BAKED SHALE AND SLAG FORMED BY THE BURNING OF COAL BEDS

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By G. Sherburne Rogers.

INTRODUCTION.

The baking and reddening of large masses of strata caused by the burning of coal beds is a striking feature of the landscape in most of the great western coal-bearing areas. The general character and broader effects of the burning have been described by many writers,[1] but the fact that in places enough heat is generated to fuse and thoroughly recrystallize the overlying shale and sandstone has received less attention. Some of the natural slags thus formed simulate somewhat abnormal igneous rocks, but others consist largely of rare and little known minerals. A wide range in the mineral composition of such slags is to be expected, depending on the composition of the original sediment and the conditions of fusion and cooling. These products of purely thermal metamorphism offer a fertile field for petrologic investigation.

The writer has observed the effects produced by the burning of coal beds in several localities in Montana, particularly along upper Tongue River in the southern part of the State, in the district lying southeast of the mouth of Bighorn River, and in the Little Sheep Mountain coal field north of Miles City. A number of specimens of the rock formed have been examined under the microscope, though time has not been available for a systematic examination. The writer is greatly indebted to Mr. E. S. Larsen for assistance in the study of some of the minerals.

CAUSES OF BURNING.

Most writers on the burning of coal beds have attempted to explain the mode of their ignition, which they usually ascribe to lightning, to prairie or forest fires, to the agency of man, or to spontaneous combustion. All these agencies have probably been effective in one place or another.

Lightning has doubtless ignited some beds, especially those exposed on the higher hills, but it is apparently inadequate to account for the burning of beds over great areas. There are also well-authenticated reports of the ignition of beds by prairie fires,[2] but it may well be doubted whether this agency has often been effective in the sparsely grassed badlands, where burning is so common. Similarly, the writer knows of one locality in which a bed of coal 11 feet thick was ignited by the camp fires of a round-up outfit, but much of the burning evidently took place many thousands of years ago and some of it probably dates back to Pleistocene time.[3] Ignition from an extraneous source is perfectly possible and may be the most plausible explanation in any given instance, but the fact that burning on the outcrop is so common as to be actually characteristic of the coal beds over an area greater than 200,000 square miles indicates a more widespread mode of origin and one less dependent on special local conditions.

Ever since coal first became widely used as fuel the possibility of its spontaneous combustion has been recognized. Disastrous fires have started through spontaneous combustion in mines, many others at the surface in piles of

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[1] Allen, J. A., Metamorphism produced by the burning of lignite beds in Dakota and Montana territories: Boston Soc. Nat. Hist. Proc., vol. 16, p. 246, 1874. See also Lewis, Meriwether, and Clarke, William, History of the expedition under the command of Lewis and Clarke, vol. 1, pp. 180, 189, Philadelphia, 1814; Hayden, F. V., Geological report of the exploration on the Yellowstone and Missouri rivers, pp. 56–103, 1869; and Dawson, G. M., Report on the geology and resources of the region in the vicinity of the forty-ninth parallel, pp. 164–169, Montreal, 1875.

[2] Allen, J. A., op. cit., p. 261.
[3] Idem, p. 258. Also Collier, A. J., and Smith, C. D., The Miles City coal field, Mont.: U. S. Geol. Survey Bull. 341, p. 45, 1909.

culm or slack coal, and others in stocks of coal held in storage or undergoing shipment, especially at sea. Because of its economic importance the phenomenon has been carefully studied by many observers, and although there is considerable disagreement as to detail the main determining conditions have been well outlined. Thus, it is generally recognized that only coals that contain a moderate to high proportion of volatile matter are subject to spontaneous combustion; that the more finely divided the coal the more liable it is to ignite; and that a small increment of heat from an outside source is an important contributing cause.

Most of the coal in the Western States that has burned at the outcrop is of lignitic or subbituminous grade; this coal when exposed to the air loses moisture and tends to slack or crumble to fragments. All freshly mined coal absorbs oxygen and according to Lewes [1] may, if in fairly small fragments, absorb two to three times its own volume. This absorption of oxygen takes place at ordinary temperatures but proceeds more rapidly at higher temperatures, and as the process itself generates some heat it is self-accelerating. The heat first generated may be due merely to the compression of the gas, but a slow oxidation of resins or unsaturated hydrocarbons in the coal, with the formation of humic or other acids, probably soon begins. The elaborate experiments of Parr and Kressmann [2] indicate that this reaction assumes positive activity at about 80° C. With rise in temperature the occluded oxygen becomes more active, combining with certain hydrocarbons and converting them to carbon dioxide and water. According to Parr and Francis [3] this reaction begins only when the coal becomes heated to 120° to 140° C., but it represents a critical stage in the process of oxidation, for so much heat is generated that the temperature thereafter rises rapidly. At a little over 200° C. autogenous oxidation begins and at 350 to 450° C. actual ignition takes place.

According to experiments by Fayol,[4] however, coal in a state of fine dust ignites at a much lower temperature, gas coal igniting at 200° C. and lignite at 150° C.

The oxidation of pyrite or marcasite in the coal was once considered the chief cause of spontaneous combustion, but it is now known that coals practically free from iron sulphides may spontaneously ignite. Some authorities therefore hold that the influence of pyrite is negligible and that at the most it merely increases the general rise in temperature and by swelling splits up the coal, thus exposing fresh surfaces to the action of atmospheric oxygen.[5] Parr and Kressmann find, however, that the oxidation of pyrite in the presence of moisture results in a distinct increment of heat, and as this reaction takes place at ordinary temperature they believe that it is one means by which the mass is heated to the point at which active oxidation of the coal itself commences. They state that the oxidation of one-fifth of the pyrite in a coal containing 6 per cent generates sufficient heat to raise the temperature of the mass 70° C., assuming no loss by radiation.[6] As the conductivity of coal is very low compared with that of the surrounding rocks, according to figures given by Prestwich,[7] it seems probable that loss of heat by radiation is slow and that small amounts of heat generated within the coal may well be conserved to produce far-reaching results.

It is generally recognized that the presence of moisture favors spontaneous combustion.[8] In fact, Dennstedt and Bünz,[9] as a result of experiments, conclude that "self-ignition increases in a ratio corresponding to the amount of moisture [water of constitution] in air-dry coal." Opinions differ, however, as to whether its action is chiefly mechanical, catalytic, or chemical. It is also known that inflammable gases are occluded in coal, and though it may be doubted that these gases are the direct cause of spontaneous combustion it is evident that if the coal is heated by oxidation to the temperature at which these gases can unite with atmos-

[1] Lewes, V. B., The carbonization of coal, p. 23, London, 1912. See also Parr, S. W., and Barker, Perry, The occluded gases in coal: Illinois Univ. Eng. Exp. Sta. Bull. 32, 1909; White, David, The effect of oxygen in coal: U. S. Geol. Survey Bull. 382, pp. 63–71, 1909; and Chamberlin, R. T., Notes on explosive mine gases and dusts: U. S. Geol. Survey Bull. 383, pp. 15, 60, 1909.

[2] Parr, S. W., and Kressmann, F. W., The spontaneous combustion of coal: Illinois Univ. Eng. Exp. Sta. Bull. 46, pp. 24, 52, 1911.

[3] Parr, S. W., and Francis, C. K., The modification of Illinois coal by low temperature distillation: Illinois Univ. Eng. Exp. Sta. Bull. 24, 1908.

[4] Fayol, Henri, Études sur l'altération et la combustion spontanée de la houille exposée à l'air: Soc. ind. min. Bull., 2d ser., vol. 8, pt. 3, 1879.

[5] Lewes, V. B., op. cit., pp. 21–22.

[6] Parr, S. W., and Kressmann, F. W., op. cit., p. 34.

[7] Boulton, W. S., Practical coal mining, vol. 2, p. 331, London, 1907.

[8] Parr, S. W., and Kressmann, F. W., op. cit., p. 52.

[9] Dennstedt, M., and Bünz, R., Die Gefahren der Steinkohle: Zeitschr. angew. Chemie, vol. 21, pp. 1825–1835, 1908.

pheric oxygen they may become an important contributing cause. Penhallow [1] believes that the burning of lignite beds is caused by the spontaneous ignition of escaping gases, particularly sulphureted hydrogen, carbureted hydrogen (methane ?), and phosphureted hydrogen.

Analyses of lignite and coal from Montana and Wyoming.

Made at the Pittsburgh laboratory of the Bureau of Mines; F. M. Stanton and A. C. Fieldner, chemists in charge.]

	10898	6469	17711	8465	14755
SAMPLE AS RECEIVED.					
Proximate:					
Moisture..........	42. 8	26. 8	22. 6	29. 4	19. 8
Volatile matter....	25. 7	32. 8	31. 9	25. 4	30. 7
Fixed carbon......	26. 9	27. 9	39. 5	38. 8	35. 2
Ash..................	4. 6	12. 5	6. 0	6. 4	14. 3
Sulphur.............	. 24	. 64	. 51	. 37	1. 50
Ultimate:					
Hydrogen..........	7. 21	6. 04	......	......	......
Carbon............	36. 21	42. 72	......	......	......
Nitrogen...........	. 62	. 60	......	......	......
Oxygen............	51. 08	37. 53	......	......	......
British thermal units ..	6, 110	7, 340	8, 811	7, 170	8, 579
Loss of moisture on air drying................	35. 3	20. 5	3. 7	19. 3	8. 5
AIR-DRIED SAMPLE.					
Proximate:					
Moisture..........	11. 6	7. 9	19. 6	12. 5	12. 3
Volatile matter......	39. 7	41. 3	33. 1	31. 4	33. 5
Fixed carbon......	41. 5	35. 1	41. 1	48. 1	38. 5
Ash.................	7. 2	15. 7	6. 2	8. 0	15. 7
Sulphur.............	. 37	. 81	. 53	. 46	1. 64
Ultimate:					
Hydrogen..........	5. 09	4. 73	......	......	......
Carbon............	55. 97	53. 74	......	......	......
Nitrogen...........	. 96	. 75	......	......	......
Oxygen............	30. 44	24. 28	......	......	......
British thermal units...	9, 440	9, 238	9, 153	8, 880	9, 376

LIGNITE OR COAL KNOWN TO BURN ON OUTCROP.

10898. Lignite from Culbertson lignite field, Mont. Red Bank open-cut mine, sec. 10, T. 28 N., R. 59 E. Fort Union formation.

6469. Subbituminous coal from Buffalo coal field, Wyo. Mitchell mine, sec. 26, T. 51 N., R. 82 W. Fort Union formation.

17711. Subbituminous coal from Tullock Creek coal field, Mont. Prospect in sec. 30, T. 1 N., R. 38 E. Fort Union formation.

8465. Subbituminous coal from Bull Mountain coal field, Mont. McCleary prospect, sec. 26, T. 9 N., R. 30 E. Fort Union formation.

COAL NOWHERE BURNED ON OUTCROP.

14755. Subbituminous coal from Tullock Creek coal field, Mont. Prospect 12 miles southeast of Bighorn. Lance formation.

It is evident from the foregoing summary that both chemical and physical factors enter into spontaneous combustion. As regards chemical composition, coals highest in volatile matter, moisture, and sulphur are most liable thus to ignite. In the accompanying table the chemical character of four typical coals that have burned extensively on the outcrop is shown by the first four analyses, and the character of a coal that has nowhere burned by the last analysis. A considerable range in composition is shown by these analyses, though all show high moisture and volatile matter but fairly low sulphur. It will be noted that the coal that has nowhere burned is much higher in sulphur than any of the others; whether its lack of tendency to burn is due to the offsetting of this factor by the low percentage of moisture and the high ash content is a matter of conjecture.

The physical factors promoting spontaneous combustion are a finely divided condition of the coal, a slight increment of heat from an outside source, and a sufficient volume of coal to retard loss of heat by radiation. A pile of coal exposed to the direct rays of the sun would thus be liable to become heated and finally ignite. In general, the outcrop of a coal bed, even in the arid western coal fields, weathers down slowly and is more or less covered by talus, so that the oxidation of the coal is too slow to generate much heat. Where a young, rapidly cutting gulch intersects a coal bed, however, a perpendicular face of coal may be formed, and as this is undercut by the stream a considerable mass of finely broken but fairly fresh coal may accumulate at the base of the bed. Under such conditions oxidation would be fairly rapid, especially as the normal temperature of the coal, if exposed to the direct heat of the sun, would reach 130° F. (55° C.), or more on summer afternoons.

In the writer's opinion most of the burning of western coal beds has been spontaneous and has originated under conditions similar to those just described. C. H. Wegemann,[2] who has studied particularly the relation of topography to burning, finds that burning is most prevalent along rapidly cutting streams and believes that it is partly a function of the character of the topography. The writer has observed beds actually burning at six localities, and in all of them combustion evidently started in a gulch on a small, rapidly cutting stream. Field studies indicate that two other generalizations can be made: First, thin beds are less commonly burned than thick ones, probably

[1] Penhallow, D. P., Tertiary plants of British Columbia: Canada Geol. Survey Pub. 1013, pp. 148–149, 1908.

[2] Personal communication.

because piles of coal large enough to retain self-generated heat can not accumulate along their outcrop; and second, beds of impure coal burn less commonly than those of clean coal.

GENERAL EFFECTS OF BURNING ON THE OVERLYING STRATA.

The rocks overlying a burned-out coal bed present widely different appearances, ranging from reddened and only slightly hardened shale or sandstone through vesicular glassy slag to gray medium-grained rock. These broader differences are due chiefly to the degree of heat to which the material has been subjected, and their relations to the coal bed may be more clearly understood if the process of burning is briefly considered.

Whatever the cause of ignition, the combustion apparently always starts at the surface and spreads first along the outcrop. The presence of the burning bed is disclosed by the smoke and fumes which rise from it, and by the heat at the surface of the earth near the outcrop or above the bed, which becomes so intense that all vegetation is killed. As the coal burns out the overburden generally caves, and large fissures may be opened in the surface of the ground above the bed. During this stage of the burning the heat is for the most part dissipated and the overlying strata are only slightly affected. However, thin red bands may be formed by the baking of clay partings in the bed, and as these slump down they become curiously contorted and form, with white bands of ash or cinders, a structure resembling somewhat that of a crumpled schist. Plate I, B, shows a burning coal bed 11 feet thick exposed on Custer Creek, near Yellowstone River, between Miles City and Terry, Mont. To the left the bed is slowly burning but has not perceptibly affected the overlying sandstone; to the right it is entirely consumed at the outcrop and the overburden has slumped down irregularly.

As the burning progresses back from the outcrop the heat is conserved and tends to act more strongly on the overlying rocks, until finally a point is reached where combustion is smothered by the lack of oxygen. The underlying strata are scarcely affected, if at all, and in many places the coal does not burn entirely to the base of the bed. Baking and hardening of the overlying strata doubtless begin a few

feet back from the outcrop, and as the coal burns out and these beds cave they tend to break into irregular fragments. Incipient fusion may occur on the edges of these fragments, which therefore have a tendency to cohere and thus form a stable rock 30 or 40 per cent of whose volume is air space. It is chiefly through the crevices in this rock that oxygen is supplied to the coal burning farther back.

How far the burning extends back from the outcrop is a matter on which there is little positive information. Field studies indicate that a bed under 20 feet or less of cover may burn out completely under large areas, and similarly that all the coal underlying a small butte or a narrow neck of land may burn out even though the overburden is 100 feet or more thick. Bowie [1] cites an instance in which the coal burned out to a point almost 500 feet from the outcrop, as ascertained in the course of mining the unburned portion of the bed. According to F. R. Clark,[2] development at Sunnyside, Utah, has shown that burning may extend even farther back under high spurs jutting out from the main ridge. In general, however, where there is a cover of more than 50 or 100 feet, and where the outcrop of the bed is fairly straight, it seems probable that burning does not extend more than 200 or 300 feet back from the outcrop.

Although the rocks within a few feet of the top of the burning bed may be partly fused, those beyond are in general merely baked and still further up are only slightly reddened. The great bulk of the rock retains its original texture, and though much of the shale is vitrified or hardened the sandy strata may be only slightly affected. The most striking effect is the reddening of the rock, which is due to the action of moderate heat under conditions favorable to simple oxidation and which therefore implies no very extensive chemical changes.

Though fusion is for the most part confined to the rocks directly above the burning bed, it may locally extend many feet above. The gases formed during combustion of the coal escape chiefly through fissures in the overlying strata and apparently are hot enough to fuse the rock thoroughly along their paths of escape.

[1] Bowie, Alexander, The burning of coal beds in place: Am. Inst. Min. Eng. Trans., vol. 48, p. 181, 1915.
[2] Personal communication.
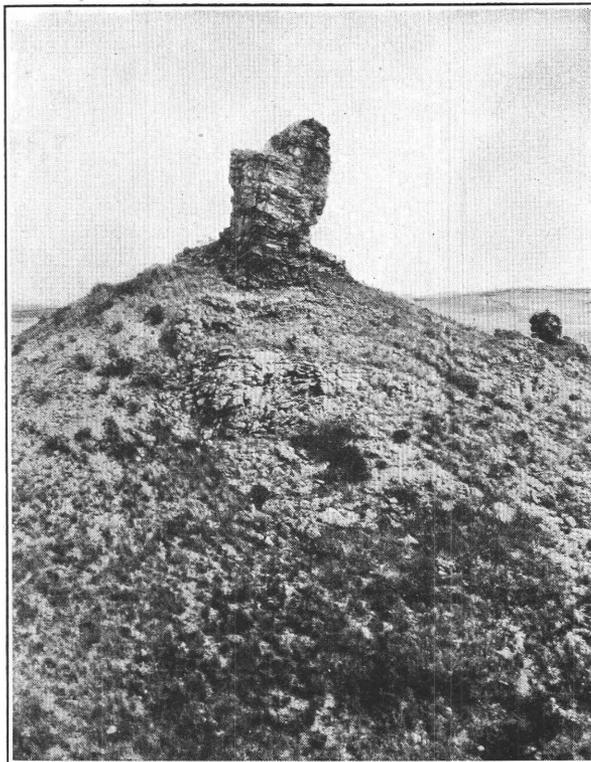
A. A CHIMNEY OR CORE OF HARD FUSED ROCK PROJECTING THROUGH PARTLY BAKED STRATA NEAR MILES CITY.

Photograph by C. D. Smith.
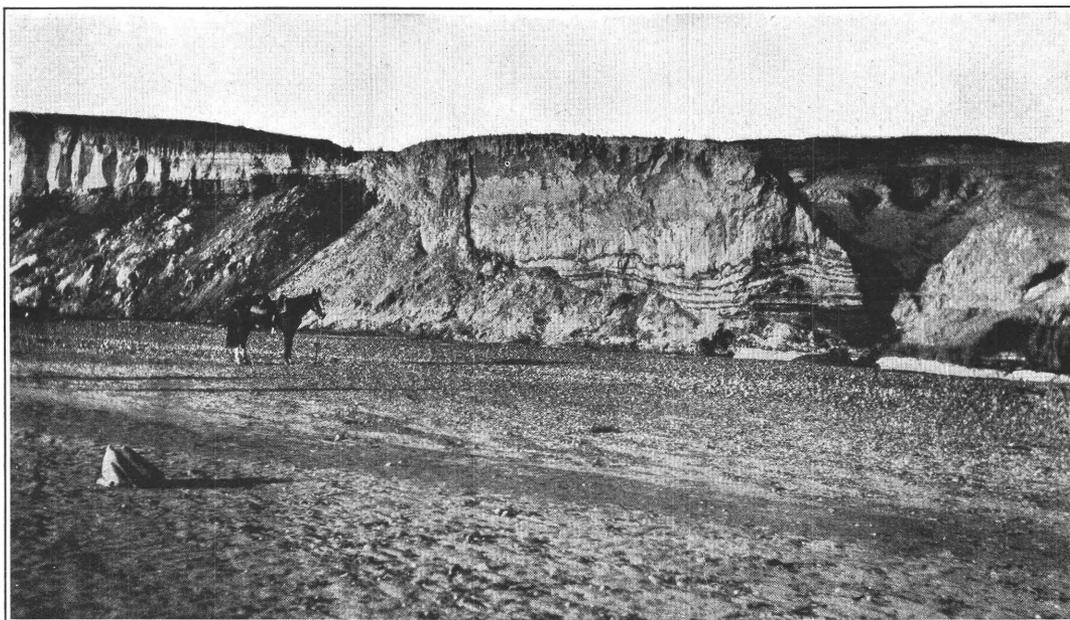
B. COAL BED 11 FEET THICK ON CUSTER CREEK NEAR YELLOWSTONE RIVER BETWEEN MILES CITY AND TERRY.

To the left the bed is slowly burning but has not yet perceptibly affected the overlying strata; to the right it is entirely consumed, leaving only contorted white bands of ash and darker bands formed by the baking of clay partings.

EFFECTS OF THE BURNING OF COAL BEDS IN EASTERN MONTANA.

As the melting point of silica is above 1,600° C., however, it is highly improbable that this action is accomplished by the spent gases, the products of combustion, alone. It is reasonable to suppose that the coal itself becomes highly heated, as well as the overlying rocks, and that considerable distillation goes on a short distance back of the burning face. According to Bowie,[1] in the King mine, on North Fork of Gunnison River, Colo.,

the coal adjacent to the burned-out area seemed to have its cohesive quality entirely destroyed. It was soft and very easily mined but could not be utilized even for steam fuel, as the volatile constituents of the coal seemed to have been expelled by the heat. We had a zone of several hundred feet of this kind of coal.

It is probable that the gases arising through fissures in the overlying rocks contain a considerable proportion of combustible matter, which explodes or burns on reaching a supply of oxygen, and that the intense heat necessary to fuse rock 75 feet or more above the bed is thus transmitted.

Apparently small fissures may control the paths of the gases and thus start the formation of well-defined chimneys. As the material forming the immediate walls of the fissures becomes molten it tends to sink and clog the passage, so that the gases may be slightly diverted and thus be caused to act on a greater volume of material. A similar effect is produced when a fissured zone rather than a single fissure controls the escape of the gases. In this case, however, the heat is less concentrated and may not be sufficient to melt more than the edges of the interfissural blocks. A single fissure may lead to the formation of a core of molten material extending many feet up through partly baked rock, whereas a fissured zone apparently produces a larger and less sharply defined core of partly fused fragments. On cooling, the fused or partly fused rock coheres and forms a roughly cylindrical mass of hard "clinker." Chimney-shaped masses of this kind resist erosion to a greater degree than the partly baked strata around them and weather to the curious pinnacles that commonly surmount clinker bluffs or buttes (Pl. I, A).

Aside from the strictly thermal effects of the heated gases, they also play an important part as reducing agents. As the combustion of the coal takes place in a scanty supply of oxygen, a considerable proportion of carbon monoxide is probably formed, and if the rock is ferruginous the reducing action may be very striking. Directly above the burning bed and along the paths of the escaping gases the iron is partly or wholly reduced and gray, green, yellow, or black slag is formed. When the reduction is partial magnetite may be produced, in some places in sufficient quantity to affect the compass needle. When the rock is thoroughly fused under reducing conditions, however, a great deal of the ferrous iron formed is taken up in the formation of new minerals and a light-colored slag results. A reducing atmosphere may also be developed in beds of carbonaceous shale that are highly heated by the burning coal bed, but most of the rock outside of the chimneys is merely baked under oxidizing conditions to the characteristic reddish color.

PETROLOGIC CHARACTER OF THE ROCKS FORMED.

CHARACTER OF THE ORIGINAL SEDIMENTARY ROCKS.

Although the degree of heat and the rapidity of cooling govern to a large extent the general character of the materials formed, the fundamental factor is of course the composition of the original rock. The coal-bearing formations of the Western States are made up largely of shale and sandstone. The shale may be yellow, bluish or greenish gray, or brown and carbonaceous; less commonly it is reddish. The sandstone, which is usually gray, yellow, or brown, is generally more or less arkosic and may carry 25 per cent or more of feldspar, hornblende or pyroxene, and mica. Under the microscope the rock from some localities or formations is seen to be made up of predominantly angular grains, and the feldspars and ferromagnesian minerals are surprisingly fresh. In other specimens, however, the grains are more rounded, the feldspars kaolinized, and the ferromagnesian minerals altered to chlorite or serpentine. Accessory minerals, such as garnet, zircon, and magnetite, are present in most of the sandstone in minor quantity, and there is usually much fine clayey interstitial material, commonly iron stained. Some of the rocks examined, notably those of the Lebo shale member of the Fort Union formation (Tertiary), are evidently derived from fairly basic

[1] Bowie, Alexander, op. cit., p. 182.

igneous rocks and contain as much as 50 per cent of chloritic material. Calcite occurs in many specimens, and in some localities the rocks are distinctly calcareous, though beds containing more than 20 per cent of lime carbonate are probably uncommon.

Although unfortunately only generalized data on the composition of the sedimentary rocks are available, the foregoing notes are sufficient to indicate that the rocks differ widely in mineral and chemical character. Moreover, variation in composition may be abrupt; contiguous beds may be very different in character and in many localities the same bed differs more or less from point to point.

BAKED ROCK.

Shale or sandstone more or less baked constitutes by far the largest part of the metamorphosed strata. Although the prevailing colors are pink, red, or purplish red, the rocks may be mottled in red and bright yellow, green, or black. The mottling is more common in baked shale; the sandstone is generally altered to a uniform pinkish red and is only moderately hardened. In general only the edges of the grains are fused and in many specimens no alteration can be detected under the microscope.

The shales apparently respond more readily to the heat, losing their original texture and becoming hard and massive. A splintery or conchoidal fracture is not uncommon, even where the rock retains clear impressions of fossil leaves or invertebrates. Many specimens resemble jasper, their appearance suggesting the terms porzellanit and porzellanjaspis, under which this material is described by Zirkel.[1] The mottled rock is probably produced by a higher temperature, though its colors are due primarily to irregular oxidation of the iron. As disclosed by the microscope the red color is due to the formation of minute scales of hematite, whereas the black and green areas contain abundant small grains of magnetite.

VITRIFIED SHALE.

In many localities the shale near the top of the burning bed or near the chimneys has been rendered pasty or molten and has flowed slightly. In some places the material has been rendered sufficiently fluid to develop a ropy

[1] Zirkel, Ferdinand, Lehrbuch der Petrographie, Band 3, pp. 75-76, 1894. References are given to earlier accounts, dealing mostly with occurrences in European coal fields.

surface on cooling, closely resembling that characteristic of certain lavas. The rock is irregularly banded red and green or black, and thin sections across the flow lines usually reveal the presence of hematite in the red areas and magnetite in the green and black. The rock is not smooth like ordinary baked shale but is rough and very finely vesicular like some kinds of brick. Ordinarily the grain is so fine that little can be made out under the microscope, though occasionally small areas of amorphous glass may be seen. Some varieties contain small grains of clayey material, reddish in the center and surrounded by a gray or black zone.

GLASSY SLAG.

Bodies of glassy slag large enough to be observable in the hand specimen apparently occur only near the top of the burning bed or in the chimneys. Entirely glassy slag is not common, for where the heat is sufficient to cause complete fusion cooling is generally slow enough to allow more or less recrystallization. Most of the true glass seems to occur as small veinlets penetrating crevices in the baked or vitrified rock. The rock around the chimneys is generally fractured or brecciated, and sudden settling or caving apparently forces some of the molten rock out into the crevices of this brecciated mass, where it is more rapidly cooled. In some places, however, conditions have led to the sudden cooling of larger masses of the molten slag and good-sized specimens may occasionally be found. Some of them resemble obsidian very closely, being perfectly glassy and in spots highly vesicular. All of the specimens seen by the writer are black, but translucent in thin splinters.

In thin section this material appears as an amorphous glass, generally containing a few minute grains of a black mineral that is presumably magnetite. One specimen is characterized by a kind of spherulitic structure, as shown in the accompanying photomicrograph (Pl. II, A). Another shows a few clusters of acicular crystals too small to be identified, thus illustrating the transition to the recrystallized phases described below.

RECRYSTALLIZED SLAG.

The rocks that have been thoroughly fused and cooled with sufficient slowness to allow complete recrystallization are of considerable petrographic interest, though constituting a

minor facies of the metamorphic products. The recrystallized material is generally, if not invariably, confined to the chimneys. As a rule it is gray to dark greenish gray, and except for its vesicularity is very similar in appearance to a fairly basic igneous rock. The grain is generally fine, though in one specimen a crystal a tenth of an inch in diameter resembling pyroxene was observed. All gradations between holocrystalline material and glassy slag may be found, and in most of the specimens examined a small amount of interstitial glass occurs. In one slide remnants of the original quartz grains appear together with amorphous glass and small, slender newly formed crystals.

A specimen from Tongue River near the Wyoming-Montana line (T. 9. S., R. 40 E.) was studied under the microscope and found to consist chiefly of diopside and basic plagioclase. The mineral called diopside has the following optical characters: Biaxial positive; axial angle about 60°; dispersion weak with red greater than violet; extinction angle, 36°; and indices of refraction about 1.675 and 1.702. The plagioclase has a maximum extinction angle of 38° in microlites and refractive indices of 1.57 and 1.58, which indicate a basic labradorite or bytownite of the approximate composition Ab_1An_3. As shown in the accompanying photomicrograph (Pl. II, B), the diopside crystals have a tendency to form radiating groups, and the plagioclase occurs in well-formed laths and microlites. Some garnet, apparently almandite, was observed, and magnetite in small grains is fairly abundant. As near as can be ascertained the rock from which this material was derived is a sandy shale, consisting largely of kaolin, feldspar, and altered ferromagnesian minerals, together with subordinate quartz and some calcite.

A specimen collected near the head of Sarpy Creek (T. 1 N., R. 37 E.) resembles the specimen from Tongue River megascopically, but under the microscope appears to be a very different rock. A larger number of minerals are present and the characters of the most important of these do not correspond with those of any of the ordinary rock-forming minerals. The rock consists largely of greenish phenocrysts—at first sight suggesting epidote—set in a mosaic of colorless grains resembling melilite. The optical characters of the green mineral are as follows: Biaxial

positive; axial angle nearly 90°; dispersion strong, and red greater than violet; extinction angle 23°–25°; and indices of refraction about 1.655 and 1.675. The mineral is pleochroic, deep yellow to apple-green. These properties indicate that it is not epidote and suggest that it may be clinoenstatite. The colorless mineral is biaxial negative in character, has a large axial angle, and has strong dispersion, red being less than violet. Its birefringence is about that of quartz, and its refractive indices are about 1.615 and 1.625. These properties suggest andalusite or some form of wollastonite, though the mineral does not resemble either of these in habit. Two other minerals are present that could not be identified. One is pleochroic, yellow to colorless; it is uniaxial negative in character and its refractive indices are about 1.62 and 1.64. The other, which is not abundant, is isotropic, colorless, and lacks cleavage; its index of refraction is about 1.61. In addition the rock contains a basic labradorite, occurring in small but well-twinned laths, magnetite, and a few grains of garnet, probably almandite. Several rounded xenoliths of shale surrounded by contact rims of the yellow and white minerals already described were observed. (See Pl. III.)

A specimen collected in T. 1 N., R. 36 E., not far from the one just described, appears to have been derived from a more highly aluminous shale. It is only partly recrystallized and consists largely of glass, but acicular crystals of sillimanite (fibrolite) are abundant, and several grains of what seem to be cordierite were observed. Spinel may be present but could not be positively identified. Close to the chimney in which this mineral occurs a mass of specular hematite about a foot in diameter was found. The hematite appears to be closely associated with the chimney, although it lay rather in the partly baked shale through which the chimney projects. This remarkable occurrence is discussed on pages 9–10.

All the rocks described appear to be irregular in composition, and different portions of the same specimen may contain different minerals. It is probable that a detailed study would reveal many more species, and some have indeed been reported by other observers. In slags from eastern Wyoming

Bastin [1] finds oligoclase, pyroxene, and cordierite, in addition to magnetite and hematite. He describes a vein of slag about one-tenth of an inch in diameter penetrating red argillite as follows:

In passing from the reddish argillite toward the center of the vein the contact zone shows a gradual decrease in the normal shale constituents and a development, in increasing amount and coarseness, of purplish-blue pleochroic cordierite. Next the coarser part of the vein this mineral is present to the exclusion of all others. In this contact zone the red iron oxide of the argillite has been wholly reduced to magnetite. The central portion of the vein is a somewhat vesicular, holocrystalline mass, consisting of abundant magnetite in irregular masses, some hematite, usually lining the vesicles and following fractures, and abundant cordierite, feldspar, and pyroxene.

Hibsch [2] has described similar material from the Mittelgebirges (northern Bohemia) under the name Kohlenbrandgesteine. In the recrystallized specimens he finds magnetite, cordierite, epidote in well-formed crystals, plagioclase, tridymite, and abundant dark grains that may belong to the spinel group.

CHEMICAL CHANGES.

The most widespread chemical change produced in the overlying strata by burning coal beds is dehydration under conditions favorable to oxidation. This change affects chiefly the limonite and the siderite or other ferrous iron compounds, which are converted into hematite, with consequent reddening of the rock. Some of the hydrous silicates may be partly or wholly dehydrated without fusion under some conditions, but if this change takes place it is difficult to detect. In one specimen, however, the writer observed a large fresh grain of green augite in a sandy shale that had been baked but not fused. The augite could not be a product of secondary crystallization, and all the other constituents of the rock were considerably altered. This suggests that it may have been re-formed by the dehydration of alteration products, such as chlorite or serpentine, though the writer is aware that such a process is not well supported by laboratory results.[3]

Within the chimneys and directly above the burning bed, where the rocks are fused under conditions favorable to reduction, more extensive changes take place. The conditions are, of course, very different from those under which igneous rocks are formed, and are analogous rather to those in the slag furnace. The pressure is low, mineralizing agents are absent, and much of the water that the rocks contained is doubtless quickly driven off. The material involved, however, is different from that which enters into the composition of most furnace slags, being generally argillaceous rather than calcareous, and many of the minerals formed are therefore probably unlike those common in artificial slags. In this connection the classic researches of Vogt and Morozewicz, on prepared slags of known composition, are of interest.

It is impracticable to correlate many pieces of slag with the unaltered rock from which they were derived, owing to the irregularity in composition of the strata. Furthermore, unless fusion is very complete and the molten mass is well mixed its mineral composition may also be irregular. However, the diopside-plagioclase rock described above is evidently derived from a sandy shale, and after microscopic study a sample of this shale was analyzed by the writer in the hope that the analysis as recast might explain the mineral character of the slag. The composition of the shale is shown by analysis 1 in the accompanying table.

The sample analyzed had been partly baked, which explains the ferric condition of nearly all the iron. The analysis accounts in a general way for the mineral composition of the slag, indicating rather high iron, lime, and magnesia. According to Morozewicz,[4] diopside or hedenbergite is formed in a slag in which the molecular ratio of $Fe+Mg:Ca$ is less than $3:1$. This analysis shows a ratio of only 94 to 89, or if all the iron is calculated as ferrous, of $140:89$, and pyroxene of the diopside-hedenbergite type is therefore to be expected. According to the same investigator,[5] augite is generally formed when the melt contains more than 50 per cent of silica, and though no augite was observed in this slag it might, if irregularly distributed, easily escape observa-

[1] Bastin, E. S., Note on baked clays and natural slags in eastern Wyoming: Jour. Geology, vol. 13, pp. 408–412, 1905.

[2] Hibsch, J. E., Geologische Karte des böhmischen Mittelgebirges: Min. pet. Mitt., vol. 27, pp. 35–40, 1908.

[3] Clarke, F. W., and Schneider, E. A., Experiments upon the constitution of certain micas and chlorites: U. S. Geol. Survey Bull. 113, pp. 27–33, 1893.

[4] Morozewicz, Josef, Experimentelle Untersuchungen der Minerale im Magma: Min. pet. Mitt., vol. 18, pp. 113–128, 1898.

[5] Idem, pp. 113, 120, 123–124.
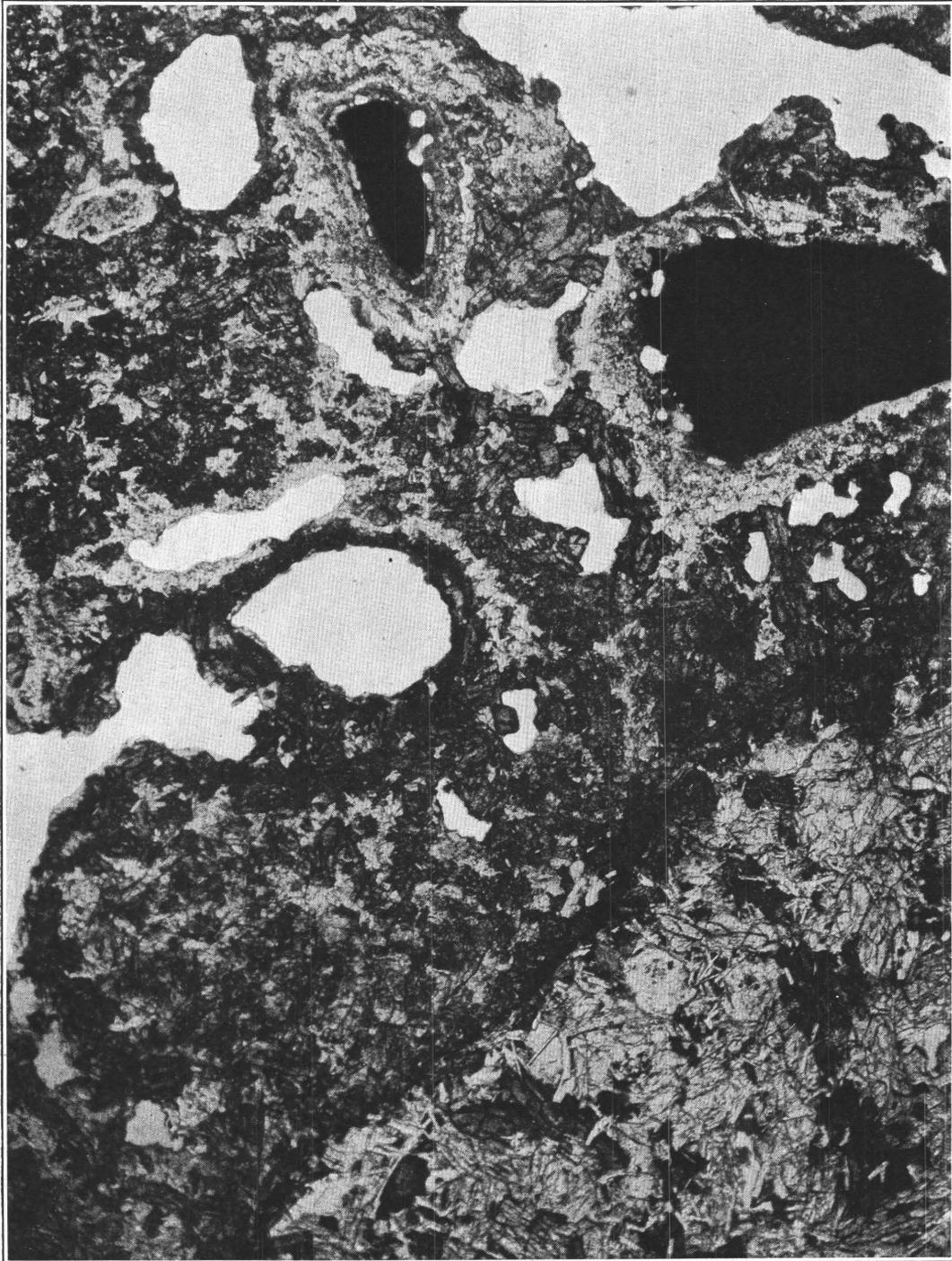
PHOTOMICROGRAPH OF HOLOCRYSTALLINE SLAG.
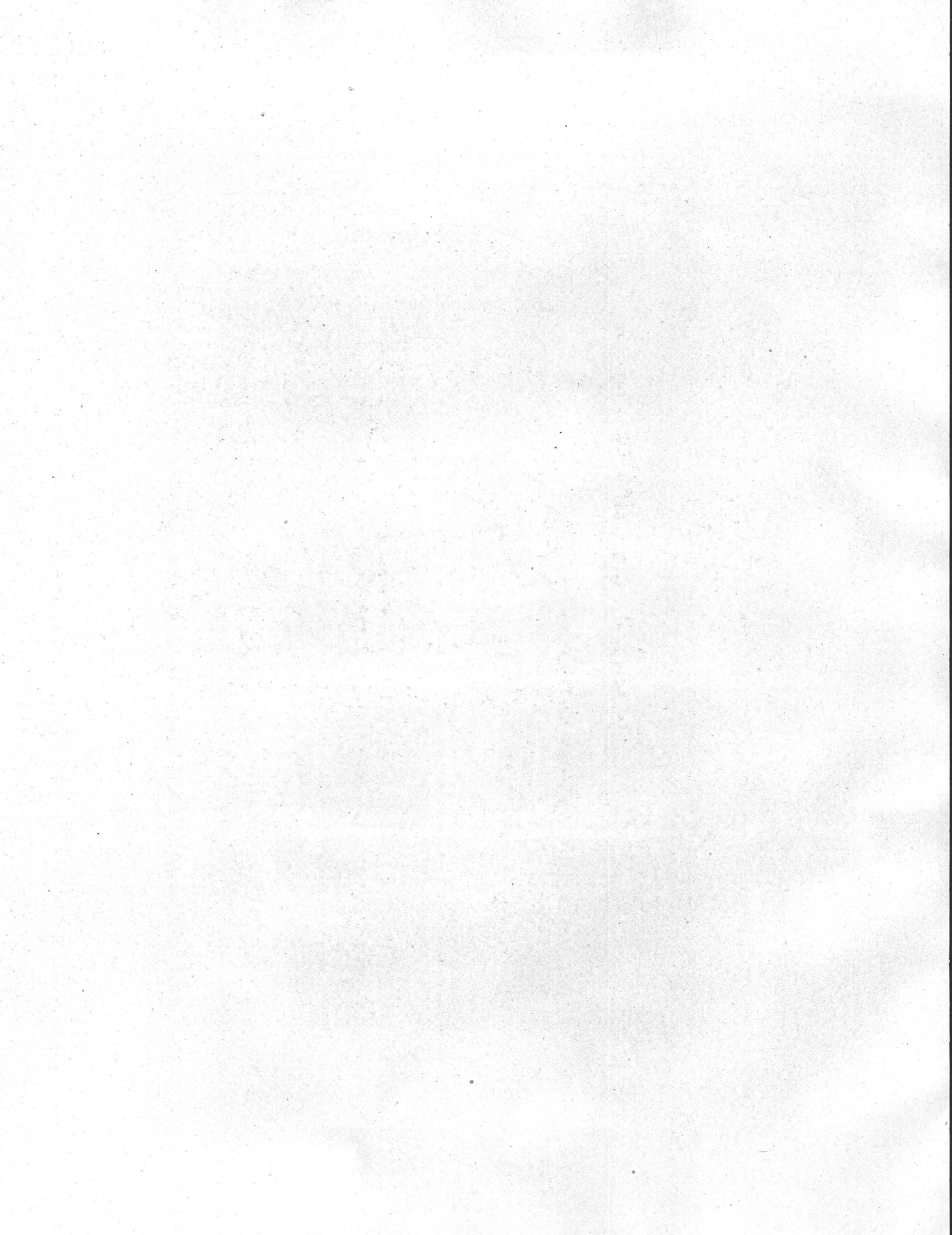
tion. The analysis, however, indicates a more acidic plagioclase than that found in the slag and suggests that an excess of silica would probably be left to crystallize as quartz or tridymite, which are apparently absent. These discrepancies are presumably due to irregularities in the composition of both the shale analyzed and the slag.

Analyses of baked shale from Fort Union formation, Montana.

[G. S. Rogers, analyst.]

	1	2
SiO_2	65.41	58.30
TiO_2	1.17	.28
Al_2O_3	11.94	20.50
Fe_2O_3	7.38	4.23
FeO	.76	.46
MnO		.18
MgO	1.50	1.31
CaO	5.02	4.40
K_2O	1.96	2.28
Na_2O	2.83	1.46
H_2O-	.08	1.03
H_2O+	.50	1.90
CO_2	1.57	3.37
SO_3	.22	.19
P_2O_5	Trace.	Trace.
	100.34	99.89

1. Sandy shale from upper Tongue River, T. 9 S., R. 40 E.
2. Clay shale from T. 1 N., R. 36 E.

The third specimen described, containing sillimanite, cordierite, and probably spinel, is of interest as indicating the minerals that form in a melt more highly aluminous than any normal igneous magma. The composition of the shale from which this slag is derived is shown by analysis 2. The specimen analyzed had been moderately baked. It is uniformly fine grained and under the microscope appears to consist largely of clayey material together with a few grains of quartz and some calcite.

The analysis indicates a slag similar in composition to some of those studied by Morozewicz,[1] who was able to formulate the conditions under which the several aluminous minerals form. If the molecular ratio of alumina is greater than the sum of the ratios of lime, soda, and potash, the magma is supersaturated with respect to alumina. If the general formula of the magma is written $1RO.mAl_2O_3.nSiO_2$ the following rules apply: When magnesia and iron are very low, if n is less than 6 corundum will form, but if n is greater than 6 sillimanite will crystallize out. When magnesia and iron

[1] Op. cit., pp. 22–83.

are present in appreciable amount, if n is less than 6 corundum and spinel are produced, but if n is greater than 6 spinel and cordierite will form. Analysis 2 indicates the formula $125RO.201Al_2O_3.971SiO_2$, or $1RO.1.6Al_2O_3.7.7SiO_2$; as m is greater than 1 and n is greater than 6 the melt is supersaturated with respect to alumina, and the alumina should form spinel, cordierite, and sillimanite. The sum of the molecular ratios of iron and magnesia is 64, or less than the difference between those of RO and Al_2O_3. It may be supposed that cordierite and spinel would be formed until the magnesia and iron were nearly exhausted, and that the balance of the alumina would then be consumed in the formation of sillimanite. Unfortunately the slag examined was incompletely crystallized, and the order of formation of the minerals could not be determined. Cordierite is reported by both Bastin and Hibsch, and a mineral resembling spinel was found by Hibsch, which indicates that the aluminous silicates are probably common in the slags formed by the fusion of shales, and as magnesia and iron are generally present in considerable amount cordierite and spinel are doubtless more common than sillimanite or corundum.

As already mentioned, a mass of hematite weighing several pounds was found close to the chimney from which the slag described above was taken. A partial analysis of the hematite is as follows:

Analysis of hematite from T. 1 N., R. 36 E., Montana.

[Chase Palmer, analyst.]

Ferric iron (Fe_2O_3)	83.57
Sulphur (S)	Traces.
Chloride (insoluble) (Cl)	Traces.
Metallic iron (Fe)	None.
Ferrous iron (FeO)	None.

The origin of this mass of hematite is not easy to understand. So far as the writer knows hematite has never been observed elsewhere in these flat-lying and only partly consolidated strata, and the specimen described must therefore have been formed in some way through the agency of the burning coal. It might be ascribed to the oxidation of a large pyrite or ironstone nodule, but a careful search failed to reveal any such nodules in the unaltered beds near by. On the other hand, if it is considered to have resulted from segregation during heating or fusion, the details of

the process are very difficult to explain. As shown by analysis 2 (p. 9), the surrounding rock contains less than 5 per cent of iron, and rather extensive concentration would therefore have to be postulated. According to Vogt,[1] hematite rarely occurs in ordinary furnace slags, as it can crystallize only when ferrous compounds are present in very subordinate amounts. In the surrounding rock ferrous iron is practically absent, but in order to concentrate the ferric iron complete fusion would appear to be necessary, and as this seems always to take place under conditions favorable to reduction, much of the ferric iron would become ferrous. If the iron had occurred directly in the chimney as native iron, or even as magnetite, it might therefore be supposed that a smelting process akin to that in the ordinary blast furnace had taken place, but as it was found at the edge of the chimney and is completely oxidized to hematite this view does not appear to be tenable.

A third hypothesis that might be suggested is that the hematite formed as it forms around volcanoes, through the decomposition of ferric chloride or sulphate by steam or heated air. The ground water of the region in which the hematite was found carries a considerable proportion of sodium chloride and of sodium, calcium, and magnesium sulphate, and as these salts are not uncommon as incrustations on the rocks an adequate supply of chloride or sulphate is undoubtedly present. On the assumption that hydrated ferric oxide (limonite) is capable of uniting with sodium chloride under the influence of intense heat, it seems probable that the ferric chloride so formed would ascend as vapor with the other gases and would be deposited as hematite in the upper part of the chimney. It is by no means certain that the primary reaction between disseminated limonite or siderite and soluble chlorides or sulphates is chemically possible under the conditions prevailing, but the presence of traces of basic (insoluble) chloride in the hematite is difficult to explain on other grounds and therefore tends to support this hypothesis.

Native iron of secondary origin has been observed near coal beds in other localities. On North Saskatchewan River, 70 miles above Edmonton, Alberta, lignite beds have burned and have reduced the large clay ironstone nodules in the overlying strata to metallic iron, masses of which weighing from 15 to 20 pounds have been found.[2] At three localities in Missouri drill holes have penetrated small masses of soft malleable iron in the sedimentary rocks above coal beds,[3] but the genetic relations of the iron and coal in this case are not so clear.

[1] Vogt, J. H. L., Beiträge zur Kenntniss der Gesetze der Mineralbildung in Schmelzmassen, pp. 215-217, 1892

[2] Tyrrell, J. B., Naturally reduced iron: Am. Jour. Sci., 3d ser., vol. 33, p. 73, 1887.

[3] Allen, E. T., Native iron in the coal measures of Missouri: Am. Jour. Sci., 4th ser., vol. 4, pp. 99-104, 1897.