AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS
Technical Publication No. 891
(Class I, Mining Geology, No. 78)
DISCUSSION OF THIS PAPER IS INVITED. Discussion in writing (2 copies) may be sent to the Secretary, American Institute of Mining and Metallurgical Engineers, 29 West 39th Street, New York, N. Y. Unless special arrangement is made, discussion of this paper will close Sept. 1, 1938. Any discussion offered thereafter should preferably be in the form of a new paper.

Diatremes and Certain Ore-bearing Pipes

By W. H. Emmons,* Member A.I.M.E.

(New York Meeting, February, 1938)

A diatreme is a hole blown through a rock by gases, presumably of volcanic origin. Not all pipes of ore have formed by deposition of metals in such openings, but a considerable number have so formed. In this paper are described peculiar vein patterns that are believed to be incipient diatremes or "perforation pipes." Grading into this group is one showing thorough brecciation without rotation of fragments and into the latter a group of ore pipes showing brecciation with rotation of fragments—many of them with well rounded fragments. Also, volcanic craters or volcanic necks are explosion pipes. These may carry ore deposits along their contacts and some carry deposits within the pipes. As new data appear this group becomes increasingly impressive. It has been shown that veins are concentrated in and about cupolas of batholiths and that such veins commonly lienearly parallel to the long axes of cupolas as these are shown on plans. It would be supposed that conical cupolas would have radial patterns, but few vein systems exhibit radial patterns. It is probable that explosion pipes also may form in areas above conical cupolas. From these the gases escape more violently because the loads above them are less than above an elongated cupola where larger bodies of rock are affected. The hypothesis is sound mechanically, for the top of an elongated cupola is a line whereas the top of a conical cupola is a point.

Introduction

Long ago Daubrée[1] made experiments in drilling small pipelike holes through granite, which he called diatremes.† He compared the experiments to the processes by which gases seem to penetrate and form holes in rocks in certain volcanic areas.

In Swabia, according to Branco and Frass,[2],[3] there are 127 "explosion vents," which they believed to be embryonic volcanoes. These form a disklike cluster and they assumed that these vents were above an intrusive igneous mass not yet exposed by erosion. Five basalt plugs are exposed in this area.

In Scotland,[4] Carboniferous beds are perforated by clusters of necks, in all about 165 vents. Geikie believed them to be formed by gaseous explosions that were attended by the extravasation of little or no lava.

In southwestern Ste. Genevieve County,[5,6] Missouri, about 60 miles south of St. Louis and about 6 miles east of Farmington, there is an area

Manuscript received at the office of the Institute Nov. 26, 1937.

* Director, Minnesota Geological Survey, Minneapolis, Minn.

[1] References are at the end of the paper.

† From the Greek "hole through"; first used by Daubrée.

Copyright, 1938, by the American Institute of Mining and Metallurgical Engineers, Inc.
Mining Technology, May, 1938. Printed in U. S. A.

of Cambrian beds about 75 square miles in extent in which igneous intrusions are closely spaced. Some of these intrusives cut Bonne Terre limestone of Cambrian age. Lithologically some of them resemble dikes that cut Pennsylvanian beds in Illinois and Kentucky, and may be of post-Pennsylvanian age. In Ste. Genevieve County there are 71 occurrences, most of which are said to be debris-choked explosion tubes, or diatremes. About 6 miles northeast of Farmington, an altered basic intrusive 275 ft. wide occurs in Cambrian sediments. It carries numerous inclusions of sedimentary rocks, some of which contain Devonian fossils. The intrusive, therefore, is of post-Devonian age. About one mile north of Avon[7] and 11 miles east of Farmington, a pipe 200 ft. in diameter intrudes Bonne Terre dolomite. The pipe consists of alnöite, a basic rock high in alkalies and magnesium; in its periphery, sulphide ores are deposited in the dolomite. These carry calcite, siderite, sphalerite, galena, chalcopyrite, marcasite and pyrite. A little smoky quartz is present.

Bucher[8] has described circular areas with strong deformation in Ohio, Indiana, Kentucky, Tennessee, Missouri and Arkansas. He attributes the deformation to volcanic action, the agents being gases under high pressure. No igneous rocks are noted in the deformed areas. While all seem to agree that gases were the agents that blew out such openings, some consider these gases to be of volcanic origin while others believe that the gas was steam formed from water in the rocks, which was heated by volcanic materials. Hydrothermal alterations of the deformed areas are not mentioned in reports.

An ore-bearing pipe is a roughly cylindrical deposit, generally extensive in depth. The term "chimney" commonly is used as synonymous with pipe. In general, the pipe or chimney has a comparatively steep dip, but both terms have been used to describe ore bodies that dip not more than about 16°. In the older literature of ore deposits, many pipes and chimneys were believed to be localized by the intersections of fractures, but in recent years there has been a tendency to regard many of them as channels formed through the agency of volcanic gases under high pressures.[9] They utilized fractures or intersections of fractures where these were available. In many chimneys and pipes there are fragments of rocks that were brecciated, rolled and rounded before they were cemented by ore.

The "circle" is a body of metallized rock that is thoroughly fractured and fissured, but in which generally few fragments have been rolled and rounded. Most of the "circles" are elongated. In plan generally they are elliptical, but some of them approach true circular disks.

Many metallized pipes and chimneys are related to openings that seem to have no direct connection with gas explosions or other volcanic processes. The great Brown Hill-Oroya deposit of Kalgoorlie, which is called a chimney, dips south 16° and is formed where one or more faults cross beds that are favorable to replacement. The Great Carbona tin pipe of St. Ives, Cornwall, probably is another example, and there are scores of others.

It is the belief of the writer that many of the pipes, chimneys and circles fill openings that have formed by explosions of gases given off by underlying cooling masses. There is nothing new in this theory. Spurr discussed it in 1923.[9] As long ago as 1896, S. F. Emmons (ref. 10, pp. 430–438) adopted that theory to explain the origin of the Bassick pipe in Custer County, Colorado. At a still earlier date, Elie de Beaumont[11] urged that metalliferous deposits in general were deposited by volcanic emanations.

S. F. Emmons believed that the Bassick pipe filled the neck of an old volcano and that the ore was deposited by metallic vapors as a phase of dying activity of the volcano. Discussing the genesis of the Bassick ore body, he says it has "an origin and manner of formation differing from that of the ordinary ore deposit . . . Here, if anywhere, was presented a typical instance of a deposit due to fumarolic action . . . an explanation that the writer has been unwilling to accept for most of the deposits he has studied."

Morey's experiments[12] show that gas pressures sufficient to lift nearly a mile of granite are developed by a silicate and water system cooling from 500° to 420°, and there are reasons for supposing that considerably higher pressures are developed when granite crystallizes.[13] Without much doubt this pressure is sufficient to lift two or three miles of granite.

In recent years a considerable number of reports with detailed maps of ore pipes and ore-bearing craters have appeared. From these and from other sources the sketches presented in this paper were prepared, in some of which the outlines of several pipes and craters are plotted on the same scale. It is evident that in certain districts ore pipes form groups and at places several pipes are found near together. That is true at Cananea, Mexico; at Mount Lyell, Tasmania; at Whipstick, New South Wales; at El Chivato, Chile. Other examples are the tin and bismuth pipes of New England in New South Wales, and the tin pipes of Zaaiplaats, Transvaal.

In the following discussion the examples cited are divided into groups:

1. Pipes and circles with closely spaced fractures, but with little rotation of fragments in the pipes: at Kidston, Queensland, and the Alice and Jessie pipes, Colorado. To this group should be added probably most of the disseminated copper ores in porphyry that crop out as circles or elongated ovals, the Mount Morgan deposit, Queensland, and the famous Altenberg stock of the Saxon Erzgebirge, which crops out almost as a square, and many other tin-bearing stockworks.

2. Pipes in which there has been considerable rotation of material with brecciation and at places rounding of fragments in the pipes. The

rounding of fragments probably resulted from movement of fluids in the pipes. Evidently gases continued to pass through the pipes after they were blown out. Examples include: Anna Lee, Bassick, Bull Domingo, Espiritu Santo, probably some of the pipes of the Transylvanian Erzgebirge, particularly Cstátye and Rákosy near Veraspaták.

3. Another group closely related to group 2 includes the hollow "cylinders" of ore, such as Los Pilares deposit near Nacozari, Sonora, and the Duluth Cananea pipe, near Cananea, Sonora. Plans of these pipes show hollow elongated rings of ore. Neither of these deposits has formed in the crater of a volcano. At Los Pilares a contact of latite and andesite breccia is followed through the central part of the pipe and except by

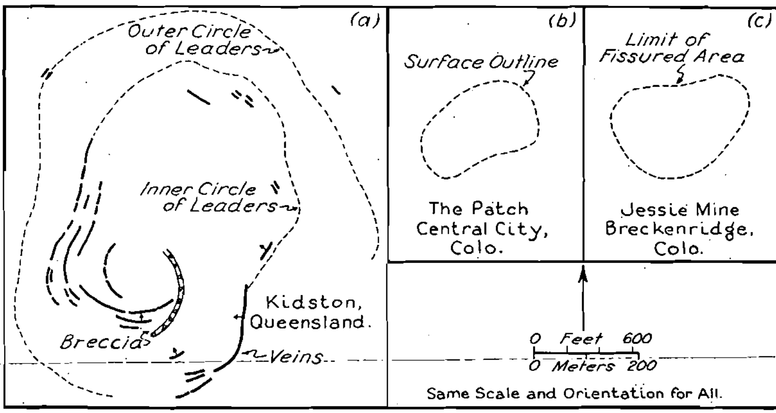

Fig. 1.—Outlines of outcrops of circular areas of (a) Kidston, Queensland, (b) The Patch, Central City and (c) Jessie mine, near Breckenridge, Colorado. Data from Jensen, Bastin and Hill, and Ransome.

faulting it is not greatly disturbed. In the ring itself the country rock is greatly brecciated, but the fragments are not rounded by movement. In the Cananea-Duluth deposit the oval ring is greatly brecciated, but the material it encloses is only weakly brecciated. The Cresson pipe at Cripple Creek, Colo., exhibits an incomplete oval ring of ore, but since it is believed to have formed in a "crater" it is included in a following group.

4. Deposits that have formed in and around the vents of volcanoes. These include Cerro de Pasco, Peru; Braden, Chile; Nagy Kirnik, Veraspaták, Transylvania; Stan Trg, Trepča, Yugoslavia; Cresson pipe, Colorado.

1. Circles of Fracturing without Much Rotation of Fragments

The Kidston district (Fig. 1), about 160 miles southwest of Geraldton, Queensland, Australia, probably represents an early stage of the formation of a circle or pipe where the process was halted before brecciation was far advanced. It lies in metamorphic rocks, in granite and in porphyry.

The vein system[14] is about 1850 ft. in diameter and its pattern resembles an uncoiled watch spring. The veins cross contacts of the country rocks

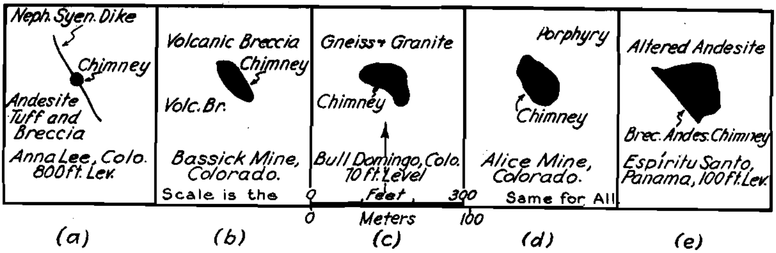

FIG. 2.—PLANS SHOWING SEVERAL ORE PIPES REDUCED TO SAME SCALE. ORIENTATION OF BULL DOMINGO PLAN UNCERTAIN.
Data from Lindgren and Ransome, S. F. Emmons, Bastin and Hill, and Woakes.

without displacing them. There seems to be little brecciation except in a zone about 600 ft. long near the center of the area. At places where a

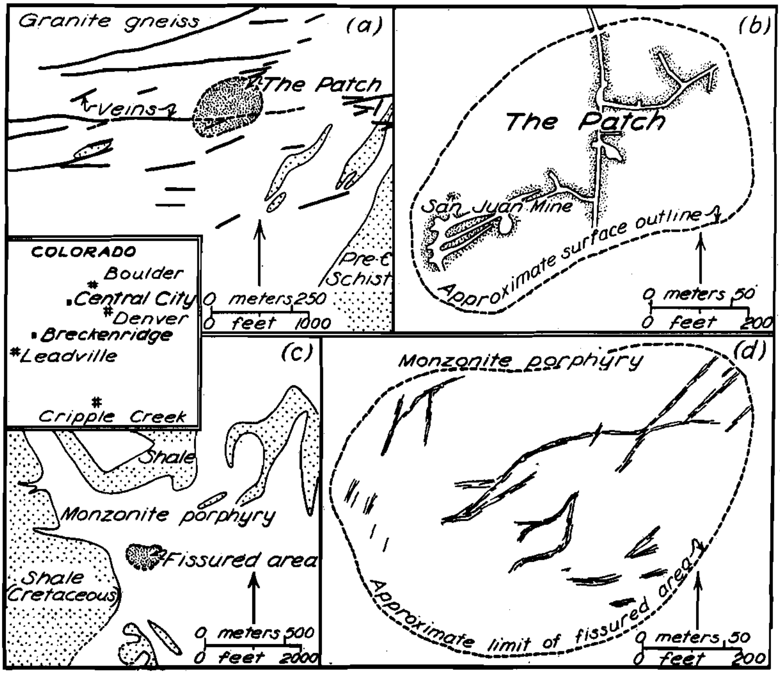

FIG 3.—SOME ORE VEINS IN COLORADO.
a. Veins striking into the Patch near Central City. After Bastin and Hill.
b. The Patch, near Central City. Mine workings are on LaCross tunnel. After Bastin and Hill.
c. Fissured area at Jessie mine, Breckinridge. After Ransome.
d. Fissures of Glenwood-Jessie level of Jessie mine.

wide ore body was mined open cast, low costs were achieved, but no large operation was established.

At the Alice mine (Fig. 2*d*), ¾ mile southwest of Alice and 4 miles north-northeast of Empire, Colo., a mass of monzonite porphyry 0.5 mile long and 0.2 mile wide intrudes pre-Cambrian schist. The deposit is a pipe of fractured and shattered porphyry from 100 to 200 ft. in diameter. The ore replaces the porphyry and fills fractures in it. Fragments of the porphyry are not rotated. Values are chiefly gold and copper. The Commercial Union mine, near Alice, worked a similar deposit of gold ore. (Ref. 9, p. 886; ref. 15, pp. 323–326.)

At the Jessie[16] mine (Figs. 1*c*, 3*c* and *d*), near Breckenridge, Colo., an oval area in monzonite porphyry, 900 ft. long and 600 ft. wide, is devel-

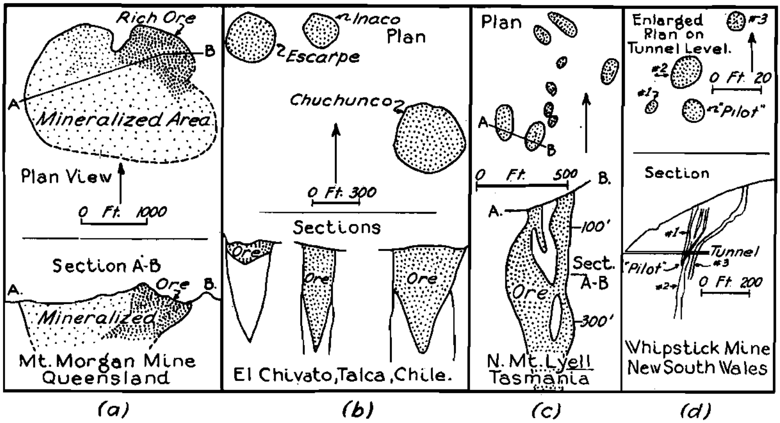

FIG. 4.—MAPS AND CROSS SECTIONS OF ORE PIPES IN AUSTRALIA AND CHILE. Data from Newman and Brown, Geier, Gregory and Andrews.

oped 300 ft. deep and has been fissured in many directions, chiefly by fissures striking east to northeast (Fig. 3*d*). There is no brecciation like that of the Bassick pipe, Colorado. The Jessie contains several bodies of ore that were stoped, in which the fractures are closely spaced and the ore lies in true stockworks. The principal minerals of the ore are pyrite, sphalerite, galena and gold, and a little silver.

Mount Morgan,[17] Queensland, 20 miles south of Rockhampton, is one of the world's greatest gold-copper mines. It is in an area of quartz-porphyry tuff that lies between two bodies of intruding granite. A nearly circular area of the fractured and shattered tuffs with a diameter of about 0.5 mile is mineralized (Fig. 4*a*). The mineralized area decreases with depth and is thus an inverted cone. The workable deposit is a stockwork in the northeast part of the circle. Between the 430-ft. and 750-ft. levels its size reaches a maximum, being 1150 ft. long and 720 ft. wide. Below 950 ft. the mineralization is spotted. In 1934 the reserves were 9,000,000 tons of ore with 4.7 dwt. gold and 1.73 per cent copper.

2. ORE PIPES WITH BRECCIATION AND ROTATION OF FRAGMENTS

The Patch (Figs. 1*b*, 3*a* and *b*), near Central City, Colo., is an oval area about 750 ft. long and 450 ft. wide, and is known to extend to the Argo tunnel, at a depth of 1600 ft., its long axis lying nearly vertical. It consists of fractured and partly brecciated rock (Fig. 3*b*). It lies in granite gneiss, intruded by bostonite porphyry, and its breccia consists chiefly of fragments of the gneiss with some porphyry. At places the rock is merely fractured by many fissures; at other places the rock is brecciated and the fragments are well rounded. The minerals include quartz, pyrite, chalcopyrite and tennantite and the values are chiefly gold. The production is small. (Ref. 15, pp. 1–379.)

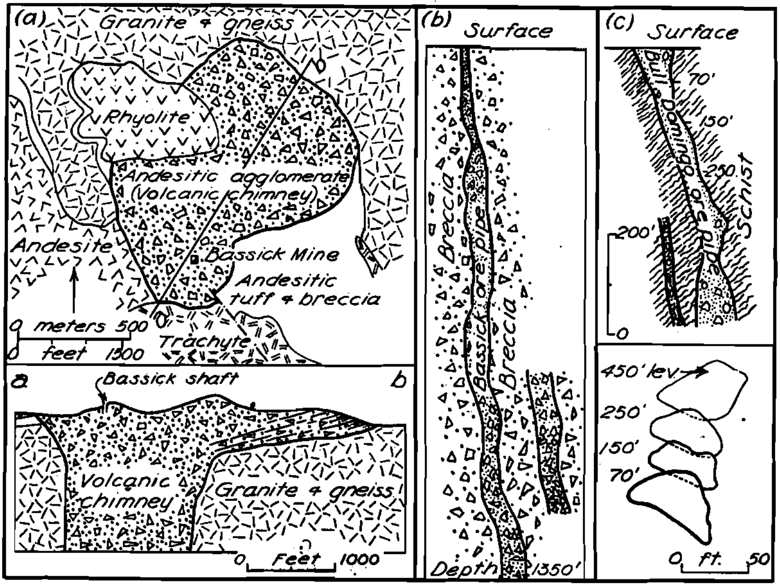

FIG. 5.—ORE PIPES.

a. Volcanic pipe, Bassick Hill, Querida Rosita hills, near Silver Cliff, Custer County, Colorado, with cross section on line *ab*. After Whitman Cross, U. S. Geol. Survey.

b. Cross section showing ore pipe, Bassick mine. After S. F. Emmons.

c. Cross section Bull Domingo mine near Silver Cliff, Colo. After S. F. Emmons.

The Anna Lee[18,19] chimney or stock (Fig. 2*a*) of the Portland mine, Cripple Creek, Colo., follows a basalt dike and extends downward 1130 ft. or more. It is nearly circular in plan and is from 15 to 30 ft. in diameter. It stands almost perpendicular. It is made up of well rounded pebbles surrounded by rock powder, both of which carry about equal amounts of gold. It was mined to the depth of the 900-ft. level of the Portland mine, where metal content declined. The dike it follows is 4 or 5 ft. wide, but at the pipe it expands to a width of 15 ft. or more. The dike cuts andesitic breccia and the ore consists of cemented andesitic breccia and basalt.

The Bassick mine (Figs. 2*b*, 5*a* and *b*), in the Rosita Hills, about 120 miles south and a little west of Denver and 6 miles east of Silver Cliff, Colo., is in a volcanic chimney or neck about 3500 ft. in diameter (ref. 20; ref. 10, pp. 411–472; ref. 9, pp. 863–871). This vent cuts through granite gneiss and Tertiary andesite and is filled with andesitic agglomerate (Fig. 5*a*). The Bassick pipe lies within the agglomerate body and plans show an ellipse about 90 ft. long and 30 ft. wide. The pipe is explored to a depth of 1350 ft. The filling consists of rounded fragments of andesite from 0.4 to 24 in. in diameter surrounded by successive shells of sulphide ore. The chief values are gold and the rich ore carries considerable tellurium.

The Bull Domingo mine (Figs. 2*c* and 5*c*), also near Silver Cliff, Custer County, Colorado, worked a pipe that cuts through granite and gneiss. In plan the pipe is rudely an ellipse with a long axis of about 100 ft. It was developed to a depth of 550 ft. or more. Like the Bassick, the Bull Domingo pipe is filled with rounded fragments of the wall rock surrounded by shells of ore (ref. 10, pp. 439–447).

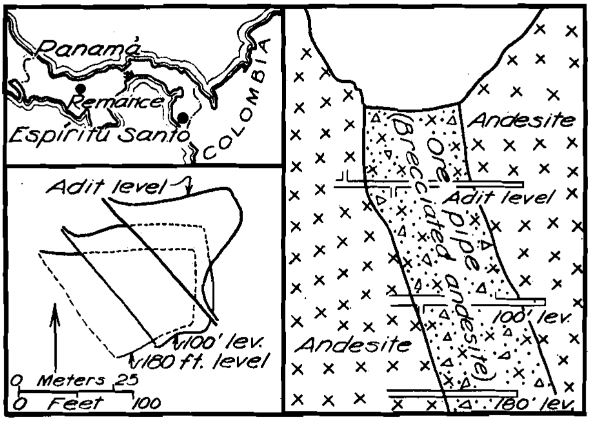

FIG. 6.—MAP AND SECTION ESPÍRITU SANTO MINE, PANAMA. AFTER WOAKES.

The Espíritu Santo mine (Figs. 2*e* and 6) near Cana, Panama, worked a pipelike mass of decomposed andesitic breccia outlined by fracture planes and enclosed in andesitic breccia. The plan of the deposit is rudely circular and is about 110 ft. in diameter. Woakes[21] believed that the deposit fills an explosion pipe. Like the Bassick and Bull Domingo pipes, the ore of the pipe consists of fragments cemented by auriferous sulphides. These fragments are partly rounded, but are more angular than those of the Bassick and Bull Domingo mines. The Espíritu Santo ore also consists of shells of sulphides surrounding the fragments. The chief metal content is gold.

The outward succession of the shells of ore around the fragments of rock in the three mines is:

Bassick: (1) sphalerite, galena, some antimony sulphide; (2) galena (high in gold and silver); (3) sphalerite and pyrite, very rich in gold; (4) a little chalcopyrite associated with quartz and carbonates.

Bull Domingo: (1) sphalerite and galena; (2) galena; (3)carbonates.

Espíritu Santo: (1) pyrite; (2) sphalerite; (3) galena; (4) calcite.

The Cactus mine,[22] San Francisco district, Utah, is 3 miles northwest of Frisco. It lies near the north edge of a stock of quartz monzonite that is 3 miles in diameter, and in an ore zone 2700 ft. long that strikes N.55°W. The ore shoot in horizontal cross section is 800 ft. long and 200 ft. wide. The deposit is a stockwork of monzonite fragments, cemented by ore with copper, gold and silver. In the upper levels the monzonite is broken into irregular fragments from less than one inch to several feet in diameter, some of them so corroded by the ore depositing solutions that they present the appearance of a boulder conglomerate with spaces between the fragments filled with ore and gangue. The ore was worked for copper; it consists of pyrite, chalcopyrite, hematite, sericite, quartz, tourmaline, siderite, anhydrite and barite.

In the Mount Lyell[23,24] district (Fig. 4*c*), 15 miles northeast of Strahan, Tasmania, are the Mount Lyell, North Mount Lyell and Tharsis mines. The country rock consists of mica schists, which, according to Gregory, are altered porphyries. They dip steeply and are faulted against conglomerates. Both are older than the granites that were intruded in post-Silurian time. The Mount Lyell deposit is a short, broad lens of pyritic copper-gold ore 800 ft. long and 200 ft. wide near the surface, but becomes shorter and broader with depth. The North Mount Lyell mine also is a pipe. The ore is brecciated schist and quartzite and is highly siliceous.

At El Chivato[25] mine (Fig. 4*b*), near Talca, Chile, a large granodiorite mass is cut by diorite and by granite. It contains stockworks of crushed and mineralized rock in which are deposited quartz, sericite, chlorite, tourmaline, pyrite and gold. The pipes are nearly upright cylinders. Those mapped by Geier have diameters of about 200, 300 and 500 feet.

At the Whipstick[26] mine (Fig. 4*d*), about 14 miles west of Panbula, southeastern New South Wales, pipelike ore bodies are found in granite near the top of a granitic batholith. The pipes are cylinders only 10 or 15 ft. in diameter and some are followed 400 ft. or more down dip. They branch upward on approaching the contact of granite with overlying rocks. According to Andrews,[26] they were deposited by gases rising from the granite into the overlying granitic hood shortly after it solidified. The metals won are bismuth, molybdenum, silver and gold.

3. Cylindrical Shells of Ore and Other Pipes

The Pilares[27,28,29] mine, Fig. 7*b*, is 7 miles east of Nacozari, Sonora, Mexico, which is 90 miles south of Douglas, Ariz. At the mine a latite tuff overlies andesite tuffs and breccias. Diorite is found in the lower parts of the mine. In plan the deposit forms an ellipse, about 2000 ft. long and 1000 ft. wide. Fractures border an elliptical cylinder with nearly vertical walls, which is developed to a depth of 1800 ft. The walls of the cylinder are fractured and in the fractures copper ore is deposited. The contacts of latite and andesite afford a horizon of reference that shows the amount of downward movement of the material of the cylinder. The average subsidence, as estimated by Bjorge, is 200 ft., although the central region has subsided more than that. The hollow pipe has been regarded as the seat of a volcanic crater, but the contact of bedded lavas passes through the "crater."[27] It could not have been the vent, therefore, for anything except fluids. The fractured and brecciated zone around the walls of the cylinder averages about 50 ft. wide but varies greatly.* It is filled with copper ore, which cements the fragments. The outer wall is sharp, the inner one gradational. A smaller amount of ore is found in the interior of the cylinder. The minerals fill fractures

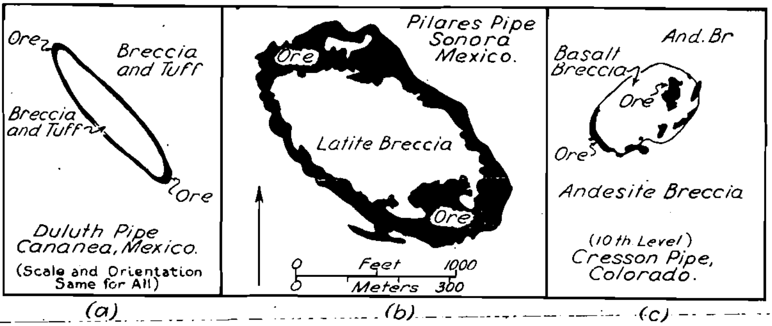

FIG. 7.—PLANS OF ORE CYLINDERS AT CANANEA AND NACOZARI, SONORA, AND THE CRESSON PIPE, COLORADO.
Data from Perry, Locke, Wade, Wandke, Loughlin and Koschmann.

between fragments and to some extent replace them. They include pyrite, chalcopyrite, specularite, quartz and sericite. In upper levels, but chiefly above a depth of 200 ft., there is considerable chalcocite.

D. D. Smyth,[30] geologist for the mine when it closed, who mapped the lower levels, found that the diorite is a sill. He believes that the deposit lies above a concealed cupola of a batholith and that upward pressure from it elevated the cylinder, weakened already by joints. Subsequent contraction caused subsidence of the cylinder. From 1902 to 1925 the Pilares mine yielded 575,000,000 lb. of copper, 4,000,000 oz. of silver and 11,300 oz. of gold, the ore averaging about 2.75 copper. The mine was closed in 1931.

The O.K. mine,[31] San Francisco district, Utah, opened a cylindrical pipe of pegmatitic quartz 100 ft. in diameter, with crystals of quartz 2 ft. long. This pipe lies on a strong fissure and from it, pointing upward like branches of a tree, extend prongs of quartz with some chalcopyrite. The cylinder of quartz contains altered bodies of quartz monzonite

* Pilares (Fig. 7*b*) is a projection and the ore zone is shown wider than it is on any single level.

and it is surrounded by a jacket of altered quartz monzonite, which contains disseminated chalcopyrite. Near one of the quartz prongs there is a mass of high-grade copper ore with sulphides of copper partly oxidized in a quartz gangue.

At Cananea, Sonora, among other deposits there are three types of pipes. The Cananea Duluth pipe in plan is an elliptical ring, 1200 ft. long and 250 ft. wide. It is developed downward as the shell of a "compressed" cylinder 1400 ft. or more (Fig. 7*a*). It cuts through nearly flat-lying volcanic beds.[28,32]

The Capote pipe is a nearly upright cylinder of jumbled and mineralized fragments of quartzite, limestone, granite and porphyries extending to and beyond the bottom of the mine, which is the 1600-ft. level. The

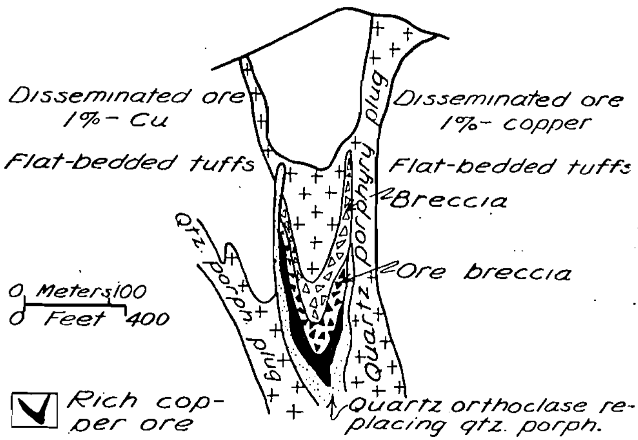

FIG 8.—VERTICAL CROSS SECTION OF COLORADA PIPE, CANANEA, MEXICO. After Billingsley. The rich copper ore consists of chalcopyrite and bornite and is hypogene. The disseminated ore is largely supergene chalcocite ore. The breccia is pyritized sericite rock below commercial grade. Brecciation of ore breccia is in part post sulphide. A cross section at right angles to this would be nearly similar. The various bodies designated are stacked like an inverted nest of cones.

ore is scattered through the pipe in masses and bunches. The pipelike character is maintained in hard, brittle rocks, but above a depth of 400 ft. it cuts through limestone and mushrooms to form large deposits in the limestone.

The Colorada pipe, which is the most productive deposit in the district, is a nest of inverted conical shells nearly surrounded by a plug of quartz porphyry. The plug, according to Perry,[32] cuts through flat-bedded volcanic tuff. The ore body is approximately ring-shaped in plan, about 600 ft. long and 500 ft. wide on level 6. It converges downward and becomes a solid ore pipe (Fig. 8) at level 10. The axis is vertical from level 5 to level 10, but plunges to the northeast below that level. The quartz-porphyry plug surrounds a shell of quartz-orthoclase-phlogopite rock, which is a replacement of the porphyry. Within this shell is the rich, massive ore consisting of bornite, chalcopyrite and molybdenite with some pyrite, tennantite, covellite and chalcocite. Within the shell of rich ore is one of breccia ore, and within that a smaller one of essentially barren breccia that partly encloses quartz porphyry.

4. Metallized Volcanic Vents

The metallized craters or vents treated here include Cerro de Pasco, Braden, Nagy Kirnik (Verespaták), Cresson and probably Stan Trg. Igneous material probably passed upward through all of these vents. Forgan[37] does not state that the Stan Trg pipe is a volcanic vent but he shows that it is an elongated, nearly cylindrical body that contains an andesitic rock surrounded by andesitic breccia.

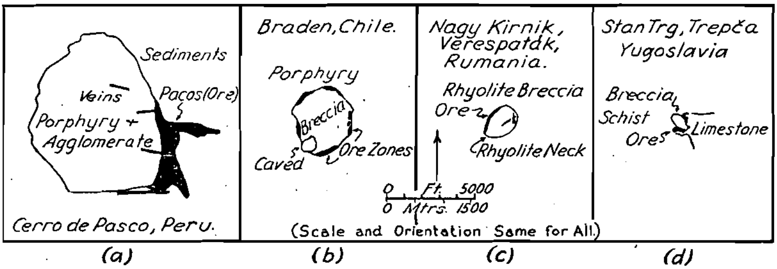

Fig. 9.—Plans of four deposits all probably metallized volcanic vents. Cerro de Pasco (*a*) and Braden (*b*) are surface maps. Nagy Kirnik is plan of Saint Kereszt tunnel. Stan Trg is plan of an upper tunnel. Data from McLoughlin and Bowditch, Lindgren and Bastin, von Palfy and Forgan.

In the Cerro de Pasco[33] region, Peru, a rudely circular mass about 1.4 miles in diameter crops out and is surrounded by invaded limestone, slate and other rocks (Fig. 9*a*). It is composed of a volcanic agglomerate intruded by porphyry and represents the vent of a Tertiary volcano. On the east side of this vent there is a long, wide deposit of material (Pacos) consisting of oxidized silver ore near the surface passing downward into copper ore and into pyrite. The pyrite at places is high in copper and at others is rich in silver, and joining it on the east is a great body of zinc and lead ore. Valuable veins are found in and near the vent.

The Braden (Teniente)[34,35] mine, Chile (Fig. 9*b*), is 70 miles southeast of Santiago at an elevation of 8000 ft. It produces about 226,000,000 lb. of copper annually from ore with 2.18 per cent copper, and has developed 340,000,000 tons of ore. Andesitic lavas are intruded by andesitic and monzonite porphyries and were perforated by a volcanic vent 2600 ft. in diameter. At the same time, the andesite porphyry was brecciated and shattered at the borders of the volcanic vent. Subsequently the crater was filled with tuffs, parts of which are stratified, probably in a crater lake. Subsequently solutions rose into the crater, depositing ore of the main period of deposition in the hollow cylinder of shattered andesite porphyry that surrounds the cylinder of water-laid tuffs. The cylinder of tuffs is at least 2600 ft. long and stands nearly upright. The tuff beds, being less permeable, were little mineralized. Ores of this period carried tourmaline, biotite, pyrite and chalcopyrite and formed large bodies of material with 0.5 to 1.5 per cent copper. After the ore was formed, the Teniente breccia was intruded, forming a hollow cylinder between the ore breccia and tuff beds.

The Teniente intrusion greatly refractured the old cylinder of ore breccia and of ore, making it highly permeable. Tourmalinization followed, altering the Teniente breccia and at places the tuff, but no ore was formed at this time. Following the tourmalinization, granite porphyry breccia also intruded the tuffs. Subsequently ores without tourmaline were deposited. These were not so extensive as those of the preceding period, but locally were rich. The ores include pyrite, chalcopyrite, bornite, enargite, tennantite, quartz, carbonates, anhydrite, etc. A more feeble period of mineralization followed. Subsequently the crater was tilted about 15°. Supergene chalcocitization followed, enriching some of the ore to its present grade.

Nagy Kirnik,[36] Verespaták, Rumania (Fig. 9*c*), differs from Cerro de Pasco, Braden and Stan Trg, in that the breccia is outside of the neck and the neck is rhyolite intruding the breccia. The plan of the vent is oval, the long axis being about 1400 ft. and the short one 1200 ft. The gold ore is found around the north part of the neck and also within it.

In the Stan Trg mine,[37] Trepča, Yugoslavia, 50 miles northeast of Cetinje, a pipe consisting of andesite, nearly surrounded by a breccia composed of schists, quartzite, limestone and rounded andesite fragments breaks through schists and limestones. The core on plan is 800 ft. long and 400 ft. wide and is opened to a depth of 1900 ft. or more (Fig. 9*d*). It leans about 50° from the perpendicular. Although Forgan,[37] to whom we are indebted for an excellent set of maps and cross sections, does not state that the pipe is a volcanic vent, it is pretty clear from his descriptions that it may be one. The ore replaces limestone on the underside of the pipe. The vent itself and the schist above it seem to carry little ore. The deposit replacing the limestone is wide and rich, carrying about 9 per cent zinc, 8 per cent lead and some gold and silver.

The Cresson[38] "blowout" (Fig. 7*c*) is a minor crater in the Cripple Creek crater. The Cresson crater is elliptical in plan in its upper levels, the major axis being about 700 ft. long and the minor one about 500 ft. It is developed to a depth of about 2100 ft. and it lies along a zone of northeast fracturing. The pipe is younger than most dikes outside it. It becomes smaller in depth and divides into two parts on the 1900-ft. level. From 1903 to the end of 1933, the Cresson mine produced $35,331,-783 gold, most of it coming from the crater deposits. This ore averaged

$16.65 per ton. The Cresson pipe is a nearly upright elliptical body of basaltic breccia, which carries a small amount of fragmental andesitic material of the main crater in which it lies. The ore lies in elongated, irregular deposits in and near the contact of the Cresson pipe and the andesitic breccia that surrounds it and lies in irregular bodies within it. The cylinder contracts slightly with depth and dips about 84° south-southeast.

Relations of Pipes to Roofs of Batholiths

As new data on their occurrences are presented, it becomes increasingly probable that most lode deposits are formed by solutions expelled from cooling granitic batholiths. The deposits are found in such definite positions with respect to the roofs of batholiths that any other hypothesis appears unwarranted.

The part played by gases in the volcanic processes becomes more and more evident. In their study of the hot springs of Yellowstone Park, Allen and Day[39] had a hole drilled in Norris Basin to a depth of 265 ft. Steam at a temperature of 205° C. and a pressure of 300 lb. per sq. in. issued from the bore. The steam was difficult to control and from time to time burst through the surrounding ground in new jets. It was considered so menacing that the work was stopped and the hole filled with cement.

It is probable that metals are carried from the parent batholiths as gases. Field studies of the geophysicists lend support to this theory. Discussing the hot springs of Yellowstone Park, Allen and Day[39] say:

> . . . the valuable metals in ore deposits may be transported in a gaseous state. . . . The conception of a continuous gaseous exhalation from a hot body containing volatile matter is not only the simplest but is in agreement with all our knowledge of hot springs, while the alternate view—the transportation of any aqueous solution from the magma to the surface—has so far proved impossible to harmonize with the facts.

This opinion is in harmony with that of Fenner,[40] who believes that the metals depart from the magmas as gases, which later become in part liquid and then deposit ore.

Veins are greatly concentrated near cupolas and fingers of batholiths. Most of them lie almost parallel to the long axes of cupolas, as these are shown on plans.[13] It would be supposed that conical cupolas would have radial vein patterns, but there are very few radial patterns of vein systems. It is probable that explosion pipes may form in areas above conical cupolas. From these the gases escape more violently because the load is less than above an elongated cupola, where larger bodies of rock are affected. The hypothesis is sound mechanically, for the top of an elongated cupola is a line while the top of a conical cupola is a point.

Acknowledgments

This is one of a series of papers on mineral deposits recording the results of investigations that were supported by a grant from the Graduate

School of the University of Minnesota. The drawings are chiefly by Mr. L. K. Lancaster.

References

1. A. Daubrée: *Bull.* Soc. Geol. France (1891) **19,** 317.
2. W. Branco and E. Frass: *Abhand.* k. preuss. Akad. Wiss. (1905) 1–64.
3. K. Hausmann: *Abhand.* k. preuss. Akad. Wiss. (1904) pt. 4, 137.
4. A. Geikie: The Ancient Volcanoes of Great Britain, **2,** 62. 1897.
5. G. W. Rust: *Jnl. Geol.* (1937) **45,** 48–75.
6. S. Weller and S. St. Clair: Missouri Geol. Survey. (1928) [2] **22,** 249–250.
7. J. T. Singewald, Jr. and C. Milton: *Jnl. Geol.* (1930) **38,** 54–66.
8. W. H. Bucher: Rept. of XVI Int. Geol. Cong. (1936) **2,** 1055–1084.
9. J. E. Spurr: The Ore Magnias, Ed. 1, 858–891. New York, 1923. McGraw-Hill Book Co.
10. S. F. Emmons: U. S. Geol. Survey 17th Ann. Rept. (1896) pt. 2.
11. E. de Beaumont: *Bull.* Geol. Soc. France (1847) [2] **4,** pt. 2, 1272.
12. G. H. Morey: *Jnl.* Wash. Acad. Sci. (1922) **12,** 219–310.
13. W. H. Emmons: Gold Deposits of the World. New York, 1937. McGraw-Hill Book Co.
14. H. I. Jensen: *Queensland Govt. Min. Jnl.* (1920) **2,** 186–199.
15. E. S. Bastin and J. M. Hill: U. S. Geol. Survey *Prof. Paper* 94 (1917).
16. F. L. Ransome: U. S. Geol. Survey *Prof. Paper* 75 (1911) 144–147.
17. J. M. Newman and G. F. Brown: *Trans.* Inst. Min. Engrs. (1911) **55,** 439–470.
18. R. A. F. Penrose, Jr.: U. S. Geol. Survey 16th Ann. Rept. (1895) pt. 2, 205–207.
19. W. Lindgren and F. L. Ransome: U. S. Geol. Survey *Prof. Paper* 54 (1906) 447.
20. W. Cross: U. S. Geol. Survey 17th Ann. Rept. (1896) pt. 2, 262–409.
21. E. R. Woakes: *Trans.* A.I.M.E. (1899) **29,** 249–280.
22. B. S. Butler: U. S. Geol. Survey *Prof. Paper* 80 (1913) 172–178.
23. J. W. Gregory: *Trans.* Aust. Inst. Min. Engrs. (1905) **10,** 1–134.
24. W. T. Batchelor: Trans. Aust. Inst. Min. Engrs. (1905) **10,** 108–116.
25. B. Geier: *Ztsch. prakt. Geol.* (1933) **41,** 61–69.
26. E. C. Andrews: New South Wales Geol. Survey *Min. Res.* (1916) **24,** 150–156.
27. W. R. Wade and A. Wandke: *Trans.* A.I.M.E. (1920) **63,** 382–407.
28. A. Locke: *Econ. Geol.* (1926) **21,** 431–453.
29. J. B. Tenney: Copper Resources of the World. XVI Int. Geol. Cong. (1936) 419–424.
30. D. D. Smyth: Quoted by Tenney, ref. 29, 422.
31. B. S. Butler: U. S. Geol. Survey *Prof. Paper* 111 (1913) 517.
32. V. D. Perry: Copper Resources of the World, XVI Int. Geol. Cong. (1936) **1,** 413–418.
33. D. McLaughlin, S. I. Bowditch and Others: Copper Resources of the World, XVI Int. Geol. Cong. (1936) **1,** 516–527.
34. W. Lindgren and E. S. Bastin: Copper Resources of the World, XVI Int. Geol. Cong. (1936) **2,** 459–472.
35. W. Lindgren and E. S. Bastin: *Econ. Geol.* (1922) **17,** 75–99.
36. M. von Palfy: *Mitt. Jahrb.* Ungar. Geol. Reichsanstallt (1912) **18,** 230–526.
37. C. B. Forgan: *Min. and Met.* (Oct. 1936) **17,** 481–484.
38. G. F. Loughlin and A. H. Koschmann: *Proc.* Colorado Sci. Soc. (1935) **13,** No. 6, 252–270.
39. E. T. Allen and A. L. Day: Carnegie Inst. of Washington *Pub.* 466 (1935).
40. C. N. Fenner: In Ore Deposits of the Western States, 104. New York, 1933. A.I.M.E.

diatreme breccia. Figure 22. Selected styles and geometries of epithermal deposits to illustrate influence of structural, hydrothermal and lithological permeability. Typical examples: massive vein - Umuna (papua New Guinea); vein swann - Waihi (New Zealand); stockwork - Bellavista (Costa Rica); shallowly dipping veins abutting a ring fault - Emperor (Fiji); hydrothermal breccia -Choque1impie (Chile); residual vuggy si1ica - Kasuga (Japan); dispersed in penneable rock beneath an aquitard - Round Mountain (Nevada)Â At Summitville, highly silicified ore zones form irregular, steeply dipping pods, pipes, and tabular bodies.Â Gold and gold-bearing minerals in epithermal gold deposits are mostly fine-grained and dispersed. 10. Collapse breccia pipe deposits: Deposits in this group occur in circular, vertical pipes filled with down-dropped fragments.Â Under certain conditions uranium minerals may also crystallize in an oxidizing environment when complexing agents such as vanadium compounds are present to fix the uranyl-ion in the form of uranyl vanadates which are fairly stable in oxidized rocks.Â Mineralization in volcanic deposits is largely structure bound, occurring in intrusive veins or stockworks in volcanic intrusions, diatremes, and flow or bedded pyroclastic units.Â Ore lodes consist of gold-bearing metasomatic rocks intersected by thin brannerite stringers and a younger generation of small quartz and carbonate veinlets with pyrite, native gold, native silver, and acanthite.