3, 389-395, 1913.

Palisades of New Jersey. The inclusions showed no evidence of having been melted, even when examined in section under the microscope. When heated in a laboratory furnace, the material of the arkose inclusions was not melted at 1023° C., but was more than half melted at 1150°. The arkose inclusions, then, have never reached 1150° after being caught up and surrounded by the diabase. The diabase must therefore have been at a temperature lower than 1150° when it was still fluid enough to permit included fragments to float up into the intrusive sheet.

Further study of the diabase itself brought out that although it showed evidences of a beginning of melting at 1150°, the action ceased with the formation of a small amount of liquid, and the rock had to be heated to 1225° before enough liquid was formed to permit it to flow. Yet the properties of the inclusions, as just shown, indicate that the diabase must have been fluid below 1150°. The authors suspected that volatile constituents of the diabase magma, now absent from the crystallized rock, had lowered its original temperature of liquefaction to some unknown value below 1150°.

Similar experiments, unfortunately not accompanied by microscopic examination, have been made recently by von Wartenberg[2] on inclusions of slate and sandstone in nepheline-basalt at Wolfshagen, near Kassel, Germany. Heated in an electrical resistance furnace, the slate melted and bloated at 1260°, and had evidently never reached this temperature when in the basalt. The basalt itself melted fairly sharply at 1220°. In contrast with the Palisades occurrence, then, the Wolfshagen slate and basalt set consistent upper and lower limits to the temperature of intrusion, namely 1260° and 1220°.

INCLUSIONS IN PERIDOTITE.

An opportunity for a similar study of a peridotite is found in the rather unusual association of an igneous dike with beds of coal in western Pennsylvania. In Fayette County, in the southwestern corner of the State, a peridotite dike several feet in width cuts the Pittsburgh and Waynesburg coal seams. This dike, first described by Kemp and Ross,[3] is now accessible

[2] Wartenberg, Hans v.: Ueber die Stabilität eines Tonschiefer-Einschlusses in Basalt, Nachr. Ges. Wiss. Göttingen, Fachgruppe IV, 1, 119-121, 1935.

[3] Kemp, J. F., and Ross, J. G.: A peridotite dike in the Coal Measures of southwestern Pennsylvania, Annals New York Acad. Sci., 17, 509-518, 1907. Preliminary announcement by Kemp, Bull. Geol. Soc. Am., 17, 691, 1907.

in a coal mine, the Gates Mine of the H. C. Frick Coke Company, a subsidiary of the United States Steel Corporation. I was interested to learn recently from W. O. Hickok, who was doing geologic mapping in Fayette County at the time, that he had found fragments of the Pittsburgh coal included within the peridotite. Mr. Hickok was kind enough to send me one of these specimens (No. 467B) on which a part of the experiments described below were made. I subsequently visited the mine and secured specimens of the dike rock, the bordering coke, and the unaltered coal.

Mr. Hickok's specimen was about 8 x 12 cm. in section, somewhat rounded. It lay within 6 inches (15 cm.) of the western wall of the dike, at a place where the dike was 4 to 5 feet in width. The bordering peridotite showed some effects of cooling in a slight refinement of the grain size.

EXPERIMENTS ON INCLUDED COAL.

A program of laboratory tests on some commercial electric furnace controllers offered an incidental opportunity to try the effect of long-continued high temperatures upon the Fayette County coal inclusions. Small angular fragments of the coal inclusion, 1 to 2 mm. in diameter, were sealed in evacuated Pyrex glass tubes of 4 mm. inside diameter. Some of the specimen tubes were 6 cm. long; such a tube, when placed inside an Alundum boat at the middle point of the platinum-wound electric resistance furnace, 29 mm. inside diameter, were uniform in temperature within about 10 or 15° C. Other specimen tubes were 22 cm. long; such a tube, when the end containing the coal specimen was placed at the middle of the furnace, projected a few centimeters into the outside atmosphere.

The results of these experiments, which turned out unexpectedly definite, are shown in Table I. No change whatever could be observed in the fragments until a certain fairly well defined temperature was attained, whereupon the tube became coated inside with a deeply colored distillate of tar.

The experiment is not complete without a parallel test of the unaltered coal. No specimen being available, I had to wait about a year until there was opportunity to visit the locality and secure a specimen from the Gates Mine. Specimens of the Pittsburgh coal were secured about 100 feet from the dike, at

TABLE I.

Effect of Laboratory Heating on Coal that Has Been Included in and Altered by Peridotite.

Specimen No. 467 B.

Sub-Specimen	Temperature, °C.	Time hours	Tube Length cm.	Effects
a	68-84	17	6	Appearance unchanged.
a	111-120	20		Appearance unchanged.
a	187-206	22		Appearance unchanged.
a	299-320	87		Appearance unchanged.
a	463-480	20		Appearance unchanged.
a	612-617	21		Tube coated inside uniformly with brown transparent coating.
d	511	½	22	Drops of colorless liquid (water?) condense in colder end of tube.
d	504-519	½		Drops colored light brown.
d	502-510	141		Light brown coating in first 2 cm. of tube.
d	556-563	45		Deep brown transparent coating over inside of hot part of tube.
d	563-575	168		Coating deeper color, fragments not fused.
b	643-654	140	6	Tube exploded, coal destroyed.

a cross section where the dike was about three to five feet wide and where its contact effects could not be observed for a distance of more than one foot into the coal. Tests of this unchanged coal were made in a sealed evacuated Pyrex tube in the controlled furnace, with the results shown in Table II. It is evident that the coal begins to distil at least 200° below the

TABLE II.

Effects of Laboratory Heating on Unmetamorphosed Coal. Specimen No. 517d. Tube 22 cm. long.

Temperature, ° C.	Time hours	Effects
149	17	Unchanged.
192-205	71	Barely visible brown color in tube.
247-249	70	Some surfaces a little cracked and roughened.
268-271	19	Cloud of small colorless drops at cold end.
269-274	70	Ring of drops of light brown tar at cold end.
354-359	8	Orange-yellow tar distillate forms.

temperature at which the natural coke first gave a tarry distillate.

The results set forth in Tables I and II indicate that the coal included in the dike has been previously heated to at least

480° C., but has never been heated to 550° C. From these results its probable upper temperature may be placed at 520° ± 30° C.

ANALYSIS OF INCLUDED COAL.

In looking about for some other method of estimating the temperature to which the included coal had been heated, I learned of H. H. Lowry's experiments on the effect of temperature on residual hydrogen in coals, charcoals, and similar products formed by the thermal decomposition of compounds of carbon, hydrogen and oxygen. Lowry's published data[4] show remarkably consistent correlation between the percentage of hydrogen (on an ash-free basis) and the temperature.

Subsequent investigations, not yet published, and also an analysis of the large amount of data available in the publications of the United States Bureau of Mines, confirm the correlation of residual hydrogen with temperature and extend it to residual oxygen and nitrogen. It would appear that a carbohydrate breaks down into a structure of carbon atoms which has a fairly definite set of available spaces for hydrogen, oxygen, and nitrogen atoms, and these available openings decrease in number in a definite way with increasing temperature.

Doctor Lowry was kind enough to offer to have an analysis made of the inclusion from Fayette County, in the Coal Research Laboratory of the Carnegie Institute of Technology in Pittsburgh, of which he is the Director. The analysis was made by Mr. Frank C. Silbert, with the results shown in Table III. The percentages are calculated to a dry basis, the sample having 0.36 per cent moisture as received.

TABLE III.

Composition of Coal Inclusion from Peridotite.

Fayette County, Pa.

Carbon	72.12
Hydrogen	3.98
Nitrogen	1.69
Sulfur	0.82
Ash	17.32
Oxygen, by difference	4.07
	100.00

[4] Lowry, H. H.: The significance of the hydrogen content of charcoals, J. Phys. Chem., 33, 1332-1342, 1929.

Doctor Lowry's estimate of the maximum coking temperature from the analysis given in Table III is as follows:

From hydrogen	450° ± 10°
From oxygen	440° ± 20°
From nitrogen	410° ± 70°

He remarks in a letter: "I may confess that I was somewhat surprised at the excellent agreement of estimating temperatures from these three elements." The agreement with the value 520° C., that had previously been reached from my crude distillation tests described in Table I, is even more surprising.

DISCUSSION.

The geochemical puzzle posed by these results is this: Peridotite is an orthosilicate rock, consisting mainly of the orthosilicates of magnesia, lime, and ferrous iron, $2MgO.SiO_2$, $2CaO.SiO_2$, and $2FeO.SiO_2$ (forsterite, di-calcium silicate, and fayalite, respectively). No such orthosilicate mixture has been observed in the laboratory to melt lower than 1093° C.[5] Yet here is evidence that a peridotite magma has penetrated long distances into sedimentary rocks while it was at a temperature in the neighborhood of 500°.

Many specimens of these peridotites from western Pennsylvania, western New York, and Kentucky show a considerable proportion of carbonate. This is true of the specimens that I collected in the Gates Mine. This carbonate has often been assumed to be a result of weathering but Honess and Graeber[6] have shown, by examination of a similar occurrence, that some of the carbonate may be primary, while the greater part of it may be interpreted as the result of hydrothermal alteration immediately following the intrusion. Dikes even higher in carbonate than these are regarded by Daly[7] as true magmatic intrusions.

Hess[8] has summarized the characteristic relations of the serpentinized low-temperature peridotites, and concludes: "The

[5] Bowen, Schairer, and Posnjak: This Journal, 26, 193-284, 1933; Bowen and Schairer, ibid., 29, 151-217, 1935.

[6] Honess, A. P., and Graeber, C. K.: Petrography of the mica peridotite dike at Dixonville, Pennsylvania, Penn. State Coll. Mining & Met. Exp. Sta., Bull. No. 2, 16 pp., 1926.

[7] Daly, R. A.: Carbonate dikes of the Premier Diamond Mine, Transvaal, J. Geol., 33, 659-684, 1925.

[8] Hess, H. H.: A primary ultramafic magma, Trans. Am. Geophys. Union, 18, Pt. I, 247-249, 1937.

relatively low temperature of this peridotite magma is difficult to account for though its demonstrated high water-content is probably the cause."

Bowen and Schairer[9] have considered the similar problem of dunite and related mono-mineralic rocks, showing that an intrusion-temperature approaching 1900° C. would have been necessary to emplace some of them as dry melts. Such a temperature is impossibly high when the character of the contact metamorphism is considered. These authors hesitate, however, to admit the presence of the large amount of water that would be needed to lower the temperature of liquidity to something reasonable.

Everyone has been assuming that the intrusive rocks under consideration were originally liquid magmas, either homogeneous liquids or liquids carrying crystals in suspension. The evidence on temperature makes such hypotheses improbable. The only remaining choice seems to be the hypothesis of a hot, plastic stiff mud. The ceramist is familiar with the artificial intrusion of clay mixes containing relatively little water, especially when certain organic chemicals are added that have a specific plasticizing effect. What is needed is, first, crystals of the right shape, and second, thin films of lubricating liquid separating these crystals, films sometimes only one or two molecular diameters in thickness. Such films, when consisting of water or water solutions, can be heated far above the boiling point without developing enough vapor pressure to escape rapidly.

It may be necessary, then, to give up our familiar concepts drawn from experience with flowing lavas, molten glasses, and fluid furnace siags, and go over to the concept of a mass of crystals lubricated by very thin films of a liquid which is not a silicate melt but is simply water or a water solution at a temperature far below the melting temperature of any rock constituent or system of constituents.

[9] Bowen, N. L., and Schairer, J. F.: The problem of the intrusion of dunite in the light of the olivine diagram, Rept. XVI, Intern. Geol. Congress, 1933, Washington, pp. 391-396, 1936.