GEOLOGY OF THE FURNACE CREEK BORATE AREA, DEATH VALLEY, INYO COUNTY, CALIFORNIA

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GEOLOGY OF THE FURNACE CREEK BORATE AREA, DEATH VALLEY, INYO COUNTY, CALIFORNIA

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INTRODUCTION

Desert scenery of both colorful and dismal rocks has long surpassed borax as an attraction to the Furnace Creek area, which is on the eastern side of Death Valley. Yet borate deposits that were major producers in the 1920s, and other deposits lying discontinuously in the rocks between the black-capped Greenwater Range at Ryan and the mustard-colored hills by the salt flats, still contain borates for future needs. The geology of the area was therefore mapped in some detail. The map sheet shows which rocks contain the exposed borate deposits and how the rocks lie, to help in the search for concealed deposits. The map thus contributes for specialists a small portion of geologic groundwork in the region, but it also offers to inquiring minds of visitors some information about conspicuous elements of the scenery—bare rock and stark mountains.

The main features of the geology shown on the map are visible from the roads. The Precambrian and Paleozoic rocks of the Funeral Mountains extend into the northeastern margin of the area as far as the foot of the mountains. Here light-colored Tertiary rocks of the Furnace Creek Formation are faulted against the somber Paleozoic rocks and are capped at the eastern end of the area by dark volcanic flows and conglomerate of the Funeral Formation. The Furnace Creek Formation is gently folded beneath the broad valley of Furnace Creek, where much of it is masked by Quaternary gravel. The formation is tilted steeply along faults on the northeastern side of the valley and along the southwestern side in the Black Mountains. The tilting and displacements along many faults in the Black Mountains and near Ryan made a complex pattern of the colorful greenish, pinkish, yellowish, and brown rocks of the underlying Tertiary Artist Drive Formation. The sedimentary rocks change along the beds or interfinger with different kinds of sedimentary and volcanic rocks. In the Black Mountains of the southern part of the area, the sedimentary Tertiary rocks end as they interfinger with both dark and pale volcanic rocks.

In the Furnace Creek Formation, the principal borate deposits are in continental sedimentary rocks and are generally near the base of the formation. Smaller borate deposits are in some basaltic rocks and gypsiferous beds higher in the formation. The largest extensively mined deposits are in the rubble-strewn west flank of the Greenwater Range, at sites marked by conspicuous mine dumps between Ryan and the Widow mines east of Dantes View road. Other borate deposits are irregularly distributed for 18 miles along the favored zones in the Furnace Creek Formation as far north as Mustard Canyon. Hillside exposures of white borates are readily seen at Monte Blanco from the Twenty Mule Team Canyon road and more distantly in Gower Gulch from the road at Zabriskie Point.

The map is a product of the cooperative program of the California Division of Mines and Geology with the U.S. Geological Survey. Constant support and essential improvements were contributed throughout the project by Ward C. Smith of the Geological Survey. The field work was facilitated at different times from 1955 to 1960 by the following colleagues: C. J. Bowser, H. D. Drewes, W. B. Rogers, G. C. Cone, and D. W. Reeser. Major contributions include the geologic background provided by T. P. Thayer in a field review of his earlier work (*in* Noble, 1941,

p. 954–957); the exacting work on diatoms by K. E. Lohman to determine the age of Tertiary formations; identifications of Cambrian and Ordovician fossils in collections from the part of the area in the Funeral Mountains by A. R. Palmer, R. J. Ross, Jr., and Ellis Yochelson; the collaboration by R. C. Erd on borate mineralogy; and the improvement of the manuscript by the critical review of W. C. Smith and D. C. Ross. Other persons too numerous for individual acknowledgment gave valuable aid. The United States Borax & Chemical Corp. and the Kern County Land Co. granted permission for work on their mining properties. The National Park Service approved working in the large part of the area within Death Valley National Monument, where staff members were cordially helpful.

PRECAMBRIAN AND PALEOZOIC ROCKS

The oldest rocks in the area are in the Funeral Mountains. The sedimentary sequence extends concordantly from the youngest Precambrian into the oldest Paleozoic rocks and continues in geologic age through the Cambrian and Ordovician. A few structurally isolated blocks represent the Silurian and Early Devonian. In general terms of years, these sediments accumulated within the interval from somewhat more than 600 million to perhaps 400 million years ago.

The sediments were deposited in seas that spread over the Death Valley region and far across Nevada. At first predominantly siliceous clastic sediments accumulated as sand and mud, but soon after the Early Cambrian Epoch carbonate constituents of limestone and dolomite became dominant. Some distinctive beds of contrasting rocks—limestone or dolomite in the lower part, and quartzite or sandstone and shale in the upper part—relieve the lithic monotony. The marker beds and marine fossils diagnostic of the geologic age are most useful guides in mapping parts of the rock sequence. Their persistence through many a mountain range greatly aids in correlating the parts beyond each desert basin, and their wide distribution indicates the vastness of the ancient seas.

The Wood Canyon Formation, of Precambrian and Early Cambrian age, in the northeastern segment of the map area, forms the least conspicuous olive-gray slopes on the flank of the Funeral Mountains. The Wood Canyon consists of generally dark interlayered shale, siltstone, and quartzite, in which a few beds of lighter, brownish-weathering dolomite or limestone distinguished a lower member (p€wl) and an upper one (€wu) from a more quartzitic middle member (€pCwm). The oldest Cambrian trilobites first appear in the regional correlative of the middle member, and Early Cambrian archaeocyathids as well as olenellids are widespread in the upper member, so that by convention the ages of the three members in ascending order are designated Precambrian, Precambrian and Early Cambrian, and Early Cambrian. The top of the Wood Canyon is well outlined by the Zabriskie Quartzite's contrastingly lighter color.

The Zabriskie Quartzite (€z), of Early Cambrian age, is generally shattered here by faulting and forms rough steep slopes, where it weathers from very pale orange to brown. The fresh quartzite is commonly pale red, ranging from vitrually white to grayish red. Although diagnostic fossils have not been found anywhere in the Zabriskie, those above and below limit the age to Early Cambrian.

The Carrara Formation (€c), of Early and Middle Cambrian age, displays the transition from siliceous clastic to carbonate rocks, apparent even from a distance, by a diversity of colors and varied relief of different layers. In the lowest part of the Carrara, light-colored quartzite and dark shale resemble rocks in the underlying Zabriskie and Wood Canyon Formations, whereas silty limestone in the highest part resembles limestone in overlying formations. Three prominent sets of limestone beds, separated by predominantly shaly and silty beds, stand out as ridges or as ribs on steep slopes. The two lower sets are conspicuously gray, but the highest is partly subdued by brown-weathering clastic material. Much of the limestone, either silty or purer, contains concentrically structured ovoids as much as two inches long, generally attributed to the alga *Girvanella.* Diagnostic trilobites in particular beds well spaced through the Carrara make it one of the most significantly fossiliferous formations in the section. They demonstrate that the lower part is Early Cambrian and the upper part is Middle Cambrian (A. R. Palmer, written communications, 1957–1965).

The Bonanza King Formation, Middle and Late Cambrian in age, is distinguished on mountainsides by broad bands and narrow stripes of dark- and light-gray dolomite and limestone. The lower part, generally dark, makes up the Papoose Lake Member (€bp). The upper part, of contrastingly light and dark layers, constitutes the Banded Mountain Member (€bb). The pattern of the layering in the Banded Mountain Member is uniform for many miles, and some parts of it are traceable across the region. The base of the Banded Mountain Member is defined by conspicuous brownish-weathering clastic beds, which are a regional stratigraphic key, lying somewhat below the middle of the Bonanza King. In the Funeral Mountains, Middle Cambrian trilobites have been collected from these beds and from similar but much less conspicuous beds in the lower part of the Papoose Lake Member. No younger fossils have yet been found here in the Bonanza King Formation.

The Nopah Formation (€n), of Late Cambrian age, resembles the underlying Banded Mountain Member in that it consists of dark- and light-gray layers of dolomite above brownish-weathering clastic beds at the base. But the combination of light and dark gray is different from that of the Banded Mountain and may vary from place to place. The basal shale and silty limestone beds are persistently fossiliferous throughout the region and beyond, containing species of trilobites and acrotretid brachiopods diagnostic of a Late Cambrian age. The main, lower part of the basal unit is equivalent to the Dunderberg Shale, a formation of long standing in east-central Nevada. Dark dolomite above the middle of the Nopah Formation contains small silicified gastropods and another mollusk, the singular *Matthevia* Walcott, that are also Late Cambrian (Yochelson and others, 1965).

The Pogonip Group (Op), here of Early and Middle Ordovician age, includes limestone or dolomite, shale, siltstone, minor sandstone or quartzite, and some cherty beds in distinctive combinations that at other places are designated formations, and even members of a formation. The lowest dolomite or limestone, although somewhat gradational with the underlying Nopah, contains enough iron-bearing silt or other clastic material to add a light-olive or brownish tinge to the gray of the Pogonip. Within the lower part, shaly and silty beds are concentrated in a thin but readily discernible light-brown or grayish-orange zone in the carbonate rock. The middle third of the Pogonip Group consists of thicker similar zones interlayered with darker brown siliceous zones and gray carbonate rock. The shaliest layers, lightest in color, make notches on spurs and benches on mountainsides, supported by brown or gray ledges and crags. The upper third of the Pogonip consists mainly of cliff-forming dark- to medium-gray limestone or dolomite, tinged brown or pale red, but the topmost beds are varied and more colorful. The Early and Middle Ordovician age of the entire Pogonip Group in the southern Funeral Mountains is well documented by R. J. Ross, Jr. (written communications, 1962–67; 1967, p. D32–D34), who shows that the few trilobites collected from the lowest part are clearly Early Ordovician, although not of the earliest, and that abundant brachiopods and trilobites from near the middle of the Pogonip mark the change from Early to Middle Ordovician. The most conspicuous fossils are large gastropods, which occur widely in the upper, cliff-forming limestone or dolomite.

Three younger formations of Paleozoic rocks, although remaining closely associated, are broken up in faulted masses and ancient landslides widely spaced along the range front from Travertine Point to about two miles northwest of Echo Canyon. The fault boundaries of the formation blocks are much too generalized on the map to express the true disorder. The Eureka Quartzite (Oe), of Middle Ordovician age, is characterized by nearly white, pure quartzite in the upper part and brown-weathering quartzite and thinly interbedded less coherent, finer grained clastic rocks in the lower part. The Ely Springs Dolomite (Oes), of Middle and Late Ordovician age, consists of somewhat cherty dark-gray dolomite that contrasts sharply with the underlying Eureka and contains at the top some lighter gray dolomite, which outlines the boundary with the overlying dark part of the Hidden Valley Dolomite (DSh). Light-gray dolomite in the Hidden Valley is conspicuously thick above the dark cherty dolomite in the lower part of the formation. No Paleozoic formations younger than the Hidden Valley Dolomite, which is Silurian and Early Devonian in age, extend into the map area, although Middle and Late Devonian and Early Mississippian formations remain farther east in the Funeral Mountains. The younger formations contributed to the Cenozoic sediments.

CENOZOIC ROCKS

Long after the Paleozoic seas withdrew from the region and after the record of Mesozoic events here was obliterated, Cenozoic rock materials accumulated in a continental environment of basins among rugged mountains. Torrential streams carried muddy gravel from the mountains to gentler slopes in dry basins or into the margins of lakes. The finer sediments were distributed more evenly in lakes that fluctuated for long intervals over the length of the area and farther southeastward. Lakes in the area during the Tertiary Period occasionally became saline enough to precipitate calcium carbonate in widespread but irregular beds, limited dolomite, some gypsum also in beds, and easily soluble salts dispersed in the fine sediments. The lakes left no beds of rock salt or more soluble evaporites here although some accumulated in lower basins beyond. While Paleozoic rocks of the Funeral Mountains were providing sediments from the north, volcanoes erupting in the Black Mountains and the Greenwater Range supplied much more material. This material was washed down or settled as volcanic ash directly into the lakes or remained around the volcanoes as tuff-breccia, solidified lava flows, and intrusions.

Artist Drive Formation

The Artist Drive Formation is the oldest Tertiary formation in the Furnace Creek area, its age extending back from early in the Pliocene Epoch to perhaps the Oligocene. The base of the Artist Drive remains covered in the area, but southward in the Black Mountains equivalent volcanic rocks rest on exposed Precambrian metamorphic rocks. The typical Artist Drive Formation, as designated originally by T. P. Thayer (*in* Noble, 1941, p. 955; oral communication in the field, 1954), stands out imposingly along the mountain front north of Artists Drive and surmounts the crest of the Black Mountains. The thickness of the formation, according to sections derived from the geologic map, exceeds 4,000 feet. The Artist Drive Formation is divided into five successive parts, or informal members. Two massive pyroclastic members of vivid colors separate three well-stratified sedimentary members.

The lower sedimentary member (Tal), which is nearly half the thickness of the Artist Drive Formation, consists of brown-weathering mudstone, sandstone, and conglomerate. The brown color generally ranges from light brown to grayish orange, but some is grayer and much is redder, as seen in the hills north of the side road to Ryan. Most of the clastic constituents are the sizes of sand, silt, and clay and are cemented by calcite. Calcareous sandstone at some places grades into sandy limestone. Pebbles and cobbles are scattered through some of the finer grained sedimentary rocks or concentrated into conglomerate lenses or beds that are rarely more than a few inches thick in the Black Mountains but as much as 400 feet thick north of Ryan. The pebbles and cobbles consist of Paleozoic limestone, dolomite, and quartzite; granitic rocks like those in the region's intrusions of quartz monzonite, syenite, and gabbro; and coarse-grained marble along with a few other contact-metamorphic rocks. No source for these is known in the Black Mountains or the Greenwater Range, where only Precambrian and Cenozoic rocks are visibly in place.

The lower pyroclastic member of the Artist Drive Formation (Tapl) is a massive unit of tuff-breccia about 500 feet thick. The fragmental volcanic rock is well lithified, at least partly by alteration to the zeolite clinoptilolite. The most distinctive aspect of the member is green and buff coloration. The green is pale blue green approaching very pale green in the isolated hills south of the Dantes View road junction or grayish yellow green near the northwestern end of the Black Mountains. The buff part, lying above the green or distributed irregularly through it, is very pale orange or grayish orange.

The middle sedimentary member (Tam), about 600 feet thick near the northwestern end of the Black Mountains, is generally an olive color or a light brown; the olive ranges from pale olive and greenish gray to yellowish gray and light greenish gray. The unit consists of mudstone, sandstone, and conglomerate, containing at some places basalt as fragments in a calcareous mudstone or as thin flows or sills. The finer grained sedimentary rocks contain much volcanic tuff, whereas the conglomerate has the same kinds of nonvolcanic constituents as the conglomerate in the lower sedimentary member.

The upper pyroclastic member (Tapu) consists of massive tuff-breccia about 350 feet thick. The lowest part is pale blue green, resembling the lower pyroclastic member, but most of it is a distinctive grayish pink. It grades upward into very pale orange and is somewhat browner at the top. The pink and green pyroclastics, contrasting with dark basalt in jumbled masses of the member, compose the Artists Palette, a scenic point on Artists Drive.

The upper sedimentary member (Tau) comprises well-stratified rocks, about 800 feet thick, that are the most varied in color and lithology of the Artist Drive. Brown, in many variations, is the commonest color of the weathered rocks and is uniformly darker in the lower part, which contains conglomerate and basalt. But greenish and reddish colors of volcanic detritus in freshly exposed lacustrine sandstone and mudstone are increasingly conspicuous upward. The volcanic constituents of some of the lake beds grade laterally southeastward into coarse pyroclastics south of Corkscrew Canyon.

Felsite and basaltic rocks recur as flows, sills, dikes, and volcanic necks in different parts of the Artist Drive Formation. The felsite (Taf) is generally light brownish gray and has flow laminae. The basaltic rocks (Tab) are darker gray, commonly tinged green or olive. Some of the basalt is conspicuously porphyritic from large phenocrysts of calcic plagioclase, but much of it is finer grained and indistinguishable from basalt in the Furnace Creek Formation.

The age of most of the Artist Drive Formation has not yet been clarified by fossils. The only fossils known from the lower part of the Artist Drive are fish (Noble, 1941, p. 955) that remain undiagnostic of the age within the Tertiary. Previous assignment of an Oligocene age by the tentative correlation (Noble, 1941, p. 956) with the Titus Canyon Formation of Stock and Bode (1935), which 25 miles north of the Black Mountains contains Oligocene mammal fossils, is tenuous. Nevertheless, an Oligocene age of the lower part of the Artist Drive is still possible.

The terms Oligocene, Miocene, and Pliocene in the text and explanation of the map follow the usage with the North American mammalian stages and ages. The Pliocene Epoch by this usage arbitrarily contains the Clarendonian, Hemphillian, and Blancan Ages respectively in the early, middle, and late parts.

The first direct clue to the age of any part of the Artist Drive Formation, from fossils collected in the area, is contributed by Kenneth E. Lohman. Along with Thomas P. Thayer in 1938, he collected samples 150 feet below the top of the Artist Drive Formation, at an outcrop 5,000 feet in a straight line S. 4° W. from the west junction of the Twenty Mule Team Canyon road. On examining the samples to assist the borate project, he found diatoms, the first from the Death Valley area. All the identified forms in the scrappy assemblage of highly altered diatoms, according to Lohman's written communications (1954, 1961, 1967, on USGS diatom loc. 3967), are still represented in living assemblages elsewhere, with one exception, a species known in late Miocene beds in Humboldt County, Nevada, but dominant in an early Pliocene (Clarendonian) formation in Nye County, Nevada. Two of the genera, which he has not found in strata older than early Pliocene, have a known geologic range of early Pliocene to Holocene. Therefore, according to Lohman, the best age assignment for the assemblage of 11 diatom genera from the uppermost part of the Artist Drive Formation is early Pliocene (Clarendonian).

Furnace Creek Formation

The base of the Furnace Creek Formation is marked by a conglomerate member (Tfc) composed of detritus from the Artist Drive Formation in the southwestern part of the area and from Paleozoic rocks in the Funreal Mountains. The basal conglomerate lies concordantly on the uppermost member of the Artist Drive in the Black Mountains, but a few exposures in the valley west of Ryan show the conglomerate on the middle member or the lower pyroclastic member of the Artist Drive. In the Funeral Mountains, the basal conglomerate rises stratigraphically as the Furnace Creek Formation laps higher over the Paleozoic rocks of the basin's side. The conglomerate unit in a measured section across Twenty Mule Team Canyon is nearly 400 feet thick in 3,400 feet of incomplete Furnace Creek Formation. The total thickness of sedimentary rocks in the formation, as derived from structure section B-B′, is about 7,000 feet.

The most characteristic, borate-bearing part of the Furnace Creek Formation, as exposed along Furnace Creek Wash from the floor of Death Valley to the Greenwater Range, is conspicuously made up of light-colored fine-grained rocks derived from lake sediments and darker, more variegated, coarser rocks derived from stream sediments. The sedimentary rocks end southeastward along the flank of the Black Mountains, where they interfinger abruptly with volcanic rocks. These pyroclastic rocks and flows of vitrophyric and basaltic rocks are retained, in accordance with early definitions (Curry *in* Axelrod, 1940, p. 527-528; Thayer *in* Noble, 1941, p. 956), as a major part of the Furnace Creek Formation. Three kinds of volcanic rocks, which recur in the sequence, are distinguished as map units.

Pale volcanic rocks in one of the map units (Tfp) are mostly pyroclastic but include some vitrophyre and vitrophyre breccia. Thick, well-lithified pyroclastic masses of pumice, vitrophyre, and felsite show no internal layering of the tuff-breccia, unlike some of the thinnest sheets that contain stratified volcanic conglomerate and sandstone deposited by streams between basalt flows. The color, although variegated in detail, effectively is greenish gray or pale orange and grades into lighter tints. The vitrophyre is gray, except where altered to pale red or virtually white, and is much less conspicuous than the other volcanic rocks on the northeastern flank of the Black Mountains.

Basaltic rocks (Tfb) in flows and intrusions make up the darkest masses in the Black Mountains and extend as layers into the light-colored sedimentary part of the Furnace Creek Formation. Close inspection shows that the gray color is commonly tinged green or olive from some alteration of the dark minerals, and many vesicles are lined if not filled with zeolites, calcite, or borate minerals at some places. The basalt contains generally calcic plagioclase and varied proportions of clinopyroxene, generally much altered olivine accompanied at places by extraneous quartz, and magnetite. Some of the basalt in contact with lacustrine mudstone is altered and veined by analcime. The map unit (Tfb) includes minor reddish scoria and gray pyroclastic basalt closely related to the ancient vents.

Another map unit (Tfa) consists of greatly altered fragmented basalt in large masses transgressing the mudstone sequence of the Furnace Creek Formation or in layers extending concordantly into it. Internal stratification, where discernible, is indistinct, and the unsorted or poorly sorted fragments range commonly from sand to pebble sizes. The rock in outcrops is distinctively colored pale olive to light olive gray or dusky yellow and is poorly coherent. It now consists of analcime and montmorillonite, according to X-ray diffractometer charts, but a few pieces of fresher basalt remain scattered through some of the masses. The fragmented basalt, probably from explosive eruptions through a saline lake, filled small vents and spread over the surrounding lake bottom. It contains basalt dikes, some of which are not distinguished on the map, and local concentrations of gypsum (including very coarse selenite) or borate veins.

Lacustrine mudstone and sandstone are prevalent in the main part of the Furnace Creek Formation (Tf). The light colors of these well-stratified rocks, ordinarily yellowish gray to light greenish gray or very pale orange in outcrops and shallow mine workings, have changed from darker colors, ranging from dark greenish gray to dark gray, seen in some deeper mines and drill cores. The constituents are clay minerals (montmorillonite and illite, in samples examined by John B. Droste, written communication, 1960) and predominantly volcanic debris cemented by calcite. Salines dispersed through mudstone are apparent to the taste and as efflorescent accumulations under the mud crusts produced by weathering.

A few beds of tuff, limestone, and minor dolomite, along with some conglomeratic or gypsiferous beds that are not distinguished from the main unit, are interstratified with the mudstone and sandstone. The tuff, in extensive beds as much as two feet thick but mostly a few inches thick, lacks calcite cement and is generally altered to clinoptilolite. A conspicuous color of the tuff is very pale blue green, but most of the tuff is very light gray tinged pinkish or yellowish and nearly white. Limestone in discontinuous beds grades from the cleanest limestone, showing algal structure in laminated beds and knobby columns, to marlstone and calcareous sandstone. Some of the thinly stratified limestone was broken into flat-pebble conglomerate. The rare dolomite is very fine grained, clay-bearing, and nearly white. No beds of salines are exposed. The principal borate deposits are widely distributed in the stratigraphically lowest part of the main unit and in some of the underlying muddy or calcareous conglomerate.

Gypsiferous beds are mapped as a member (Tfg), generally 100 to 200 feet thick, within the main part of the Furnace Creek Formation. The gypsiferous member forms the crest of the ridge between Twenty Mule Team Canyon and Furnace Creek Wash and continues westward, although interrupted by faults, along the highest ridge between Zabriskie Point and Gower Gulch to the floor of Death Valley. The member as mapped in widely separate places, such as in the East Coleman Hills, west and north of Navel Spring, and along Furnace Creek Wash northwest of Ryan, is perhaps not at the same stratigraphic horizon. Rough or knobby limestone at some places is closely associated with the top of the gypsiferous beds. Thin beds of granular gypsum, recrystallized to many sizes of grains and retaining some granular anhydrite, are interlayered with little or much mudstone in the member. Veins of fibrous gypsum are abundant. The gypsiferous member contains small quantities of borates widely distributed in the area.

The upper member of the Furnace Creek Formation (Tfu) is marked by distinctive pumiceous tuff beds overlain by light-colored mudstone. The member is generally about 350 feet thick, but thickens to as much as 800 feet. The white or pale orange-tinted tuff is mostly fine grained (sand and finer sizes) but at many places contains pebble-size fragments of pumice. Despite varied amounts of calcite cement, it is generally softer than the tuff beds in the lower part of the formation. Some thin beds of tuff are irregularly opalized at the eastern end of the area, where a thermal-spring environment during sedimentation is indicated by certain diatoms, according to K. E. Lohman (written communications, 1967), and by traces of certain elements in the locally manganiferous beds, according to D. F. Hewett (oral communications, 1967). The mudstone, which contains some swelling clay and a few thin beds of pale limestone and dolomite, grades into beds of sandstone and conglomerate.

Upper conglomerate members of the Furnace Creek Formation (Tfcu) intertongue with the finer grained rocks through much of the sedimentary sequence of the formation above the basal conglomerate, but most of the large masses are in the upper part. The occurrence of conglomerate is not as clear-cut as shown by the map; for example, gravelly mudstone is abundant between the conglomerate members mapped on the Death Valley side of the Black Mountains, and fine-grained sediments are abundant in the conglomerate member southeast of Zabriskie Point. Nevertheless, the conglomerate member as outlined from Texas Spring Camp Ground southeastward past Zabriskie Point depicts a tilted alluvial fan extending northeastward into lake sediments that tongue into the fan. The conglomerate is a poorly sorted mixture of fragments that range in size from boulders to clay. The predominance of the coarser sizes commonly decreases gradually both vertically in the sequence and laterally. An outstanding exception is exposed in the Hole in the Wall, where coarse fluvial conglomerate abruptly intertongues with lacustrine mudstone. The conglomerate here continues upward to the top of the Furnace Creek, where it takes the place of the upper finer grained member northeast of Navel Spring and again southwest of Travertine Point. The conglomerate along the Funeral Mountains was derived from pre-Tertiary sedimentary rocks, whereas the conglomerate along the Black Mountains was derived from Tertiary volcanic and sedimentary rocks, including the great variety of pre-Tertiary rocks reworked from conglomerate in the Artist Drive Formation.

The age of the Furnace Creek Formation, according to K. E. Lohman's diagnosis (written communications, 1961, 1967) of his diatom collections in terms of the North American mammalian chronology, is clearly middle Pliocene (Hemphillian) for the uppermost part of the formation and less definitely early Pliocene for the lower part. His lower collection (USGS diatom loc. 4159, foot of the Black Mountains 2.56 miles in a straight line S. 36° W. from Navel Spring) contains one extinct species having a known range of late middle Miocene to early Pliocene and two genera having ranges in nonmarine sediments from early Pliocene to Holocene; the combination thus suggests for the lower part an early Pliocene age (K. E. Lohman, written communication, 1967). The only significant fossil previously reported from the Furnace Creek Formation was found in about the same part of the formation at a locality for leaf fragments discovered by H. D. Curry (Axelrod, 1940, p. 526), almost 3 miles north-northwest of the diatom locality. From the impression of one diagnostic leaf fragment, Axelrod (1940, p. 531) derives an age probably not older than late Miocene or younger than early Pliocene. Mammal tracks in beds correlated with the Furnace Creek Formation, but isolated in Copper Canyon 10 miles south of the area, were found by Curry (1941), who states, ". . . preliminary study of the size of the horses as well as other diagnostic features of the fauna [as indicated by the footprints] suggests that the age of the Copper Canyon beds is middle Pliocene." Lohman's diatom collections from the uppermost part of the Furnace Creek (locs. 4070 and 4357, in the hills along the south side of California Highway 190 between Travertine Point and the east boundary of Death Valley National Monument) contain abundant and well-preserved assemblages extraordinarily similar to a diatom assemblage from the San Pedro Valley, Arizona, beds that have yielded a vertebrate fauna of middle Pliocene (Hemphillian) age (John Lance according to Lohman, written communications, 1967). Lohman concludes: "Based upon the known geologic ranges of many of the diatom species in the assemblages from localities 4070 and 4357, plus the very close similarity to the well-dated San Pedro Valley material, an age assignment of middle Pliocene can be made with considerable confidence."

Funeral Formation

The Funeral Formation of conglomeratic and basaltic rocks lies on the most conspicuous angular unconformity within the Tertiary sequence in the area. Basalt flows capping the Greenwater Range from Travertine Point southward past Ryan lie across the deformed and eroded Furnace Creek and Artist Drive Formations. The angularity at the contact disappears northwestward where conglomerate and pebbly or sandy mudstone of the Funeral were deposited along a trough in the Furnace Creek Formation. The thickness of the sedimentary part of the formation in structure sections near Death Valley is between 1,000 and 1,500 feet, whereas between Navel Spring and Travertine Point it is about 700 feet. The thickest exposure of volcanic flows, a mile east of Ryan, is about 500 feet.

The characteristic sedimentary part of the Funeral Formation (QTf), as exposed between Travertine Point and Navel Spring, consists of poorly sorted, indistinctly stratified conglomerate of pebbles, cobbles, and boulders in a mud and sand matrix. It is lithified sufficiently to stand in cliffs, particularly where supported by spring travertine and vertical calcite veins. The constituents here are from the Furnace Creek Formation and Paleozoic rocks in the Funeral Mountains, whereas along the road to Dantes View they are entirely of volcanic rocks—basalt from the Funeral Formation in the Greenwater Range and silicic volcanics from the Black Mountains.

A lower member (QTfl) consists mainly of gravelly sandstone and mudstone that grades into conglomerate or sandy mudstone in the northwestern part of the area near Death Valley and attains a thickness of a thousand feet, as shown in structure sections. It contains some isolated, very light colored limestone deposited by springs. The member intertongues into conglomerate of the upper Funeral, as readily seen around the lookout hill northwest of Texas Spring. Sandy mudstone in the lower member is distinguished from underlying Furnace Creek Formation by the Funeral's pinkish, brownish, and grayer tinges. At the eastern end of the area (north and east of Travertine Point), well-lithified sedimentary breccia (QTfx) and conglomerate, partly interlayered between giant landslide blocks of Paleozoic formations, are assigned somewhat questionably to the lower member of the Funeral. Similar jumbles of blocks, or megabreccias, extend into the Furnace Creek Formation around the Red Amphitheater and across the deformed Furnace Creek Formation farther northwest along the foot of the Funeral Mountains. The main conglomerate of the Funeral, in which basalt flows end, laps over the breccias near Travertine Point.

Lava flows in the Funeral Formation consist of olivine-phenocryst basalt (QTfb), which is fresh gray compared with the greenish-tinged gray of most of the basalt in older formations and lacks the conspicuous vesicle fillings. An exception exposed at the highway 1½ miles west of Travertine Point is greenish-gray altered basalt in a thin layer that extends into conglomerate of the Funeral. The usual color is medium to dark gray or brownish gray, made darker by a film of desert varnish after long exposure. A characteristic sample of the fresh basalt, collected about a mile southeast of Travertine Point, is microcrystalline except for about 2 percent olivine phenocrysts, commonly 0.5 to 1 mm in diameter, ten times larger than the olivine and clinopyroxene grains in the groundmass. The mineral composition is 63 percent plagioclase (labradorite), 30 percent total olivine and clinopyroxene, and 7 percent magnetite.

Basaltic agglomerate (QTfa) centered at explosive vents of the basalt consists of red scoria, some volcanic bombs, and breccia. The agglomerate, where it was solidified by basalt permeating a volcanic throat or reinforced by basalt dikes, has resisted erosion and stands out in relief against the surrounding agglomerate and flows. Shapes that resemble small volcanoes are merely resistant cores. Thin layers of scoria and breccia, as well as basalt dikes in agglomerate, are not distinguished on the map.

Surficial Deposits

Deposits that conceal the Funeral or older formations and express to some degree their original topography are grouped here as surficial deposits. Boundaries between the units of the group, as well as between them and the older rocks, are derived from aerial photographs. Differences between some of the units are gradational and difficult to apply uniformly. Talus rubble is not shown separately, but where it effectively conceals geology, the rubble is shown as the alluvium with which it merges. Remnants of old alluvium are not distinguished from the underlying Funeral Formation midway between the Funeral Mountains and Death Valley at the northern end of the area, and none of the basalt alluvium and rubble veneering much of the basalt in the Greenwater Range is shown at the eastern end. Most of the mapped alluvium is a thin cover (a few tens of feet or less) on pediments under present stream channels and on pediments that were left as alluvium-covered terraces by faults along the edge of the Death Valley floor and by intrenchment.

Alluvium is mapped in two generalized units. The alluvium in each unit was deposited by streams during immensely different lengths of time. The older alluvium represents the vastly greater span. The older alluvium (Qao) upstream is generally much dissected in a series of terraces, the highest of which is as much as 500 feet above the nearby valley floor, yet some parts of the older alluvium downstream coincide with or are covered by the younger alluvium. The surface of the older alluvium has been smoothed by the breaking down of coarse material and the development of desert pavement; rock fragments on it, if susceptible to desert varnish, are dark. Near the surface in favorable places, calcite is concentrated into caliche. Younger alluvium (Qal) along recent channels consists of stream sediments having rough gravel at most of the surface, from which the finer material has been sieved by the waning flow of the infrequent torrents. The finer sizes are thus concentrated in some major channels and at the lower margins of the alluvial fans. The surficial gravel is fresh gray in the youngest channels and brown from desert varnish along abandoned courses.

Other surficial deposits distinguished on the map are the salines and fine-grained clastic sedimentary deposits (Qsl) on the floor of Death Valley; travertine (Qtr) crust deposited by former springs; and undifferentiated constituents of landslides (Qlds) that are related to the present topography.

STRUCTURE

Most of the Furnace Creek area is part of the Black Mountains tectonic block, a northwest-trending wedge between the Death Valley and Furnace Creek fault zones (Noble and Wright, 1954, p. 151). The northwestern corner of the area is in the Death Valley tectonic depression, where structural features are concealed by young sedimentary deposits of the valley floor. Northeast of the Furnace Creek fault zone, a marginal strip of the area lies in the Funeral Mountains. The structural features of the Funeral Mountains that are truncated by the fault zone have not been recognized in the Black Mountains block.

Displacements on the Furnace Creek and Death Valley fault zones since the Furnace Creek Formation was deposited have been downward on the southwest and Death Valley sides. A horizontal component of relative movement toward the right by the block on the far side of each fault zone was proposed by Curry (1938, p. 1874–1875) and advocated by later writers in syntheses of the regional structure. Features shown on the present Furnace Creek map are ambiguous concerning the amount of lateral displacement.

A sequence of fault movements on the Death Valley side of the Black Mountains continued after the last movement in the Furnace Creek fault zone. Stream terraces of older alluvium are truncated along the front of the Black Mountains, and even the alluvial fans at the foot of the mountains south of Furnace Creek retain segments of a fault scarp, which Hunt and Mabey (1966, p. A100) consider to be about 2,000 years old. In contrast, the surface of the oldest alluvium that caps the mesa above Navel Spring extends across the entire Furnace Creek fault zone but is not displaced by any of the faults.

Faults within the Black Mountains block generally increase in number and displacement on the Death Valley side, strike generally eastward in the part south of Golden Canyon, and show relative displacement downward on the north side of some and the south side of others. In the eastern part of the area, other faults strike north and have the major downthrow on the west. The only exposed fault that crosses the Furnace Creek valley, in the middle of the area, strikes northeast and displaces a stream terrace of older alluvium a few feet down on the west side. Previously it displaced the Funeral Formation the same way, perhaps a thousand feet. Northeastward the fault does not go beyond the first fracture in the Furnace Creek fault zone but probably curves northwestward into the fault zone. The valley-crossing fault in the opposite direction joins the fault that continues, with the same downthrow, southeastward along the foot of the mountains. Farther southeastward beyond concealing alluvium in front of the Black Mountains, the Grand View fault continues the alinement and the west downthrow. No other significant fault in the southeastern part of the area displaces the Funeral Formation. Near Ryan, those that conspicuously displace the Artist Drive and Furnace Creek Formations end at the angular unconformity beneath basalt of the Funeral Formation.

Folds are subordinate features of the structure. Even the broad syncline in the Furnace Creek valley is shaped by steepening of beds faulted against the Funeral Mountains block. The Hole in the Wall, accessible by poor road from California Highway 190, exposes the abrupt steepening from open minor folds in the axial zone of the syncline to vertical conglomerate strata dragged on the Wall fault. The open folds plunge about 15° southeast up the valley from the East Coleman Hills to the mesa at Navel Spring, where a syncline in the Funeral and the underlying Furnace Creek Formations is visible from the highway on the west. Between the Texas Spring Camp Ground and the Funeral Mountains, an asymmetric anticline shares its steeper limb with the complementary syncline on the southwestern side. The limb steepens along the strike northwestward to the East Coleman Hills and becomes vertical or locally overturned under a reverse fault. At the other end of the area, in the narrows of Furnace Creek Wash on the road to Dantes View, the steep limb of an asymmetric syncline in the Funeral Formation is the result of drag on the downthrown southwestern side of the Grand View fault. The extensive basalt of the Funeral Formation in the Greenwater Range is younger than the small folds, as well as the other faults, in the underlying formations. Sets of small, tight folds in the Furnace Creek Formation at widely separate places show local adjustment of incompetent beds to an abrupt increase in competence near a fault. The older alluvium is folded slightly into the syncline at Texas Spring, into an open syncline from drag on the valley-crossing fault, and into a low anticline in the hills at Mustard Canyon.

BORATE DEPOSITS

Borate deposits sufficiently large for mining [1], so far as they are known in the area, contain colemanite, ulexite, and probertite (see table for compositions) and are restricted to the Furnace Creek Formation of Pliocene age. Those mined extensively prior to 1928 are clustered within three miles of Ryan in the southeastern part of the area. Other large deposits are less than four miles apart northwestward along the Black Mountains to the East Coleman Hills. Small tonnages were mined from several of these in the 1950s and 1960s. The main deposits are low in the Furnace Creek Formation, starting in the top of the lowest conglomerate and continuing to about 500 feet higher. The deposits form elongate lenses as much as 200 feet thick in which the borates are interlayered with mudstone, limestone, conglomerate, and gradational variations of these lithologies. The three minable borate minerals, where found in the same deposit, are distributed in three zones in the following order of increasing abundance: probertite in the core or deepest zone, ulexite next, and colemanite in the surrounding outermost zone. The boundaries of the zones are generally transitional, but colemanite veins sharply transect some of the ulexite. Probertite is a significantly large part of only one of the deposits, whereas ulexite is a large part of many, and colemanite is predominant in most. The few associated borate minerals underground are exceedingly scarce. Meyerhofferite, inyoite, hydroboracite, nobleite, tunellite, and volkovite are rarities in one or two among three of the minable deposits.[1]

Minor lenses and veins of colemanite are widely distributed in the gypsiferous member of the Furnace Creek Formation. The adjacent mudstone at a few places has veins and clots of howlite, as well as colemanite, and veins of ulexite resembling the associated satin-spar form of gypsum. Between the gypsiferous member and the stratigraphic zone of the main borate deposits, basaltic rocks contain many irregular veins of colemanite, priceite, howlite, bakerite, ulexite, and gypsum. The veins are mostly less than a foot thick and consist of any one of these minerals or various combinations. The priceite and bakerite of the area have been found only in the basaltic rocks.

Thin accumulations of borates in surficial material at sites of intermittent evaporation were the source of the first commercial production in the area. Now some other deposits are mineralogically significant for their new and rare borate minerals. The sites are isolated on

[1] Mining property of U.S. Borax & Chemical Corp. or Kern County Land Co.

Boron Minerals in the Furnace Creek Area *

Bakerite	$Ca_8B_{10}Si_6O_{35} \cdot 6H_2O$	$8CaO \cdot 5B_2O_3 \cdot 6SiO_2 \cdot 6H_2O$
Borax	$Na_2B_4O_7 \cdot 10H_2O$	$Na_2O \cdot 2B_2O_3 \cdot 10H_2O$
Carboborite	$Ca_2Mg(CO_3)(B_2O_3) \cdot 10H_2O$	$2CaO \cdot MgO \cdot CO_2 \cdot B_2O_5 \cdot 10H_2O$
Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	$2CaO \cdot 3B_2O_3 \cdot 5H_2O$
Ginorite	$Ca_2B_{14}O_{23} \cdot 8H_2O$	$2CaO \cdot 7B_2O_3 \cdot 8H_2O$
Gowerite	$CaB_6O_{10} \cdot 5H_2O$	$CaO \cdot 3B_2O_3 \cdot 5H_2O$
Howlite	$Ca_2SiB_5O_9(OH)_5$	$4CaO \cdot 5B_2O_3 \cdot 2SiO_2 \cdot 5H_2O$
Hungchaoite	$MgB_4O_7 \cdot 9H_2O$	$MgO \cdot 2B_2O_3 \cdot 9H_2O$
Hydroboracite	$CaMgB_6O_{11} \cdot 6H_2O$	$CaO \cdot MgO \cdot 3B_2O_3 \cdot 6H_2O$
Inderite	$Mg_2B_6O_{11} \cdot 15H_2O$	$2MgO \cdot 3B_2O_3 \cdot 15H_2O$
Inyoite	$Ca_2B_6O_{11} \cdot 13H_2O$	$2CaO \cdot 3B_2O_3 \cdot 13H_2O$
Kurnakovite	$Mg_2B_6O_{11} \cdot 15H_2O$	$2MgO \cdot 3B_2O_3 \cdot 15H_2O$
Macallisterite	$Mg_2B_{12}O_{20} \cdot 15H_2O$	$2MgO \cdot 6B_2O_3 \cdot 15H_2O$
Meyerhofferite	$Ca_2B_6O_{11} \cdot 7H_2O$	$2CaO \cdot 3B_2O_3 \cdot 7H_2O$
Nobleite	$CaB_6O_{10} \cdot 4H_2O$	$CaO \cdot 3B_2O_3 \cdot 4H_2O$
Priceite	$Ca_4B_{10}O_{19} \cdot 7H_2O$	$4CaO \cdot 5B_2O_3 \cdot 7H_2O$
Probertite	$NaCaB_5O_9 \cdot 5H_2O$	$Na_2O \cdot 2CaO \cdot 5B_2O_3 \cdot 10H_2O$
Rivadavite	$Na_6MgB_{24}O_{40} \cdot 22H_2O$	$3Na_2O \cdot MgO \cdot 12B_2O_3 \cdot 22H_2O$
Sassolite	$B(OH)_3$	$B_2O_3 \cdot 3H_2O$
Sborgite	$NaB_5O_8 \cdot 5H_2O$	$Na_2O \cdot 5B_2O_3 \cdot 10H_2O$
Searlesite	$NaBSi_2O_6 \cdot H_2O$	$Na_2O \cdot B_2O_3 \cdot 4SiO_2 \cdot 2H_2O$
Tincalconite	$Na_2B_4O_7 \cdot 5H_2O$	$Na_2O \cdot 2B_2O_3 \cdot 5H_2O$
Tunellite	$SrB_6O_{10} \cdot 4H_2O$	$SrO \cdot 3B_2O_3 \cdot 4H_2O$
Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	$Na_2O \cdot 2CaO \cdot 5B_2O_3 \cdot 16H_2O$
Volkovite	$(Sr,Ca)_2B_{14}O_{23} \cdot 8H_2O$	$2(Sr,Ca)O \cdot 7B_2O_3 \cdot 8H_2O$
Wardsmithite	$Ca_5MgB_{24}O_{42} \cdot 30H_2O$	$5CaO \cdot MgO \cdot 12B_2O_3 \cdot 30H_2O$

* Identified, in collaboration with R. C. Erd, by their optical properties and X-ray diffraction patterns; compositions from the literature.

the Death Valley flats and above them at seeps, terraces, surfaces of mine workings, and around weathered outcrops of old borates. Cottonball ulexite in mud of the salt flat was treated at the Harmony Borax Works in the 1880s. Although the old productive diggings are outside the area, examples of the ulexite are found on the flat near Harmony. Silky white clots of ulexite are closely spaced in brown mud near the surface, and some larger clots form within large blisters of rock salt on mud. Very fine grained probertite, in a layer an inch or two thick on mud, is somewhat grayer and less silky than the ulexite. At a few places on terraces capped with older alluvium, accumulations of minerals at ancient seeps have ulexite as the common borate and, rarely, tincalconite, dehydrated from borax, accompanied at one place by searlesite. Mine seepage has left, on evaporating at different places in the workings, efflorescences of borax (mostly dehydrated to tincalconite), carboborite, inderite, macallisterite, nobleite, rivadavite sassolite, sborgite, and ulexite.

Around weathered outcrops of borates in the Furnace Creek Formation, fine-grained borate minerals form in surficial debris weathered from the enclosing rock. Basaltic rocks below the gypsiferous member hold the most varied assemblages. A sponge of weathered basaltic debris around partly destroyed veins of priceite and colemanite contains fine-grained aggregates of crystallized boric acid and hydrous borates of calcium, sodium, or magnesium, alone or paired. Ulexite in fluffy pellets is the most abundant and widely occurring of the 15 borate minerals so far identified in the assemblages produced by weathering. They include four new minerals (gowerite, nobleite, macallisterite, and wardsmithite) and five other borate minerals listed here or previously from the project as the first known published occurrence in California (ginorite, hungchaoite, rivadavite, sassolite, sborgite). These additions may enhance the district's early mineralogical fame for new (colemanite, meyerhofferite, inyoite) and rare borate minerals.

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