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GEOLOGICAL SURVEY BULLETIN 962-A

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By IVAN F. WILSON *and* VICTOR S. ROCHA

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A study undertaken to aid industrial development of the region

Prepared in cooperation with the SECRETARIA DE LA ECONOMIA NACIONAL DE MEXICO, DIRECCION GENERAL DE MINAS Y PETROLEO *and the* UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO INSTITUTO DE GEOLOGIA
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GEOLOGIC INVESTIGATIONS IN AMERICAN REPUBLICS, 1948

COAL DEPOSITS OF THE SANTA CLARA DISTRICT, NEAR TONICHI, SONORA, MEXICO

By IVAN F. WILSON and VICTOR S. ROCHA

ABSTRACT

The Santa Clara coal district is 7 to 10 kilometers west of Tónichi, a small town on the Río Yaqui, in southeastern Sonora, Mexico. Tónichi was the terminus of a branch railroad from Corral until May 1945, when the end of the line was removed. The coal deposits were developed by the Southern Pacific Railroad from the 1890's until about 1911, when the mines were abandoned, partly because the coal was found unsuitable for use in locomotives. Other coal deposits, near Los Bronces and San Javier, west of the Santa Clara district, were mined for a number of years to provide coal for a silver smelter at San Javier which was abandoned sometime during the 1920's. Since 1942 the Santa Clara deposits have been reopened; through 1945 about 50,000 tons of coal had been shipped, at first to the Boleo copper smelter at Santa Rosalía, Baja California, and more recently to Guadalajara, Jalisco, for the manufacture of calcium carbide.

The coal deposits occur in the Barranca formation, of Upper Triassic and perhaps Lower Jurassic age, a thick sequence, partly marine and partly nonmarine, of quartzitic sandstones, conglomerates, shales, and intercalated coal beds. This formation is overlain by the Tarahumara volcanics of Cretaceous (?) age and is extensively intruded by sills and dikes, perhaps also of Cretaceous age. Stocklike bodies of diorite and quartz-diorite, perhaps of Tertiary age, occur in various parts of the region, probably representing the apophyses of a large batholith. The beds of the Barranca formation have a general northeasterly strike and homoclinal dip averaging 30° SE. They are offset by numerous small faults, but only one major fault, the Potrero, was noted in the district.

The coal beds lie in two areas, the Calera and Santa Clara Basins, separated by the Potrero fault. The Calera Basin contains at least nine coal beds and the Santa Clara Basin at least seven; each bed has a thickness of at least 1 meter at some place. Weathering has generally completely destroyed the coal to depths of 10 to 30 meters. The maximum continuously explored length of any single bed along the strike is 230 meters, but, making favorable assumptions regarding their continuity, some beds may have strike lengths as great as 1,050 meters. The possible extent of the beds down the dip is unknown—the maximum continuously explored dip length being 112 meters—as exploration has been confined mainly to a shallow zone between the water table and the surface zone of alteration. Down the dip the coal beds may be cut out by igneous intrusions and by faulting. The thickness of the beds mined is as much as 3 meters, averaging between 1 meter and 2 meters.

The coal has been highly metamorphosed to a rank between anthracite and meta-anthracite. It has a higher specific gravity and is harder, though more friable, than typical anthracite. The most troublesome impurity is graphite. Natural coke has developed in places, probably because of the heat from igneous intrusions. The coal is characterized by very low hydrogen, fairly high moisture, and moderate to fairly high ash. As a fuel, it is less desirable than typical anthracite because of its lower heating

value and slowness in igniting and burning. The coal is unsuitable for use in locomotives, but special burning equipment might be developed to make it usable in stationary boilers and domestic heating units. Combustion might be improved by burning in fine sizes under a strong forced draft.

Reserves are difficult to estimate because of the poor exposures, strong alteration, lack of exploration, and unknown effects down the dip of igneous intrusions, faulting, or lensing out of the coal beds. The estimated totals of minable coal are: Measured reserves, 30,000 tons; indicated reserves, 230,000 tons; inferred reserves, 2,000,000 tons; and possible reserves, 4,000,000 tons. The last figure is based on the most favorable assumptions that could reasonably be made concerning the continuity of the coal beds, and the figure of 2,000,000 tons of inferred reserves seems the better estimate, although drilling would be necessary to establish even this amount. It is recommended that 10 inclined holes be drilled to depths of 200 to 250 meters in order to explore thoroughly the possibilities of the district.

If these deposits were in a region of fairly abundant coal resources, they would probably not be commercial because of their relatively small size, the difficulties of mining them, and the inferior combustion characteristics of the coal. As they represent practically the only known coal resource on the Pacific coast of Mexico, however, their commercial utilization on a scale larger than has been attempted previously might be possible. Before any large project based on the use of this coal is carried out, it is recommended that the deposits be extensively drilled to determine exactly what quantity of coal is available and that combustion tests be made on large samples of the coal to determine under what conditions it can be burned successfully.

INTRODUCTION

LOCATION AND ACCESSIBILITY OF THE AREA

The Santa Clara coal deposits are located in the drainage area of Arroyo de Tarahumara, 7 to 10 kilometers[1] west of Tónichi, in the Muni-

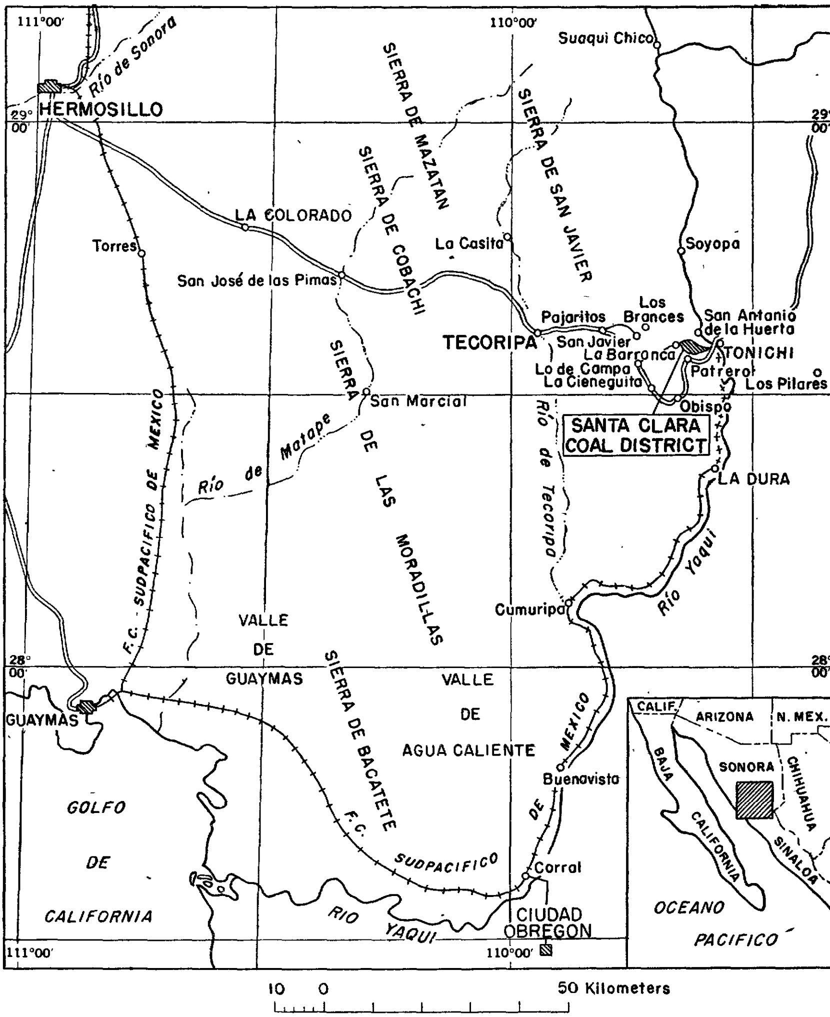

FIGURE 1.—Index map showing location of the Santa Clara coal district.

cipio[2] of San Javier, southeastern Sonora, Mexico (see fig. 1). Tónichi is a small town on the east bank of the Río Yaqui, a fairly large river that drains most of the eastern part of Sonora. A hand-propelled ferry and

[1]The metric system of measurement is used throughout this report. A chart of metric equivalents is given on p. 80.

[2]A municipio is approximately equivalent to a county in the United States.

rowboats provide service to the town from the former railhead, called Punta de Fierro, which is on the west bank of the river (see pl. 3).

Until recently Tónichi was the terminus of a branch line, 165 kilometers long, of the Sud Pacífico de México Railroad, which leaves the main line from Nogales to Guadalajara at Corral, a small station southeast of Guaymas, Sonora. In May 1945, however, the railroad company began to remove the track between Tónichi and La Dura, a station 29 kilometers farther south, and it is said that abandonment or rerouting of the rest of the line within the next few years will be necessitated by construction of a dam near Corral. Coal from the Santa Clara deposits was formerly hauled 7 kilometers by truck to the railhead at Tónichi, but in June 1945, after removal of the last 29 kilometers of track, the coal was being trucked over a newly constructed road to La Dura. At that time a mixed train ran once a week between Corral and La Dura.

The coal deposits were probably an important factor leading to the construction of the branch railroad line from Corral to Tónichi, built in the period from 1907 to 1910.[3] It was originally planned to extend this line northward up the valleys of the Río Yaqui and the Río de Moctezuma to Nacozari, to connect there with the railroad extending south from Douglas, Ariz., but the project was not completed. In 1910 it was also planned to extend the small branch railroad line running between Torres, south of Hermosillo, and La Colorada, to as far east as the Río Yaqui, passing through San Javier and La Barranca, but this project also was abandoned.[4]

The Santa Clara district (pls. 1, *A*, and 2) is most easily reached by road from Hermosillo, capital of the State of Sonora, which has highway, railway, and airline communications with Nogales, Ariz. Tónichi is 190 kilometers by road east of Hermosillo, and a stationwagon, carrying passengers and mail, makes the trip about twice a week, passing through the towns of Willard, La Colorada, San José de Pimas, and Tecoripa. For the first 115 kilometers east of Hermosillo there is a good graded highway, but the rest of the road, though partly improved, has stretches that are in very poor condition and passable only with difficulty during the rainy season (generally June to October). From Tecoripa, 124 kilometers east of Hermosillo, the road goes by way of the ranches known as Pajaritos, Lo de Campa, La Cieneguita, Obispo, and El Potrero (see fig. 1). At a distance of 139 kilometers from Hermosillo, a branch road leads northward to San Javier, an old silver-mining town near which are other coal deposits mentioned in this report. At Lo de Campa, 153 kilometers from Hermosillo, another branch leads northward to La Barranca, also an old silver-mining town, situated between San Javier and the Santa Clara coal

[3] Anonymous, Sonora, Sinaloa, y Nayarit; estudio estadístico y económico social elaborado por el Departamento de la Estadística Nacional, México, D. F., Imprenta Mundial, 1928.

[4] Nelson, C. N., San Javier, an old silver district of Sonora: Eng. and Min. Jour., vol. 90, pp. 660–661, 1910.

mines. La Barranca is about 5 kilometers west of the Santa Clara mines, with which it is connected by a poor road that is wide enough for passage of automobiles but is seldom used because of its steep grades. This road could readily be made passable, thereby greatly shortening the distance from Hermosillo to the Santa Clara mines, as the road to Tónichi makes a wide semicircle to the south of La Barranca. The distance from Tónichi westward to Santa Clara station, headquarters for the coal mines, is 7 kilometers by a fairly poor road.

The coal deposits of the Santa Clara district, which are those most easily accessible to the railroad and which were examined in detail, are shown on the map in plate 2. These deposits have also been referred to in the past as the Tarahumara or La Barranca deposits. Other coal deposits are 2 to 3 kilometers south of Los Bronces, between San Javier and the Santa Clara district, in the drainage of Arroyo de los Bronces and Arroyo de los Jacalitos. Another group of deposits, the Santa Julia, is 4 to 5 kilometers southwest of San Javier, and a few other deposits are scattered through the area between San Javier and Santa Clara.

HISTORY OF MINING

COAL

It is not known when the coal deposits in Sonora were first developed, but the existence of the coal seams near Los Bronces was known at least as early as 1866, when they were described by Rémond.[5] The deposits of the Santa Clara district were developed by a subsidiary of the Southern Pacific Railroad Co. sometime during the 1890's, and work was continued, at least intermittently, until about 1911, all of it being mainly exploratory. The coal was blocked out by inclined shafts and intersecting drifts, but little stoping seems to have been done. A few shallow exploratory holes were drilled, but the records are not available. It was found that the coal was unsuitable for locomotives, and that the only way it could be burned satisfactorily, because of its high rank, was under a forced draft.

In 1911 a project for using the coal in a power plant to be constructed at Tónichi or some other nearby place was discussed but never carried out. At that time a survey was made for a proposed aerial tramway from Santa Clara station to Tónichi, a distance of 6.2 kilometers, and from Santa Clara station to San Javier, a distance of 10.9 kilometers. The cost of the tramway was estimated to be $60,000 United States currency, but it was not built, and the coal mines were abandoned.

Some of the factors that caused the Southern Pacific Railroad Co. to abandon the coal mines are said to have been: (1) The high cost of mining and development; (2) the unsuitability of the coal for use in locomotives; (3) difficult conditions brought about by the Mexican Revolution of 1910;

[5] Rémond, A., Notice of geological explorations in northern Mexico: California Acad. Sci. Proc., 1st ser., vol. 3, pp. 250–251, 1866.

and (4) difficulties with the Yaqui Indians, who at that time made frequent depredations in the region and killed one of the last superintendents of the coal mines. The production of coal during the period of operation by the Southern Pacific Co. is not known, and it is uncertain whether much of the coal then mined was actually used or shipped only for testing purposes. The coal may have been used for a time in a copper-and-lead smelter at Toledo, a station on the railroad 4 kilometers south of Tónichi, but this smelter was short-lived because of financial difficulties.

The coal deposits near Los Bronces, west of the Santa Clara district, were mined for many years for use in the silver smelter at San Javier. Coal mining in that district may have begun in the 1880's or 1890's, and it apparently continued until sometime in the 1920's. During the later years the smelter was operated by the Cía. W. C. Laughlin, which operated the largest coal mines and purchased coal from gambusino[6] operators of the smaller deposits. The coal was carried to the smelter by burro from the deposits in Arroyo de los Bronces and Arroyo de los Jacalitos, east of San Javier, and from the Santa Julia deposits, southwest of San Javier. The total production is not known but probably amounted to several tens of thousands of tons of coal and natural coke, both of which were used in the steam boilers at the smelter. The coal was not very satisfactory, as it decrepitated in the fire box; preparations were being made to grind it to a fine powder when operations ceased because of the shutdown of the smelter sometime during the 1920's.

The coal mines seem to have been inactive from that time until about 1942, when practically all the deposits in the district were claimed by the Cía. Carbón Sonora, S. A., under the direction of Sr. Ignacio Soto of Hermosillo. This company reopened some of the old Southern Pacific Railroad Co.'s mines of the Santa Clara district and initiated shipments to the Boleo copper smelter at Santa Rosalía, Baja California. The coal was trucked to Tónichi, hauled by rail to Guaymas, Sonora, and from there carried by ship across the Gulf of California to Santa Rosalía. It is said that after being sprinkled with fuel oil the coal was burned satisfactorily in the reverberatory furnaces of the smelter. Shipments to Santa Rosalía were discontinued later, however, and more recently the coal has been shipped to Guadalajara, Jalisco, 1,415 kilometers by rail southeast of Tónichi, for use in making calcium carbide, for which purpose it is said to be satisfactory. These shipments have been continued intermittently until October 1945, although they have been impeded recently by removal of the railroad track from La Dura to Tónichi. The production of coal from the Santa Clara district since the mines were taken over by the Cía. Carbón Sonora is said to have been about 50,000 tons.

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[6]Gambusinos are miners who work independently, on a small scale, generally by hand methods for lack of resources.

SILVER AND GOLD

Four old silver-mining camps are in the region under discussion: San Javier, Los Bronces, La Barranca, and Tarahumara. San Javier, a picturesque town in the heart of the mountains, reportedly has a history of nearly 300 years as a mining camp. According to Nelson,[7] the period of greatest mining activity began in 1860, under the direction of Matías Alsúa, who built a leaching plant at Los Bronces in which several million ounces of silver are said to have been recovered. After Alsúa's death in the late 70's, the properties were sold to a British company, which failed 2 or 3 years later because of bad management. Subsequently a smelter was built by the Cía. W. C. Laughlin and operated until sometime in the 1920's, since when there has been little mining activity. The population of San Javier, which had once been 10,000 to 15,000, had declined to 887 in 1930. Los Bronces, which is about 3 kilometers northeast of San Javier, is now a ghost town. At the time of the writers' visit, it was hoped that the mines at San Javier and Los Bronces might be reopened soon.

La Barranca, situated in a mountain valley between San Javier and Santa Clara, is a small settlement of a few dozen persons; it had a population of 573 in 1893, when five silver mines, two silver-gold mines, and a beneficiating plant were being operated near the town.[8] These mines have long since been shut down, but at the time of the writers' visit a new silver-gold mine, the Tescalama, on the west flank of Cerro del Candelero, was being operated under the direction of A. E. Johnson, and plans to install a mill were being discussed.

In the past, several silver-gold deposits were mined in the Santa Clara coal district (pl. 2), including the Nochebuena, Santa Ana, Santa Fe, and Mulateña mines, all of which are now abandoned. The principal mining camp was at Tarahumara, where the Nochebuena mine is located. The main shaft of this mine is said to have cut a coal bed at a depth of about 400 feet (122 meters).

In 1945, except for the Tescalama mine and the Santa Clara coal mines, no organized mining operations were being carried on in the region. At several places individuals were engaged in prospecting and searching for "pockets" in the gold and silver veins; when such pockets are found the vein matter is crushed in crude arrastres propelled by burros. Small dry placer operations were also being carried on in places, but the recovery of gold was small.

PREVIOUS GEOLOGIC INVESTIGATIONS

The coal deposits in the vicinity of Los Bronces were visited more than

[7]Nelson, C. N., op. cit., pp. 660–661.

[8]Velasco, A. L., Geografía y estadística de la República mexicana: tomo 14, Geografía y estadística del Estado de Sonora, México, p. 174, 1893.

80 years ago by Rémond,[9] during a geologic investigation made in the period 1863–65 of the mountainous region of Sonora and parts of Sinaloa, Durango, and Chihuahua. He was the first to obtain positive evidence of the age of any of the geologic formations of this region, having found in the coal-bearing beds near Los Bronces plants that were determined by Newberry to be of Triassic age. Rémond described the general sequence of the Triassic beds and published two stratigraphic sections of the coal-bearing strata near Los Bronces. Newberry[10] described the fossils collected by Rémond and later published some notes on the coal[11] as a result of studies of specimens sent him by Rémond and by J. H. Banks.

Aguilera[12] published a brief description of the Santa Clara coal deposits and those near Los Bronces in 1896, as part of a report on the geologic reconnaissance of various parts of Mexico made at that time by him and his associates of the Instituto Geológico de México.

E. T. Dumble made a thorough study of the Santa Clara coal deposits and surrounding area during the period 1898 to 1900, while they were being developed by a subsidiary of the Southern Pacific Railroad. Some of the results of these studies have been given in three published papers,[13] of which the one called "Triassic coal and coke of Sonora, Mexico", contains the most detailed description of the coal deposits. An unpublished report written by Dumble in 1910 contains still more details, including much useful information about the individual mine workings then existent, many of which are now caved. Unfortunately Dumble's maps, none of which were published, were destroyed by the San Francisco fire of 1906.

A report by Paredes[14] published in 1920 gives a description of the coal deposits near Los Bronces, which were then being mined by the Cía. W. C. Laughlin. Burckhardt[15] in 1930 reviewed the literature that had been published to that date concerning the stratigraphy and paleontology of the Triassic beds in Sonora. Some other references on fossils in the Triassic beds will be listed later in the discussion of the Barranca formation. A number of relatively brief summary descriptions of the coal

[9]Rémond, A., op. cit., 1866.

[10]Newberry, J. S., Descriptions of the Carboniferous and Triassic fossils, in Macomb, Capt. J. N., Report of the exploring expedition from Santa Fe, N. Mex., to the junction of the Grand and Green Rivers of the Great Colorado of the west, in 1859; pp. 141–148, U. S. Army, Engineer Dept., 1876.

[11]Newberry, J. S., Geological notes: School of Mines Quart., vol. 8, pp. 334–335, Columbia University, New York, 1887.

[12]Aguilera, J. G., Itinerarios geológícos, in Bosquejo geológico de México: Inst. geol. México Bol. 4, 5, 6, pp. 118–119, 1896.

[13]Dumble, E. T., Notes on the geology of Sonora, Mexico: Am. Inst. Min. Eng. Trans., vol. 29, pp. 122–152, 1900; Natural coke of the Santa Clara coal field, Sonora, Mexico: Am. Inst. Min. Eng. Trans., vol. 29, pp. 546–549, 1900; Triassic coal and coke of Sonora, Mexico: Geol. Soc. America Bull., vol. 11, pp. 10–14, 1900.

[14]Paredes, Trinidad, El carbón y la grafita (sic) del Estado de Sonora: Bol. minero, vol. 9, pp. 608–613, 1920.

[15]Burckhardt, Carl, Etude synthétique sur le Mésozoíque mexicain, première partie: Soc. paléont. Suisse Mem., vol. 49, pp. 39–42, 1930.

deposits, based principally on the work of the authors mentioned above, has also been published.[16]

The most important geologic study of the surrounding region is that by King,[17] who made a reconnaissance investigation of a large area in southeastern Sonora and western Chihuahua. His 1939 report includes a colored geologic map, on a scale of 1:500,000, of much of the part of Sonora that lies southeast of Hermosillo, between 27° and 29° N. latitude and 108° and 110° W. longitude. He did an excellent piece of work in unraveling the stratigraphic and structural complexities of a large and difficultly accessible region; the essential geologic features of the area studied by the writers were found to accord with his description.

FIELD WORK

The present study was undertaken to aid in determining the feasibility of using the coal of the Santa Clara deposits as fuel in a proposed thermoelectric power plant, the purpose of which would be to supply power to the towns of Hermosillo, Guaymas, Ciudad Obregón, and Navojoa and to aid in the industrial development of the region. The Geological Survey undertook the investigation as part of its program of cooperation with the American Republics, sponsored by the Interdepartmental Committee on Scientific and Cultural Cooperation of the United States Department of State. These studies are being carried on in Mexico jointly with the Comité Directivo para la Investigación de los Recursos Minerales de México.

The investigation was made by Ivan F. Wilson and Kenneth Segerstrom, geologist and topographic engineer, respectively, of the United States Geological Survey, and Ing. Victor S. Rocha of the Comité Directivo. Field work was done from March to June 1945. By plane-table methods, Segerstrom made a topographic map of the district on a scale of 1:5,000 with a contour interval of 5 meters. Wilson and Rocha studied the surface geology and mapped the underground workings on a scale of 1:500 by means of tape and Brunton compass. They also made a reconnaissance study of the coal deposits near Los Bronces and San Javier, and the intervening area west of the Santa Clara district, by horseback

[16] Anderson, A. D., Los yacimientos de carbón de piedra en México: Minero Mexicano, vol. 11, No. 7, p. 83, 1884. Parker, E. W., Coal in Mexico: Eng. and Min. Jour., vol. 77, p. 190, 1904. Thomas, Kirby, Mexican coal deposits: Min. World, vol. 22, p. 472, 1905. Hill, R. T., The coal fields of Mexico, in Coal resources of the world, vol. 2, pp. 554–555, Internat. Geol. Cong., 12th, Canada, 1913. Anonymous, El carbón mineral en México: Bol. minero, vol. 11, pp. 642–643, 1921. Obregón, M. B., Carbón y petróleo en los Estados Unidos Mexicanos; sus yacimientos, origen, distribución, y manera de utilizarlos: Soc. cient. Antonio Alzate Mem., vol. 43, pp. 259–261, 1924. Anonymous, Breve estudio sobre los yacimientos carboníferos de la República y resumen de las opiniones autorizadas sobre lugares en los cuales se ha encontrado carbón mineral: Bol. minero, vol. 35, p. 91, 1933. Jiménez, L. G., Los carbones minerales, su origen, historia, leyenda y desarrollo en México, pp. 52–55, México, D. F., Imprenta Universitaria, 1944.

[17] King, R. E., Geological reconnaissance of central Sonora: Am. Jour. Sci., 5th ser., vol. 28, pp. 81–101, 1934; Geological reconnaissance in northern Sierra Madre Occidental of Mexico: Geol. Soc. America Bull., vol. 50, pp. 1625–1722, 1939.

traverses, using aerial photographs as a base for locations. They sampled the mines of the Santa Clara district according to the standard method used by the Bureau of Mines, and complete analyses of the coal samples were made by the Bureau's Experiment Station in Pittsburgh, Pa.

ACKNOWLEDGMENTS

The Governor of Sonora, General Abelardo L. Rodríguez, provided the cooperation and facilities of his office in carrying out the investigation. Mr. William G. Kane, of the Foreign Economic Administration, who had made a preliminary investigation of the coal deposits, accompanied the writers in the field at the start of the project and gave helpful advice and assistance. The writers are greatly indebted to the mine operators and their representatives for their kind hospitality and cooperation, particularly to Sres. Ignacio Soto, Enrique Soto, and Francisco Cano. Sr. Jesús Ycedo ably and courteously served as guide and general assistant during the field work. The local residents were unfailingly hospitable and generous, and although a complete list of individuals to whom thanks are due cannot be given here, special mention is due to Mr. A. E. Johnson, of La Barranca; Sr. Adolfo Estrella, of Tónichi; and Sra. E. N. Yanes, of San Javier.

Aerial photographs were supplied through the courtesy of the Comisión Geográfica Militar of Mexico. The coal analyses were made by the Bureau of Mines Experiment Station under the direction of H. M. Cooper. Four thin sections of rocks collected from the district were examined by Sr. Eduardo Schmitter, of the Instituto de Geología of Mexico. Discussions with Mr. L. C. Raymond, of the engineering firm of Ford, Bacon & Davis, who visited the coal deposits, were very helpful.

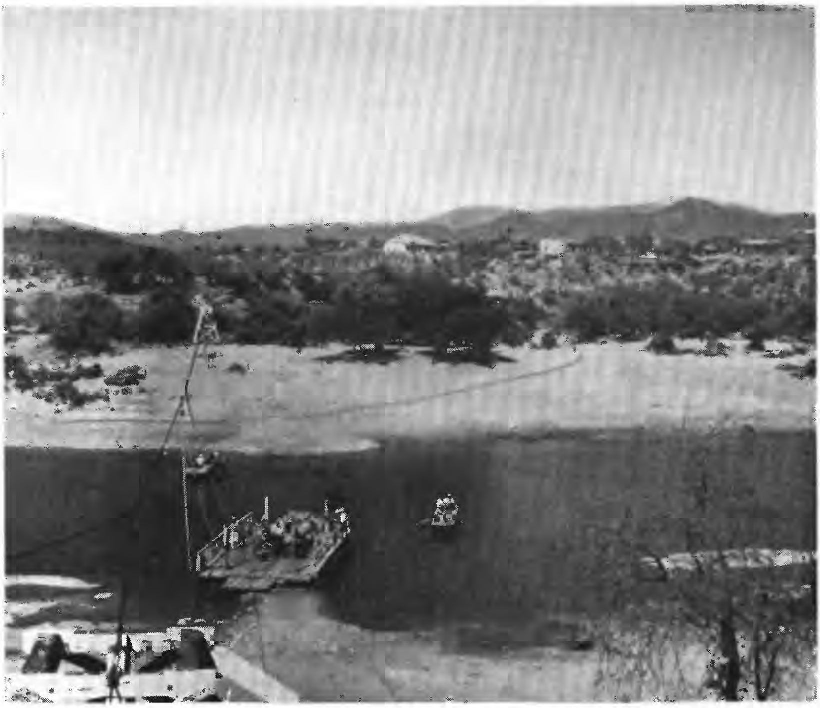
Kenneth Segerstrom's proficiency in topographic mapping and his agreeable companionship helped to make the field work proceed more rapidly and pleasantly than would otherwise have been possible. A. A. Baker, of the Fuels Section of the Federal Geological Survey, gave helpful advice on methods of sampling coal at the outset of the field work. Paul Averitt and T. A. Hendricks, also of the Fuels Section, kindly gave the benefit of their experience in the interpretation of the coal analyses. R. W. Brown, of the Geological Survey, identified the fossil plants that were collected, and Carl Fries, Jr., gave helpful advice during the preparation of the report. The work was under the general supervision of J. V. N. Dorr 2d.

GEOGRAPHY

GEOMORPHOLOGY

The Santa Clara deposits are near the south end of the Sierra de San Javier, which forms part of what King[18] has called the "province of parallel ranges and valleys." This geomorphic province is bounded on the

[18]King, R. E., op. cit. (Sierra Madre Occidental), p. 1635.



HAND-OPERATED FERRY ON RIO YAQUI, SHOWING TOWN OF TONICHI IN BACKGROUND.

A. CERRO DE LA AGUJA, A RUGGED PEAK FORMED OF RESISTANT QUARTZITE.

B. TOWN OF SAN JAVIER, IN A VALLEY CUT IN DIORITE.

west by the Sonoran Desert province, characterized by isolated mountain ranges separated by broad alluvial plains and pediments, and on the east by the Sierra Madre Occidental province, a high plateau dissected along its west edge by deep barrancas. The intermediate province of parallel ranges and valleys is characterized by fairly long mountain ranges of moderate elevation, trending north and separated by narrow longitudinal valleys. One of the most prominent of these longitudinal valleys is that followed by the Río Yaqui, from its right-angle bend at Suaqui Chico to as far south as La Dura (see fig. 1). The same valley line extends, with interruptions, to the southeast as far as Alamos, following parts of the Río Chico and Río Cedros. A continuation of the valley north of Suaqui Chico is followed by the Río de Moctezuma and Río Nacozari, which are northern tributaries of the Río Yaqui.

The Sierra de San Javier is one of the most prominent ranges in the province of parallel ranges and valleys. It is 50 kilometers or more long and 10 to 15 kilometers wide, and has an average trend of N. 20° W. It is formed largely of the Barranca formation and includes several high, jagged peaks of resistant quartzite, such as Cerro del Candelero, having an elevation of 1,127 meters; Cerro del Carrizo, 1,219 meters; and Cerro de la Aguja, 1,203 meters (see pl. 4, *A*). The mountains have steep slopes and are dissected by deep, narrow, youthful canyons. The total relief is about 900 meters, and the general aspect of the topography is that of early maturity.

The mountains are bordered on the east, between the Santa Clara coal mines and the Río Yaqui, by a belt of low rolling hills and benches formed, from west to east, of Cretaceous and Tertiary volcanic rocks and gently dipping conglomerate of the Báucarit formation. The sierra is bordered on the west also by low rolling hills formed mainly of Cretaceous volcanic rocks and smaller areas of the Báucarit formation. Within the sierra are a few basinlike valleys formed in easily weathered bodies of diorite and other deep-seated igneous rocks. Such valleys form the sites for the mining towns of La Barranca, San Javier, and Los Bronces (see pl. 4, *B*). Another prominent valley, 2 or 3 kilometers wide, formed in dioritic and other igneous rocks, is in Arroyo de La Barranca, south of the Santa Clara district, and is crossed by the road from Hermosillo to Tónichi. Broad pediments, now dissected by intermittent streams, have been formed in this valley.

DRAINAGE AND WATER SUPPLY

The only permanent stream in the region is the Río Yaqui, which drains most of eastern Sonora and part of western Chihuahua. It is said to have a length of 680 kilometers and a drainage area of 76,000 square kilometers; it is the fifth largest of the rivers of Mexico.[19] It drains most

[19] Medina, Francisco, Monografía de Sonora, pp. 27–28, México, D. F., 1941.

of the area lying between the 108th and 110th meridians, from the 28th parallel on the south to slightly north of the United States border. Its principal tributaries are the Río Bavispe, which drains the northeastern part of Sonora, and the Río de Moctezuma, a southward-flowing stream that joins the Río Yaqui at Suaqui Chico (see fig. 1). Since the construction of the Angostura Dam on the Río Bavispe northeast of Nacozari, a supply of water is assured the year round. Formerly, parts of the river were reduced to isolated pools of water during the driest season in May and June. According to Medina,[20] the average annual discharge of the river at a point called Los Limones, over a period of 30 years, was 3,630,000,000 cubic meters.

All the Santa Clara district proper, shown on plate 2, is drained eastward by Arroyo de Tarahumara, which discharges into the Río Yaqui near Tónichi. The main branches of Arroyo de Tarahumara are Arroyo de Santa Clara, on the south, and Arroyo de Agua Blanca,[21] with its tributaries Arroyo de la Calera, Arroyo del Refugio, and Arroyo del Tren, on the north.

A striking example of near stream capture is found 200 meters east of the Nochebuena mine (pl. 2, coordinates 1400 E., 900 S.), where a branch of Arroyo de Santa Clara, having a steeper gradient, has nearly cut into a bend of Arroyo de Tarahumara, from which it is separated by only a narrow saddle. The operators of the Nochebuena mine diverted the drainage into Arroyo de Santa Clara, by means of a narrow trench through this saddle, in order to prevent the washout of a road that follows Arroyo de Tarahumara farther downstream.

The next important arroyo north of Arroyo de Tarahumara is Arroyo de los Arrayanes, which discharges into the Río Yaqui just south of the small town of San Antonio de la Huerta, 3 kilometers northwest of Tónichi. The next arroyo south is Arroyo de La Barranca, which has a wider drainage area than Arroyo de Tarahumara and has its headwaters in the small valley in which the town of La Barranca is situated. This arroyo discharges into the Río Yaqui at Toledo, 4 kilometers south of Tónichi.

The western part of the Sierra de San Javier is drained by the Río de Tecoripa, which occupies a long, nearly straight, southward trending valley that joins the Río Yaqui Valley at Cumuripa. Its main tributaries are Arroyo de Los Bronces, which has its source near the deserted mining camp of Los Bronces, and Arroyo de San Javier, which heads in the valley containing the town of San Javier. These two arroyos join south of San Javier.

Aside from the Río Yaqui, all the arroyos in the region are nearly always dry except immediately after storms. At other times water is

[20] Idem, p. 28.

[21] On some maps the name Arroyo de Agua Blanca is applied to the entire course of the arroyo to its junction with the Río Yaqui.

found only in a few scattered pools, usually in small rock-bound basins in the stream beds.

Water for the domestic needs of the residents of the region is scarce, which creates a serious problem during the dry season. The supply is confined mainly to small springs having a very slight flow and to water found in some of the old mine workings. The principal springs within the Santa Clara district proper, all shown on plate 2, are the Pitahaya or Pilita (coordinates 270 E., 1020 S.), Agua Blanca (coordinates 1290 E., 160 S.), and Mulateña (coordinates 180 E., 190 S.). Farther west there is a spring in Arroyo de La Barranca, just below the town of La Barranca, and another, called Agua Fría, on the northeast side of Cerro de la Aguja, near the headwaters of Arroyo de los Arrayanes.

CLIMATE AND VEGETATION

The climate of the region is hot and dry. The winters are mild, but the summers are extremely hot and temperatures of 110° F. are not uncommon. The valley of the Río Yaqui is especially hot, as a result of its low elevation above sea level and its shield of mountains. The high peaks of the Sierra de San Javier are somewhat cooler. The rainy season generally begins in the latter part of June or in July and ends usually in October. During this season mosquitos are prevalent, and malaria is very widespread among the inhabitants of the region.

Table 1 gives published figures[22] of the rainfall at three towns lying in and near the district under discussion: San Javier, the silver-mining camp in the mountains west of the Santa Clara district, La Dura, on the Río Yaqui 29 kilometers south of Tónichi; and Tecoripa, in the valley of the Río de Tecoripa west of the Sierra de San Javier. The rainfall at the Santa Clara mine is probably intermediate between that at San Javier and at La Dura.

TABLE 1.—*Average rainfall in the period 1921–35*

Month	San Javier		La Dura		Tecoripa	
	Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
January	21.1	0.83	21.1	0.83	4.2	0.17
February	8.0	.32	3.9	.15	1.9	.07
March	37.2	1.47	9.8	.39	3.3	.13
April	5.1	.20	2.1	.08	.0	.00
May	3.0	.12	15.7	.62	7.3	.29
June	37.8	1.49	20.0	.79	25.3	1.00
July	206.9	8.15	180.7	7.12	127.8	5.04
August	213.2	8.40	123.1	4.85	97.5	3.84
September	113.0	4.45	103.5	4.08	83.1	3.27
October	46.0	1.81	25.1	.99	16.1	.63
November	25.9	1.02	12.3	.48	21.0	.83
December	100.2	3.95	98.4	3.88	62.1	2.45
Total	817.4	32.21	615.7	24.26	449.6	17.72

[22]Anonymous, Boletín Anual del Servicio Meteorológico Mexicano, Año de 1937, Secretaría de Agricultura y Fomento, Dirección de Geografía, Meteorología e Hidrología, Servicio Meteorológico Mexicana, pp. 68–69, 1938.

According to a climatic classification based on the "Thornthwaite system,"[23] the temperature of the Santa Clara and Tónichi region is classified as "hot," with a mild winter; the humidity as "dry," with winter and spring dry.

Most of the region is thickly covered with brush, cactus, and low shrubby, thorny, deciduous trees of several varieties. The brush is so thick that in many places it is difficulty penetrable except along trails. In the higher parts of the Sierra de San Javier there are more open, grassy savannas containing scattered oak trees. Few trees suitable for timber grow in the region, and those that are used locally for mine timbers are of such poor quality that they must be replaced after a short period of use.

CULTURE

The area described in this report has little present or potential economic importance except as a mining region. Livestock does poorly for lack of forage and water during the dry season, when death from thirst and starvation is common. Arable land is confined mainly to the narrow valleys in the mountains and to the alluvial and terrace deposits along the valley of the Río Yaqui, where small crops are raised for local consumption.

The region is sparsely populated, and in 1940 the entire Municipio of San Javier, which includes all the coal-bearing area, had a population of only 819.[24] The supply center for the coal district has been Tónichi, a town of about 300 inhabitants, which, as terminus of the railroad, supplied a large and remotely accessible region to the north and east, extending as far as Sahuaripa (see fig. 1), and containing many scattered mines and small agricultural centers. If the railroad from Corral is removed completely, the region may have to depend upon trucking from Hermosillo for supplies. Hermosillo, the commercial and political capital of the State of Sonora, is a thriving city whose industrial and agricultural development should be enhanced by completion of a dam now being constructed on the Río de Sonora just east of the city.

GEOLOGY

STRATIGRAPHY

GENERAL SEQUENCE IN SANTA CLARA DISTRICT AND SURROUNDING REGION

Paleozoic strata, though not occurring in the Santa Clara district proper, are found northwest of the Sierra de San Javier, where they are best exposed in the Sierra de Cobachi and in an area northeast of La Casita (see fig. 1).[25] These beds are mainly limestone, partly Ordovician and partly Permian in age, although formations of other systems also may be

[23] Anonymous, Mapa climatológico de la República Mexicana, Secretaría de Agricultura y Fomento, Dirección de Geografía, Meteorología e Hidrología, Instituto Geográfico, 1942.

[24] Medina, Francisco, op. cit., p. 57.

[25] Dumble, E. T., op. cit. (Geology of Sonora), pp. 148–150. King, R. E., op. cit. (Sierra Madre Occidental), pp. 1641–1643.

present. In the Sierra de San Javier only two patches of rocks of possible Paleozoic age have been noted. Specifically, in the Los Bronces valley, in a small area surrounded by shattered quartzites, King[26] noted gray limestone with stringers of chert that he says lithologically resembles older Paleozoic of the La Casita area, although, as no fossils were found, it may belong to the surrounding Triassic beds. Dumble[27] reported a large exposure between Los Bronces and Soyopa (see fig. 1) of rocks that he referred provisionally to the Cambrian, although he found no fossils.

The Sierra de San Javier is formed largely of the Barranca formation, of Upper Triassic and perhaps Lower Jurassic age, consisting of a thick sequence of clastic rocks, principally quartzitic sandstones, conglomerates, and shales, and containing intercalated coal beds. It is overlain by the Tarahumara volcanics probably of Cretaceous age, consisting mainly of andesitic flows, agglomerates, breccias, and intercalated sediments. These rocks cover large areas south and west of the Santa Clara district.

Between the Santa Clara district and the Río Yaqui there is a fairly narrow northwestward-trending belt of volcanic rocks thought by King[28] to be of early Tertiary age. He gives the following section between Tónichi and San Antonio de la Huerta: "At top indurated brown conglomerate, underlain successively by thick andesite agglomerate, thick flow of white rhyolite, and andesite flows and agglomerates at base."[29] The early Tertiary volcanic rocks dip east-northeast and are overlain to the east by the Báucarit formation.

The Báucarit formation, originally called the "Baucari division" by Dumble[30] and renamed by King,[31] underlies the valley of the Río Yaqui in the vicinity of Tónichi. It consists chiefly of terrestrial conglomerate, containing a wide variety of pebbles that represent all the rock types commonly found in the surrounding region. The formation is found in intermontane depressions in various parts of Sonora, particularly in the province of parallel ranges and valleys. A long narrow belt follows the valley of the Río Yaqui, and other belts are found along the Río de Tecoripa, the Río Cedros, and the Río de Sahuaripa. A few vertebrate fossils have been found that suggest a late Tertiary or a Quaternary age for the formation.[32]

Intrusive rocks of several types occur in the region, including fairly large stocklike bodies of diorite and quartz diorite. Dikes and sills of quartz latite, latite, and similar rocks are common.

In the coal-bearing area studied in detail during the present investigation, the only rocks exposed are the Barranca formation, the Tarahu-

[26] King, R. E., op. cit. (Sierra Madre Occidental), p. 1649.
[27] Dumble, E. T., op. cit. (Geology of Sonora), p. 150.
[28] King, R. E., op. cit. (Sierra Madre Occidental), pp. 1678–1679.
[29] Idem, p. 1686.
[30] Dumble, E. T., op. cit. (Geology of Sonora), pp. 126-128.
[31] King, R. E., op. cit. (Sierra Madre Occidental), p. 1681.
[32] Idem, p. 1692.

mara volcanics, and various intrusive igneous rocks; to these rocks the ensuing discussion will therefore be limited.

BARRANCA FORMATION (UPPER TRIASSIC AND LOWER JURASSIC?)

GENERAL FEATURES, DISTRIBUTION, AND THICKNESS

The Barranca formation consists of a thick sequence of quartzitic sandstones, conglomerates, and various types of shale with intercalated coal beds. Part of the formation is nonmarine in origin, as evinced by coal beds and by carbonaceous shales containing abundant fossil plant remains, but at least some of the beds are marine, for they contain marine invertebrate fossils. These latter strata are stratigraphically near beds containing plant fossils, and are similar in lithology. It is believed that the formation was deposited on a broad coastal plain nearly at sea level, and that slight fluctuations in level produced alternating marine and nonmarine beds.

The Barranca formation was named by Dumble[33] for exposures near the town of La Barranca. It forms the greater part of the Sierra de San Javier, covering an area at least 50 kilometers long from north to south and 10 kilometers wide, according to King,[34] and it crops out in smaller areas farther west, in the Sierra de Cobachi, the Sierra de Tecoripa, the Sierra de las Moradillas, and at other scattered localities. In the Sierra de las Moradillas, west of San Marcial and south of La Colorada (see fig. 1), beds of graphite and coal are found in this formation. There the graphite has been mined extensively,[35] but the coal, so far as known, has not been exploited. Beds similar to these occur also east of the Río Yaqui, near Los Pilares (see fig. 1), 20 kilometers east of Tónichi.

As neither the base nor the top of the Barranca formation is exposed in the area studied the total thickness could not be determined. It must be considerably greater, however, than the thickness represented between Arroyo de los Arrayanes and Arroyo de Santa Clara, which is at least 1,500 meters.

LITHOLOGY AND STRATIGRAPHIC SECTIONS

In the area investigated, the Barranca formation consists broadly of three divisions: The lowest and highest are composed mainly of massive quartzitic sandstones, interbedded with thin shales, such as those exposed between Arroyo del Refugio and Arroyo de los Arrayanes; the middle division consists of alternating beds of sandstone and shale, including black carbonaceous shales that enclose coal seams. The boundaries between these three divisions are gradational.

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[33] Dumble, E. T., op. cit. (Geology of Sonora), 139.

[34] King, R. E., op. cit. (Sierra Madre Occidental), pl. 1.

[35] Hess, F. L., Graphite mining near La Colorada, Sonora: Eng. Mag., vol. 38, pp. 36–48, October 1909. Paredes, Trinidad, El carbón y la grafita (sic) del Estado de Sonora: Bol. minero, vol. 9, pp. 608–613, 1920. Honigmann, E., La industria del grafito en el Estado de Sonora: Bol. minero, vol. 20, pp. 49–60, 1925. García, J. A., Monografía del grafito: Bol. minero, vol. 21, pp. 64–75, 1926. Flores, Teodoro, Reconocimientos geológicos en la región central del Estado de Sonora: Inst. geol. México Bol. 49, pp. 125–129, 1929.

The sandstones of the lowest and highest divisions of the Barranca formation are massive, well-cemented, and generally coarse-grained. Many of them, consisting almost entirely of quartz grains cemented by silica, can properly be called quartzites. They are gray when fresh but weather to a reddish brown, and in places they are heavily stained with iron and manganese oxides. They are highly resistant and form the rugged high peaks of the Sierra de San Javier, such as Cerro del Candelero, Cerro de la Aguja, and Cerro del Carrizo.

The sandstones in the middle division of the formation are in general finer-grained, less quartzitic, and more poorly indurated than the rest. Some exceptions were noted, however, for in the vicinity of the El Tren mine a massive, well-cemented quartzitic sandstone is intercalated with the shales of the middle division. Fine-grained micaceous sandstones also appear in this division, and all gradations exist from shaly sandstones to sandy shales.

The shales are generally dark gray or black and thin-bedded, grading from sandy to clayey and carbonaceous shales, in which most of the coal beds are intercalated. Although most of the shales are well-bedded, in some places fairly massive, poorly bedded claystones were noted. Some of the shales are well-indurated, hard, and platy, but slaty cleavage has not been developed.

Fine-grained conglomerates appear at various horizons in the Barranca formation, in many places occurring as lenses in sandstone. They consist mainly of subrounded pebbles of white milky quartz and chert. A thick, coarse-grained conglomerate exposed southwest of San Javier, on the trail to the Santa Julia mines, is composed mainly of quartzite and chert fragments, some of them angular, in a hard siliceous matrix, and parts of it are heavily stained red and brown by iron oxides. This conglomerate appears to be in fault contact with Cretaceous volcanic rocks and might be younger than the Barranca formation.

An idea of the lithology of the middle, or coal-bearing, division of the Barranca formation may be obtained from the following measured section along Arroyo del Pie de la Cuesta southward to its junction with Arroyo de Tarahumara, and then along Arroyo de Tarahumara to Santa Clara station. This is an incomplete section of the formation, but in no other part of the area examined in detail were the exposures sufficiently continuous to provide a satisfactory section of any great thickness. The base of the section begins on top of the highest massive resistant quartzitic sandstone or quartzite in Arroyo del Pie de la Cuesta, which was taken as the boundary between the lower and middle divisions of the Barranca formation. The top of the section is at the southernmost exposure in Arroyo de Tarahumara, opposite Santa Clara station. The section is given from top to bottom.

Incomplete section of Barranca formation along Arroyo del Pie de la Cuesta and Arroyo de Tarahumara

	Thickness (meters)
1. Sandstone, fine-grained, thick-bedded, gray. A few thin shaly partings	7.7
2. Shale, clayey and sandy, thin-bedded	.6
3. Sandstone, fine-grained, massive to thick-bedded, gray, shaly in part	3.7
4. Shale, clayey, thin-bedded, dark-colored	.5
5. Sandstone, fine-grained, thick-bedded, gray, somewhat shaly in part	4.8
6. Shale, sandy, in part clayey, thick-bedded; and interbedded fine-grained sandstone	4.5
7. No exposure	36.3
8. Claystone, massive, containing scattered quartz grains in a greenish-gray, dense matrix	23.6
9. No exposure	14.8
10. Claystone, massive, similar to No. 8	7.1
11. No exposure	14.0
12. Claystone, massive, gray. Poorly exposed	6.3
13. No exposure	5.7
14. Sandstone, massive, poorly sorted	2.5
15. Claystone, massive, in part slightly sandy, light gray, resistant	6.5
16. Sandstone, fine- to medium-grained, massive, gray, resistant; becomes coarser-grained and more quartzitic toward the top	11.5
17. Shale, clayey, in part sandy, thin- to thick-bedded; contains invertebrate fossils	10.0
18. Sandstone, micaceous, fine-grained, gray, resistant	2.45
19. Shale, clayey, carbonaceous, thin-bedded, dark colored, nonresistant; grades upward into thick-bedded sandy shale	17.1
20. No exposure	7.3
21. Shale, sandy, thick-bedded, black, resistant; and shaly sandstone	4.3
22. No exposure	6.8
23. Shale, carbonaceous, partly clayey, partly sandy, thin- to thick-bedded; contains plant fragments; interbedded with fine-grained shaly sandstone	12.2
24. Altered coal bed? Zone of yellowish clayey material and iron oxides similar to that found along altered coal outcrops in the district; very small exposure	.45
25. Sandstone, micaceous, fine-grained, well-bedded, gray	3.05
26. "Feldspar porphyry" sill, highly altered. Porphyritic, gray, aphanitic groundmass; phenocrysts of biotite and other ferromagnesian minerals altered to chlorite; feldspars both orthoclase and plagioclase, mainly altered to clay and sericite, with inclusions of chlorite. Composition that of latite?	3.3
27. Sandstone, micaceous, fine-grained, well-bedded, gray	1.4
28. Shale, clayey, thin-bedded, dark-colored	3.95
29. Sandstone, quartzose, gray	.55

Incomplete section of Barranca formation along Arroyo del Pie de la Cuesta and Arroyo de Tarahumara—Continued

30. Shale, clayey and sandy, thin-bedded, dark-colored; contains a few poorly preserved plant fragments	1.05
31. Sandstone, quartzose, medium-grained, thick-bedded to massive, gray	6.25
32. Shale, carbonaceous, thin-bedded, dark gray; contains two or three beds of gray sandy shale	4.4
33. Sandstone, quartzose, somewhat micaceous, fine- to medium-grained, massive, gray	7.25
34. Shale, sandy, thick-bedded, dark gray	2.95
35. "Feldspar porphyry" sill; contains phenocrysts of highly altered feldspars and biotite in a gray aphanitic groundmass	5.6
36. Shale, clayey, thin-bedded, black	3.0
37. Sandstone, quartzitic, thick-bedded, resistant, grading upward into fine-grained sandstone and thick-bedded sandy shale	9.3
38. Sandstone, shaly, thin- to thick-bedded, poorly exposed	8.0
39. Shale, clayey, thin-bedded, black, alternating with a few thick-bedded sandy layers	9.1
40. Sandstone, fine-grained, thin-bedded, grayish	5.5
41. Shale, thin-bedded, black to dark gray, nonresistant	1.3
42. Sandstone, fine-grained, thin-bedded	2.1
43. Sandstone, quartzitic, medium-grained, thick-bedded, gray, resistant; contains a few fine-grained beds	21.1
44. Shale, sandy to clayey, thin- to thick-bedded, dark-colored; contains a few thin beds of shaly sandstone. Grades into No. 45	15.8
45. Sandstone, micaceous, fine-grained, thin-bedded, gray	3.7
46. Shale, sandy, massive, dark-colored; bedding indistinct	8.1
47. Shale, clayey, thin-bedded, black, nonresistant	.4
48. Sandstone, micaceous, fine-grained, gray; slightly resistant	11.0
49. Shale, sandy, massive to thin-bedded; contains scattered quartz grains	14.3
50. Sandstone, fine-grained, massive, gray	.5
51. Shale, clayey, thin-bedded, black	.4
52. Sandstone, micaceous, fine-grained, massive, gray	7.0
Total	370.05

Stratigraphic sections of the rocks exposed in the individual coal mines of the Santa Clara district are presented in plate 5.

FOSSILS AND AGE

Fossil plants are fairly abundant in some of the shales of the Barranca formation, particularly in the carbonaceous shales occurring adjacent or close to the coal beds. Marine invertebrate fossils were found at only one locality, in shale (No. 17 of the measured section) in Arroyo de Tarahumara, 400 meters northwest of Santa Clara station. The invertebrate fossils were examined by Ralph W. Imlay, who reports that the species are all different from described forms and apparently new. Both pelecypods and gastropods are present, most of the forms being rather small.

The fossil plants collected by the writers were identified by Roland W. Brown, of the Geological Survey, as follows:

TABLE 2.—*Fossil plants collected from Barranca formation*

Species	Locality[1]			
	9064	9065	9066	9067
Cf. *Asterocarpus*				X
Cf. *Ctenophyllum grandifolium* Fontaine	X			
Cf. *Danaeopsis*		X		X
Macrotaeniopteris magnifolia (Rogers) Schimper	X			X
Cf. *Pecopteris*		X		X
Podozamites emmonsi Newberry	X	X		
Podozamites longifolius Emmons	X			
Cf. *Podozamites*			X	X
Cf. *Ptenophyllum*		X		
Sphenozamites rogersianus Fontaine				X
Cf. *Thinnfeldia*	X			
Cf. *Zamites*	X		X	X

[1]9064, El Voladero mine No. 2; 9065, El Refugio mine No. 3; 9066, head of Arroyo de la Calera; 9067, Santa Clara mine No. 3.

Brown remarks:

> Some of the specimens in these collections are well preserved and reveal their distinguishing features clearly. Others are fragmentary and poorly preserved, so that identification is uncertain. The specimens that can be identified are, so far as present knowledge of Triassic and Jurassic floras goes, found in the Triassic. The general aspect of the collections is Late Triassic.

Fossil plants have previously been collected from the Barranca formation, particularly in the vicinity of Los Bronces, by Rémond, Dumble, Benjamin F. Hill, and King, and have been examined by Newberry,[36] Humphreys,[37] Wieland,[38] and Read.[39]

The fossils reported by these writers are listed as follows:

Fossil plants previously reported from Barranca formation

Species	*Authority*
Alethopteris whitneyi Newberry	Newberry
Asterocarpus falcatus (Emmons) Fontaine	Humphreys
Asterocarpus virginiensis Fontaine	Do.
Camptopteris rémondi Newberry	Newberry
Cycadeomyelon(?) sp.	Humphreys
Jeanpaulia radiata Newberry	Newberry
Lacopteris munsteri Schenk	Wieland
Lacopteris(?) sp.	Read
Macrotaeniopteris sp.	Humphreys
Neocalamites carrerei (Zeiller) Halle	Do.
Otozamites macombii Newberry	Humphreys, Newberry

[36]Newberry, J. S., Descriptions of the Carboniferous and Triassic fossils, in Macomb, Capt. J. N., Report of the exploring expedition from Santa Fe, N. M., to the junction of the Grand and Green Rivers of the Great Colorado of the west, in 1859, pp. 141–148, U. S. Army, Engineer Dept., 1876.

[37]Humphreys, E. W., Triassic plants from Sonora, Mexico, including a Neocalamites not previously reported from North America: New York Bot. Garden Mem., vol. 6, pp. 75–78, 1916.

[38]Wieland, G. R., The El Consuelo cycadeoids: Bot. Gazette, vol. 81, p. 77, 1926.

[39]Read, C. B., of the Federal Geological Survey, identified the fossils reported in King, R. E., op. cit. (Sierra Madre Occidental), p. 1656.

Fossil plants previously reported from Barranca formation—Continued

Palissya sp.	Humphreys
Pecopteris bullatus Bunbury	Humphreys, Newberry, Read
Pecopteris falcatus Emmons	Humphreys, Newberry
Pecopteris mexicanus Newberry	Newberry
Podozamites crassifolia Newberry	Do.
Pterophyllum fragile Newberry	Newberry, Read
Pterophyllum robustum Newberry	Newberry
Taeniopteris elegans Newberry	Do.
Taeniopteris glossopteroides Newberry	Do.
Taeniopteris magnifolia Rogers	Newberry, Read
Zamites powellii Fontaine	Humphreys
Zamites (*Otozamites*?) sp.	Do.

The age of the fossil plant collections has been discussed by Burckhardt[40] and Freudenberg.[41] All the paleobotanists mentioned assign the collections studied by them to the Triassic, most of them specifying the Upper Triassic, thus agreeing with the conclusion of Brown given above. There appears to be little doubt, therefore, that the coal-bearing strata of the Santa Clara district are Upper Triassic in age.

In the Sierra de las Moradillas, 80 kilometers west of the Santa Clara district, both marine invertebrate and plant fossils have been found. Rémond collected, in addition to some plant remains, the pelecypod *Panope rémondi* Gabb,[42] considered Triassic in age, and Flores[43] collected a *Pecten* group of *P. pradoanus* Verneuil and Collomb (*Neithea mexicana* Jaworski) and *Pecten* cf. *textorius* Schlotheim, considered by Burckhardt[44] to be lower or middle Lias (Lower Jurassic) in age. It was evidently on the basis of the fossils collected by Flores that King[45] referred the Barranca formation to the Upper Triassic and Lower Jurassic. No evidence has so far been found, however, that any of the Barranca formation in the Sierra de San Javier is of other than Triassic age.

TARAHUMARA VOLCANICS (CRETACEOUS?)

General features, distribution, and thickness.—The Barranca formation is unconformably overlain by a considerable thickness of volcanic rocks, consisting chiefly of flows, agglomerates, and breccias, and in places some intercalated sediments. These rocks, which are probably of Cretaceous age, are herein named the Tarahumara volcanics for exposures in Arroyo de Tarahumara.

Rocks of the Tarahumara volcanics are found in the following areas in the Santa Clara district: (1) As a capping on hill 685 shown in the southwest

[40] Burckhardt, Carlos, Etude synthétique sur le Mésozoïque mexicain; première partie: Soc. paléont. Suisse Mém., vol. 49, p. 39, 1930.

[41] Freudenberg, Wilhelm, Geologie von Mexiko dargestellt nach der Literatur und nach eigenen Forschungen, pp. 67–68, Berlin, Verlag von Gebrüder Borntraeger, 1921.

[42] Gabb, W. M., Description of the Triassic fossils in California and adjacent territories, in Whitney, J. D., Geological Survey of California; Paleontology, vol. 1, p. 28, 1864.

[43] Flores, Teodoro, op. cit., p. 107.

[44] Burckhardt, Carlos, op. cit., p. 24.

[45] King, R. E., op. cit. (Sierra Madre Occidental), pp. 1645, 1656–1657.

corner of the geologic map (pl. 2, coordinates 80 E., 1420 S.). In this area the volcanic rocks are in fault contact with the Barranca formation on both west and east sides, and they are intruded by diorite on the southeast. To the north they seem to lie unconformably on the Barranca formation, although the contact is obscured by talus. (2) In a long, narrow belt in the central part of the map, lying east of the Nochebuena mine and west of the Potrero fault, which crosses the central part of the district. The exposures along Arroyo de Tarahumara form part of this belt (pl. 2, coordinates 1300-1500 E., 800-1000 S.). This belt has been faulted down against the Barranca formation along the east side. In places it has been intruded by diorite. (3) As a capping on the ridge southeast of Santa Clara station. The contact with the underlying Barranca formation descends eastward from the top of the ridge and crosses Arroyo de Tarahumara 400 meters east of Santa Clara station (pl. 2, coordinates 2650 E., 500 S.). This is the westernmost tip of a belt that continues down Arroyo de Tarahumara toward the Río Yaqui, where it is overlapped successively eastward by early Tertiary volcanic rocks and by the late Tertiary or Quaternary Báucarit formation. (4) As a capping on the ridge east of Arroyo del Potrero, forming the Mesa de las Chivas, near the southeast edge of the map (pl. 2, coordinates 2300 E., 1700 S.). This belt merges to the east with the one just described, and, like it, seems to lie unconformably on the Barranca formation and to dip gently eastward.

The belts described above merge southward to form a large mass of volcanic rocks lying south of the Sierra de San Javier, interrupted in places by intrusive bodies of diorite and other plutonic rocks. The volcanic rocks are fairly well exposed in Arroyo del Obispo, which is followed by the road from Hermosillo to Tónichi, forming a belt of low rounded hills, in contrast to the jagged peaks of the Sierra de San Javier composed of the Barranca formation.

The incomplete thickness of the Tarahumara volcanics exposed in the area studied in detail is at least 200 meters, but the total thickness is probably much greater in the surrounding region.

The Tarahumara volcanics limit the areas in which exploitation of the coal deposits would be possible. Areas having a thick cover of the volcanic rocks, such as the belt west of the Potrero fault, must be excluded from any consideration of possible reserves of the district and possible sites for exploratory drilling.

Lithology.—The Tarahumara volcanics consist mainly of highly altered aphanitic volcanic rocks, ranging in composition from andesite to latite. Most of the rocks are purplish or gray to reddish and give rise to a reddish-brown soil. Phenocrysts are rare; they consist of plagioclase and a very few ferromagnesian minerals, in part augite, highly altered to chlorite and iron oxides. The rocks have been extensively affected by pyritization and hydrothermal alteration, and small crystals of pyrite and, less commonly, chalcopyrite are scattered widely throughout the formation.

A thin section of a sample from Arroyo del Potrero was studied by Sr. Eduardo Schmitter of the Instituto de Geología, who described the rock as having a porphyritic texture with a microcrystalline groundmass. The phenocrysts are totally altered feldspars, and the secondary minerals are clay, calcite, quartz, pyrite, limonite, and magnetite. The rock was classified questionably as a highly altered latite.

Breccias and agglomerates are fairly common in the formation. They contain angular fragments of aphanitic rocks similar to those of the flows. Bedding and flow structure are rare in the formation, but jointing is prominent.

The volcanic rocks are for the most part highly altered and weathered near the surface, so that exposures of fresh rock are rare. They are less resistant than most of the rocks of the Barranca formation and tend to form low rolling hills. The contrast in topography developed on the two formations is especially noticeable along the Potrero fault, where it marks the boundary between the formations in the southern part of the area shown in plate 2.

Age.—These volcanics were considered by Dumble[46] to form part of the "Lista Blanca division," which he named for Lista Blanca Mountain, a few kilometers southwest of the town of San Marcial (see fig. 1). Dumble thought that the Lista Blanca rocks were probably of Triassic age, because of his impression that "they and the underlying Triassic beds were part of one system,"[47] but he adds that it is entirely possible that they may be younger than Triassic. King,[48] however, considers the volcanic rocks south of the Sierra de San Javier to be of Cretaceous age and says that "there is some uncertainty as to whether the volcanic rocks of the type locality (of the Lista Blanca) are not actually of Tertiary age." Because of this uncertainty as to the age of the rocks at the type locality of the Lista Blanca, it seems undersirable to extend that name to the Santa Clara district, and the local name of Tarahumara is proposed instead.

It does not seem possible that the rocks of the Tarahumara volcanics are Triassic in age, as believed by Dumble, because they rest unconformably on the Barranca formation, which, in the Sierra de Moradillas, contains Lower Jurassic fossils in its upper part (see section on age of Barranca formation). Dumble's impression that the volcanic rocks and the underlying Barranca formation were part of one system was not shared by the writers; there appears, rather, to be a strong angular unconformity between the two groups of rocks. King[49] considered these volcanic rocks to be probably of Cretaceous age, because of their resemblance to similar

[46] Dumble, E. T., op. cit. (Geology of Sonora), pp. 143–147.
[47] Idem, p. 147.
[48] King, R. E., op. cit. (Sierra Madre Occidental), p. 1675.
[49] Idem, p. 1675.

volcanics interbedded with fossiliferous Cretaceous rocks near Sahuaripa (see fig. 1), northeast of the Santa Clara district.

Dumble[50] found fossils in a 25-meter limestone bed in Arroyo del Obispo, south of the Santa Clara district. These fossils, most of them poorly preserved siliceous pseudomorphs, included many oysters, a few gastropods, a *Cypremaria*, plates of a large echinoid of the Cidaridae class, and a small *Gryphaea*, which he considered sufficient to prove the Cretaceous age of the beds. Although Dumble considered the limestone as dividing two volcanic complexes, the lower of Triassic and the upper of Tertiary age, King,[51] on the other hand, considered the limestone to be interbedded in a single volcanic complex of Cretaceous age, an interpretation that seems more plausible to the writers. In another paper Dumble[52] reported finding a large unidentified oyster shell in andesitic agglomerate assigned to the Lista Blanca, near La Barranca.

In summary, the Tarahumara volcanics must be younger than the Triassic because they rest unconformably on the Barranca formation. Evidence for a probable Cretaceous age includes the occurrence of Cretaceous fossils in a limestone that is probably interbedded in the formation, and the similarity of the formation to Cretaceous volcanic rocks in the Sahuaripa district.

SILLS AND DIKES (CRETACEOUS?)

General features, mode of occurrence, and distribution.—Sills and dikes of porphyritic to aphanitic igneous rocks are fairly common in the Santa Clara district. For the most part they consist of latite or quartz latite, but some are probably of andesite, and at least one rhyolite body was noted. The rocks mainly form sill-like bodies intruding the sediments of the Barranca formation. Dikes, where present, are generally elongate parallel to the strike of the Barranca formation. The larger sills and dikes are shown on the geologic map (pl. 2), but some of the smaller bodies are omitted. Some good examples are found: (1) In Arroyo de la Calera at the entrance to the La Calera mine (coordinates 720 E., 490 S.); (2) on the ridges between Arroyo de las Amarillas and Arroyo del Tren, west of the El Tren mine (coordinates 100 E., 490 S.); (3) in Arroyo del Tren near its junction with Arroyo de la Calera (coordinates 550 E., 480 S.); (4) at the junction of Arroyo del Pie de la Cuesta with Arroyo de Tarahumara (coordinates 1950 E., 130 S.); (5) in Arroyo del Potrero east of hill 363 (coordinates 2070 E., 360 S.); and (6) in Arroyo de la Milpa (coordinates 2500 E., 1150 S.). Dikes and sills were noted in various parts of the Sierra

[50] Dumble, E. T., Cretaceous of Obispo Canyon, Sonora, Mexico: Texas Acad. Sci. Trans., vol. 4, p. 81, 1901.

[51] King, R. E., op. cit. (Sierra Madre Occidental), p. 1675.

[52] Dumble, E. T., Occurrence of oyster shells in volcanic deposits in Sonora, Mexico: Texas Acad. Sci. Trans., vol. 4, p. 82, 1901.

de San Javier traversed by the writers, as far west as the Santa Julia coal deposits and as far north as Los Bronces.

The sills and dikes have had detrimental economic effects upon the coal deposits, of two types: (1) Cutting out of the coal beds, and (2) metamorphism of the coal. The metamorphic effects include the formation of graphite and natural coke. Furthermore, the dikes and sills are probably at least partly responsible for the metamorphism of the coal to the rank of meta-anthracite, resulting in inferior combustion characteristics as compared to typical anthracite.

Lithology.—The sills and dikes consist of several lithologic types. One type, a moderately coarse grained gray or greenish-gray quartz latite, occurs chiefly in dikes, such as those exposed at the entrance to the La Calera mine and at the junction of Arroyo del Pie de la Cuesta with Arroyo de Tarahumara. It contains fairly large phenocrysts in an aphanitic groundmass. The phenocrysts consist of about equal amounts of white plagioclase and pink orthoclase, besides a little quartz and, less commonly, ferromagnesian minerals altered to iron oxides.

Another common type, occurring mainly in sills, is a gray, highly altered aphanitic rock with very few phenocrysts. It is usually fairly soft as a result of strong alteration. Thin sills of this rock lie near, and in places intrude, the coal seam in the El Tren mine. Thin sections of two specimens from the sills in the El Tren mine were examined by Sr. Eduardo Schmitter of the Instituto de Geología, who described the rocks as being porphyritic with a hypohyaline groundmass. The only phenocrysts visible are of completely altered feldspar, besides a little quartz in one thin section, and the secondary minerals are clay, quartz, calcite, and pyrite. The rocks were classified questionably as highly altered latite.

A different type of sill also occurs in a part of the El Tren mine, above the coal seam. This is a fairly coarse-grained porphyritic rock, greenish in color, containing phenocrysts of feldspars and biotite in an aphanitic groundmass.

A thin section of a specimen from a small dike in Arroyo de Tarahumara, near its junction with Arroyo del Agua Blanca, was studied by Schmitter and classified questionably as an altered porphyritic rhyolite. The rock has a porphyritic texture with a microcrystalline to cryptocrystalline groundmass, and possesses brecciated and spherulitic structures. The phenocrysts are quartz and sanidine; the secondary minerals are clay, chlorite, limonite, and quartz. The spherulites are dark-colored and are composed mainly of chlorite and limonite.

Age.—The age of the sills and dikes cannot be determined more definitely than post-Triassic, for they intrude the Upper Triassic sediments of the Barranca formation. It seems likely, though not proved in the field, that many of them were feeders to the Tarahumara volcanics, and that they are therefore probably of Cretaceous age. It is possible that more than one period of intrusion is represented, as the coarser-grained porphyritic quartz latite dikes, such as the one at the entrance to the Calera mine, are quite different in character from the aphanitic latite sills that occur in the El Tren mine.

DIORITE AND QUARTZ DIORITE (TERTIARY?)

General features, mode of occurrence, and distribution.—Stocklike bodies of diorite and quartz diorite occur in various parts of the district, representing probably the apophyses or irregular top of a large batholith lying at some depth below the surface. Virtually no contact metamorphism was observed around the bodies, but their intrusive nature is evinced by two lines of evidence: (1) The distribution and shape of the bodies with respect to the surrounding rocks, and (2) the presence of sills extending outward from the larger dioritic masses and intruding the sedimentary layers of the Barranca formation. The best example of such a sill was observed in the Tescalama gold mine, on the west slope of Cerro del Candelero, where the mine workings follow a thin dioritic sill that leads from a larger mass in the La Barranca Valley. Veins containing gold and silver occur near this sill.

In the area shown on plate 2 six dioritic masses were noted: (1) An irregular body about 300 meters long lying north of the Nochebuena mine, which is north of Arroyo de Tarahumara, near the center of the map (pl. 2, coordinates 1200 E., 700 S.). (2) A small body 100 meters long in Arroyo de Tarahumara west of the Nochebuena mine, exposed at the entrance to the Santa Fe mine tunnel (coordinates 1000 E., 1000 S.). (3) A large mass near the head of Arroyo de Tarahumara, extending southward along Arroyo del Triunfo to Puerto de la Bronzuda (coordinates 500 E., 1500 S.). This body is 300 to 400 meters wide and is probably at least a kilometer long in a southerly direction. It extends southward beyond the limits of the area mapped. (4) A body near the head of Arroyo del Potrero, just west of the Potrero fault, at the southern extremity of the map (coordinates 2000 E., 1900 S.). The area mapped extends only to the north edge of this body, which is actually much larger and has been eroded in the form of a broad valley. (5) A small body 30 meters wide near the head of Arroyo de Santa Clara (coordinates 1500 E., 1200 S.). (6) A very small outcrop in the headwater of Arroyo de los Coyotes (coordinates 1020 E., 1220 S.).

In the Sierra de San Javier outside the Santa Clara district intrusive masses of diorite crop out in several other valleys, such as those in which the towns of La Barranca and San Javier are situated. South of the Sierra de San Javier, in Arroyo de la Barranca, along the road from Arroyo del Obispo to Tónichi is another broad valley eroded in plutonic rocks. As the diorite is less resistant than the surrounding rocks, erosion tends to carve valleys in the intrusive masses.

The dioritic intrusions have invaded the Barranca formation and destroyed any coal beds that may have been present in the intruded areas. In the immediate vicinity of the intrusive bodies, moreover, considerable disturbance can be expected, including faulting and metamorphism of the coal to natural coke and graphite. Thus areas above and immediately surrounding the intrusive bodies must be eliminated in calculating coal reserves or planning exploratory drill sites. The size of the surrounding areas to be eliminated from consideration will depend partly on the extent of disturbances or metamorphism, and especially upon the steepness of dip of the sides of the intrusive bodies, for if the bodies have gentle dips the coal beds may be affected long distances from the surface outcrops of intrusive rocks.

Lithology.—These rocks have the general composition of diorite, although in some places quartz diorite is also present. In general they have a medium-grained granitic texture. A thin section of one specimen of quartz diorite, collected from an outcrop west of the Nochebuena mine, revealed the presence of plagioclase (andesine), a small amount of quartz, and fairly abundant, highly altered hornblende and biotite. Minor accessories present were magnetite, apatite, and zircon, and the principal secondary minerals were chlorite and calcite.

The rocks are gray where fresh, but yellow or yellowish-brown where weathered, and form a yellowish soil. Near the surface they are generally so highly decomposed that they crumble readily between the fingers. Even at some depth, as in the Tescalama gold mine, they are thoroughly decomposed. Some of this extensive decomposition may be due to hydrothermal alteration, as indicated by the presence of quartz veins in many places. The gold and silver veins mined around La Barranca, San Javier, and Los Bronces represent a period of mineralization that probably followed closely upon the intrusion of the diorites.

Age.—As the dioritic rocks intrude both Barranca and Tarahumara formations in the Santa Clara district, the period of intrusion can be determined only as probably Cretaceous or later. In surrounding areas in Sonora, however, King[53] found similar plutonic rocks intrusive also into early Tertiary volcanic rocks. The intrusives are older than the Báucarit formation of late Tertiary or early Quaternary age, which contains granite fragments. From this evidence King concluded that most of the intrusives in this region were of middle Tertiary age, although some might be older.

TERRACE DEPOSITS AND ALLUVIUM (QUATERNARY)

Recent terrace and alluvial deposits, consisting of unconsolidated gravel, sand, and silt, are confined mainly to the bottoms and sides of the arroyos. The deposits are generally not more than 2 or 3 meters thick. Landslides were noted in various parts of the district, and many of the

[53] King, R. E., op. cit. (Sierra Madre Occidental), p. 1698.

hill slopes are covered with loose rubble and talus; so exposures of the underlying rocks are far from continuous.

Gold has been obtained from the alluvium in some of the creek bottoms and terraces by dry placer mining, as for example in Arroyo de Tarahumara just north of Santa Clara station. It is found mainly in depressions in the underlying bedrock. The deposits are not rich, however, and only a small amount of gold has been recovered.

STRUCTURE

STRUCTURE OF SANTA CLARA DISTRICT

Structure of Barranca formation.—In the Santa Clara district the beds of the Barranca formation have a more or less homoclinal dip to the southeast. The strike averages N. 55° E., ranging in general from N. 45° to 65° E., and in the extreme from N. 10° E. to N. 80° E. The dip averages 30° SE., ranging in general between 20° and 40° SE., although the extreme limits are as low as 6° and as high as 75°. In only one part of the area mapped do the beds have a northwesterly dip. This is found along Arroyo de Agua Blanca, east of the junction of Arroyo de la Calera with Arroyo del Refugio, and appears to be the result of overturning along a fault zone. Locally along this zone the beds dip 60° NW.

Structure of Tarahumara volcanics.—The structure of the Tarahumara volcanics is difficult to ascertain because of the general absence of flow planes or bedded structures. Judging from the basal contacts on the Barranca formation, however, the rocks appear to have a gentle dip to the east and southeast. There appears to be a strong angular unconformity between the Barranca and Tarahumara formations, in terms of both dip and strike.

Potrero fault.—Only one important fault, here named Potrero, crosses the area mapped. For a short distance it follows Arroyo del Potrero, shown in the southeast corner of plate 2, and then it turns northwestward, across the central part of the area mapped, to the junction of Arroyo de la Calera with Arroyo del Refugio, which it follows northward. The fault has an average strike of N. 40° W., ranging from N. 20° to 60° W., and it appears to dip steeply southwest, the block on that side being relatively downthrown. Gouge and breccia occupy the fault zone. Between Arroyo de Tarahumara and Arroyo de Santa Clara the fault causes the coal-bearing beds of the Barranca formation on the northeast side to abut against Tarahumara volcanics on the southwest. Along Arroyo del Refugio, in the northern part of the mapped area, the fault marks the contact between the coal-bearing beds of the La Calera, El Tren, and El Refugio mines, on the southwest side, and quartzitic sandstones and quartzites of the lower division of the Barranca formation, on the northeast.

The effect of the Potrero fault is to divide the coal deposits into two parts; the northwest part, lying between Arroyo de la Calera and Arroyo del Refugio, is called the Calera Basin, and the other, between Arroyo de Santa Clara and Arroyo de Tarahumara, the Santa Clara Basin. The apparent horizontal displacement of the beds on the southwest side of the fault has been 700 or 800 meters to the northwest. As the beds dip 30° SE., however, this apparent horizontal shift could have been produced if the southwest side of the fault had dropped vertically about 500 meters. No evidence was found as to whether the movement on the fault was mainly vertical or horizontal.

The Potrero fault is well marked topographically, being followed by a series of saddles and ravines. This is due largely to a difference in the resistance of the rocks on the two sides of the fault. In the southern part of the area the highly altered Tarahumara volcanics on the southwest side are less resistant than the beds of the Barranca formation on the northeast, and form a belt of low, rolling hills. In the northern part of the area, likewise the coal-bearing shales and sandstones southwest of the fault are less resistant than the stratigraphically lower, massive sandstones and quartzites northeast of the fault.

GENERAL STRUCTURE OF SIERRA DE SAN JAVIER

In those parts of the Sierra de San Javier traversed by the writers the Barranca formation has the same general structure that it possesses in the Santa Clara district. The beds have a general northeast strike and a homoclinal dip averaging about 30° SE. In a few places the strike swings around to north or northwest, the dip being east or northeast. No true folds were seen; except minor crumpling, the structural variations seem rather to consist of broad swings in strike. It was believed likely that other transverse faults similar to the Potrero occur between the Santa Clara district and San Javier, but the details of these faults were not established. An area of Tarahumara volcanics along part of Arroyo de los Bronces appears to have been dropped down between faults.

The western front of the Sierra de San Javier is described by King[54] as an overthrust fault line, along which the eastward-dipping Barranca formation has been thrust westward over the Báucarit formation. Although this area was not studied in detail by the writers, the general field relations seem to accord with King's conclusions.

LOCAL STRUCTURES AFFECTING COAL MINING

In most of the coal mines the Barranca formation has a fairly regular northeast strike and a dip averaging about 30° SE. In part of the El Refugio mine the dip is almost horizontal, and in parts of the El Refugio and La Calera mines dips of as high as 50° are found, but these dips are exceptional.

[54]King, R. E., op. cit. (Sierra Madre Occidental), pp. 1706–1707.

The coal beds are offset by numerous small faults, but very few large faults are exposed in the mines. The only large one noted is a zone of two closely spaced faults in the Santa Clara mine, in a raise at the north end of the main crosscut tunnel. There the coal seam has been upthrown about 6 meters in a wedge between the two faults, and offset an unknown amount north of the fault zone—one of the few places in the mines in which a coal bed was "lost" because of faulting.

Aside from this fault zone in the Santa Clara mine, most of the faults exposed in the mines have displacements of less than 2 meters. All the faults on which the displacement could be determined were normal. Some of them strike northeast, roughly parallel to the strike of the beds, and dip 25°–40° NW., across the beds, being downthrown on the northwest. Two such faults were noted in the El Tren mine, and one in the El Refugio mine No. 3 nuevo. A number of faults strike northwest and dip generally 30°–60° NE., although a few dip southwest. Such faults were found in the Santa Clara, El Tren, La Calera, El Refugio, and Yaqui mines.

In a few places bedding-plane faults affect the coal beds by causing them to wedge down, as was noted in the Santa Clara mine. Faults nearly parallel to the bedding are believed to have caused the coal seams in the western part of the mine to wedge down to less than a meter in thickness, and practically to disappear at the bottom of the inclined shaft at the south end of the mine.

No evidence was found for any large-scale repetition of the coal beds by longitudinal faulting. The only important repetition of beds believed to occur in the region is that produced by transverse faults, such as the Potrero. According to an unpublished report on the Santa Clara district written by E. T. Dumble in 1910, a thrust fault that caused repetition of the beds was found in the main "Z" workings (Nos. 1 and 2). The attitude and displacement of the fault were not given, however, although from the context of the report the horizontal displacement is judged to amount to a few tens of meters. As these workings were completely caved at the time of the writers' visit, no further information on the nature of this fault could be obtained.

COAL

DISTRIBUTION

The coal beds of the Santa Clara district occur in two separate areas, the Calera and Santa Clara Basins. The Calera Basin extends for about 1 kilometer westward from the junction of Arroyo de la Calera with Arroyo del Refugio. The Santa Clara Basin is south of Arroyo de Tarahumara and includes the drainage areas of Arroyo de Santa Clara and Arroyo del Potrero, extending as far west as the Potrero fault. Its eastern border is formed by Arroyo de la Milpa, to the east of which the coal-bearing rocks are largely buried by the Tarahumara volcanics. Each of the basins has an area of about 1 square kilometer in which coal deposits have been found.

The two areas are separated by the Potrero fault, and the beds in the two basins are believed to be stratigraphically equivalent, the beds in the Calera Basin having been displaced northwestward with respect to those in the Santa Clara Basin. It is of interest to note that Dumble, in an unpublished report written in 1910, likewise suggested that the beds of the Calera Basin were probably stratigraphically equivalent to those of the Santa Clara Basin, a conclusion that was reached independently by the writers before they saw Dumble's report.

STRATIGRAPHIC POSITION AND NUMBER OF BEDS

At least nine separate beds, each having a thickness of more than 1 meter, have been found in the Calera Basin, and at least seven in the Santa Clara Basin. Although the beds in the two basins cannot be correlated with certainty, it is tentatively concluded that four of the beds in the Santa Clara Basin may have equivalents in the Calera Basin, but that three are probably separate beds. If this conclusion is correct, there are at least 12 coal beds in the district having a thickness at some point of at least 1 meter, besides others that are thinner or that consist of bony coal.

These 12 or more coal beds can by no means be traced on the surface over the full extent of the separate basins; some of them, in fact, have been found only in a single outcrop or in a single shaft or prospect pit. It is very difficult to trace them for any distance, because the coal has, in general, been completely altered by weathering to depths of 10 to 30 meters. Characteristic weathering products serve to indicate an underlying coal bed, and most of the coal outcrops indicated on the map consist of such material rather than of the coal itself. Even these alteration products cannot be traced far, because they are usually poorly exposed and covered by talus or soil. The Southern Pacific Railroad Co. explored the area by trenching across the various shale belts, but as these trenches have long since been filled with debris it is generally difficult to determine what was exposed. Most of the mine workings of this company, moreover, except those recently reopened by the Cía. Carbón Sonora, are caved and inaccessible, and the only clue as to what was found lies in examining the dumps for fragments of coal. This, of course, gives no indication of the thickness or structure of the coal beds. Consequently, many uncertainties are involved in correlating the coal beds from place to place, and very little can be said as to the probable or possible extent of each individual bed. Dumble's unpublished report of 1910 has been freely drawn upon in correlating the beds, as it contains information obtained from numerous mine workings that are now caved. Unfortunately, the map accompanying Dumble's report could not be found, so that some of the localities to which he refers are difficult to identify.

The system of numbering the coal beds on the accompanying maps and sections is as follows: The prefix "C" appears before all the beds in the

Calera Basin, and "SC" before all those in the Santa Clara Basin. The beds are numbered separately in each basin, beginning with number 1 for the lowest stratigraphically. Only beds having a thickness at some point of at least 1 meter (3 feet for the beds reported by Dumble) are numbered, for it is assumed that thinner beds could not be mined commercially. Where beds found at two different places are thought but not proved to be equivalent, they are assigned the same number, to which different letters are affixed. For example, the El Tren bed is numbered C4a, and the El Refugio bed is numbered C4b, indicating that these two beds are thought but not proved to be equivalent.

Table 3 gives the numbers and names[55] of the various beds, the approximate stratigraphic intervals between them, their thicknesses, and the distances explored along their strike and dip. The column headed "possible strike length" gives the total distance between outcrops that are believed to represent the bed in question, although in many places it is uncertain whether the outcrops actually represent the same bed or whether the bed is continuous between the outcrops.

TABLE 3.—*Coal beds exposed in the Santa Clara district*

No.	Name of bed	Thickness (meters)	Continuously explored strike length (meters)	Possible strike length (meters)	Dip length (meters)	Stratigraphic interval above underlying bed (meters)
	CALERA BASIN					
C9	Upper Pitahaya	1.2	None	(?)	None	160?
C8	Lower Pitahaya	.6 coal .15 shale .4 coal	None	100	None	60?
C7	Upper Calera[1]	.3–.4 coal .4–.5 shale 1.0 coal	158	545	37	13?–21
C6	Lower Calera	.4–.45 coal .3–.6 shale .35–.8 coal	26	550	18	14
C5	La Confluencia	.9	20	550	(?)	62–66
C4b	El Refugio[1]	2.5	150	560–840	130	27–31
C4a	El Tren[1]	.3 coke 1.05 coal	230		112+	
C3b	Yaqui[1]	.5 coke .1 shale .8 coke .2 coal	100	1,040	65	52–62
C3a	Las Amarillas[1]	.65 coal .45 shale 1.05 coal	120?		(?)	
C2	Whitewood	1.2	None	450	None	30?
C1	Boca del Agua	1.2	None	(?)	None	....
	SANTA CLARA BASIN					
SC7b	Potrero No. 6	.6 coal 1.5 coke	None	(?)	(?)	(?)
SC7a	Potrero No. 5	.9	None	(?)	(?)	(?)
SC6b	Santa Clara[1]	2.0	73+	730	25+	16
SC6a	El Voladero[1]	2.0	95+	330–730	17	
SC5	Casa Blanca	.9+	None	(?)	None	16
SC4	Upper Parvin	1.35+	None	(?)	None	6
SC3	Lower Parvin	.9	None	(?)	None	45?
SC2	Upper Z[1]	(?)	150?	(?)	(?)	35–40?
SC1	Lower Z	1.3	22	150	53+	....

[1]Yielded a significant production.

[55]Some of the names are those used currently by the Cía. Carbón Sonora; some are taken from Dumble's unpublished report; and some have been originated by the writers, where no previous name seems to exist.

According to evidence discussed by Dumble, which seems reasonable to the writers, the "Z" beds, Nos. SC1 and SC2, in the Santa Clara Basin are probably equivalent to the La Calera beds, Nos. C6 and C7, in the Calera Basin. This correlation is by no means certain and does not necessarily mean that the beds were ever continuous but only that they represent approximately the same stratigraphic horizons. The rest of the coal beds in the Santa Clara Basin, such as those in the Parvin and Casa Blanca shafts and the El Voladero-Santa Clara beds, would therefore be equivalent to some of the Pitahaya beds of the Calera Basin, of which two, known to have a thickness of more than 1 meter, are assigned numbers in this report. At least 3 beds in the Santa Clara Basin would still remain without numbered equivalents in the Calera Basin, which, added to the minimum of 9 beds in the Calera Basin, make a total of 12 as a probable minimum number for the two basins. If the beds of the Santa Clara Basin are entirely distinct from those of the Calera Basin, however, the total number in the district would be at least 16.

The greater part of the coal mined from the district has come from five beds, three in the Calera Basin and two in the Santa Clara Basin. In the Calera Basin, they are the El Tren-El Refugio bed (C4a-b), which has yielded probably the largest amount of coal in the district; the Upper Calera (C7); and the Las Amarillas-Yaqui (C3a-b), which has yielded a much smaller amount of coal. In the Santa Clara Basin the most productive beds have been the Upper Z (SC2) and the El Voladero-Santa Clara (SC6a-b).

EXTENT AND THICKNESS OF BEDS

None of the individual beds have been followed for any great distance along their strike. The longest continuously explored bed is the El Tren (C4a), which has been followed in the El Tren mine for 230 meters. If the assumption is correct that this is the same as the El Refugio bed (C4b), and accepting a statement by Dumble that an outcrop of the same bed was discovered in an open cut near Arroyo de las Amarillas, it would have a total possible strike length of at least 840 meters. Likewise, if the Las Amarillas (C3a) and Yaqui (C3b) beds are the same, a possible strike length of 1,040 meters would be represented between their known extremities. None of the other coal beds have a greater length than this. For most of them, in fact, lengths of 100 to 200 meters are the greatest that can be assumed on the basis of present development, and many are exposed only in a single outcrop or mine working.

None of the beds have been followed very far down the dip. The greatest distance known to have been continuously explored down the dip appears in the El Tren mine, in which the coal has been followed by an inclined shaft for 112 meters, from the surface (including the altered zone) to water level, plus an unknown but probably short distance below water.

The total dip length indicated in the El Refugio mine is 130 meters, although the coal is not exposed continuously for this distance, at least not in workings that are now accessible. Most of the development carried on by the Cía. Carbón Sonora in the various mines has been confined to a fairly narrow zone between the lower limit of surface alteration and the water level.

There is every reason to suppose that the dip length of any individual coal bed would be comparable to its strike length, but there are two possible factors that could cause the bed to become lost as it is mined downward: (1) Igneous intrusions, either latitic dikes and sills or larger masses of diorite, and (2) faulting. The best way of evaluating the extent of these possible effects would be by an extensive drilling program.

The coal beds that have been extensively mined have averaged from 1 meter to 2 meters in thickness. The thickest bed observed is in the Santa Clara mine, where the coal is as much as 2.8 meters thick. In part of the El Refugio mine the coal is at least 2.6 meters thick, and in some of the caved parts of this mine it may have been as much as 3 meters thick. Measured thicknesses in the more important mines are indicated at frequent intervals on the accompanying mine maps (pls. 7 to 11). Many beds less than 1 meter thick occur in the district, but they are assumed not to be commercial.

DESCRIPTION OF INDIVIDUAL BEDS

CALERA BASIN

The Boca del Agua bed, C1, was described by Dumble as having been found in a slope 40 feet (12 meters) long in the arroyo northwest of the Las Amarillas mine (which he called the Gopher mine). He states that the coal had a thickness of 4 feet (1.2 meters) and was of fair quality. This bed was not seen by the writers. It appears to be the lowest bed discovered in the Calera Basin, but nothing may be said of its possible extent.

The Whitewood bed, C2, was found, according to Dumble, in slopes in Arroyo del Tren and Arroyo del Refugio, in both of which it had a thickness of 4 feet (1.2 meters). He describes the bed in Arroyo del Tren as consisting of natural coke. An outcrop believed to represent this bed was found by the writers in Arroyo del Tren 175 meters northwest of the El Tren mine, and it is indicated on plate 2 (coordinates 340 E., 300 S.). The locality in Arroyo del Refugio referred to by Dumble, however, could not be identified by the writers. He describes the bed at that place as consisting of fair coal with a 3-inch (8-centimeter) parting of slate.[56] If this bed should extend from Arroyo del Tren to Arroyo del Refugio, it would have a strike length of at least 450 meters.

The Las Amarillas bed, C3a, called the Gopher by Dumble, was ex-

[56]The "slate" referred to in various parts of Dumble's report is classified by the writers as shale, because no slaty cleavage seems to have developed.

tensively developed in the Las Amarillas mine in Arroyo de las Amarillas (see pl. 2, coordinates 110 W., 540 S.). The entrance to this mine is now completely caved, but judging from an old map of the district the mine probably had a total length of about 120 meters. According to Dumble, the Las Amarillas bed had a regular section in this mine as follows: "41 inches (1.05 meters) coal, good; 18 inches (45 centimeters) slate; 26 inches (65 centimeters) coal, good."

The Yaqui bed, C3b, exposed in the Yaqui mine (see pl. 2, coordinates 800 E., 120 S., and pl. 8), was considered to be the same as the Las Amarillas bed by Dumble, both beds seeming to occur at about the same stratigraphic position. The intervening distance of 880 meters between the two mines is so great, however, that the correlation cannot be considered as certain. Dumble states that the outcrop was uncovered by open cuts at two places between the two mines, but these localities were not identified by the writers. If the beds in the Las Amarillas and Yaqui mines should be the same, the total strike length between the extremities exposed in the two mines would be 1,040 meters. In the Yaqui mine the bed consists mainly of natural coke, having a thickness of as much as 1.6 meters, and it has been developed for a length of about 100 meters.

Below the succeeding El Tren-El Refugio bed are some thin beds of coal that have not been assigned numbers. In the El Refugio mine a bed of bony coal having an average thickness of 50 centimeters occurs about 7 meters below the main coal bed, and it is also exposed in the adit No. 3 nuevo (see pl. 10). In the crosscut of the El Tren mine (see pl. 11) two lower beds are exposed, one having a thickness of 75 centimeters and the other of 40 centimeters. The lowest of them might be the same as the Las Amarillas-Yaqui bed. Three other thin beds of bony coal are exposed in this mine.

The El Tren bed, C4a, is exposed in the El Tren mine (see pl. 2, coordinates 470 E., 410 S., and pl. 11), from which a considerable amount of coal has been produced by the Cía. Carbón Sonora. In this mine the coal contains a thin layer of natural coke, which occurs at some places at the top of the bed, at other places in the middle, and at still others at the bottom. The total thickness of the coal and coke averages 1.35 meters, but the average thickness of minable coal, occurring separately from the coke, is about 1 meter. The length of the part of the bed continuously exposed in this mine is 230 meters.

The El Refugio bed, C4b, exposed in the El Refugio mine (see pl. 2, coordinates 700 E., 250 S., and pl. 10), is probably the same as the El Tren, as was thought by Dumble, although the correlation cannot be proved. In the El Refugio mine the bed has an average thickness of about 2.5 meters, and is said to have been as much as 3 meters thick in certain workings that are now caved. The total length of the part of the bed exposed in this mine is about 150 meters. The distance between the extremities of the El Tren and El Refugio mines is 560 meters. Dumble also reports that an outcrop of what he considered the same bed was found in an open cut in Arroyo de las Amarillas. If all these exposures should prove to be the same bed, the total strike length would be at least 840 meters.

The La Confluencia bed, C5, is named for an outcrop of natural coke at the junction (confluencia, in Spanish) of Arroyo del Tren with Arroyo de la Calera (see pl. 2, coordinates 590 E., 540 S.). Another outcrop in Arroyo de la Calera 170 meters southwest of the junction is believed to represent the same bed. This bed is thought to be the one described by Dumble as having been found near the mouth of Arroyo del Tren in a drift (now completely caved) 67 feet (20 meters) long. In the drift, according to Dumble, the bed was irregular, having a maximum thickness of 3 feet (90 centimeters), and was disturbed by igneous rocks. An outcrop of "chicle" (the usual alteration product of the coal), in Arroyo de la Calera 90 meters southwest of its junction with Arroyo del Refugio, appears to be about the same stratigraphic horizon and might represent the same bed. This outcrop has not been explored. If all these outcrops in Arroyo de la Calera are of the same bed, which is far from certain, the total strike length indicated would be 550 meters.

The Lower Calera bed, C6, is followed by a short drift branching from the main adit of the La Calera mine (see pl. 2, coordinates 720 E., 490 S., and pl. 9), 20 meters southeast of the mine entrance. This drift is now accessible for a length of only 15 meters, but according to Dumble it originally had a length of 86 feet (26 meters). The coal is divided into two layers separated by a shale parting. Near the junction of the drift with the adit the thicknesses are 80 centimeters of coal at the base and 45 centimeters at the top, separated by 60 centimeters of shale. Farther northeast in the drift the bed consists of 35 centimeters of coal at the base and 40 centimeters at the top, separated by 30 centimeters of shale. No stoping has been done on this bed. A completely altered coal bed, about 60 centimeters thick, exposed just inside the Pitahaya adit No. 1 (see pl. 2, coordinates 380 E., 760 S.), 430 meters southwest of the La Calera mine, appears to lie about the same horizon and might be the same bed. If it should be the same, and if some caved workings northeast of the La Calera mine are also on the same bed, the total strike length would be 550 meters.

The Upper Calera bed, C7, is the principal coal bed exploited in the La Calera mine, and it occurs 21 meters stratigraphically above the lower bed. It has been explored in the main drift of the La Calera mine for a distance of 157 meters and has been extensively stoped out from this level up to the zone of alteration. Like the lower bed, it consists of two layers of coal separated by a shale parting. The lower layer, which is the only part that has been stoped, has an average thickness of 1 meter; the shale parting averages 40 to 50 centimeters, and the thickness of the upper coal averages 30 to 40 centimeters. In the La Pitahaya adit No. 1, mentioned above, a second coal bed said to have been found in a part now caved, seems to lie about the same horizon as the Upper Calera bed. If it should be the same bed, the total strike length would be 545 meters.

A thin seam of coal, 1 foot 6 inches (45 centimeters) thick in one place and 2 feet (60 centimeters) thick in another, is described by Dumble as occurring above the Upper Calera bed in two workings that are now inaccessible.

The La Pitahaya beds comprise several coal beds in the drainage of Arroyo de la Pitahaya[57] (see pl. 2, coordinates 250–400 E., 750–1100 S.). Several small workings were opened along these beds, but all except one are now completely caved. The presence of coal in the dumps of several of these caved workings indicates that coal seams were found. According to Dumble, seven different beds were discovered, but only two were described as having a thickness greater than 1 meter and are assigned numbers in this report. No stoping has been done on any of these beds, so far as known.

The Lower Pitahaya bed, C8, is one described by Dumble as having been found at a depth of 20 feet (6 meters) in a slope 37 feet (11 meters) long. He states that the face showed 15 inches (40 centimeters) of coal, 6 inches (15 centimeters) of slate, and 24 inches (60 centimeters) of coal, of only fair quality. The working Dumble refers to is believed to be the one (now completely caved) at the junction of the two forks of Arroyo de la Pitahaya (see pl. 2, coordinates 340 E., 830 S.), although this is uncertain.

The Upper Pitahaya bed, C9, is described by Dumble as having a thickness of 4 feet (1.2 meters). This bed has not been located with certainty, but it may be the one appearing in the working that is called Pitahaya No. 4 on plate 2 (coordinates 380 E., 960 S.).

Coal is said to have been found in the Nochebuena shaft of the Tarahumara silver mine (see pl. 2, coordinates 1150 E., 915 S.) at a depth of about 400 feet (120 meters). Although the shaft is now full of water, coal fragments were seen on the dump, and the occurrence of the coal was substantiated by several people. The exact depth at which the coal occurs is not well verified, however, and the writers have found no record as to its thickness. Judging from its stratigraphic position, this bed appears to be one of the higher Pitahaya beds.

SANTA CLARA BASIN

The lowest coal bed mined in the Santa Clara Basin is called the Lower Z, but a few weak outcrops of typical coal alteration products occur at still lower horizons in this basin. These lower beds are not numbered, as none of them is known to be as much as 1 meter thick. An outcrop of "chicle" was noted in Arroyo de Tarahumara 65 meters east of its junction with Arroyo del Pie de la Cuesta (see pl. 2, coordinates 2010 E., 150 S.),

[57]Dumble called this arroyo "Spring Creek" and called these beds the "Spring Creek beds." The Spanish name used by the local residents is preferred for this report.

and three others, at different horizons, were noted in Arroyo de Tarahumara southwest of its junction with Arroyo de Agua Blanca (see pl. 2, coordinates 1630 E., 430 S.; 1580 E., 570 S.; and 1550 E.; 670 S.). Caved workings are located on two of these outcrops; judging from the small dumps, they were evidently not extensive and the coal seams were probably not very promising.

The Lower Z bed, SC1, is at present best exposed in Z workings Nos. 7 and 11 (see pl. 2, coordinates, 1900 E., 450 S., and pl. 8). This bed was presumably also followed in Z workings Nos. 3, 4, 6, 8, and 9, which are now inaccessible, and is probably the bed exposed in the bottom of No. 5, where it has a thickness of 1.3 meters. In Nos. 7 and 11 the coal is 1.2 to 1.45 meters thick but is of poor quality because of much intercalated shale, and only one very small stope has been made in it. The maximum continuously exposed strike length in these workings is 22 meters. Assuming that all these workings are on the same bed, the total possible strike length between the extremes, Nos. 3 and 9, is 150 meters.

The Upper Z bed, SC2, has been extensively developed in Z workings No. 1 (also called Estación) and No. 2 (see pl. 2, coordinates 2100 E., 420 S.), which were caved at the time of the writers' field work, although the entrance was being reopened by the Cía. Carbón Sonora. The bed is said to have been offset by a fault, resulting in a Z-shape, from which Dumble applied the name "Z" to the bed and the workings. The nature of the faulting, however, is difficult to decipher from Dumble's description. The average thickness of this bed is not known to the writers. Much of the coal mined by the Southern Pacific Railroad Co. is said to have come from these Z workings, and, judging from the large dumps, they must have been very extensive.

The Parvin beds are named for the Parvin shaft, 25 meters south of the "Casa Blanca," on the north side of Arroyo de Santa Clara near its junction with Arroyo de Tarahumara (see pl. 2, coordinates 2260 E., 525 S.). Five different coal seams were cut in this shaft, of which only two are thicker than 1 meter and have been assigned numbers. All these seams are believed to lie above the Z beds. The shaft is now flooded with water below a depth of 16.7 meters, but the original depth of the shaft, according to Dumble, was 93 feet (28 meters). The lowest beds, according to Dumble, were an 8-inch (20-centimeter) coal seam at the bottom of the shaft and a 3-foot (90-centimeter) bed at a depth of 74 feet (23 meters), which is herein called the Lower Parvin bed, SC3. The higher beds lie above the water level and were observed by the writers (see columnar section, pl. 5). The Upper Parvin bed, SC4, is a coal seam 1.35 meters or more thick lying at the water level. At a stratigraphic interval of 80 centimeters above this bed is a layer of bony coal 20 centimeters thick. Some 7.75 meters higher in the section is a coal bed 60 centimeters thick, overlain by 15 centimeters of bony coal, 5 centimeters of carbonaceous shale, and 5 centimeters of coal.

These upper beds are not assigned numbers because of their thinness. As no outcrops of the Parvin beds were found, nothing can be said as to their possible extent.

The Casa Blanca bed, SC5, is exposed at a depth of 3.8 meters (3.6 meters stratigraphically) in the Casa Blanca shaft (see pl. 2, coordinates 2280 E., 540 S.), on the south side of Arroyo de Santa Clara, 24 meters southeast of the Parvin shaft. Taking the dip into consideration, this bed must be stratigraphically higher than all those in the Parvin shaft. The bed exposed above the water level in the shaft is 90 centimeters thick, according to the writers' measurements. As Dumble described it as consisting of two benches, each 2 feet (60 centimeters) thick, separated by 1 foot (30 centimeters) of shale, the lower bench is doubtless below the water level (5.1 meters deep). The outcrop of this bed was not found.

The El Voladero bed, SC6a, has been developed rather extensively in the El Voladero mine (see pl. 2, coordinates 2220 E., 580 S., and pl. 8). In the principal mine working now open, No. 1, the bed is exposed for a length of 95 meters and has an average thickness of about 2 meters. The total length of the bed for the complete extent of the old caved workings, which seem to be on the same bed, is 330 meters.

The Santa Clara bed, SC6b, is one of the thickest in the district and contains some of the highest quality coal, which has been extensively stoped in the Santa Clara mine (see pl. 2, coordinates 1890 E., 900 S., and pl. 7). In this mine the thickness ranges from 1.2 to 2.8 meters and averages 2 meters. In the parts of the mine that are now open the developed length is 73 meters, but older caved workings followed the bed for a greater but unknown distance. The coal has been largely stoped out between the water level and the zone of alteration. The outcrop of this bed near the mine was not found. This coal lies nearly in the line of strike of the El Voladero bed and probably represents the same horizon, although the bed cannot be traced continuously between the two mines. Assuming that the El Voladero and Santa Clara beds are the same, the total strike length represented between the extremities of the two mines is 730 meters.

The El Potrero beds were found in two places in Arroyo del Potrero, according to Dumble, in small workings that are now inaccessible. They are called the El Potrero No. 5 bed, SC7a, and the El Potrero No. 6 bed, SC7b, the numbers "5" and "6" referring to numbers applied by Dumble to the workings in which they were found. It is not known whether they represent the same or different horizons, or what the stratigraphic relation between them might be. The location of these workings could not be identified from Dumble's description. Dumble states that in working No. 5 an opening 84 feet (26 meters) deep cut 3 feet (90 centimeters) of coal, and that working No. 6 revealed 2 feet (60 centimeters) of coal underlain by 5 feet (1.5 meters) of coke. He adds that the latter coal is believed to be stratigraphically above a sandstone overlying the Santa Clara bed, but that it might, on the other hand, represent the Santa Clara coal bed. These beds have not been mined.

A thin bed of "chicle" was noted in Arroyo del Potrero 500 meters south of the Santa Clara mine (see pl. 2, coordinates 2070 E., 1350 S.), at a horizon that is probably much higher than those of the El Potrero beds described by Dumble. In Arroyo de la Milpa a 2-foot (60-centimeter) bed of coal was found, according to Dumble, although the exact locality is uncertain. It may have been in a small shaft, now full of water, situated in a prominent bend in the arroyo 460 meters southeast of the Casa Blanca (see pl. 2, coordinates 2450 E., 915 S.). A small caved working whose dump contains fragments of coal lies at a much higher horizon 400 meters farther south in Arroyo de la Milpa (see pl. 2, coordinates 2500 E., 1315 S.), just below the contact between shales and overlying quartzites that was taken as the dividing line between the middle (coal-bearing) and upper members of the Barranca formation.

PHYSICAL CHARACTERISTICS

The coal found in the Santa Clara district is black and has a black to brownish-black streak. It seems to be harder but more friable than typical anthracite, and its specific gravity is much higher. The real specific gravity of 10 samples tested by the Bureau of Mines (see table 4) averages 1.940, and ranges from 1.888 to 1.987. Pennsylvania anthracite ranges from 1.46 to 1.7,[58] and it has been stated that "few, if any, coals which have a specific gravity over 1.6 are worth burning."[59] Only Rhode Island coal, among coals of the United States, has a specific gravity as high as Santa Clara coal, its range being reported as 1.65 to 2.20.[60] The high specific gravity of Santa Clara coal is probably a result of its advanced stage of metamorphism, which in places has brought about the formation of natural coke and graphite.

Most of the coal has a bright luster, although parts are somewhat duller. Some specimens show an iridescence or play of colors, probably caused by the deposition of thin films of iron oxide along cracks.[61] The fracture is generally conchoidal to subconchoidal, but in places it is inclined to be somewhat blocky. The degree of fracturing varies greatly in different beds, and from place to place in the same bed. Some of the coal is quite massive and breaks off in coarse fragments, but in other places it is fine-grained and friable, forming a fine powder when broken out. In places parts of the same bed are massive, and others, either above or below, are

[58] Turner, H. G., Anthracites and semianthracites of Pennsylvania: Am. Inst. Min. Met. Eng. Trans., Coal Div., vol. 108, p. 332, 1934.

[59] Porter, J. B., and Durley, R. J., An investigation of the coals of Canada: Canada Dept. Mines, Mines Branch, vol. 1, p. 194, 1912.

[60] Ashley, G. H., Rhode Island coal: U. S. Geol. Survey Bull. 615, pp. 21–22, 1915.

[61] Moore, E. S., Coal, its properties, analysis, classification, geology, extraction, uses, and distribution p. 106, New York, John Wiley & Sons, 1940.

fine-grained. For this reason it is difficult, in the course of mining operations, to obtain a product of uniform size.

The main impurities in the Santa Clara coals are partings of bone, shale, or graphite, their extent varying greatly from place to place. An idea of their range in thickness and number may be obtained from the columnar sections of coal and coke beds sampled in the Santa Clara district, given in plate 6. It is seen that in one part of the El Refugio mine, for example, as many as six shale partings from 1 centimeter to 3 centimeters thick occur in the coal, which has a total thickness of 2.06 meters at this point, whereas in part of the Santa Clara mine a section of coal 2.84 meters thick does not contain any visible partings. In many places, as in both the La Calera beds, a bed may be split into two benches by a thick parting of shale or bony coal, and, as a result, part of the bed, above or below the parting, may not be thick enough to be mined commercially.

Graphite is one of the most troublesome impurities. It occurs generally in thin bands, either at the top or at the bottom of the coal, but in places it fills fractures within the coal. Graphite may also occur disseminated through the coal to a greater extent than is apparent to the naked eye. The presence of graphite might account for some of the unusual physical and chemical properties of the coal, such as its high specific gravity and its low heating value in comparison with its high percentage of fixed carbon. In other parts of Sonora, graphite has developed extensively from former coal beds of the Barranca formation, as for example in the Los Pilares district, 20 kilometers east of Tónichi, and in the Sierra de las Moradillas, near San Marcial, where large quantities of graphite have been mined (see footnote on p. 16).

Finely disseminated pyrite was noted in the coal in a few places, but it does not appear to be sufficiently widespread to have a detrimental effect on the quality of the coal. The sulfur content of all the samples analyzed is comparatively low.

EFFECTS OF WEATHERING

The coal is deeply weathered, for the most part being entirely altered or destroyed to depths of 10 to 30 meters. Its characteristic alteration products, known locally as chicle and congo, serve as guides to the presence of coal at depth. They consist mainly of a bluish-gray or whitish clayey material and of powdery yellowish to brownish iron oxides. Small fragments of highly altered coal may be scattered through this material, becoming more abundant as the solid bed is approached. In some inclined shafts that follow the coal beds down from the surface, all stages of the alteration may be observed. Where the coal first appears there is ordinarily a gradational zone about a meter or so wide in which the coal is highly fractured, porous, has a dull luster, and is coated with reddish, yellowish, or brownish iron oxides. Below this zone the coal assumes its more massive structure and brighter luster. The depth of the zone of alteration is important economically and has been indicated on the mine maps. The greatest depth of alteration was noted in the inclined shaft of the El Tren mine, in which the coal has been completely destroyed to an inclined depth of 70 meters below the surface. The shaft followed the original bedding planes of the coal, and it is possible to observe, on the sides of the shaft, the original structure of the coal bed, including shale partings near the top and latite sills near the base, even though the coal is completely altered.

The original position of the coal beds may thus be traced by the characteristic alteration products in various parts of the district, although the thickness of the space occupied by the alteration products is generally less than the original thickness of the coal. True outcrops of coal are very rare in the district. They were observed by the writers only in a few places, in the bottoms of arroyos where erosion has apparently kept pace with the process of weathering.

CHEMICAL CHARACTERISTICS

ANALYSES

In table 4 analyses are given of 10 samples of coal and 2 of natural coke collected from the mines of the Santa Clara district, and of 1 additional sample of coal from the Palo Pinto mine of the Santa Julia group, southwest of San Javier. The samples from the Santa Clara district were collected by the standard Bureau of Mines method[62] and were analyzed by the Bureau's Experiment Station in Pittsburgh, Pa. The sample from the Palo Pinto mine was substandard, however, owing to the inaccessibility of the deposit. The location of each sample, according to its field number, has been indicated on the mine maps (pls. 7–11). Columnar sections of the beds that were sampled, at the exact place of sampling, are given in plate 6. To obtain unweathered coal, channels were cut into the walls of the mine workings before taking the sample, but as most of the mine workings are 35 to 50 years old the possible effects of weathering must be considered. Samples that were taken from new mine workings, however, showed no marked differences in their analyses from those of samples from old workings.

The analyses in table 4 are presented in four forms. Form A shows the composition of the sample "as received" and indicates the approximate composition of the coal as mined; form B shows the composition of the sample after being air-dried at a temperature of 30° to 35° C. until its weight is constant; form C is computed as moisture free; and form D is

[62] Fieldner, A. C., and Selvig, W. A., Notes on the sampling and analysis of coal: Bur. Mines Tech. Paper 586, pp. 1–2, 1941.

computed as moisture free and ash free. Forms C and D do not exist in nature but are useful for comparative studies. Both proximate and ultimate analyses are presented. The proximate analysis gives the percentages in the coal of moisture, volatile matter, fixed carbon, and ash. The ultimate analysis expresses the composition of the coal in percentages of ash, sulfur, carbon, hydrogen, nitrogen, and oxygen. The heating value of the coal is given in British thermal units (B. t. u.). The fusibility of the ash, in degrees Fahrenheit, is given in terms of the initial deformation temperature, softening temperature, and fluid temperature of the ash produced in burning the coal.

In the final columns, headed "data for classification," are given three figures computed from the analyses that are most used in classifying and comparing coals with one another. The first of these is the "fuel ratio," obtained from the proximate analysis by dividing the fixed carbon by the volatile matter. The next column shows the fixed carbon on a dry, mineral-matter-free basis. This is obtained from the moist fixed carbon (form A) by multiplying by 100 ÷ [100 — (moisture + 1.1 × ash)]. The last column shows the British thermal units on a moist, mineral-matter-free basis, obtained from the moist British thermal units (form A) by multiplying by 100 ÷ (100 — 1.1 × ash).[63] The quantities given in the last two columns are the ones most used in determining the rank of a coal.

CLASSIFICATION OF SANTA CLARA COALS AND COMPARISON WITH OTHER COALS

Coals are classified by rank according to their degree of metamorphism, or progressive alteration, in the natural series from lignite through anthracite to graphite. The most significant changes accompanying this alteration are a decrease in moisture and volatile matter, and an increase in fixed carbon. In the very last stage of metamorphism before graphite is reached, however, there is a slight retrogression, marked by an increase in moisture and a corresponding decrease in fixed carbon (on a moist basis) from the proportions found in anthracite. This is shown in a diagram prepared by Campbell.[64] The heating value, also, which starts at a minimum in lignite and gradually increases to a maximum in high-rank bituminous to semibituminous coal, shows a marked decrease in going from anthracite to this highest rank of coal, which is called meta-anthracite or superanthracite. The best examples in the United States of coal of meta-anthracite rank are found in Rhode Island. All the coals of the Santa Clara district are of very high rank, and their analyses show evidence of the retro-

[63]These are formulas used in the paper by Fieldner, A. C., Selvig, W. A., and Frederic, W. H., Classification chart of typical coals of the United States: U. S. Bur. Mines Rept. Inv. 3296, p. 5, 1935. More exact formulas include corrections for sulfur, but this is unnecessary where the sulfur content is as low as it is in the Santa Clara analyses.

[64]Campbell, M. R., Coal as a recorder of incipient rock metamorphism: Econ. Geol., vol. 45, p. 688, 1930.

TABLE 4.—*Analyses of coal from the Santa Clara district, Sonora, Mexico*

Field No.	Kind of coal and locality	Thickness in sample (meters)	Laboratory No.	Air-drying loss	Form of analysis[1]	Proximate: Moisture	Proximate: Volatile matter	Proximate: Fixed carbon	Proximate: Ash	Ultimate: Sulfur	Ultimate: Hydrogen	Ultimate: Carbon	Ultimate: Nitrogen	Ultimate: Oxygen	Heating value (British thermal units)	Fusibility of ash, °F.	Real specific gravity	Data for classification: Fuel ratio	Data for classification: Dry, mineral-matter-free fixed carbon	Data for classification: Moist, mineral-matter-free B.t.u.
1	Anthracite, Santa Clara mine.	2.36	C-43349	0.7	A	10.5	7.0	76.5	6.0	0.2	1.7	81.3	0.4	10.4	11,860	[2]2190	1.957	10.9	92.3	12,630
					B	9.9	7.1	76.9	6.1	.2	1.6	81.8	.4	9.9	11,940	[3]2250	......	......	......	......
					C	......	7.9	85.3	6.8	.2	.6	90.7	.4	1.3	13,240	[4]2440	......	......	......	......
					D	......	8.4	91.6	......	.2	.6	97.3	.5	1.4	14,200	......	......	......	......	......
2	Semianthracite, Santa Clara mine.	2.24	C-43350	2.2	A	15.0	7.4	70.7	6.9	.2	2.2	76.1	.3	14.3	10,990	[2]2140	1.987	9.6	91.3	11,894
					B	13.1	7.6	72.3	7.0	.2	2.0	77.8	.3	12.7	11,240	[3]2200	......	......	......	......
					C	......	8.7	83.2	8.1	.3	.6	89.5	.3	1.2	12,930	[4]2440	......	......	......	......
					D	......	9.5	90.5	......	.3	.6	97.4	.4	1.3	14,070	......	......	......	......	......
3	Meta-anthracite, El Refugio mine No. 2 nuevo.	2.06	C-43345	1.6	A	7.0	3.1	73.1	16.8	.6	1.6	72.6	.3	8.1	10,790	[2]2540	1.958	23.6	98.1	13,239
					B	5.5	3.2	74.3	17.0	.6	1.4	73.8	.4	6.8	10,970	[3]2740	......	......	......	......
					C	......	3.3	78.7	18.0	.6	.9	78.1	.4	2.0	11,600	[4]2840	......	......	......	......
					D	......	4.1	95.9	......	.7	1.1	95.3	.5	2.4	14,150	......	......	......	......	......
4	Meta-anthracite, El Refugio mine No. 3 nuevo.	2.42	C-43346	1.7	A	7.2	3.0	70.9	18.9	.3	1.6	71.2	.3	7.7	10,470	[2]2540	1.969	23.6	98.5	13,220
					B	5.7	3.1	72.0	19.2	.4	1.5	72.4	.4	6.1	10,650	[3]2730	......	......	......	......
					C	......	3.2	76.5	20.3	.4	.9	76.8	.4	1.2	11,290	[4]2860	......	......	......	......
					D	......	4.1	95.9	......	.5	1.1	96.4	.5	1.5	14,170	......	......	......	......	......
5	Anthracite, El Refugio mine No. 4 viejo.	1.44	C-43347	.6	A	6.7	4.8	78.1	10.4	.3	1.5	79.1	.4	8.3	11,740	[2]2180	1.921	16.3	95.4	13,251
					B	6.1	4.8	78.6	10.5	.3	1.5	79.6	.4	7.7	11,810	[3]2400	......	......	......	......
					C	......	5.2	83.7	11.1	.4	.8	84.8	.4	2.5	12,580	[4]2620	......	......	......	......
					D	......	5.8	94.2	......	.4	.9	95.4	.5	2.8	14,150	......	......	......	......	......
7	Anthracite, La Calera mine.	1.17	C-43342	1.1	A	7.8	3.5	81.1	7.6	.4	1.7	81.7	.3	8.3	12,070	[2]2210	1.888	23.2	96.8	13,177
					B	6.8	3.5	82.0	7.7	.4	1.6	82.6	.4	7.3	12,200	[3]2390	......	......	......	......
					C	......	3.7	88.0	8.3	.4	.9	88.6	.4	1.4	13,090	[4]2540	......	......	......	......
					D	......	4.1	95.9	......	.5	1.0	96.6	.4	1.5	14,270	......	......	......	......	......
8	Meta-anthracite, La Calera mine.	1.34	C-43343	5.0	A	10.4	2.1	79.0	8.5	.4	1.9	77.8	.4	11.0	11,620	[2]2200	1.898	37.6	98.4	12,811
					B	5.7	2.2	83.1	9.0	.5	1.4	81.9	.4	6.8	12,230	[3]2470	......	......	......	......
					C	......	2.4	88.1	9.5	.5	.8	86.9	.4	1.9	12,970	[4]2640	......	......	......	......
					D	......	2.6	97.4	......	.5	.9	96.0	.4	2.2	14,330	......	......	......	......	......

9	Anthracite, El Tren mine.	1.46	C-43338	.6	A	5.3	4.3	79.6	10.8	.3	1.5	80.1	.4	6.9	11,770	[2]2330	1.908	18.5	96.1	13,360
					B	4.8	4.3	80.0	10.9	.3	1.4	80.5	.4	6.5	11,840	[3]2510	......	......	......	......
					C	......	4.5	84.1	11.4	.3	.9	84.6	.4	2.4	12,440	[4]2640	......	......	......	......
					D	......	5.1	94.9	......	.4	1.0	95.5	.5	2.6	14,050	......	......	......	......	......
10	Anthracite, El Tren mine.	1.39	C-43339	.6	A	6.3	7.2	72.6	13.9	.5	1.4	76.3	.4	7.5	11,170	[2]2210	1.957	10.1	92.6	13,188
					B	5.8	7.2	73.0	14.0	.5	1.4	76.7	.4	7.0	11,240	[3]2380	......	......	......	......
					C	......	7.7	77.5	14.8	.5	.8	81.5	.4	2.0	11,930	[4]2530	......	......	......	......
					D	......	9.0	91.0	......	.6	.9	95.6	.5	2.4	14,000	......	......	......	......	......
12	Anthracite, Santa Clara mine.	2.84	C-43351	1.9	A	12.2	6.0	76.0	5.8	.4	1.9	79.5	.3	12.1	11,650	[2]2120	1.959	12.7	93.4	12,447
					B	10.5	6.1	77.4	6.0	.4	1.7	81.1	.3	10.5	11,880	[3]2200	......	......	......	......
					C	......	6.8	86.5	6.7	.4	.6	90.6	.4	1.3	13,270	[4]2470	......	......	......	......
					D	......	7.3	92.7	......	.5	.7	97.0	.4	1.4	14,220	......	......	......	......	......
13	Anthracite, Palo Pinto mine, Santa Julia group, southwest of San Javier.	2.6	C-45836	3.1	A	6.7	6.5	72.2	14.6	.6	1.6	74.1	.4	8.7	10,740	[2]2080	......	11.1	93.5	12,801
					B	3.7	6.7	74.5	15.1	.6	1.3	76.5	.4	6.1	11,090	[3]2280	......	......	......	......
					C	......	7.0	77.3	15.7	.6	.9	79.4	.4	3.0	11,510	[4]2420	......	......	......	......
					D	......	8.3	91.7	......	.7	1.0	94.1	.5	3.7	13,640	......	......	......	......	......
6	Natural coke, Yaqui mine.	1.36	C-43353	.9	A	3.0	5.2	73.0	18.8	1.2	1.3	72.9	.6	5.2	10,830	[2]2030	1.987	14.0	95.7	13,657
					B	2.1	5.3	73.6	19.0	1.2	1.2	73.6	.6	4.4	10,930	[3]2140	......	......	......	......
					C	......	5.4	75.2	19.4	1.2	1.0	75.2	.6	2.6	11,170	[4]2310	......	......	......	......
					D	......	6.7	93.3	......	1.5	1.2	93.3	.7	3.3	13,860	......	......	......	......	......
11	Natural coke, El Tren mine.	.47	C-43340	.1	A	1.4	3.9	81.1	13.6	.6	1.2	80.4	.5	3.7	11,880	[2]2260	1.913	20.8	97.0	13,976
					B	1.3	3.9	81.2	13.6	.6	1.1	80.5	.5	3.7	11,890	[3]2420	......	......	......	......
					C	......	4.0	82.2	13.8	.6	1.0	81.6	.5	2.5	12,050	[4]2620	......	......	......	......
					D	......	4.6	95.4	......	.7	1.2	94.6	.6	2.9	13,980	......	......	......	......	......
	Average of 10 analyses from Santa Clara district (excluding natural coke).	......	....	1.6	A	8.8	4.8	75.8	10.6	.36	1.70	77.6	.35	9.46	11,413	[2]2266	1.940	18.6	95.3	12,922
					B	7.4	4.9	77.0	10.7	.38	1.55	78.8	.38	8.13	11,600	[3]2427	......	......	......	......
					C	......	5.3	83.2	11.5	.40	.78	85.2	.39	1.72	12,534	[4]2602	......	......	......	......
					D	......	6.0	94.0	......	.46	.88	96.2	.46	1.95	14,161	......	......	......	......	......

[1]A, As received; B, air-dried; C, moisture free; D, moisture and ash free.
[2]Initial deformation temperature.
[3]Softening temperature.
[4]Fluid temperature.

gressive effects of the change from anthracite to meta-anthracite. Their rank, in general, seems to be intermediate between that of typical anthracite and that of Rhode Island coal, and it falls about on the line between anthracite and meta-anthracite. In places, however, the Santa Clara coals have attained the ultimate stage of graphite.

The rank of a coal must not be confused with the grade of a coal, which refers merely to the presence or absence of impurities, expressed in the analyses mainly in percentages of ash and sulfur. From this standpoint, the Santa Clara coals are of fair to moderately high grade.

The standard classification of coals by rank established by the American Society for Testing Materials[65] and adopted by the Geological Survey, Bureau of Mines, and other Government agencies concerned with coal, has been expressed as follows: "The basic scheme of classification is according to fixed carbon and caloric value (expressed in B. t. u.) calculated to the mineral-matter-free basis. The higher-rank coals are classified according to fixed carbon on the dry basis, the lower-rank coals according to British thermal units on the moist-free basis." These quantities have been calculated for the analyzed samples of Santa Clara coals and given in the last two columns of the table of analyses (table 4). The higher ranks of coal are classified according to the dry, mineral-matter-free fixed carbon (F. C.), regardless of the British thermal units. The classification of the higher ranks is shown in table 5, as follows:

TABLE 5.—*Classification of higher-rank coals*

Class	Group	Limits of fixed carbon
Anthracitic	Meta-anthracite	Dry F.C., 98 percent or more.
	Anthracite	Dry F.C.; 92 percent or more and less than 98 percent.
	Semianthracite	Dry F.C., 86 percent or more and less than 92 percent.

On the basis of the foregoing classification, three of the Santa Clara samples shown in table 4 fall within the group of meta-anthracite, one is classed as semianthracite, and the remaining seven are classed as anthracite. This is an arbitrary classification, however, and several differences between the Santa Clara coals and typical anthracite will be pointed out later. The one sample classed as semianthracite differs greatly in its properties from typical coal of that rank. The samples of natural coke included in the table are distinguished from the coals by their physical properties, but chemically they fall into the anthracite group.

Fieldner and others[66] have prepared a chart of typical coals of the United States, showing the British thermal units on a moist, mineral-

[65]A. S. T. M. Standards on coal and coke: "Standard specifications for classification of coal by rank," A. S. T. M. Designation: D 338-38, p. 104, October 1938.

[66]Fieldner, A. C., Selvig, W. A., and Frederic, W. H., Classification chart of typical coals of the United States: U. S. Bur. Mines Rept. Inv. 3296, fig. 1, facing p. 4, 1935.

matter-free basis, plotted against fixed carbon on a dry, mineral-matter-free basis. The analyses of Santa Clara coals have been plotted on this chart, which is presented in figure 2. As it became apparent that the Santa

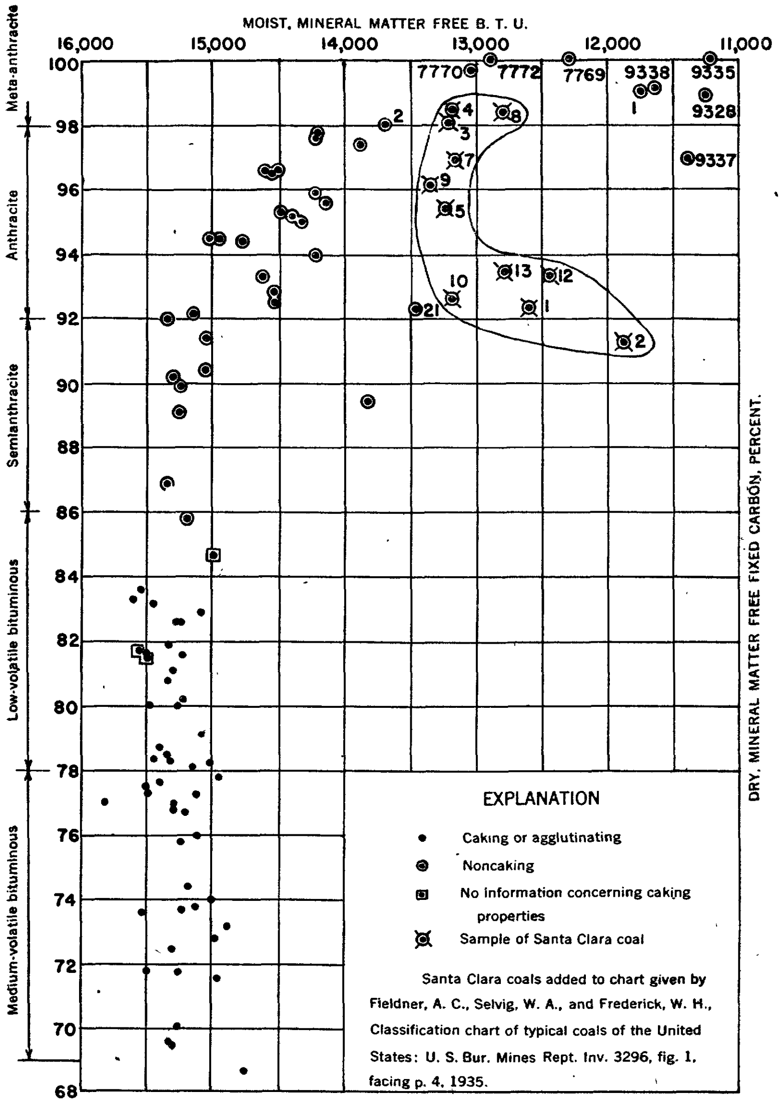


FIGURE 2.—Comparison of Santa Clara coals with typical coals of the United States on the basis of moist mineral-matter-free British thermal units versus dry mineral-matter-free fixed carbon.

Clara coals were more nearly similar to Rhode Island coals than to any others, all the additional analyses of Rhode Island coals that could be found were also plotted on the chart. These were taken from a report by Ashley,[67] and are labeled according to the laboratory number of the analysis. Three of the analyses of Rhode Island coal fell off the right side of the chart and were omitted.

It may be seen from this chart (fig. 2) that the Santa Clara coals have no exact counterparts among the typical coals of the United States. The main difference they show from typical anthracite is that the British thermal unit (heating value) is much less in comparison with the fixed carbon. Nearly all the anthracites of the United States plotted on this chart have a British thermal unit value (on the moist, mineral-matter-free basis) of more than 14,000, whereas the value of the Santa Clara coals on the same basis averages 12,922 and does not exceed 13,360. The coals on the chart falling closest to the Santa Clara coals are the ones from Rhode Island. Santa Clara samples Nos. 3, 4, and 8, which are the ones classed as meta-anthracite, fall between chart Nos. 1 and 2, which represent samples of Rhode Island coal. All the analyses of Rhode Island coal except No. 2, however, fall on the chart above or to the right of the Santa Clara analyses, indicating that they are higher in fixed carbon or lower in British thermal units, or both. The only other analysis on the chart that lies fairly close to the Santa Clara analyses is No. 21, which is near Santa Clara No. 10, although it has a higher British thermal unit value. This coal is from the White Ash bed in the Cerrillos coal field of Santa Fe County, N. Mex. It is of some interest that the anthracitization of this New Mexico coal has been attributed, at least in part, to the heat from the intrusion of sills of igneous rocks,[68] a situation that is paralleled in the Santa Clara district. A Colorado coal, found in direct contact with basalt, is described as having the properties of meta-anthracite although on the basis of its fixed carbon content it is classified as semianthracite;[69] its analysis would fall on the chart below and to the right of the Santa Clara analyses. Its calculated dry, mineral-matter-free fixed carbon is 89.3 percent, and its moist, mineral-matter-free British thermal unit value is 11,253.

Barkley and Burdick[70] give a chart showing various coals of the United States in a different way, by plotting the volatile matter, on a dry basis, against the British thermal units, on both a moisture- and ash-free basis and a dry, mineral-matter-free basis. The Santa Clara coals have been plotted on this chart and also all the analyses of Rhode Island coals referred to above, which had not previously been included. This chart

[67]Ashley, G. H., Rhode Island coal: U. S. Geol. Survey Bull. 615, pp. 26–27, 1915.

[68]Lee, W. T., The Cerrillos coal field, Santa Fe County, N. M.: U. S. Geol. Survey Bull. 531, pp. 299–300, 1913.

[69]McFarlane, G. C., Igneous metamorphism of coal beds: Econ. Geology, vol. 24, p. 10, 1929.

[70]Barkley, J. F., and Burdick, L. R., The various British thermal unit values of a coal: U. S. Bur. Mines Inf. Circ. 7193, fig. 2, facing p. 10, 1941.

(fig. 3) again illustrates that the Santa Clara coals are unique. Again, they are similar to Rhode Island coals (which take a lower position on the chart, on the basis of B. t. u.), and take an intermediate position between typical anthracite and Rhode Island coal. With the British thermal units plotted on a dry, mineral-matter-free basis, there is a slight overlap between the Rhode Island and Santa Clara coals, but on a moisture-and ash-free basis there is no overlap, for the Rhode Island coals all have a lower British thermal unit value on this basis, and most of them are also lower in volatile matter. This chart, like the previous one, illustrates the decrease in heating value involved in the change from anthracite to meta-anthracite.

In table 6 the analyses of Santa Clara coal are compared with analyses of typical anthracite and of Rhode Island coal, on both an "as received" and moisture- and ash-free basis. The range in composition of typical anthracite is shown as given by Moore,[71] taken from analyses from various sources, but not including Rhode Island anthracite. The range in composition and average composition of Rhode Island anthracite is based on 12 analyses of mine samples as given by Ashley.[72] The range in composition and average composition of Santa Clara coal are based on the 10 analyses presented in table 4, excluding the samples of natural coke and the sample from the Palo Pinto mine.

Table 6 shows that Santa Clara coal is more nearly similar to Rhode Island coal, particularly on a moisture- and ash-free basis, than it is to typical anthracite. One of the most significant features is the low percentage of hydrogen, and low proportion of hydrogen to total volatile matter, in both Santa Clara and Rhode Island coal. This is particularly true on a moisture- and ash-free basis, in which the hydrogen that is combined with oxygen in the moisture is eliminated. The low percentage of hydrogen has important detrimental effects on the combustion characteristics of the coal.

Both Santa Clara and Rhode Island coal are higher in moisture than typical anthracite, Rhode Island coal ranging considerably higher than Santa Clara coal. Both are fairly high in oxygen on a moist basis, owing to the high moisture, but on a moisture- and ash-free basis, in which oxygen in the moisture is eliminated, the oxygen content of Santa Clara coal is similar to that of typical anthracite, although Rhode Island coal runs higher. The possible cause for the high moisture will be discussed in the section on "origin of the meta-anthracite."

The main difference between Santa Clara coal and Rhode Island coal is the very high ash content of the latter, which averages 23.16 percent and ranges up to 33.90 percent. The ash content of Santa Clara coal lies within the range of typical anthracite, only a few samples having fairly high ash. Rhode Island coal, on an "as received" basis, may be fairly low

[71]Moore, E. S., op. cit., p. 105.
[72]Ashley, G. H., op. cit., pp. 26–27.

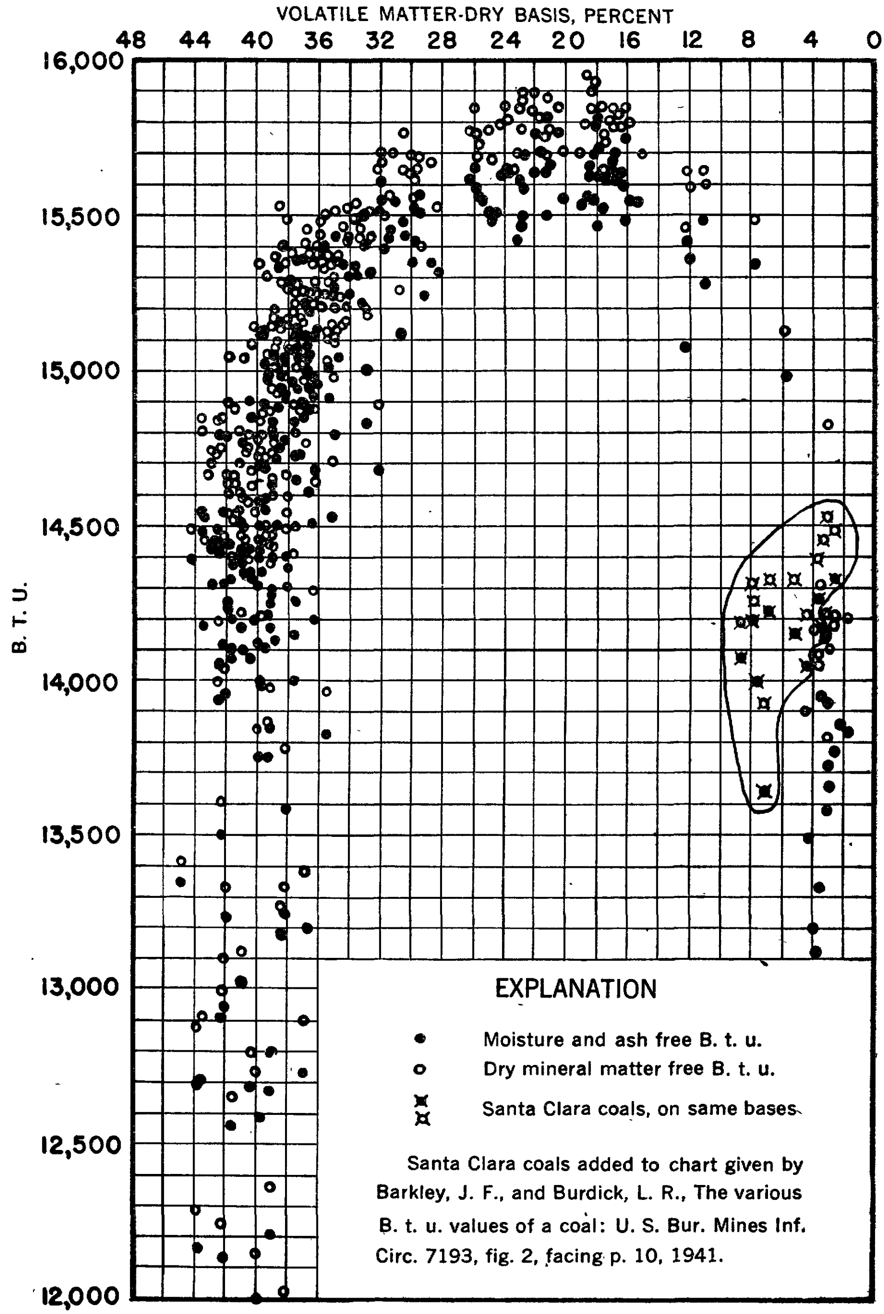


FIGURE 3.—Comparison of Santa Clara coals with typical coals of the United States on the basis of dry volatile matter versus moisture-free and ash-free British thermal units and dry mineral-matter-free British thermal units.

TABLE 6.—*Comparison of analyses of Santa Clara coals with those of typical anthracite and Rhode Island anthracite*

Constituent	Moist ("as received") basis					Moisture- and ash-free basis				
	Typical anthracite (range)	Rhode Island anthracite		Santa Clara anthracite		Typical anthracite (range)	Rhode Island anthracite		Santa Clara anthracite	
		Range	Average	Range	Average		Range	Average	Range	Average
Moisture	3.5–6.50	4.51–23.68	13.60	5.3–15.0	8.8	....	....	....	....	....
Volatile matter	1.72–10.75	1.69–4.00	2.79	2.1–7.4	4.8	3.5–6.50	2.26–7.00	4.61	2.6–9.5	6.0
Fixed carbon	73.71–90.90	46.00–78.69	60.41	70.7–81.1	75.8	93.00–97.00	93.00–97.74	95.39	90.5–97.4	94.0
Ash	3.20–30.09	13.76–33.90	23.16	5.8–18.9	10.6	....	....	....	....	....
Sulfur	.17–2.60	.03–1.34	.32	.2–.6	.36	.50–1.50	.05–2.04	.48	.2–.7	.46
Hydrogen	1.89–5.61	.94–3.15	2.13	1.4–2.2	1.70	1.75–4.00	.37–1.20	.65	.6–1.1	.88
Carbon	78.41–83.89	42.36–78.65	58.26	71.2–81.7	77.6	90.00–94.00	91.39–96.26	93.99	95.3–97.4	96.2
Nitrogen	.63–1.57	.08–.27	.16	.3–.4	.35	.60–1.25	.12–.41	.26	.4–.5	.46
Oxygen	3.80–11.54	5.71–23.59	16.62	6.9–14.3	9.46	1.25–2.75	2.04–7.08	4.51	1.3–2.8	1.95
Heating value (B. t. u.)	9,230–13,298	5,976–11,097	8,627	10,470–12,070	11,413	14,500–15,000	13,120–13,946	13,619	14,000–14,330	14,161

in fixed carbon as well as in volatile matter because of the high moisture and ash; but on a moisture- and ash-free basis the proportion of fixed carbon to volatile matter is slightly higher in Rhode Island coal than in Santa Clara coal. Both coals are comparatively low in sulfur and nitrogen. The heating value of Santa Clara coal is higher than that of Rhode Island coal but less than that of typical anthracite. Rhode Island coal has been metamorphosed into graphite in places, as has Santa Clara coal. The metamorphism of the former is attributed to intense folding and compression, however, whereas at least part of that of Santa Clara coal appears to be a result of igneous intrusions.

In short, Santa Clara coal shows most of the characteristics of Rhode Island coal, except that it is not as high in ash or moisture. Past experience in attempts to use Rhode Island coal for various purposes, as related by Ashley,[73] should therefore be of interest to any prospective user of Santa Clara coal.

ECONOMIC SIGNIFICANCE OF THE CONSTITUENTS

Moisture lowers the value of a coal, as it not only displaces its own weight of combustible matter but also absorbs the heat required in raising its temperature to the boiling point. The moisture content of the Santa Clara coal is somewhat higher than that of typical anthracite. Moisture in a coal is in part extraneous and in part inherent, but the analysis does not differentiate between them, for air-drying removes not only the extraneous or superficial moisture but also part of the inherent moisture. Only one sample from the Santa Clara district, No. 8 from the La Calera mine, showed an appreciable air-drying loss (5.0 percent). This sample was collected near the water table and felt moist to the touch. The samples showing the highest total moisture were three from the Santa Clara mine, Nos. 1, 2, and 12, containing 10.5, 15.0, and 12.2 percent, respectively. As these samples did not show high air-drying losses, and as the coal was above the water table and appeared to be dry, most of this moisture is assumed to be inherent.

The volatile matter and fixed carbon represent the relative proportions of gaseous and solid combustible matter obtained from heating a coal, but they are not definite compounds. The proportion of fixed carbon to volatile matter increases with the rank of the coal. The heating value of a coal is generally considered to increase with the percentage of fixed carbon, but this is not true of the highest ranks of coal, for, as has been noted, there is a decline in heating value in going from semibituminous through anthracite to meta-anthracite. The fixed carbon on an "as received" basis decreases inversely with the moisture and ash, so that the percentage of fixed carbon in the "pure coal" substance, which determines the rank of a coal, is evident only on a moisture- and ash-free or mineral-matter-free

[73] Ashley, G. H., op. cit., pp. 7–14, 38–58.

basis. The percentages of volatile matter and fixed carbon in the Santa Clara coal on an "as received" basis are within the range shown by typical anthracite. On a mineral-matter-free basis, however, the proportion of fixed carbon to volatile matter approaches that of meta-anthracite. The fuel ratio, obtained by dividing the fixed carbon by the volatile matter, ranges from 9.6 to 37.6 and averages 18.6 for the Santa Clara analyses. Anthracites generally have fuel ratios of more than 10, semianthracites from 7 to 10, and lower ranks of coal less than 7. Among the various mines of the Santa Clara district the fuel ratio is lowest in the Santa Clara mine and highest in the La Calera and El Refugio mines.

Ash is second in importance only to heating value in the commercial evaluation of coal, according to Fieldner and Selvig;[74] the efficiency of combustion in the ordinary furnace decreases inversely with the percentage of ash. The ash content of the Santa Clara coal is within the range of typical anthracite, although in two samples, Nos. 3 and 4, containing 16.8 and 18.9 percent of ash, respectively, the content is fairly high. The percentage of ash in the Santa Clara coal bears a close relation to the number of partings of shale and bony coal in the sections sampled, as shown in the columnar sections in plate 6. The rule was followed of including in the samples such partings as were being included in the coal during the ordinary course of mining operations. The samples containing the highest percentages of shaly and bony partings, Nos. 3 and 4, also contained the largest amounts of ash. The samples with less than 1 percent of partings, Nos. 1, 2, 7, and 12, contain only 5.8 to 7.6 percent ash, which probably represents approximately the amount of "inherent ash" or mineral matter intimately mixed with the carbonaceous material of the coal. Usually the percentage of inherent ash is fairly uniform in different parts of the same coal bed. The additional percentages of ash found in the other samples probably represent the extraneous impurities provided by the partings, which could be partly eliminated by great care in mining and perhaps by washing, picking, or screening. If this were done, the ash content of Santa Clara coal perhaps could be kept below 10 percent.

Sulfur, in the form of pyrite, increases the tendency of a coal to clinker when present in amounts of more than 2 percent. The sulfur content of the Santa Clara coal samples is fairly low, ranging between 0.2 and 0.6 percent, and cannot be considered objectionable.

Hydrogen is second in importance only to carbon as a heat-producing element in a coal and is calculated to yield 62,028 British thermal units per pound. It also has an important effect on the ease of ignition and rapidity of burning. Not all the hydrogen in a coal is in a combustible form. It is assumed that all the oxygen in a coal is combined with hydrogen in the proper ratio to form water (8:1). The remaining, or "available hydrogen," is assumed to be combined in heat-producing volatile hydrocarbons. The

[74] Fieldner, A. C., and Selvig, W. A., op. cit., p. 21.

hydrogen content of the Santa Clarà coals is very low, being below the range for typical anthracite on both an "as received" and a moisture- and ash-free basis. After the oxygen is satisfied, less than 1 percent of hydrogen is left in a heat-producing form in each of the samples of Santa Clara coal, whereas in typical anthracite from 2 to 4 percent of "available" or heat-producing hydrogen is generally present. This is partly responsible for the low heating value of Santa Clara coal as compared with typical anthracite, and for its difficulty in ignition and slowness in burning.

Carbon as given in the ultimate analysis is closely related to the heat-producing power of a coal. It should be noted that the carbon determined in the ultimate analysis is not the same as the fixed carbon of the proximate analysis, for it includes carbon in both a solid and a volatile form, and it may also include carbon in an incombustible form. The fixed carbon of the proximate analysis, furthermore, is not pure carbon but includes small amounts of hydrogen, oxygen, nitrogen, and sulfur. The percentage of carbon in Santa Clara coal is at the low end of the range for typical anthracite on an "as received" basis, but is higher than the range for typical anthracite on a moisture- and ash-free basis. As pointed out in the succeeding section on "combustion characteristics," the heating value of Santa Clara coal is not commensurate with the percentage of carbon, and the possibility is suggested that some of the carbon reported in the analyses may be in the form of graphite, which is incombustible.

Nitrogen is inert and has no value in a coal, except as a possible by-product of coking operations, which is out of the question for the Santa Clara coal. The percentage of nitrogen in Santa Clara coal is very low, being below the range given for typical anthracite on both an "as received" and a moisture- and ash-free basis.

Oxygen is a detrimental constituent of coal, as it has no heating value. Oxygen and ash are considered the two great impurities in a coal, and, according to White,[75] they "are of very nearly equal anticalorific or negative value, ash being probably slightly more injurious in most coals; the negative value of the oxygen of moisture is not far different from that of the oxygen combined in the coal." The percentage of oxygen in the Santa Clara coal is fairly high on an "as received" basis, because of the fairly high moisture, but on a moisture-free or a moisture- and ash-free basis, in which the amount of oxygen in the dry coal is revealed, it is within the range of typical anthracite.

COMBUSTION CHARACTERISTICS

The Santa Clara coals have a lower heating value than typical anthracite, as previously noted. The heating value on an "as received" basis is lowered by the moisture and ash, but on a moisture- and ash-free basis it

[75] White, David, The effect of oxygen in coal: U. S. Geol. Survey Bull. 382, p. 70, 1909.

is a function of the composition of the "pure coal" substance. Even on this basis the heating value of Santa Clara coal is less than that of typical anthracite, mainly because of the lower hydrogen content. In typical anthracite much of the heat value, besides that provided by the carbon, comes from the hydrogen. Even allowing for the low hydrogen content however, the heating value of Santa Clara coal is still less than that which it should theoretically give as calculated from its analyses.

The heating value of a coal may theoretically be calculated from its analysis by means of Dulong's formula, which is: "Calorific value in British thermal units per pound = 14,544 carbon + 62,028 (hydrogen — ⅛ oxygen) + 4,050 sulfur."[76] The formula is based on the assumption that the element carbon, upon combustion, provides 14,544 British thermal units per pound; that the "available hydrogen" produces 62,028 British thermal units per pound; and sulfur 4,050 British thermal units per pound. The "available hydrogen" is that left after subtracting an amount equal to one-eighth of the oxygen content, the part assumed to form water. Fieldner and Selvig point out four theoretical objections to Dulong's formula, but report fairly close agreement, nevertheless, between the heating values calculated by this formula and those determined by the calorimeter, particularly in the higher ranks of coal. In 20 samples of Pennsylvania anthracite the mean algebraic error in the heating value as determined by Dulong's formula was +0.6, the maximum negative error was 0.3, and the maximum positive error was 1.5. The error was greater for the lower ranks of coal. The theoretical heating values of the Santa Clara coals were calculated by the writers from Dulong's formula and were found to be 43 to 434 British thermal units higher than the determined heating values. The errors ranged from +0.3 to +3.1 percent, and averaged +1.9 percent. Thus the average error for the Santa Clara coal was higher than the maximum error of 1.5 percent for Pennsylvania anthracite. A possible reason for this, suggested only tentatively, is that part of the carbon in the Santa Clara coal may be in the form of graphite, which, of course, would give no heat. The ultimate analysis of coal as usually made does not distinguish between organic or combustible carbon and carbon in an incombustible form.[77] If graphite makes up 1 or 2 percent of the carbon in Santa Clara coal, it would readily account for the excess in heating value as calculated theoretically over that actually determined by the calorimeter.

The softening temperatures of ash in the Santa Clara coals range from 2,200° to 2,740° F. and average 2,427° F., which places them in class 2, ashes of medium fusibility, of the threefold classification of Selvig and Fieldner[78]. The tendency of a coal to form clinker is related in a general

[76]Fieldner, A. C., and Selvig, W. A., op. cit., p. 29.

[77]Idem, p. 27.

[78]Selvig, W. A., and Fieldner, A. C., Fusibility of ash from coals of the United States: U. S. Bur. Mines Bull. 209, p. 10, 1922.

way to the softening temperature of the ash, although it cannot always be predicted in advance because it depends also on other properties of the coal and on the method of burning.[79]

The following statement on the burning characteristics of coal of the Santa Clara type, based upon a study of its analyses, has been prepared by Paul Averitt and T. A. Hendricks of the Fuels Section of the Geological Survey:

> Coal of this nature is characteristically difficult to ignite, due to the small percentage of easily inflammable hydrogen in the volatile matter, and burns very slowly. The difficulties of combustion may be in part overcome by burning in fine sizes under a strong forced draft, although the exact sizes and the nature of the draft required for optimum combustion conditions could only be determined by careful experimental work. The ash content is low enough in the samples analyzed to make it a satisfactory fuel under suitable conditions of combustion. Special burning equipment would doubtless be required for satisfactory utilization of the coal for steam generation in stationary boilers and domestic heating units. The very slow rate of burning of this coal makes it unsuitable for use in locomotives.

Past experience in using this coal bears out the statement of Averitt and Hendricks. The Southern Pacific Railroad Co. found, after extensive tests, that the coal was unsuitable for use in locomotives. It was found usable in stationary boilers at San Javier, however, but several difficulties were encountered, principally decrepitation; the slow burning rate and difficulty of ignition were also noted. Before any large-scale use of this coal is planned, extensive combustion tests of carload samples are recommended, in order to determine in exactly what form the coal can be utilized satisfactorily.

NATURAL COKE

At several places in the Santa Clara district the coal has been metamorphosed into natural coke. In some places the entire bed has been affected, as in the Yaqui mine, but in others, as in the El Tren mine, only part of the bed has been changed into coke. The occurrence in the El Tren mine is quite irregular as the layer of coke lies near the top of the coal in one part of the mine, then gradually descends through the middle of the bed, and lies near the bottom in another part of the mine. About one-fourth of the thickness of the bed, on the average, has been converted to natural coke; coke has been extensively developed in the Los Jacalitos deposits, south of Los Bronces.

The natural coke is dark gray, brownish-gray, or grayish-black, has a dull luster, and is very hard and tough. It does not have the vesicular structure of artificial coke. The specific gravity of two samples tested by the Bureau of Mines was 1.913 and 1.987, which is within the range of the coal. A columnar fracture is well developed in some places, particularly

[79] Nicholls, P., and Selvig, W. A., Clinker formation as related to the fusibility of coal ash: U. S. Bur. Mines Bull. 364, pp. 3–4, 1932.

in the Yaqui mine, the columns being perpendicular to the bedding planes. Analyses of two samples of natural coke, No. 6 from the Yaqui mine and No. 11 from the El Tren mine, are given with the coal analyses in Table 4. They differ from the average analyses of the coal mainly in their lower content of moisture and higher content of ash. Their proportions of fixed carbon and volatile matter are within the range of the coal, and their chemical classification on a dry, mineral-matter-free fixed carbon basis is within the range of anthracite. The ultimate analyses of the natural coke are similar to those of the coal, except that they show slightly less hydrogen and oxygen on an "as received" basis (owing to the low moisture) but slightly more of these constituents on a moisture- and ash-free basis. The sulfur content of the natural coke from the Yaqui mine, 1.2 percent, is twice as high as the maximum found in any of the coal samples. The heating value of the natural coke, 10,830 to 11,880 British thermal units (as received), is within the range of the coal samples. Analyses of natural coke that have been previously published[80] show considerable variation.

There is little doubt that the natural coke developed from the coal as a result of heat from the igneous intrusions. In parts of the El Tren mine the coke is in direct contact with latite sills, which are believed to be responsible for the metamorphism, but in some places the coke cannot be directly related to igneous bodies. In much of the El Tren mine the coke occurs in the middle of the coal bed, although the igneous sills may be above or below the coal and may be separated from it by a layer of sediments. Why part of the coal bed should be selectively altered to natural coke, even though not in direct contact with an igneous rock, has not been explained. In the Yaqui mine the igneous body responsible for formation of the coke was not observed, but such a body could very well occur a short distance either above or below the bed, for sills are quite common in the district.

Natural coke has been reported from several places in the United States, where in each case it is related to igneous instrusions. In the Triassic coal field of the Richmond Basin, in Virginia, bituminous coal has been converted into natural coke near dikes and sills of diabase.[81] In the Book Cliffs coal field in central Utah coke has formed from bituminous coal on both sides of a dike.[82] In the Trinidad coal field, in Colorado, bituminous coal has been converted to coke for short distances near dikes and over broad areas adjacent to sills.[83] Coke, as well as anthracite, has

[80] Moore, E. S., op. cit., p. 109.

[81] Woodworth, J. B., The Atlantic coast Triassic coal field: U. S. Geol. Survey 22d Ann. Rept., pt. 3, pp. 36–37, 1902.

[82] Taff, J. A., Natural coke in the Wasatch Plateau: Science, new ser., vol. 23, p. 696, 1906.

[83] Richardson, G. B., The Trinidad coal field, Colorado: U. S. Geol. Survey Bull. 381, pp. 391–392, 434–435, 1910.

been formed along igneous intrusions in the Yampa coal field[84] and the Anthracite-Crested Butte district of the Uinta Basin, Colo.[85] Natural coke has also been found, according to Moore,[86] in New Mexico and Alaska.

ORIGIN OF THE META-ANTHRACITE

The metamorphism of the Santa Clara coal to the rank of meta-anthracite is probably due in part to heat from the igneous intrusions. Although pressure also probably played a part, pressure alone did not produce the extreme metamorphism noted, as the beds are not tightly folded.

The natural coke probably formed while the coal still had the rank of bituminous coal, as in nearly all other occurrences of natural coke that have been described the coke has formed from such coal. Anthracite coals, moreover, are known to be noncoking. It seems likely, therefore, that the anthracitization of the coal and the formation of natural coke occurred at the same time and that both were promoted by igneous intrusions, the natural coke having formed locally where heating was greatest or where other unknown physical or chemical factors played a part.

The reason for the increase of moisture in meta-anthracite as compared with anthracite is a matter of some interest, as this increase represents the first substance added to coal in the series of changes from lignite to graphite; all other changes in the series, as pointed out by Lewis,[87] represent subtraction or expulsion of constituents. Tests made on Colorado coals by McFarlane,[88] involving changes in specific gravity and amounts of water absorbed by immersed coal specimens, indicate, he thinks, that the pores open up at temperatures above 600° C. and less than 900° C. He states: "At about 800° C. the coal loses strength and ability to withstand weathering; it is distinctly inferior and should be classed as superanthracite (meta-anthracite)." In this category he places Colorado coal found in close proximity to volcanic sills, as well as Rhode Island coal, stating that these coals are characterized by high specific gravity, high moisture, and low heating value. All these characteristics apply, to some extent, to Santa Clara coal. McFarlane's explanation for the properties of this type of coal is that the heavy coal tars volatilize at the temperatures mentioned above, opening the pores and weakening the cement of the coal.

RESERVES

The extent of the coal reserves in the Santa Clara district cannot be satisfactorily ascertained without extensive drilling, which is strongly recommended if the probable reserves are to be established with any de-

[84] Fenneman, N. M., and Gale, H. S., The Yampa coal field, Routt County, Colo.: U. S. Geol. Survey Bull. 297, pp. 67–68, 1906.

[85] Dapples, E. C., Coal metamorphism in the Anthracite-Crested Butte quadrangles, Colorado: Econ. Geology, vol. 34, pp. 382–383, 1939.

[86] Moore, E. S., op. cit., p. 108.

[87] Lewis, J. V., The evolution of the mineral coals, part II: Econ. Geology, vol. 29, p. 177, 1934.

[88] McFarlane, G. C., Igneous metamorphism of coal beds: Econ. Geology, vol. 24, pp. 10–11, 1929.

gree of certainty. Some of the factors that adversely affect reserve estimates are the following: (1) The very poor exposures of the beds; (2) the coal is generally completely altered to depths of 10 to 30 meters; (3) the lack of any very extensive exploration along the strike and particularly down the dip; (4) the workings are inaccessible below the water level, which lies at a fairly shallow depth below the surface; and (5) the unknown extent to which the beds are cut out down the dip by igneous intrusions, faulting, or lensing out, any one of which could cause the coal to be lost within fairly short distances from the present mine workings. The only satisfactory method of computing reserves in the Santa Clara district is by considering each bed separately, multiplying its known, probable, or possible strike length by its known, probable, or possible dip length, and by taking into consideration the degree of probability of its being cut off by igneous intrusions, faulting, or lensing out, as well as the probable depth limit of commercial mining.

For classifying ore reserves, the Geological Survey and the Bureau of Mines have adopted a uniform system, using the terms "measured ore," indicated ore," and "inferred ore,"[89] which indicate the relative degree of accuracy and probability of the estimates. In this report the same classification is used for coal reserves, with the addition of a fourth category, "possible reserves," consisting of those that are even more uncertain than "inferred" reserves, and which are based upon the most favorable assumptions that can reasonably be made regarding the continuity of the coal beds. This classification of reserves has been applied to the various coal beds of the Santa Clara district in the following way:

Measured reserves include coal blocked out on at least three sides in the mine workings, if any. If no coal is so blocked out in a particular mine, the area is obtained by multiplying the continuously exposed strike length in the mine workings by a dip length of 20 meters, wherever this seems reasonable, or of 10 meters where less certain. If the coal bed is exposed in only one outcrop, shaft, or prospect, no figure is given for measured reserves. The dip length assumed in each case is very conservative, and without doubt the estimated tonnage of measured reserves can readily be obtained.

For indicated reserves the area is obtained by multiplying the continuously exposed strike length, or probable strike length, by an equal distance for the dip length, wherever this seems reasonable, up to a maximum of 150 meters. In places where there is less certainty, the dip length is taken as half the strike length, but if some other evidence is available as to a more probable dip length, this, of course, is taken into consideration. For coal beds that are exposed in only one outcrop, shaft, or pros-

[89]For definitions of these terms see Dorr, J. V. N., 2d, Manganese and iron deposits of Morro do Urucum, Mato Grosso, Brazil: U. S. Geol. Survey Bull. 946-A, footnote 32, p. 36, 1945.

pect, the dimensions are arbitrarily taken as 30 meters for strike length and 20 meters for dip length.

For inferred reserves the "possible" strike length is used, as distinguished from the continuously exposed strike length. In most places the possible strike length is the distance between the extremities of outcrops or mine workings believed but not proved to be on the same bed. The dip length is taken as equal to the strike length, wherever the latter seems to be fairly well established, but a reduced figure is used where the strike length is less certain. The maximum dip length assumed for any bed is 500 meters, as this is thought to lie at the probable depth limit of commercial mining. For a bed dipping 30°, this limit would lie at a vertical depth of 250 meters below the surface, without considering topographic irregularities. If evidence is available as to the depth at which a dioritic intrusive body is likely to occur, as in the vicinity of the La Calera beds, this is taken into consideration in limiting the dip length. For coal beds that are exposed in only one outcrop, shaft, or prospect, the dimensions are arbitrarily taken as 100 meters for strike length and 50 meters for dip length.

The additional category of possible reserves is based upon the most favorable assumptions that can reasonably be made regarding the continuity of the coal beds. The assumption is made that each of the five most important beds in the district has a strike length equal to the total known coal-bearing extent of the basin in which it is found. This length is 1,050 meters in the Calera Basin and 900 meters in the Santa Clara Basin. In the Calera Basin the beds are the Las Amarillas-Yaqui (C3a-b), the El Tren-El Refugio (C4a-b), and the Upper Calera (C7); and in the Santa Clara Basin they are the Upper Z (SC2), and the El Voladero-Santa Clara (SC6a-b). Actually, not all five beds are likely to occupy the full extent of their respective basins, but this may be somewhat compensated by the appearance in minable quantities, here and there, of some of the other coal beds known to exist in the two basins. The dip length is assumed to be 500 meters, the probable maximum depth of commercial mining, for all but the Upper Calera bed, for which it is assumed to be only 200 meters because of the proximity down the dip of the dioritic bodies exposed in Arroyo de Tarahumara.

The thickness used in all estimates is the calculated average thickness of commercially minable coal. Where a thick shale parting prevents a part of the bed from being mined commercially, as for example in both the La Calera beds, this unminable part is disregarded. Likewise the coke layer in the El Tren mine is disregarded, as it seems too thin to be mined commercially, assuming that it could not feasibly be mined with the coal. Even if the coke should have a market, the coal and coke would probably be used for different purposes and thus would have to be mined separately.

For the purpose of tonnage estimates, the specific gravity is taken as 1.7. The average real specific gravity of samples tested by the Bureau of

TABLE 7.—*Measured, indicated, and inferred reserves in the Santa Clara district*

No.	Name of bed	Thickness	Measured reserves			Indicated reserves			Inferred reserves		
			Strike length (meters)	Dip length (meters)	Tons	Strike length (meters)	Dip length (meters)	Tons	Strike length (meters)	Dip length (meters)	Tons
	CALERA BASIN										
C9	Upper Pitshaya	1.2				30	20	1,200	100	50	10,000
C8	Lower Pitshaya	1.0				30	20	1,000	100	50	8,000
C7	Upper Calera	1.0	157	20	5,300	157	150	40,000	545	150	139,000
C6	Lower Calera	.6	26	10	300	30	30	900	550	100	56,000
C5	La Confluencia	1.0				30	20	1,000	550	100	93,000
C4b	El Refugio	2.5 1.2	150	20	12,700	150	150	95,600	840	500	857,000
C4a	El Tren	1.0	230	20	7,800	230	150	58,600			
C3b	Yaqui	1.0	100	10	1,700	100	50	8,500	1,040	100	177,000
C3a	Las Amarillas	1.0				120	60	12,200			
C2	Whitewood	1.2				30	20	1,200	450	100	92,000
C1	Boca del Agua	1.2				30	20	1,200	100	50	10,000
	Total				27,800			221,400			1,442,000
	SANTA CLARA BASIN										
SC7b	Potrero No. 6	2.1				30	20	2,100	100	50	18,000
SC7a	Potrero No. 7	.9				30	20	900	100	50	8,000
SC6b	Santa Clara	2.0	35	20	2,400	75	50	12,700	730	365	906,000
SC6a	El Voladero	2.0	100	20	6,800	100	100	34,000			
SC5	Casa Blanca	1.0				30	20	1,000	100	50	8,000
SC4	Upper Parvin	1.4				30	20	1,400	100	50	12,000
SC3	Lower Parvin	.9				30	20	900	100	50	8,000
SC2	Upper Z	1.5							150	150	57,000
SC1	Lower Z	1.3	22	20	1,000	100	50	11,000	150	150	50,000
	Total				10,200			64,000			1,067,000
	Grand total, both basins				38,000			285,400			2,509,000
	Minable coal (80 percent of total)				30,400			228,300			2,007,000
	Minable coal, round numbers				30,000			230,000			2,000,000

Mines is 1.94, but taking into account the porosity and fracturing of the coal, 1.7 seems a more reasonable figure to use in computing tonnages in place.

The figures are rounded more or less according to their degree of approximation. In arriving at the total figures of minable coal, a factor of 80 percent is applied, assuming that wastage in pillars and so forth would be at least 20 percent. All the estimates are computed in metric tons. Table 7 gives the estimates for measured, indicated, and inferred reserves of the various coal beds of the Santa Clara district, and table 8 gives those for possible reserves.

TABLE 8.—*Possible reserves in the Santa Clara district*

No.	Name of bed	Thickness (meters)	Strike length (meters)	Dip length (meters)	Tons
C7	Upper Calera	1.0	1,050	200	357,000
C4a-b	El Tren-El Refugio	1.2	1,050	500	1,071,000
C3a-b	Las Amarillas-Yaqui	1.0	1,050	500	893,000
SC6ab	El Voladero-Santa Clara	2.0	900	500	1,530,000
SC2	Upper Z	1.5	900	500	1,147,000
Total					4,998,000
Minable coal (80 percent of total)					3,998,000
Minable coal, round numbers					4,000,000

The totals for the district are 30,000 tons of measured reserves, 230,000 tons of indicated reserves, 2,000,000 tons of inferred reserves, and 4,000,000 tons of possible reserves. In the writers' opinion the estimate for inferred reserves of 2,000,000 tons is the most reasonable figure, as the figure for possible reserves of 4,000,000 tons is based on very optimistic assumptions. If the effects of igneous intrusions, faulting, and lensing out of the coal beds at depth are very extensive, even the figure for inferred reserves may be too high. Because of the wide range in figures, depending upon the initial assumptions that are made, drilling is strongly recommended in order to establish more closely the tonnage of minable coal that can be reasonably expected.

RECOMMENDATIONS FOR CORE DRILLING

A program of core drilling is recommended to obtain an adequate idea of the coal reserves of the Santa Clara district. Ten properly spaced inclined holes 200 to 250 meters deep should thoroughly determine the possibilities of the district. This would require 2,000 to 2,500 meters of drilling. The 10 drill sites (and one alternate) selected as most favorable are indicated on plate 9. Circles on the map indicate the drill sites, and arrows indicate the position of the bottom of the inclined holes at a depth of 250 meters.

The 10 recommended drill sites include 6 in the Calera Basin and 4 in the Santa Clara Basin. The sites in the Calera Basin consist of four in

Arroyo de la Calera (with one alternate in Arroyo de las Amarillas) to explore the El Tren-El Refugio and lower beds, and two on the ridge south of Arroyo de la Calera to explore the Calera and higher beds. The sites in the Santa Clara Basin consist of one in Arroyo de Santa Clara, two in Arroyo del Potrero, and one in Arroyo de la Milpa. The holes should be inclined downward as nearly as possible at right angles to the strike and dip of the beds. The holes should be drilled to an inclined depth of at least 200 or 250 meters, if physically possible, to provide as much information as possible concerning the number, thickness, and quality of the coal beds at each locality. If a mass of diorite or other plutonic rock is reached in any of the holes, however, drilling should be discontinued.

Most of the drill sites that have been chosen can be made accessible to a truck or tractor without great difficulty, although a small amount of road building will be necessary. Water supply will be one of the most difficult problems, for local sources are very limited, as has been noted. If these sources prove insufficient, water must be hauled 7 kilometers by truck from the Río Yaqui, which contains a plentiful supply.

MINING METHODS

The mining methods used are very primitive and must be revised completely to attain any large-scale production of coal. Practically all work has been done by hand, and in many places the coal has been carried out on the miners' backs. In some places tracks have been laid so that ore cars can be used; in other places this is impossible as the so-called adits ascend and descend along their length (see section of Santa Clara mine, pl. 7). The general plan has been either to follow the coal down by means of an inclined shaft, or to drive and adit from the surface to the coal bed, and then to follow it by means of drifts. Many of the drifts, like the adits, are not level, however, and increase the work of mining the coal. None of the workings extend to great depth, and so far as systematic development of the coal is concerned only the surface has been scratched.

As the coal in the Santa Clara district occurs in two distinct areas, the Santa Clara and Calera Basins, each area will have to be mined separately. One main shaft could serve in each of the two basins. The logical location for such a shaft in the Calera Basin would be in Arroyo de la Calera, probably close to its junction with Arroyo del Tren. All the coal beds below the La Calera dip toward this shaft and should be intersected by it (assuming that they are not cut out at depth, which could be observed by drilling). Crosscuts could be driven northward from the shaft at determined intervals to intersect the various beds. Drifts could then be driven along these beds and the coal stoped out above them. The La Calera and higher beds could be reached by driving crosscuts south from the shaft. As these beds dip away from the shaft, however, the amount of "dead work" required to reach them would necessarily be greater. In the Santa Clara Basin the best location for the main shaft should be determined in part by drilling. Probably the shaft would best be located in Arroyo del Potrero, but if the results of drilling in that area should be unfavorable, the best location would probably be in Arroyo de Santa Clara. The coal beds below the El Voladero could be reached by driving crosscuts northward from the shaft, and the El Voladero and higher beds could be reached by crosscuts driven southward. The system of drifts and stopes could be worked out the same way as in the Calera Basin.

CONCLUSIONS AND RECOMMENDATIONS

1. If the Santa Clara coal deposits were in a region of abundant coal resources, they probably would not be commercial because of their relatively small size, the difficulties of mining them, and the inferior combustion characteristics of the coal. As they represent practically the only known coal resource on the Pacific coast of Mexico, however, their commercial utilization may be possible.

2. Of the various reserve estimates, the figure of 2,000,000 tons for "inferred" reserves seems the most reasonable for minable coal likely to be found in the district, but this tonnage cannot be assured without core drilling. Several geologic factors might cause the coal beds to be cut out at shallow depths, and thus this figure might be too high.

3. The coal is difficult to ignite, burns slowly, and tends to decrepitate. It is unsuitable for use in locomotives, and obviously cannot be used for coking and byproduct recovery. Special burning equipment might be developed to use it successfully in stationary boilers and domestic heating units, probably by burning in fine sizes and under a strong forced draft. It might be used for domestic heating by forming it into briquets. It can be used successfully in the manufacture of calcium carbide, and has been used in reverberatory furnaces after sprinkling with fuel oil. A study should be made of experiences in attempted use of Rhode Island coal, which has many of the combustion characteristics of Santa Clara coal. The natural coke could perhaps be used for foundry coke.

4. Large-scale commercial production of coal from the district will be impossible if the railroad from Corral to La Dura or Tónichi is permanently removed. Assuming that the railroad is replaced, transportation from the mines to the railhead at Tónichi could probably be best accomplished by an aerial tramway. The route for such a tramway was surveyed in 1911 and the distance determined as 3.85 miles (6.2 kilometers) over an area of fairly low relief.

5. Santa Clara coal could probably be used feasibly in a thermoelectric plant, although two additional types of investigation are necessary to assure success. It is recommended (a) that core drilling be done to determine

the quantity of coal available; and (b) that experimental combustion tests be made on carload samples to determine how the coal can best be burned in a power plant.

MINE DESCRIPTIONS

SANTA CLARA DISTRICT

SANTA CLARA MINE

The Santa Clara mine is on the north side of Arroyo de Santa Clara just west of its junction with Arroyo del Potrero (see pl. 2, coordinates 1880 E., 890 S.). It contains some of the highest quality coal found in the district and is the mine that was being most actively exploited by the Cía Carbón Sonora at the time of the writers' field work.

The mine has two entries (see pl. 7), an adit 60 meters long and a shaft 20 meters long that is inclined 35°. The adit floor varies in elevation, first descending and then rising (see section, pl. 7); so coal must be carried along it on the backs of the miners. The inclined shaft, however, is provided with tracks and a gasoline hoist. The coal has been stoped out over a strike length of 65 meters and dip length of 20 to 25 meters, down to water level, by means of irregular intersecting drifts and slopes, separated by pillars. Both sides of the stoped area are reached by winzes from the main adit, and its southwest end is reached also by the inclined shaft. Most of the stopes shown on the mine map were made by the Cía Carbón Sonora. Beyond them, and especially nearer the surface, are some old workings of the Southern Pacific Railroad Co. that are filled with waste.

The coal bed in this mine, called the Santa Clara bed (SC6a), has an average thickness of 2.0 meters, ranging from 1.2 to 2.8 meters. The coal is of unusual purity, containing very few shale or bony partings. The bed does not crop out near the mine. Its dip is parallel to the slope of the surface, which is practically a dip slope, on the north side of Arroyo de Santa Clara, the bed lying several meters below the surface. The coal may once have cropped out in a small ravine west of the main adit, where there is a caved prospect pit, but if so the outcrop is now obscured by a cover of debris. In the main stoped area the coal bed has an average strike of N. 39° E., ranging from N. 20° W. to N. 60° E., and an average dip of 30° SE., ranging from 20° to 41° SE. The bed is cut off at the top, just before reaching the main adit level, by a series of gently dipping faults that drop the bed down to the north in a series of wedges (see section, pl. 7). North of these faults the coal reappears and has a thickness of 2.8 meters where it has been followed down by a slope northeast of the main adit (see pl. 7, coordinates 40 E., 30 S.). At this place the strike has changed to N. 20° W. At the extreme north end of the main adit the coal has been upthrown 6 meters in a wedge between two faults, where it has been followed by a raise. North of the northernmost fault the coal has not been found. It has probably been upthrown to the north, perhaps to a point higher than the present topographic surface.

At the southwest end of the mine, at the bottom of the inclined shaft, the coal wedges to a thin streak as a result of faulting nearly parallel to the bedding planes. Similar faulting seems to occur at the northeast end of the mine.

At the present time the main block of coal not yet stoped out of this mine, aside from pillars, is that explored by the slope near the north end of the mine (pl. 7, coordinates 40 E., 30 S.). The coal in this locality should continue down to the south and east until it reaches the faults that cut off the coal of the main stoped area just below the adit level. Aside from this, the main possibilities of the mine lie in following the coal down below water level. It was said that in old flooded workings below water level the coal thins by wedging, much as it does near the bottom of the inclined shaft. The coal might reappear farther down, however, if the zone of faulting responsible for the wedging can be passed. The best way of exploring the possibilities of the bed would be by drilling in Arroyo del Potrero, which is down dip from the mine. Two of the holes of the recommended drilling program, Nos. 8 and 9 (see pl. 2), are planned to give the most information on the continuity of this coal bed at depth.

EL VOLADERO MINE

The El Voladero mine is on the south bank of Arroyo de Santa Clara, south of the "Casa Blanca" (see pl. 2, coordinates 2220 E., 580 S.). Several exploratory workings were opened there by the Southern Pacific Railroad Co., but only one, called No. 1, is now accessible, having been reopened recently by the Cía. Carbón Sonora. The main working now accessible is a drift with an irregularly descending floor that follows the coal bed in a northeasterly direction for a distance of 95 meters (see pl. 8). This drift is connected with the surface at its southwest end by a short adit 20 meters long. At its northeast end the drift connects with some old caved and filled workings of the Southern Pacific Co. As the ground in this mine is very heavy, the walls along the greater part of the drift are lagged and the space beyond is filled, so that the beds in place cannot be seen. At the time of the field work only one small stope was accessible, near the northeast end of the mine, in which the coal had been removed over a dip length of 7 meters.

The workings are on the El Voladero bed (SC6b), which may be the same as the Santa Clara bed. This bed has an average thickness, in the El Voladero mine No. 1, of about 2 meters, ranging from 1.5 to 2.5 meters. The coal appears to be of good quality but is highly fractured, fine-grained, and friable. In this mine the strike of the bed averages N. 60° E., ranging from N. 35° E. to N. 70° E. The dip averages 30° SE. and ranges from 22° to 40°.

The trace of the original outcrop of the El Voladero bed extends for some distance along the southeast side of Arroyo de Santa Clara. The bed was explored at various places by slopes put down by the Southern Pacific Railroad Co., all of which are now caved. At least eight separate entries were once present, but the depth of the workings is not known. The total strike length covered by these old workings, starting from a few prospects southwest of No. 1 and continuing to No. 8 toward the northeast, is 330 meters.

The main future possibilities of the El Voladero mine lie in developing the coal at depth, below the present drift level of mine No. 1. There is no evidence available as to how deep the coal bed might extend. Recommended drill hole No. 10 (see pl. 2) would indicate whether or not the coal extends as much as 225 meters down the dip below the surface.

"Z" WORKINGS

The "Z" workings are a series of inclined shafts and other workings along a small ravine northwest of Santa Clara station, beginning just west of Arroyo de Tarahumara and continuing for a distance of 370 meters west of the arroyo (see pl. 2, coordinates 1850–2110 E., 420–490 S.). The name "Z" was applied by Dumble because of the supposed Z-shape, produced by faulting, of the bed in the principal working. Two separate beds are believed to be represented. The line of workings extending from No. 3 to No. 9 is on a bed known as the Lower Z (SC1), whereas workings Nos. 1 and 2 are on a bed that seems to be stratigraphically higher, called the Upper Z (SC2).

The main working, No. 1, also called Estación, is now caved, but it was evidently one of the most important of those developed by the Southern Pacific Railroad Co. The entrance was being reopened at the time of the writers' field work (see pl. 12, *A*). The dump is very large and indicates that the workings were quite extensive. The main working is a shaft inclined, near the surface, at 33° SE. This inclination is said to have continued for about 65 meters; below this the workings become nearly horizontal, continuing for a total length of about 100 meters. There were communicating drifts on the sides of the shaft. According to Dumble, the coal bed was repeated by a thrust fault, but the details of the faulting are not known. The possibilities of this mine are difficult to appraise, as it is not known what was found at depth. Recommended drill hole No. 7 and perhaps Nos. 8 and 9 (see pl. 2) should indicate, however, whether the coal bed continues to any depth.

The workings on the Lower Z bed are also caved for the most part, except Nos. 5, 7, and 11. In No. 5 a coal bed 1.3 meters thick was found at the bottom of an inclined shaft 35 meters deep. Workings Nos. 7 and 11 are inclined shafts connected by a drift (see pl. 8). The coal is 1.2 meters thick, but it is of very poor quality, containing a large number of shale partings. The coal as seen in these two shafts probably would not be worth mining. It has been mined out in a very small stope 7 meters high, leading from the drift connecting the two shafts. The bed in these shafts strikes N. 20°–25° E. and dips 35° to 45° SE. It is offset in the drift by a small fault. The coal is completely altered to an inclined depth of 21 meters from the surface.

LA CALERA MINE

The La Calera mine is on the south side of Arroyo de la Calera, east of its junction with Arroyo del Tren (see pl. 2, coordinates 720 E., 490 S.). This mine has had a fair production of coal, although the bed that has been worked is comparatively thin. The first mining was done by the Southern Pacific Railroad Co., and more recently coal was extracted by the Cía. Carbón Sonora. The principal workings are an adit 67 meters long running southeast, which intersects two coal beds, and a drift 157 meters long following the principal (upper) bed (see pl. 9). The upper bed has been stoped out above the drift level to the zone of alteration, over an inclined distance averaging about 15 meters. At one place there is a communication between the top of the stopes and the surface. The water table is only slightly below the drift level, and no exploration has been done at greater depth. A short drift, now caved at a distance of 15 meters from the adit, followed a lower coal bed found at a distance of 20 meters from the entrance to the adit. According to Dumble the drift once had a length of 26 meters. A flooded winze of unknown depth followed this lower coal bed down from the drift.

The two coal beds exposed in the La Calera mine, called the Lower Calera (C6) and the Upper Calera (C7), lie 20.8 meters apart stratigraphically, other very thin seams of coal occurring between them. Some highly altered coal, evidently at a lower horizon, is also exposed at the entrance to the adit. A quartz latite dike is penetrated just inside the entrance of this adit (see section, pl. 9), representing a small offshoot of a fairly large dike exposed in Arroyo de la Calera north of the mine.

Both coal beds in the La Calera mine are divided into two benches separated by fairly thick shale partings. The Lower Calera bed consists, near the main adit, of 80 centimeters of coal, overlain by 60 centimeters of shale and 45 centimeters of coal. Farther northeast it consists of 35 centimeters of coal, 30 centimeters of shale, and 40 centimeters of coal. The shale parting may make the two benches of coal too thin to be mined commercially. The Upper Calera bed has an average thickness of 1.0 meter of coal at the base, overlain by 40 to 50 centimeters of shale, and 30 to 40 centimeters of coal. Only the lower part of this bed has been stoped. Because of the thick shale parting, the upper part of the bed has not been considered worth stoping.

The upper bed has an average strike of N. 38° E., ranging from N. 5° E.

to N. 80° E. The dip averages 30° SE., ranging from 19° to 50°. Only small faults having a maximum displacement of about 1 meter were noted in the mine.

The future possibilities of this mine lie in following the principal bed down the dip below water level. The depth to which the beds may continue is not known. The possibilities would be partly revealed by hole No. 6 of the recommended drilling program (see pl. 2).

EL REFUGIO MINES

The El Refugio mines are on the south bank of Arroyo del Yaqui, just west of its junction with Arroyo del Refugio (see pl. 2, coordinates 630–820 E., 200–300 S.). These mines were originally developed by the Southern Pacific Railroad Co., which outlined the coal in intersecting drifts and inclined shafts, but apparently did no stoping. A considerable amount of coal was stoped out by the Cía. Carbón Sonora.

The mines consist of seven workings, at successively higher levels from east to west, which have been called No. 1 nuevo,[90] No. 1 viejo, No. 2 nuevo, No. 2 viejo, No. 3 nuevo, No. 3 viejo, and No. 4 viejo (see pl. 10). Working No. 1 nuevo is a crosscut that did not reach the coal bed, and No. 1 viejo is a completely caved working. Nos. 2 nuevo and 2 viejo are inclined shafts following the dip of the coal bed, and they are joined by intersecting drifts at varying levels. These workings are said to have extended for more than 100 meters, but most of the lower parts are flooded, and many of them are caved or in very poor condition. Working No. 3 nuevo is an adit that in part follows a thin bed of bony coal about 7 meters stratigraphically below the main coal bed. At its end a complicated raise reaches the coal bed and communicates above with working No. 3 viejo. Working No. 3 viejo is an adit that near the entrance follows the lower bony coal horizon; farther in, away from the portal, it cuts the main coal bed because of faulting and the fact that the adit crosses the strike. Working No. 4 viejo follows the main coal in from the surface, although the coal is completely altered for a distance of 20 meters. Extensive stoping has been done at the ends of workings Nos. 3 viejo and 4 viejo, and some stoping has been done in workings above the raise at the end of adit No. 3 nuevo.

The main coal bed exposed in the El Refugio mines, called the El Refugio bed (C4b), has an average thickness of about 2.5 meters. In some partly caved parts of the mine the thickness was probably as much as 3 meters. Figures for continuously exposed strike length and dip length in these mines cannot be given with much accuracy, because (1) many of the workings are inaccessible, (2) they did not follow either the strike or dip but cut diagonally across, and (3) there are several gaps between the

[90]Nuevo is Spanish for new, viejo for old.

workings. The total length explored across the strike is roughly 150 meters, however, and the length down the dip is about 130 meters. The coal exposed in the top of working No. 3 nuevo is of good quality, but that in workings Nos. 2 nuevo and 2 viejo contains several shale partings.

There are a number of variations in attitude and several small faults exposed in these mines (see pl. 10). The strike ranges from nearly north to nearly east, averaging about N. 30° E. The dip averages about 30° SE., although it is nearly flat in the stopes at the end of working No. 3 viejo, and is as high as 50° in workings No. 2. In the workings at the top of No. 3 nuevo is exposed a small anticline that plunges south.

A considerable amount of coal is partly blocked out in this mine, in workings Nos. 2 nuevo and 2 viejo, and between these and No. 3 nuevo. At the end of the No. 2 workings, in a part now flooded, the coal is said to have pinched out, but whether this was due to faulting, igneous intrusion, or lensing out is not known. The coal cannot be expected to continue much farther east because of the proximity of the Potrero fault. There seem to be good possibilities, however, of its continuing westward toward the El Tren mine, and the recommended drilling program should help to reveal its possible extent.

EL TREN MINE

The El Tren mine is situated on the south side of Arroyo del Tren, near the junction with Arroyo de la Calera (see pl. 2, coordinates 470 E., 410 S.). Its workings are more extensive than those of any of the mines now accessible in the district. The original workings, consisting mainly of an inclined shaft and two drifts, were made by the Southern Pacific Railroad Co. No stoping was done at that time, but the Cía. Carbón Sonora has since stoped out the coal above the main drift level to the zone of alteration, leaving only small pillars (see pl. 11) in an area that measures about 140 by 20 meters. The total extent of the mine is 230 meters in a southwesterly direction. The main drift, which is in suitable condition for extraction of coal, extends for 180 meters, beyond which the workings are irregular. Below this is a lower drift of irregular level. A shaft extends for an inclined distance of 112 meters from the surface to water level, and an unknown but probably short distance beyond. A few inclined winzes also extend below the water level. A crosscut adit from the surface joins the main drift at a distance of 49 meters from its entrance.

One main coal bed, the El Tren (C4a), has been exploited in this mine, and two other thin beds, besides three very thin seams or streaks, were found at lower stratigraphic levels in the crosscut (see section, pl. 11, and columnar sections, pl. 5). About one-fourth of the thickness of the El Tren bed, on the average, has been converted to natural coke. In the northeast part of the mine the coke lies near the top of the coal bed, but toward the southwest it gradually descends through the bed until, in the southwest part of the mine, it is near the bottom. The reason for this is not known. The coke is believed to have been formed as a result of heat from latite sills, which are quite abundant in the El Tren mine. The sills generally occur below the coal bed, but a few of them intrude the coal and reduce its thickness, the coal being almost entirely wedged out in the southwest end of the mine. Besides the latite sills, which are aphanitic, gray, and highly altered, some coarser-grained porphyritic rocks, perhaps quartz-latite, occur in parts of the El Tren mine, chiefly above the coal.

The coal bed has an average total thickness of 1.35 meters, of which an average of 30 centimeters is coke and 1.05 meters is coal. The average thickness of minable coal, occurring separately from the coke, is about 1 meter. The El Tren mine is noteworthy for the deep alteration of the coal, which in the inclined shaft is completely destroyed for a depth of 70 meters below the surface, although the original structure of the bed, including shale partings at the top and latite sills near the bottom, is still visible.

The strike of the coal beds averages N. 70° E. in the west half of the mine and N. 50° E. in the east half, ranging to as much as N. 80° E. in the west half and N. 20° E. in the east half. The dip averages 30° SE., ranging from 21° to 38°. Several small faults with displacements of 1 to 3 meters occur in the mine and have been indicated on the mine map (see pl. 11).

The future possibilities of this mine lie in following the coal at depth below the main drift level, and also in following it farther southwest. The bed is nearly cut off by igneous sills in the southwest end of the mine, but it may pick up again farther along the strike. The coal bed should be well explored down the dip by drill holes Nos. 2 and 3 indicated in plate 2.

YAQUI MINE

The Yaqui mine is north of the El Refugio mines, between Arroyo del Refugio and Arroyo del Yaqui (see pl. 2, coordinates 800 E., 120 S.). It once had two entrances, an adit extending southwestward from the west bank of Arroyo del Refugio (see pl. 8) and an inclined shaft with an easterly direction, on the north bank of Arroyo del Yaqui. As the shaft is now caved the mine may be entered only through the adit. Nearly the entire bed that was followed in this mine has been converted to natural coke. The mine has evidently not yielded a large production, as it contains only one fairly small stope in the coke. The workings were excavated by the Southern Pacific Railroad Co., and nothing further has been done.

This mine follows the Yaqui bed (C3b), which may be the same as the Las Amarillas bed. Where it was sampled, at the southwest end of the small stope, it has a total thickness of 1.69 meters, of which the lower 21 centimeters is coal and the rest is natural coke with shale partings. In this stope the coke is divided into three well-defined layers, separated by shaly partings, and is also separated from the coal by a thin shale parting. The individual layers of coke have prominent columnar jointing perpendicular to the bedding planes. The beds strike N. 20°–60° E., and dip 15° to 40° SE. The main part of the adit, which lies east of the short drift from which the natural coke has been stoped (see pl. 8), follows a bed of coke and coal only about 40 centimeters thick. It is not certain that this is the same bed as that followed in the stope; if it is, it must have been displaced several meters by faulting. This thin coke goes into the roof at a point 15 meters southwest of the entrance to the adit, and a 1-meter layer of coal appears 1 meter stratigraphically below it. The alteration products of this coal continue to the entrance of the adit.

The economic possibilities of this mine depend largely upon developing a market for the natural coke. The behavior of the bed at depth should be determined by the drilling program recommended in this report, especially by holes Nos. 1 and 2 (see pl. 2).

LA PITAHAYA WORKINGS

The La Pitahaya workings are scattered at several places in the drainage area of Arroyo de la Pitahaya, a southern branch of Arroyo de la Calera (see pl. 2, coordinates 250–400 E., 750–1100 S.). Altogether some 17 workings or prospects were noted, but nearly all are caved. None of them yielded any significant production of coal, so far as known. Seven different coal beds were found, according to Dumble, but only two are described as having a thickness of as much as 1 meter. Drill holes Nos. 5 and 6 (see pl. 2) of the recommended drilling program should explore the possibilities of these beds.

LAS AMARILLAS MINE

The Las Amarillas mine, which was called the Gopher while being worked by the Southern Pacific Railroad Co., is on the south bank of Arroyo de las Amarillas (see pl. 2, coordinates 110 W., 540 S.). This mine is completely caved and has not been reopened by the Cía. Carbón Sonora, but from the size of the dumps it is judged to have been one of the largest workings developed by the Southern Pacific Railroad Co. An old map of the district indicates that the mine had a length of about 120 meters. The approximate shape of the workings, as represented on this map, is shown on plate 2. The regular coal section in this mine, according to Dumble, was 1.05 meters of coal, 45 centimeters of "slate" (shale), and 65 centimeters of coal. The dip is said to be 49°. The possibilities at depth of the coal bed found in this mine should be explored by drill holes Nos. 4 or 4a (see pl. 2) of the recommended program given in this report.

LOS BRONCES AREA

Several coal mines and prospects are 2 to 3 kilometers south and southeast of the deserted mining camp of Los Bronces, principally on the sides of Arroyo de los Bronces and its tributaries, Arroyo de la Colorada, Arroyo de los Jacalitos, and Arroyo de los Amolillos. These mines were worked while coal was being used in the silver smelter of the Cía. W. C. Laughlin at San Javier, which was closed down sometime in the 1920's. None of the mines have been worked since then, and most of them are now caved. Much of the information concerning their former extent, therefore, was obtained from residents of the region who once worked in the mines, particularly from Sr. Jesús Ycedo. These mines, particularly the ones in Arroyo de los Jacalitos, might yield considerable quantities of coal, but they have the disadvantage of being much less accessible to the railroad than the mines of the Santa Clara district. The mines will be considered in the order of their location, proceeding from north to south.

SANTA MARIA PROSPECTS

The Santa María prospects are two short adits 8 meters apart on the west side of Arroyo de los Bronces, north of its junction with Arroyo de los Jacalitos. The north adit is about 10 meters long in the direction S. 72° W., and the south one is about 5 meters long in the direction S. 47° W. The north adit exposes a bed of natural coke about 60 centimeters thick, together with some graphite, but the bed is poorly defined, and the enclosing rocks are highly faulted and disturbed. Shales in the walls of the adit strike N. 75° E. and dip 50° SE. The south prospect exposes an irregular layer of natural coke about 20 centimeters thick. These prospects are not considered to have commercial value.

LA REINA PROSPECT

A completely caved working, known as the La Reina prospect, lies on the east side of Arroyo de los Bronces, a short distance south of the Santa María prospects. In it a bed of natural coke slightly over 1 meter thick is said to have been found.

LA REINA SILVER ADIT

A long adit driven into the base of Cerro de Santa Rosa for silver and gold ore, called the La Reina adit, is on the west side of Arroyo de los Bronces, just north of its junction with Arroyo de la Colorada. The adit runs N. 70° W., and is said to have been about 500 meters long. At a distance of about 130 meters from the entrance a bed of natural coke with a thickness of 1.2 meters was penetrated. It was said that a coal bed was also found 70 meters farther in, but this part of the adit is now caved

LA COLORADA SILVER ADIT

On the north side of Arroyo de la Colorada, a short distance from its junction with Arroyo de los Bronces, a fairly long adit was driven in a northwesterly direction for silver and gold. This adit, known as the La Colorada, is now in large part flooded. At its entrance is a coal bed about 30 centimeters thick that dips into the floor. This coal is highly altered at the surface. A small fault is exposed just west of the adit entrance (see pl. 12, *B*). The beds at this place strike N. 30° E. and dip 15° NW., in a direction opposite to that of the normal dip of the region, evidently as a local result of faulting.

PROSPECTS BETWEEN ARROYO DE LA COLORADA AND ARROYO DE LOS JACALITOS

Farther south along Arroyo de los Bronces between its junctions with Arroyo de la Colorada and Arroyo de los Jacalitos, there occur several caved prospects and workings, mainly on the west side of the arroyo. They seem to have followed at least two separate coal beds. Nothing may now be learned from these workings as to the thickness or quality of the coal that was found, but gambusino workers are said to have extracted a small amount of coal from them.

LOS JACALITOS MINES

The Los Jacalitos mines consist of a series of workings on both sides of Arroyo de los Jacalitos, east of its junction with Arroyo de los Bronces. These mines were operated for several years to supply the silver smelter at San Javier with coal and coke and probably ranked second in coal production among the mines of the Los Bronces area, being surpassed only by the Carbón Grande mine, described below. Most of the workings are now flooded or caved, so that hearsay evidence must be depended upon for their description. The strata are considerably disturbed, departing notably from their usual attitude in this area and dipping nearly vertically in places.

On the north side of the arroyo are some caved workings that once communicated with Arroyo de los Bronces through the hill to the west. A former operator of this mine reported, according to an unpublished report by William G. Kane, that a drift followed a seam of coal 3½ meters thick that stood nearly vertically for a distance of at least 120 meters. The coal is said to have been stoped above this level to within nearly 10 meters of the surface, but no development was done below the floor of the drift. On the south side of Arroyo de los Jacalitos is a flooded drift that follows a bed of natural coke 2 to 3 meters thick, containing a few centimeters of graphite at the top. This drift is said to have been about 60 or 70 meters long, at which point the coke was faulted off. No work has been

A. ENTRANCE TO INCLINED SHAFT AT "Z" WORKING NO. 1, SHOWING COAL LYING ON DUMP.

B. ENTRANCE TO LA COLORADA ADIT, SHOWING BEDS OF THE BARRANCA FORMATION.

Small fault may be seen to left of entrance.

done below the drift level. Near the entrance to the drift the beds strike N. 55° E. and dip 35° SE.

Farther northeast along Arroyo de los Jacalitos are a number of other caved workings and prospects, scattered for a length of several hundred meters along a coal bed that nearly follows the course of the arroyo. This bed seems to be 1½ to 2 meters thick and to be at a lower horizon than that of the natural coke in the working on the south side of the arroyo. Probably considerable quantities of coal and coke could be obtained from the Los Jacalitos area by following the beds at depth. The beds, however, may be offset by faults in several places.

ZAPUCHAL PROSPECTS

High up near the head of Arroyo de los Jacalitos, about a kilometer northeast of the Jacalitos mines, are the Zapuchal prospects, some small caved workings for coal scattered over a length of about 50 meters. An adit on the north side of the arroyo extends N. 34° E. for about 20 meters. It exposes a bed consisting chiefly of natural coke, but containing some coal, which was 1 to 1½ meters thick. A small amount of coal is said to have been produced from this place. The beds strike N. 35° E. and dip 15° SE. In the vicinity are some latite or andesite sills containing several metalliferous sulfides; several small pits have been opened for gold and silver.

EL AMOLILLO PROSPECTS

The El Amolillo prospects are on the north side of Arroyo de los Amolillos, which is the arroyo next south from Arroyo de los Jacalitos and joins Arroyo de los Bronces on the east. They consist of two small caved workings at different horizons. As the dumps are small, the workings are probably unimportant. The beds at this place strike N. 85° E. and dip 55° SE.

CARBON GRANDE MINE

The Carbón Grande mine is on the east side of Arroyo de los Bronces, fairly high up on the west slope of Cerro de la Aguja. A short distance above the mine is a prominent contact between underlying shales and fine-grained sandstones, overlain by quartzitic sandstones, conglomerates, and quartzites, which form the jagged crest of Cerro de la Aguja. The Carbón Grande mine was probably the most important in the entire region while it was being mined to supply coal for the silver smelter at San Javier. According to information obtained by William G. Kane, the mine produced about 75 tons of coal per day for 9 years. A cableway was installed to convey the coal to the west side of Arroyo de los Bronces, from where a truck road led to San Javier.

The mine consisted of four principal adits, situated from south to north at successively higher levels along the coal bed. The coal has been largely stoped out between the adit levels. These adits can be entered for only short distances at the present time, and little can be seen in them, as the coal has been stoped out and the walls are in large part either lagged or caved. The greater part of the lowest adit, No. 1, is now flooded. It has a direction of about S. 70° E. and is said to have been about 100 meters long. Coal is said to have been found at a distance of 60 or 70 meters from its entrance, but the bed was only about two-thirds of a meter thick. The coal was followed upward by a raise, but not downward, and very little was taken from this working. Adit No. 2, at a higher level and north of No. 1, is said to have been about 300 meters long. It begins with a direction of S. 50° E., then swings around to N. 80° E. The beds at the entrance, consisting of fine-grained sandstone and shale, strike N. 30° E. and dip 20° SE. Coal averaging about 2½ meters in thickness is said to have been found at a distance of about 25 meters from the entrance. This was the main haulage adit of the mine, in which mules were used for pulling the ore cars. The coal was stoped out between this level and the next higher adit, No. 3, but apparently none was stoped below the adit level. Adit No. 3, lying above and north of No. 2, was another long adit, although its exact length is unknown. Chutes connected it with No. 2, the main haulage adit. A short distance inside this adit the beds, mainly thin-bedded, fine-grained sandstone and shale, strike N. 35° E. and dip 30° SE., but farther in they swing around to N. 5° E. and dip 45° SE. Close to the entrance is a thin seam of graphite. The adit is said to have been driven a considerable distance before reaching the main coal bed. Adit No. 4, at a higher level, was not so long as either No. 2 or No. 3, although it probably had a length of at least 150 meters. It communicated with No. 3 and also had some raises. At a still higher level is another short adit, which did not reach the coal bed.

Most of the coal found in the Carbón Grande mine is said to have been worked out. What happened to the bed in the ends of the adits—whether it thinned down, was cut out by faulting or intrusions, or was merely not followed any farther—is not known. The coal is known to have thinned down the dip, as it was considered to have less than a commercially minable thickness in the lowest adit, No. 1. The possibility remains, however, that the thickness might increase again at greater depth.

OTHER SCATTERED PROSPECTS

The Agua Fría prospects are near Agua Fría Spring, in the headwaters of Arroyo de los Arrayanes, high up on the northeast slope of Cerro de la Aguja. They consist of three small caved workings in a ravine. Some fragments of coal are in the dump of one of them, and a little coal can be seen near the entrance. Nothing could be learned as to the possible extent of this coal bed, but the comparatively inaccessible location would make the commercial production of coal from this place improbable.

Some graphitic, bony coal was found in a gold prospect called the El Lucio, situated in a small arroyo north of the road from Santa Clara to La Barranca, near the divide at the highest point on this road. The beds at this place strike N. 70° W. and dip 30° to 40° N.E. This coal appears to be of no importance.

A small outcrop of coal is said to have been found in the bottom of Arroyo de la Barranca, just west of a spring called El Pocito, the chief source of water for the village of La Barranca. The outcrop is now covered by alluvium and was not seen by the writers. Some small prospects for coal that were not visited by the writers are said to be about 2 kilometers farther down Arroyo de la Barranca, to the southeast.

SANTA JULIA GROUP OF WORKINGS

The Santa Julia group of workings comprises several widely scattered coal mines and prospects situated 4 to 5 kilometers southwest of the town of San Javier. Some of them were mined while the silver smelter was in operation at San Javier, and the coal was carried on burros from the mines to the smelter. Some of these mines are thought to have possibilities for the development of fairly large quantities of coal equally as good as those for the mines of the Santa Clara district. As they are so difficultly accessible to the railroad at Tónichi, however, it is doubtful whether they can be considered a commercial source for coal. At present they are accessible only by trail. They are not far from the road between Hermosillo and Tónichi, to the south, but the distance from Tónichi by way of this road—which is in very poor condition and has steep grades—is 40 kilometers.

LOS CAPULINES MINE

The Los Capulines mine, the westernmost member of the Santa Julia group, is in Arroyo de los Capulines. It consists of two workings on the east bank of the arroyo, the upper working being 48 meters N. 60° E. of the lower one and 10 meters higher. The upper working consists of an adit about 8 meters long, in the direction S. 73° E., from the end of which a drift follows a coal bed to the northeast. The end of this drift is flooded, and its original extent is unknown. The coal bed strikes N. 55° E. and dips 35° SE. It has a thickness of 1.6 meters. Shale lies both above and below the coal, and there are a few graphitic layers at the bottom of the bed. The coal appears to be of good quality but is very fine grained.

The lower working consists of an adit about 25 meters long in the direction S. 64° E., from the end of which a drift follows the coal both to the northeast and to the southwest. This drift is now flooded and was not entered, but it is reported to have been at least 40 meters long, and the coal bed to have been about 1½ meters thick. Along the southwestern section of the drift there are said to have been two raises along the coal.

According to report, some coal was produced from these workings, but the coal was not followed downward from the drift levels. It seems that this mine might have good possibilities if the coal were followed downward and perhaps also along the strike to the northeast.

PALO PINTO MINE

The Palo Pinto mine is south and east of the Los Capulines mine, in another small arroyo. The coal is exposed in the bottom of the arroyo and forms one of the most prominent outcrops observed in the entire region. The coal has been partly altered to a porous, lightweight rock containing abundant reddish-brown iron oxides; it has not been completely destroyed as in most of the outcrops of the region, doubtless because of the rapid erosion in the bottom of this rather steep and narrow arroyo.

The mine consists of a shaft 10 meters long inclined 33° in the direction S. 64° E. The shaft connects with an adit that follows the coal bed in the direction N. 30° E. The adit continues beyond the inclined shaft, swinging around to an easterly direction at one point, then back to northeast. It is flooded and was not examined to its end but probably has a length of at least 50 meters. The coal bed has an average strike of N. 30° E. and dip of 30° SE. It has a thickness of as much as 2.9 meters at one point and 2.6 meters at another. A sample was collected at a point 20 meters northeast of the junction of the inclined shaft with the adit (see analysis No. 13, table 4). The coal is within the range of the samples from the Santa Clara district, although it is rather high in ash and is toward the low end in fixed carbon. It is medium- to fine-grained and has a peculiar spheroidal fracture, causing the formation of egg-shaped nodules of coal.

In view of the considerable thickness of the coal bed, this mine is believed to have the best possibilities of any in the region, except for its relative inaccessibility. The coal has not been worked at depth below the adit level, and its outcrop can be traced for at least 100 meters up the arroyo to the northeast.

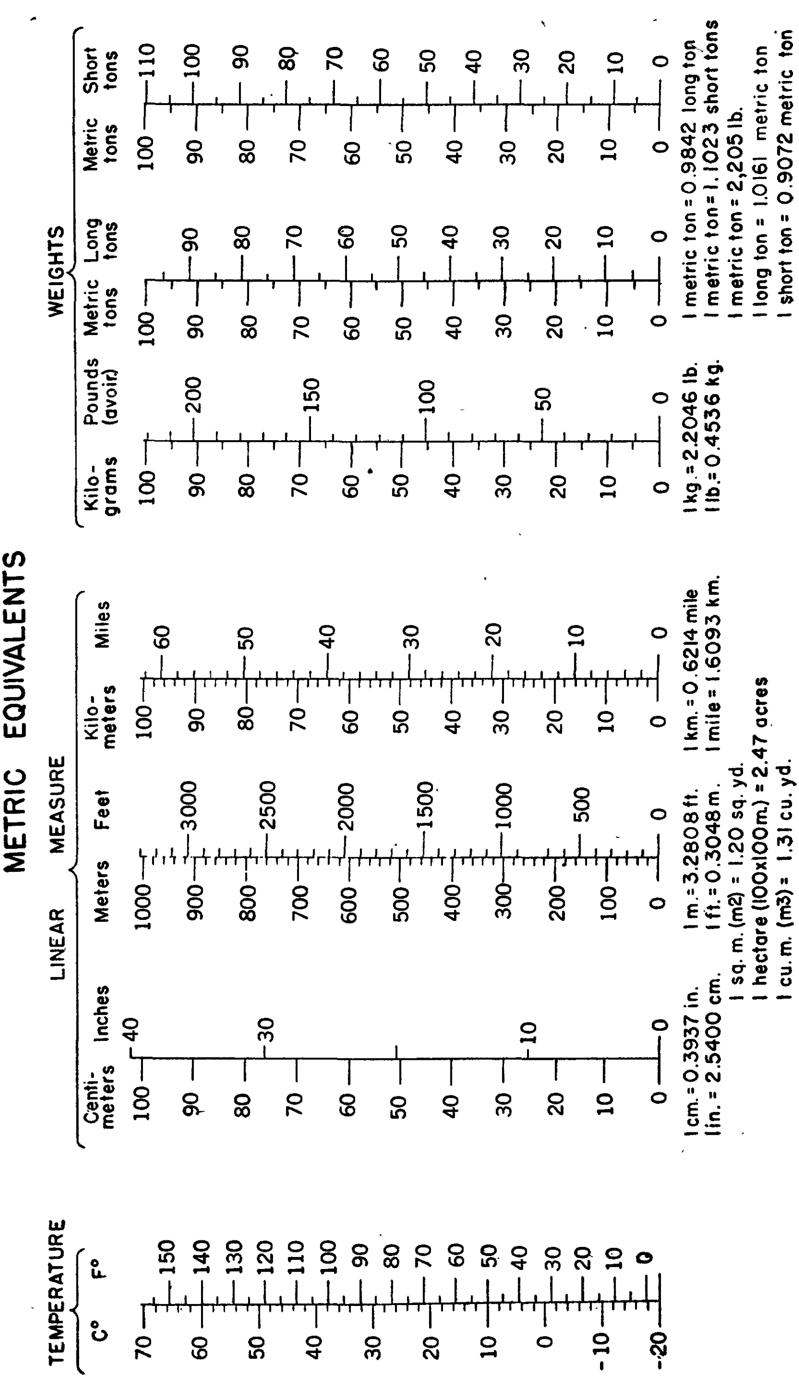
EL SOCAVON PROSPECT

The El Socavón prospect is in a small arroyo called Arroyo del Socavón, east of the Palo Pinto mine. It consists of an adit with a direction of N. 25° E., caved near the entrance. Some natural coke is said to have been obtained from it and taken to San Javier, but the bed of coke cannot be seen at present. Shales near the adit strike N. 20° E. and dip 25° SE.

LA PITAHAYA PROSPECT

The La Pitahaya prospect is east of the El Socavón prospect, in a small arroyo called Arroyo de la Pitahaya (not to be confused with the arroyo of the same name in the Santa Clara district). It consists of a flooded adit having a direction of N. 62° E. Near the entrance is a thin bed of bony coal 10 to 20 centimeters thick. The enclosing shales strike N. 30° E. and dip 40° SE. No coal is known to have been produced from this place, and the deposit appears to have no importance.

The aerial photograph (pl. 1) shows the general geographic and physiographic relationship between the Santa Clara district, the Los Bronces area, and the Santa Julia group of workings.



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