RECONNAISSANCE FOR URANIUM IN THE COPÍAPO AREA, PROVINCE OF ATACAMA, CHILE

By
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June 1962

Division of Raw Materials, AEC
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and

Instituto de Investigaciones Geológicas
Santiago, Chile
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Figure 1. Index map of the Copiapó area, Province of Atacama, Chile 7

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RECONNAISSANCE FOR URANIUM IN THE
COPIAPO AREA, PROVINCE OF ATACAMA, CHILE

ABSTRACT

The Copiapó area, as broadly defined, covers an area approximately 100 kilometers square in north-central Chile. It includes in its north-central portion the desert mining center of Copiapó, and along its Pacific coast the port city of Caldera. The area was examined for a period of about two weeks during October and November 1958 by geologists of the U. S. Atomic Energy Commission and the Instituto de Investigaciones Geológicas de Chile for the purpose of evaluating known uranium occurrences and determining the overall potential of the region for uranium.

Occurrences of uranium in the Copiapó area have been found in: (1) high-temperature veins in the Coast Range; (2) high-temperature mineral deposits in breccia pipes in the central area; (3) low-temperature veins in the central area; and (4) carbonaceous layers in late Tertiary to Quaternary stream-terrace gravels in the Andes.

No minable deposits of uranium have been found as a result of the reconnaissance, and all known occurrences of uranium minerals are small or of low grade. The authors conclude that the uranium potential of the base- and precious-metal areas is low, based on the observation that uranium apparently has accompanied other metals only as a minor or trace constituent. They believe, however, that the sediments peripheral to the base-metal areas may be favorable for the accumulation of uranium.

In order further to assess the uranium potential of certain districts in the Copiapó area on a broader scale, the authors propose that a limited hydrogeochemical sampling program be undertaken.

INTRODUCTION

Reconnaissance for uranium in the Copiapó area constituted part of a general geologic study of selected areas in Chile. The investigation was undertaken by geologists of the U. S. Atomic Energy Commission (USAEC) and the Instituto de Investigaciones Geológicas de Chile (IGG) under a cooperative agreement between the United States and Chile.

The Copiapó area was selected as a favorable region for uranium on the basis of a literature survey (Hague, 1958) which indicated widespread distribution of uranium occurrences, predominantly in the Coast Range, in
the central part of the area and in the Andes. Such distribution was con-
sidered a favorable indication of the possible existence of additional
occurrences with good uranium potential. As the Corporacion de Fomento de
la Produccion (CORFO) had already investigated many of the known uranium
deposits, a major objective of this reconnaissance study was to correlate
uranium mineralization with areal geology.

Field work was completed within a two-week period during October and
November 1958 by two separate parties. Copiapó served as the central base
for all field activities. In support of areal reconnaissance, U. S. Army
Map Service vertical aerial photographs in stereoscopic pairs (scale: 1:62,000)
were utilized. A base map prepared from 1:250,000-scale topographic maps of
the Instituto Geográfico Militar de Chile also proved useful. Each field party
was equipped with scintillation and Geiger counters and with four-wheel-drive
vehicles.

Geography

Location and accessibility

The Copiapó area is in the Province of Atacama, Department of Copiapó,
Chile (fig. 1). The area is bounded on the west by sea coast from latitude
27° 00' S. to latitude 28° 15' S., a distance of 120 kilometers, and attains
a maximum width of 160 kilometers along its southern boundary which extends
from longitude 69° 30' W. to 71° 10' W. The city of Copiapó (pop. 37,000)
lies in the north-central part of the area.

The city of Copiapó is served by railroads, airlines and highways.
Many gravel and dirt roads afford ready access to outlying areas by four-
wheel-drive vehicles, while trails extending into the higher country are
travelable by horse or mule. The Pan American Highway crosses the center
of the area in a north-northeast direction.

Topography, vegetation and climate

The Copiapo area includes three major physiographic divisions: the
Coast Range, the Central Valley, and the Andes. The Coast Range which
reaches an elevation of 1000 meters, and the Central Valley, which is ap-
proximately 600 meters above sea level, are in an early mature stage of
erosion and are characterized by rounded topography and extensive valley
fill. Alluvium in the Central Valley merges with that of the Coast Range,
and dune sands are extensive in large valleys in the northwest. The coast-
line is rocky and in places abrupt, showing evidence of recent uplift;
erosion here is in a youthful stage and is confined to the coastal slope.

The high cordillera of the Andes reaches 5000 meters in elevation within
the Copiapó area and is in a rugged, youthful stage of erosion. Rock ex-
posures are good in the mountainous eastern area but are more sparse in the
western part, owing to extensive alluvial cover.
Figure 1. Index map, Copiapó area, Province of Atacama, Chile
Figura 1. Mapa índice, área de Copiapó, Provincia de Atacama, Chile
Annual precipitation, measured over a span of 40 years, ranges normally from 30 millimeters in the west to 70 millimeters in the higher eastern region. The climate is a marginal low desert type - hot in summer and moderate to cool in winter. Strong westerly winds are common, and the coastal areas are frequently subject to nightly fogs during the winter.

The supply of water in the Rio Copiapó is limited and is used largely for irrigation of fruit crops grown in the river valley. Wells supply drinking water near Copiapó and water for agricultural purposes in the lower reaches of the Copiapó valley.

**Exploration and mining history**

The Copiapó area has been intensely mineralized and contains numerous deposits of copper, gold, silver and iron, as well as occurrences of lead, zinc, mercury, antimony, arsenic, nickel, cobalt, bismuth, manganese and uranium. Several large and many small copper and iron mines are found within the area. Abandoned mines are numerous and include some famous past producers in Chilean metal-mining history, such as Carrizal Alto, in the southwest corner of the area, and Chañarcillo, 50 kilometers south of Copiapó.

The deepest copper workings in Chile are in the currently productive Dulcinea mine, 40 kilometers northeast of Copiapó, between Llampos and Carrera Pinto. The mine has been worked to a depth of 1000 meters along a chalcopyrite-bearing 1.5 meter-thick vein in diorite. The ores contain up to 8 percent copper, over 3 ounces silver, and some gold. Other active copper-mining centers in the Copiapó area are the Punta del Cobre district, 8 kilometers south of Paipote (8 kilometers southeast of Copiapó); the Cabeza de Vaca district, 25 kilometers east of Checo (17 kilometers south of Paipote); the Ojancos district, 20 kilometers south of Copiapó; the Galleguillos mine, 40 kilometers north of Copiapó; and the Algarrobo district, near the northwest corner of the area.

The most important gold- and silver-producing districts in Chile were located in the Province of Atacama, particularly in the Department of Copiapó, where hundreds of silver mines and many gold mines were worked from the beginning of Spanish rule until World War II. Typical of the Copiapó silver camps is the famous, now abandoned, Chañarcillo silver mine. This deposit was discovered in 1832 and by 1859 had produced 60 million dollars in silver. Single masses of silver chlorobromide and native silver reportedly taken from this mine weighed up to 25 tons.

The ore at Chañarcillo occurs in Mesozoic limestones and shales metamorphosed by a nearby igneous intrusive. The highest metal values were associated with limestone in the zone of secondary enrichment. Mine values diminished rapidly with depth, chlorides being mined down to 20 meters, chlorobromides to 70 meters, and iodides to 100 meters.
Few gold-silver mines in the Copiapó area have been worked deeper than 200 meters, owing partly to the lack of good mining equipment in earlier years and to the fact that primary ores in many of the veins were too low in grade to be worked profitably.

Gold lode deposits occur in the Cerro Bramador-Cerro de las Pintadas area just south of Copiapó. These were formerly productive of free gold from quartz veins.

Operating iron mines include the Cerro Imán, El Lunar, Las Adrianitas, Cerro Negro Sur and Cerro Negro Norte. These mines are located 10 to 25 kilometers north of Copiapó. The hematite ore occurs in irregular replacement bodies in metamorphosed Mesozoic volcanic rocks near contacts with diorite intrusives. Caldera, 60 kilometers northwest of Copiapó, is the shipping center for iron ore extracted from mines in the Copiapó district.

Nonferrous mines in the Copiapó area are served by the Caja de Crédito Minero smelter at Paipote which is operated by the Government of Chile. In past years smelters were also located at Carrizal Alto and the port of Caldera, the latter serving the El Roble-Algarrobo copper district. Other smelters were located at Nantoco and Tierra Amarilla, respectively 20 and 15 kilometers south of Copiapó.

The presence of radioactivity in mines in the Copiapó area has been known for several years. In 1950 two geologists of the U.S. Atomic Energy Commission participated in a search for radioactive minerals in the north-central part of the country (Lee and Rapaport, 1950). During their stay museum specimens were systematically checked, and radioactive samples were traced through ore-buying stations to various mines which were subsequently investigated under the direction of CORFO.

Numerous occurrences of radioactivity in the Copiapó area have been studied by CORFO engineers. These investigations embraced the Carrizal Alto, El Roble-Algarrobo, Cabeza de Vaca, and Pampa Larga mining districts, and various other individual mining areas including the La Piadosa copper-uranium occurrence. None of the mines or prospects containing uranium proved commercially productive of uranium ore. Although no uranium ore was found, the CORFO studies did indicate that further geologic study was warranted and that dewatering of mines as well as sampling and mapping of the reexposed veins would enhance this work.

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GENERAL GEOLOGY

The generalized geology of the Copiapó area is shown in figure 2. The rocks exposed include granites and contorted, steeply dipping quartzites, schists, and phyllites of pre-Triassic age, sediments and volcanics of Mesozoic age, and volcanics and intrusives of Tertiary age.

The Coast Range, which occupies the eastern part of the Copiapó area, is composed of rounded hills in an early mature stage of erosion and valleys which have been extensively filled with alluvium. The bedrock complex consists of metamorphic rock types and intruded Andean diorite. Owing to the abundance of valley fill, rock exposures are limited to the higher hill slopes.

The Central Valley, as its name implies, is a wide valley in the central Copiapó area which has received much of its alluvium through erosion of the Coast Range.

To the east of the Central Valley folded volcanic and sedimentary rocks of Mesozoic age are exposed on the west flank of a north-trending anticlinorium, the major axis of which almost coincides with the Chile-Argentina boundary. The major structural, mineralogic and topographic trends in this area are oriented north-south. Youthful topography characterized by narrow canyons and steep, rugged slopes reflects rather recent orogenic development. Gravel deposits perched on ridges up to 200 meters above the Copiapó valley floor indicate the extent of recent erosion on the west flank of the Andes cordillera. High in the cordillera on isolated ridges are remnants of the upper Tertiary cap rock composed of lavas and tuffs.

Stratified rocks

The oldest formations in the Copiapó area are exposed in the Coast Range. They consist of a thick metasedimentary complex comprising primarily strongly folded, steeply dipping gray to reddish-brown quartzites and dark mica schists and phyllites of pre-Triassic age (fig. 2). The sequence forms a northeast-trending belt up to 20 kilometers wide in the western part of the Copiapó area.

Continental red beds, possibly Triassic in age, are thinly exposed on the eastern edge of the Copiapó area. Near La Piadosa, on the Río Ramadillas in the southeastern section of this area, the beds are overlain by tan and red crossbedded, ripple-marked sandstones, pebble conglomerate, and red silty shale of Jurassic age, followed by a thick series of porphyritic andesite flows. The basal red-bed sediments are deposited on an old eroded granite surface. Although fossil evidence to support a terrestrial origin is lacking, the formation has lithologic similarities to, and may be continuous with, other Triassic red beds to the northeast. The contact between Triassic(?) and Jurassic rocks is concealed by alluvium.
The Jurassic volcanic sequence is composed of a thick aggregate of porphyritic andesite flows, tuff breccias, flow breccias and ash. This series is overlain by sedimentary limestones and shales. Fossils of Early Jurassic age have been found in the sediments at the junction of the Río Pulido and the Río Potro in the southeastern Copiapó area (fig. 2). Jurassic strata are unconformably overlain by or faulted against Middle and Upper Cretaceous beds.

Lower Cretaceous rocks form a narrow north-northeast anticlinal belt, about 10 kilometers wide, east of Copiapó (fig. 2). The sedimentary sequence aggregates about 2000 meters of strata including, from the bottom of the section in sequence, thick-bedded greywackes, conglomerate, limestone, calcareous siltstone, limey mudstone, gypsum, chert and limestone. Many andesite sills and dikes are exposed near the top of the Lower Cretaceous. Lower Cretaceous beds have not been observed on the east flank of the Cretaceous syncline although outcrops are present within the Upper Cretaceous cover in the northeast Copiapó area.

Upper and Middle Cretaceous strata in the Copiapó area are predominantly volcanic. These rocks form a broad synclinal belt 2000 meters thick and about 25 kilometers wide. They unconformably overlie Lower Cretaceous strata. The basal rocks of the Middle Cretaceous consist of massive conglomerates composed of rounded andesite cobbles in a tuffaceous matrix. Above the conglomerates are lacustrine limestone, red sandstone, and andesitic lava flows, and unconformably overlying these strata are 1000 to 2000 meters of andesitic cobble conglomerates, lavas, ash, and rhyolitic tuffs. The upper part of this sequence contains local lenses of dark limestone with carbon trash. In the absence of fossils by which to date these sediments, they are mapped tentatively as Upper Cretaceous, although they may possibly be Tertiary in age.

Tertiary rocks in the Copiapó area include trachyte and dacite flows, ash, rhyolite tuffs, and welded tuffs. These rocks constitute the "Liparítica formation" which has been described by Brüggen (1950). Remnants of flat-lying Tertiary strata cap high ridges in the Copiapó area; however, these beds become more extensive farther east on the flanks of the cordillera.

Alluvium of Quaternary age is present in most of the draws and river valleys within the Copiapó area and occurs as an extensive valley fill in the central and western regions. Quaternary gravel terraces occur at elevations as high as 200 meters above the Copiapó valley floor (Biese, 1942). Sand dunes are widespread, especially in the northwestern part of the area.

Intrusive igneous rocks

The emplacement of igneous rocks in the Copiapó area occurred in three distinct geologic periods during pre-Triassic, Cretaceous-Tertiary (Andean diorite complex), and late Tertiary time.
Pre-Triassic intrusives are exposed in the southeast corner of the Copiapó area at two localities: a large exposure near La Piadosa and a small one 30 kilometers to the west at Resguardo on the Rio Pulido. Both exposures consist of light-gray to reddish-gray, coarsely crystalline granite and leucosyenite containing orthoclase phenocrysts up to 8 millimeters long. Near La Piadosa the granite erosion surface is covered by Triassic continental sediments and at Resguardo it is covered by conglomerate of Early Jurassic (Lias) age.

Intrusive igneous rocks of the coast-range batholith in the western part of the Copiapó area, and also those in the central and eastern regions, consist predominantly of the so-called Andean diorite of Cretaceous to early Tertiary age (fig. 2). Although this rock varies in composition from diorite to quartz monzonite it will generally be referred to in this report as diorite.

The texture of Andean diorite is medium fine to coarse, and the color varies from dark gray to greenish or reddish gray. Contacts between the diorite and intruded rocks are generally gradational; however, migmatites are frequently observed where diorite has intruded volcanic rock.

Elongated exposures of Andean diorite in the eastern part of the Copiapó area show migmatitic contact borders, up to 500 meters wide, developed within the intruded rock. The composition of the plutons in this region ranges from granodiorite to quartz monzonite, whereas the composition of the coast-range batholith is normally dioritic. Tourmalinized quartz breccia pipes containing copper minerals are prominent in the granodiorite in the east-central part of the Copiapó area extending southward from the Candelaria mine to the Cabeza de Vaca district, and they also occur farther south in isolated exposures. The pipes seem dominantly related to the granodiorite phase of the intrusive, and their mineralization is believed to represent a late, possibly deuteric, stage of igneous activity associated with granodiorite emplacement. Similar tourmalinized breccia pipes have also been observed by Knowles, Bowes, Klohn and Serrano (1958) in the Andean diorite complex in the Salamanca area.

Swarms of rhyolite dikes, many of which merge in rhyolite plugs, occur within the synclinal belt of Upper Cretaceous rocks at the Quebrada de Cerrillos. Basic dikes have been observed locally cutting the center of one such rhyolite mass. Alteration accompanying the rhyolite intrusion was apparently intense and probably was responsible for alunization of the intruded Cretaceous volcanic strata. Rhyolite is the youngest intrusive rock type observed in the Quebrada de Cerrillos locality. It is considered to be the intrusive equivalent of the widespread rhyolitic tuffs of Miocene age which cap ridges in the Copiapó area.

Andesite dikes are common within the coast-range intrusive and in all pre-Quaternary volcanic and sedimentary rocks, including the Liparitica formation of Tertiary age. Andesite sills up to 100 meters thick are exposed at the top of the Lower Cretaceous (Neocomian) sequence in the Quebrada de Cerrillos valley. A few basic dikes also cut pre-Triassic granite in the eastern Copiapó area.
Structure

The Copiapó area is structurally situated on the folded western flank of a major north-trending anticlinorium, the major axis of which lies near and generally parallels the Chile-Argentina border. A series of parallel folds that strike north-northeast is the dominant structural feature of the area. Major fractures are also prominent and can be traced for distances of 10 to 15 kilometers, but these appear to be related to folding and produce little offset of beds. Anticlinal folding has exposed Lower Cretaceous rocks along an axis extending through Paipote. To the east of Paipote Upper Cretaceous rocks have been down-folded into a major synclinal structure which persists toward the north and south. Upper Cretaceous volcanic rocks are well exposed along the trough of this syncline. Several lesser folds appear to the east of the synclinal axis.

The apparent regional dip of beds east of the synclinal axis is toward the west, exposing stratigraphically older rocks in the eastern region of the Copiapó area. The exposed stratigraphic sequence ranges from Triassic(?) through Jurassic and rests unconformably on pre-Triassic granite which is exposed along the anticlinorial axis.

Lineaments and related structures such as veins and faults generally trend to the north-northeast and east in the coastal area. In the central and eastern folded belt similar linear structures generally trend north paralleling fold axes but diverging toward both the northeast and northwest. The veins generally follow bifurcating shears. Those which trend northwest possibly reflect a tensional fracture pattern.

Geologic history

The Andes are believed to have been formed within a Mesozoic geosynclinal belt which was bounded on the east by a granitic high land, probably at the eastern slope of the Andes in Argentina, and on the west by a less determinate border of volcanic flows probably passing through the Coast Range. The geosynclinal stratigraphic sequence consists of great thicknesses of lavas and interstratified marine sediments of Jurassic age, a thick section of calcareous marine sediments and volcanics of Early Cretaceous age, and a great thickness of lavas and thin, intercalated continental sediments of Late Cretaceous age. Depositional basins within the geosyncline were largely marine. Geosynclinal development began in early Tertiary time and was followed in sequence by Late Cretaceous folding, intrusion of the Andean diorite (Cretaceous to early Tertiary), fracturing and metallization. Uplift was accompanied by volcanism characterized by extrusion of rhyolitic tuffs and dacitic flows of Tertiary age. During later orogenic stages gravels, which are now found as high as 200 meters above valley floors, were deposited in alluvial fans on the western flanks of the Andes. Evidence of continuing uplift is provided by the great amount of erosion below terrace levels.
URANIUM DEPOSITS

Copper has been found in Chile in a wide variety of rock types ranging in age from Precambrian to Quaternary. Uranium, however, is apparently restricted to certain host rocks, at least in the Copiapó area where it is found almost exclusively in the Andean diorite complex and in adjoining rocks within a short distance of their contact with diorite. Uranium has also been found in gravels of late Tertiary to Quaternary (Recent) age.

Five of the twelve districts in Chile that contain known occurrences of uranium lie within the Copiapo area. These consist of: (1) high-temperature veins (Carrizal Alto and El Roble-Algarrobo districts); (2) low-temperature veins (Pampa Larga district); (3) high-temperature breccia pipes (Cabeza de Vaca district and the Candelaria mine); and (4) carbonaceous beds in late Tertiary to Quaternary (Recent) stream-terrace gravels (La Piadosa). None of the occurrences has produced uranium ore.

All the known uranium occurrences have previously been studied in detail by Chilean geologists and engineers, but little was known about the broad geologic relationships that may have a bearing on uranium distribution. The primary purpose of this reconnaissance study, therefore, was to evaluate uranium distribution and potential in the Copiapó area on a regional basis. The scope of this undertaking did not allow for the accumulation of detailed geologic data on individual uranium deposits.

A summary of the general geology of the uranium deposits and descriptions of the mining districts are presented in the following pages.

High-temperature vein deposits

Carrizal Alto district

The Carrizal Alto district is near the southwest corner of the Copiapó area. Highly productive copper mines were worked more or less continuously from the time of Spanish occupation until 1907. In 1917 some of the properties were re-opened and explored for copper ore without favorable results.

The district contains many occurrences of uranium. These have been described by Sr. Carlos Ruiz F. (1952), currently Executive Director of the IIG. Uranium was discovered by Ruiz in 1950 while checking mining properties for radioactivity on the basis of cobalt association.

The host rock for uranium in the Carrizal Alto district is Andean diorite which ranges in texture and composition from coarse-grained diorite to micropegmatitic granodiorite. The rock contains 50 percent pyroxene and biotite and 50 percent andesine and labradorite feldspars. The diorite intrudes a series of pre-Triassic metasedimentary quartzites, argillites and mica schists,
and is cut by numerous fine-grained, dark-gray or green-gray, magnetite-rich basic dikes. The diorite crops out in an extensive north-south belt 1 to 2 kilometers to the west of the uranium deposits.

The basic dikes in the Carrizal Alto district follow a series of fractures trending north, north-northwest, northeast and east-northeast. Veins follow predominantly the northeast- and east-northeast-trending structures and coalesce with dikes at many localities. Dips of the northeast-trending vein-dikes range from 35° to 80° NW. Where a vein and dike coalesce the vein soon disappears in a system of small fractures.

The eight principal veins in the Carrizal Alto district, from north to south, are the Del Agua, Principal, Guía, Isla, Santa Rosa, Armonía, Santa Teresa and Venegas. The veins form an en-echelon system in which individual veins may vary in length from 1000 to 2800 meters. The "Principal" vein, which has been the most important copper producer in the district, strikes N. 50° E. to N. 80° E. and dips 37° to 80° NW. The main production from this vein has come from the Mondaca, Portezuelo and Bezanilla mines. These mines have been worked down dip to a depth of 500 meters. In many places vein thicknesses of 4 to 5 meters and, occasionally, to 13 meters have been measured.

The ore deposits of the Carrizal Alto district contain pyrite, cobaltian arsenopyrite, pyrrhotite, magnetite, chalcopyrite, molybdenite, tetrahedrite, cobaltite and uraninite. Gangue minerals associated with the ore are amphibole, tourmaline, chlorite, quartz, calcite and apatite. The suite is considered characteristic of high-temperature emplacement.

The chief copper production has come from below the oxidized zone, which extends to as much as 50 meters in depth. Production was realized largely from ore shoots containing chalcopyrite, associated with pyrite, arsenopyrite and pyrrhotite in a quartz-tourmaline gangue.

The uranium is usually associated with copper, although it also occurs away from the principal copper zones. It is found predominantly with chalcopyrite and pyrite impregnations, and is sometimes found occurring with crystals of cobaltite. Uraninite has been identified in small clusters of fine crystals, measuring about 0.006 to 0.12 millimeters, within rosettelike aggregates of chlorite in which radioactive halos have been observed. Chlorite is believed to have been formed principally through alteration of ferromagnesian minerals such as augite, hornblende and biotite, which were formed from early mineralizing solutions. Late introduction of uranium and subsequent postmineralization movement along veins may have been factors in the localization of uraninite in chlorite.

Quartz, chalcedony and limonite form gossanous outcrops in the district. Secondary uranium minerals, however, are found only below the surface in the interior of the mines. Depth of oxidation has no apparent relation to the present water level, which is generally found in the workings at or below the 200-meter level. Oxidation of the deposits has produced secondary quartz, chalcedony, cuprite, malachite, erythrite, gummite, torbernite and minor cuprosklowdowskite.
The largest concentrations of radioactive minerals in the Carrizal Alto district have been observed in the western sections of the "Principal" and "Santa Rosa" veins. In this locality access to the "Principal" vein is through the Santa Rita, Contadora Baja, Contadora Alta and the Naranjo mines and to the "Santa Rosa" vein through the Santa Rosa, Llano, Amapola, Panteón and Rincon mines. At the time Sr. Ruiz examined the area the Llano, Santa Rosa, Amapola and Rincón mines were partially accessible, and exposed portions of both veins were mapped and radiometrically surveyed. All the mines have since caved and are flooded in the lower levels.

Field measurements of radioactivity of mine dumps and slag in this section ranged from 0.1 to 0.4 mr/hr. One dump in particular, containing slag resulting from treatment of ores from the Contadora and Santa Rita mines, showed the highest radioactivity; and a sample of the slag assayed 0.048 percent equivalent $\text{U}_3\text{O}_8$. Additional studies suggest that the dump of the Rincón mine, estimated at 35,000 tons, has an average uranium content of 0.03 percent $\text{U}_3\text{O}_8$.

The Santa Rosa mine contains the best underground showing of uranium in the district. The uranium occurs within a mineralized zone about 20 meters long. One sample 0.9 meters wide averaged 0.20 percent $\text{U}_3\text{O}_8$. Additional samples from other areas of the mine assayed 0.10 and 0.20 percent $\text{U}_3\text{O}_8$ over widths of 0.2 to 0.35 meters.

In the Llano mine radiometric assays showed up to 0.7 percent $\text{U}_3\text{O}_8$ for samples taken from stringers of chlorite in the hanging wall of the vein.

Exposed workings in the Rincón mine averaged readings of 0.2 mr/hr on field counters. One zone measuring 0.8 mr/hr produced a sample that assayed 0.10 percent $\text{U}_3\text{O}_8$. The highest radiometric assay obtained on samples from the Amapola mine was 0.06 percent $\text{U}_3\text{O}_8$, and the highest assay on samples from the Naranjo mine collected at the intersection of the vein and the diorite-quartzite contact zone was 0.07 percent $\text{U}_3\text{O}_8$. The upper workings of these mines displayed less than half the radioactivity found in the deeper zones below 50 meters.

The Rincón mine dump is estimated to contain 5 tons of uranium in material averaging 0.03 percent $\text{U}_3\text{O}_8$, and the Contadora slag dump is estimated to contain 4 tons of uranium in material averaging 0.05 percent $\text{U}_3\text{O}_8$.

Comparison of radiometric and chemical assays indicates that the uranium ores are more or less in radioactive equilibrium. The degree of disequilibrium observed is indicated by the assay results of the following samples:

<table>
<thead>
<tr>
<th>Sample locality</th>
<th>Percent $\text{U}_3\text{O}_8$</th>
<th>radiometric</th>
<th>chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Llano mine</td>
<td></td>
<td>0.07</td>
<td>0.054</td>
</tr>
<tr>
<td>Santa Rosa mine</td>
<td></td>
<td>0.6</td>
<td>0.51</td>
</tr>
<tr>
<td>Contadora slag dump</td>
<td></td>
<td>0.054</td>
<td>0.048</td>
</tr>
</tbody>
</table>
From observations on uraninite associations in accessible areas of the mines it is inferred that additional uranium may have been present in the richest copper ore shoots in mine areas now flooded. Confinement of the uranium to the friable wall zones suggests, however, that this uranium was largely removed in mining of the copper ore. Mining of uranium ore independent of copper might present some difficulties owing to the close association of the two metals.

**El Roble-Algarrobo district**

The El Roble-Algarrobo district is situated 15 kilometers east of Caldera in the northwest corner of the Copiapo area. The Algarrobo district has been worked since the early 1800's; the El Roble district was discovered in 1925.

Mineral occurrences in the district are located along northeast-striking veins forming a north-trending, en-echelon belt about 4 kilometers long, and are confined to diorite host rock near its contact with schists, slates and quartzites. The metasediments crop out 12 kilometers to the northwest of the district. The diorite is cut by aplite and lamprophyre dikes. The El Roble group of mines is situated at the north end of the belt and the Algarrobo group at the south end.

Mine workings in the district extend to below 200 meters, but most of the mines are caved and inaccessible below 100 meters. Oxidation is observed down to 60 meters. Mining on a small scale is still conducted in the El Roble group.

Uranium occurrences in the El Roble-Algarrobo district are geologically similar to those in the Carrizal Alto district. Mineralization is concentrated in quartz diorite near its contact with metamorphic rock. Structural controls are similar in magnitude and orientation, and similar high-temperature mineral suites prevail. The association of uraninite with chlorite in vein walls is also prevalent throughout the district. These geologic features predominate over an extensive region outside the Copiapo area which includes other known uranium deposits in mining districts within the Coast Range not described in this report. The Las Animas and the Tocopilla districts 70 and 500 kilometers, respectively, to the north and the Tambillos district 330 kilometers to the south are perhaps the most noteworthy.

The first indication of radioactivity in the El Roble-Algarrobo district was obtained from a museum specimen in Santiago. Uranium occurrences in mine dumps and accessible workings in the district have since been examined by CORFO (Salas, 1952).

Radioactivity was noted in the Uruguay mine, part of the El Roble group, along a 1- to 2-meter vein which strikes N. 50° E. and dips 70° NW. Measurements obtained on gouge along this vein near its surface ranged from 0.1 to 0.2 mr/hr. Portions of the vein are reported to contain 15 to 25 percent copper.
Veins in the Algarrobo group averaged 0.20 mr/hr over their exposed length. The highest radioactivity was observed in the deeper levels below 50 meters in the Descubridora and Viuda mines, where a maximum radioactivity of 2.0 mr/hr was recorded in several places. Radioactivity is attributed to finely divided uraninite associated with chlorite in wall selvage zones. The ore consists chiefly of chalcopyrite together with minor amounts of pyrite, arsenopyrite, tourmaline, quartz and calcite.

Low-temperature vein deposits

Pampa Larga district

The Pampa Larga district is located about 25 kilometers southeast of Copiapo on the south side of the Quebrada de Cerrillos in a spur canyon called the Quebrada Cortadera. Mineralization is confined to veins within and at the contact of a small pluton of diorite cutting Upper Cretaceous formations. Many of the veins showed anomalous radioactivity. Uranium occurrences in the district have been described previously by Salas (1954a).

The Pampa Larga pluton is part of the Andean diorite complex. The pluton intrudes units of Upper Cretaceous calcareous sedimentary rocks and andesitic flows, tuffs and breccias. Metamorphism of volcanic rocks near the intrusive is characterized by sericitization of feldspar, silicification, and the formation of calcite and diopside. Calcareous rocks have been altered to a calc-silicate hornfels.

West-northwest-trending andesite dikes and irregular aplite dikes cut the diorite intrusive and the adjacent formations. Granodiorite, which is more widely exposed in the Cabeza de Vaca pluton to the east, forms a small segment of the Pampa Larga pluton on its southeast margin. According to Salas (1954a), the granodiorite encloses blocks of basic intrusive rocks, but contact metamorphism is not intense. Major veins in the district trend north, and minor veins trend west.

Salas proposed the following intrusive sequence: (1) emplacement of diorite with contact metamorphism and differentiation (i.e., granodiorite formation); (2) intrusion of andesite dikes into major fractures and aplite dikes into secondary fractures; (3) tectonic movement and further fracturing, followed by mineralization.

The principal silver production of the district has come from the Descubridora and Alacran mines. Arsenic and antimony have also been produced from the latter. Both mines are now abandoned. A smaller vein exposed in the Maria Catalina mine, an abandoned silver prospect, offers the best showings of uranium in the district. Intersections of veins are favorable ore structures at both the Alacran and Descubridora mines.

Uranium is spottily associated with silver-, arsenic- and antimony-bearing minerals and is also present in vein gouge in near-surface workings. The highest grade uranium samples were found in the Maria Catalina mine.
The average assay of samples collected across a width of 0.15 meters within the mine workings is 0.32 percent \(\text{eU}_3\text{O}_8\). A few select specimens from the Maria Catalina mine assayed as high as 2.0 percent \(\text{eU}_3\text{O}_8\).

**Descubridora mine**

The Descubridora vein, the most persistent mineralized structure in the Pampa Larga district, is a zone of bifurcating mineralized shears that can be traced in a general north-south direction for 2.8 kilometers. The vein has an average thickness of 1.5 to 2 meters and dips irregularly but generally vertically. Quartz and limonite form gossanous outcrops at its surface in the vicinity of the mine. The vein cannot be traced on the surface beyond the diorite-volcanic rock contact to the south, and to the north of the mine is recognized only by limonite found at the surface of the structure. The Descubridora ore body is located at the intersection of the Descubridora vein and a minor east-west vein. The mine has in the past been worked to a depth of 100 meters but, since the workings are almost completely caved and inaccessible, details of the structure and mineralization are incompletely known.

The chief mineral product of the mine was silver. In addition to native silver, the primary zone reportedly contained native arsenic and antimony, as well as stibnite, arsenopyrite and tetrahedrite. Secondary minerals included realgar, orpiment, erythrite, oxidized copper minerals and torbernite. The bulk of the gangue consisted of barite, quartz, limonite and manganese oxide.

The uranium in the outcrop is chiefly in the form of torbernite which occurs in a brecciated vein selvage containing iron oxides, secondary copper minerals, and gypsum. Select specimens from the dump recorded radioactivity up to 1.0 mR/hr. A radiometric traverse along the main vein, which is exposed for 150 meters from the mine adit, indicated spotty areas of radioactivity distributed at intervals of roughly 30 meters. The average of field counter readings was 0.20 mR/hr, and the maximum was 0.5 mR/hr. Vein walls are sheared, iron stained, bleached, and kaolinized.

**Alacrán mine**

The Alacrán mine has been worked to a depth of about 100 meters. The main structure is a vertical vein 30 to 40 centimeters wide, trending north to N. 35° E. The vein is intersected by a barren, west-trending vein which is about 20 to 30 centimeters wide.

The principal ore consisted of antimony, arsenic and silver. Near the surface the main north-trending vein carries realgar, orpiment, barite, quartz, and secondary copper minerals. Below 42 meters there is a change in mineralogy to pyrite, arsenopyrite, chalcopyrite, galena, stibnite, native arsenic, silver and antimony, with quartz, barite and calcite as gangue. Native argentine arsenic, containing 85 grams silver per ton of
29-percent arsenic ore, has been reported at the Alacrán mine. The silver reportedly was recovered by calcining the arsenic ore. Small crystals of fluorite have also been observed (Amenabar, 1923). One occurrence of uranium was found to contain finely divided pitchblende in a quartz matrix associated with stibnite.

Radioactivity in the upper mine workings ranged from 0.02 to 0.04 mr/hr, apparently increasing near the water table where readings averaged closer to 0.1 to 0.2 mr/hr.

The deepest shaft is flooded. It is collared underground and has no lateral workings.

**Maria Catalina mine**

The María Catalina mine is a small silver prospect located on a north-trending vein. The vein dips 70° W. and may be traced for 270 meters along the surface. The ore body occurs in metavolcanic rock within 100 meters of a diorite contact.

The principal workings of the María Catalina mine are reported to have contained native silver. No sulfide minerals were seen, possibly because all the workings were in the oxidized zone. Material seen on the dump contained erythrite, secondary copper minerals, manganese oxide, and torbernite. Alteration of the wall rock is characterized by bleaching and kaolinization within a few feet of both sides of the vein.

Radioactivity was discovered in the María Catalina mine by Ruiz during a 1950 investigation of uranium occurrences in the Pampa Larga area.

The mine is entered through a drift along an iron-stained, siliceous shear zone 1 meter wide. At about 105 meters the drift diverges and then re-enters the zone by means of a short crosscut, at which point the zone is about 50 to 60 centimeters wide. Radioactivity along the nearly barren vein where it is exposed in the drift averaged only 0.015 mr/hr, but in the crosscut where local discontinuous lenses of iron oxides and quartz are encountered it registered as high as 1.0 mr/hr. This section of the vein, apparently worked for silver ore, was explored or mined through a 10-meter winze and a 50-meter raise to the surface.

At the outcrop of the vein above the workings radioactivity averaged 0.25 mr/hr. Small dumps containing material from the upper workings averaged 0.45 mr/hr, and a few specimens of vein gouge on the main dump showed radioactivity up to 2.0 mr/hr. Radiometric analysis of thirty samples selected from the raise and winze by Salas showed an average value of 0.32 percent eU₃O₈ over a width of 0.15 meters.
Other occurrences

Several other veins in the Pampa Larga district, including the Hornito, Jota and ex-Veta Negra, showed anomalous radioactivity. The Jota vein, a north-trending structure in granodiorite in the southeastern part of the district, measured as high as six times background radioactivity, and the Hornito and ex-Veta Negra veins, which trend to the west, showed as much as three times background radioactivity.

High-temperature breccia pipe deposits

Cabeza de Vaca district

The Cabeza de Vaca district is located 10 kilometers due east of the Pampa Larga district. It includes the Remolinos, San Pedro and Manto Barne mines, which were studied by Salas (1955a). The area is still producing copper and gold on a small scale.

The district lies within a north-northeast-elongated intrusive of granodiorite which is cut by numerous north- and east-trending fractures. Locally, fracture intersections form large breccia pipes that are mineralized with quartz, orthoclase, calcite, fine-grained black tourmaline, pyrite and chalcopyrite. All the pipes characteristically contain copper, the content of which may range from a trace to as much as 10 percent. The granodiorite in and adjacent to the pipes is strongly silicified, argillized and sericitized. The pipes form light-brown bleached zones at the surface which are clearly recognizable from a distance. Some of these structures cut formations near the contact between granodiorite and the intruded strata.

The emplacement of ore minerals is considered by Parker, Corvalán, Salas and Pérez (1957) to have been associated with a hydrothermal phase of the Cabeza de Vaca pluton. Introduction of ore is presumed to have followed earlier phases of mineralization represented by quartz, tourmaline and feldspar. The mineralized structures may be classified with high-temperature veins. Parker et al. mention an association of a fine-grained porphyritic rock with the breccia; this was noted at the Candelaria mine.

Supergene alteration has resulted in oxidation and leaching of the ore bodies at the surface, leaving gossans containing iron oxides, quartz and tourmaline. As is characteristic of other mines in the Copiapó area, enrichment in this zone apparently extended to many tens of meters in depth. At the Remolinos mine, where the enriched oxidized zone extends to a depth of 50 meters, the principal copper minerals are brochantite, chrysocolla, malachite, azurite, cuprite, native copper, and massive gray chalcocite. The underlying supergene enrichment zone contains sooty chalcocite which, in varying degrees, has replaced hypogene chalcopyrite and pyrite. In the deepest workings (100 meters) of the mine there is an increase in pyrite and gold and a decrease in chalcopyrite.
Radioactivity was noted in various zones within the breccia pipes. At the Remolinos mine the radioactivity was low at the surface (0.04 mr/hr), somewhat higher in the enriched zones, and highest (up to 0.2 mr/hr) in the primary zones where it is associated with primary sulfides. Copper ore from the 30-meter depth averaged 0.10 mr/hr. Uranium minerals have not been identified in the deposit.

At the San Pedro mine radioactivity averaging 0.17 mr/hr was observed at a depth of 20 meters in the outer margin of the breccia pipe.

**Candelaria mine**

The Candelaria mine is located about 30 kilometers southwest of the Cabeza de Vaca district within the same granodiorite pluton. The mine has produced a small amount of copper. The mineralized structure is a tourmaline-quartz breccia pipe approximately 500 meters in diameter. The host rock is partially silicified, argillized and pyritized. The pipe occurs at the intersection of a north-trending fracture system and numerous east-trending fractures. Radioactivity was noted near its northern margin at the intersection of a north-trending fault and a closely spaced system of east-west fractures. The radioactivity, which is associated with a soft, limonite-rich gouge, registered as high as 1.5 mr/hr. Radioactivity up to 0.4 mr/hr was also observed along east-trending faults.

A siliceous, fine-grained, light-colored porphyritic rock is associated with the Candelaria breccia pipe. This may represent the last phase of intrusion associated with the copper mineralization.

No uranium minerals were identified in the Candelaria mine.

**Sedimentary deposits**

**La Piadosa prospect**

The La Piadosa prospect, located on the Río Ramadillas in the southeast corner of the area, is a rather unusual copper-uranium occurrence, differing markedly from other deposits examined in the Copiapó area. The deposit is in lower Tertiary to Quaternary (Recent) gravels in an area of Jurassic volcanic bedrock near the contact with Triassic (?) sedimentary strata. Radioactivity was discovered in 1953 in a stockpile of copper-bearing material at the buying station at Paipote. Later, CORFO engineers investigated the occurrence.

The deposit occurs in stream-terrace gravels which lie 4 to 10 meters above the present stream surface. The gravels consist of alternating layers of pebbles, sand, cobbles, and carbonaceous silts and clays in which the copper and uranium are found. At La Piadosa a 20-meter section of gravel, with about one meter of carbonaceous silts at its base, is exposed. The unweathered carbonaceous beds are friable and black; however, where they are exposed they have been oxidized and bleached to a light gray and contain green secondary copper minerals.
Radioactivity has been observed along a strike length of 100 meters, a high reading of 0.5 mr/hr being recorded by a beta-sensitive Geiger counter in soft, vegetal-rich peat layers. Radioactivity recorded by a gamma-sensitive scintillation counter, however, was only 0.2 mr/hr. Chemical analyses obtained earlier during an investigation of these deposits by the CORFO indicated disequilibrium between uranium and its daughter products. The analyses, made on four samples, ranged from 0.07 to 0.30 percent U₃O₈. The results indicate uranium contents roughly twice those to be expected from uranium ores in equilibrium. This points to disequilibrium, due to recent emplacement of the uranium.

Hydrogeochemical studies were undertaken to obtain information on variations in uranium content of stream waters draining the area. Water samples were taken from springs issuing from fractures in granite bedrock one kilometer upstream from the La Piadosa occurrence, and from springs in the Jurassic volcanic bedrock near the deposit. Samples were collected and treated according to the method suggested by Illsley and Kinnaman (1959). The resin extracts were subsequently analyzed in duplicate at the USAEC laboratory in Grand Junction, Colorado.

<table>
<thead>
<tr>
<th>Sample locality</th>
<th>U₃O₈ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring in granite 1 kilometer upstream from La Piadosa, 100 meters from contact</td>
<td>8.0, 9.6</td>
</tr>
<tr>
<td>with Triassic (?) sandstone</td>
<td></td>
</tr>
<tr>
<td>Rio Ramadillas, in granite terrane above the spring and uranium deposits</td>
<td>5.4, 4.8</td>
</tr>
<tr>
<td>Spring in volcanic rocks 2 kilometers below La Piadosa</td>
<td>1.16, 1.16</td>
</tr>
</tbody>
</table>

The analyses show twice the amount of uranium in the spring waters issuing from the granite above the deposit than is present in the Rio Ramadillas drainage water, and seven times the amount present in spring waters issuing from nearby volcanic rocks. The uranium content determined for spring waters in volcanic terrane is notably low compared to that in springs and drainage water in the granitic terrane. Since the Rio Ramadillas, where it drains granitic terrane, carries at least four to five times more uranium than is present in normal ground waters in the Copiapó area, springs issuing from the granite have up to nine times more uranium than the expected background content.

Assuming that the ground waters at La Piadosa are comparable in solvent power to those reported in other geochemical studies of uranium districts, one might conclude that the uranium content of the Rio Ramadillas is comparable to that found in other surface waters draining uraniferous areas. For example, water draining granitic-metamorphic terrane in the Sierra Nevada of California, USA, in an area containing uranium deposits and numerous springs, contains 8.0 ppb uranium (Bowes, Bales and Haselton, 1957). On the other hand, in the Mount Spokane area of eastern Washington, USA, the uranium content of waters draining granitic and metamorphic rocks in which uranium deposits have been found is around 1.5 to 5.0 ppb uranium, compared with an average regional content of 0.2 ppb uranium (Illsley, 1957).
Thermal and cold water springs are widely distributed in the Andes. The hot sulfurous waters are probably associated with vestiges of widespread volcanic activity which reached its peak during Miocene time. Solutions emanating from magmatic sources could conceivably carry uranium and copper into the groundwater environment, from which the charged solutions might be brought to the surface by springs. The springs in the La Piadosa area are warm and probably are related directly or indirectly to volcanism. In spite of the hydrogeochemical evidence to the contrary, the authors favor the hypothesis that these waters may have at one time contributed uranium to the pervaded sediments.

A study of the La Piadosa copper-uranium occurrence (Ruiz, 1953) led to the suggestion that radioactive deposits might exist in the permeable sediments overlying the mineralized gravels. The geochemical process of transfer of uranium from overlying sediments would involve oxidation and simultaneous or subsequent leaching by ground water containing carbonate or sulfate anions. Where such waters encounter a reducing environment they are most apt to precipitate their uranium.

Two prospecting expeditions were organized in 1954, one in January and the other in November-December (Salas, 1954a, 1954b and 1955b). In the course of this reconnaissance the Rio Ramadillas and all its tributaries were prospected as far as the Argentine border. The study culminated in the discovery of other radioactive carbonaceous silts in terrace gravels located as far as 10 kilometers upstream (southeast) from La Piadosa. Measurements as high as 0.3 mr/hr were recorded in these deposits. Local exposures of copper-bearing veins also were found in granite bedrock; however, no anomalous radioactivity was detected in these veins. Consequently, it was concluded that uranium is not associated with the vein deposits in the vicinity of La Piadosa but is more or less limited to near-surface sediments in which it was probably deposited from ground-water solutions.

**Other occurrences**

Several mines, including the Chañarcillo, Sierra de La Plata, Cachiyuyo, and Flor de Puquios, were examined for radioactivity. All are situated in a north-northeast-trending belt of Cretaceous rocks lying between the coast batholith and the dioritic intrusives in the eastern Copiapó area. The deposits are representative of a range of hydrothermal deposition temperatures. For example, silver-mineral suites at the Chañarcillo mine are suggestive of medium- to low-temperature deposition; chalcopyrite-gold veins at the Cachiyuyo and the Flor de Puquios mines, of medium-temperature deposition; and mineralization at the La Plata group, of medium- to low-temperature deposition. Two other mines, the Cardones and San Francisco, located in this belt at the margin of the Carrizal Alto district, were not visited by the writers, but information on them was abstracted from CORFO studies. Primary mineral suites in these mines are suggestive of medium- to high-temperature origin.
Chanarcillo mine

This famous silver mine was visited and checked for radioactivity by Chilean engineers following the discovery of radioactive specimens in the Sociedad Nacional de Mineria museum in 1950. One cobalt-silver specimen was reported to assay 0.15 percent $\text{eU}_3\text{O}_8$.

All mine dumps were examined and many rock exposures were checked, but no anomalous radioactivity was found. Any uranium that might formerly have been present was presumably associated with the high-grade ore and removed by mining.

Sierra de La Plata mine

The Sierra de La Plata mine (not shown on fig. 2) is 9 kilometers east of the Alacran mine in the Pampa Larga district. The mine is in porphyritic andesite flow rocks which are exposed at the surface between the Pampa Larga diorite and the Cabeza de Vaca granodiorite. Radioactivity up to 0.1 mr/hr was found in north-trending veins containing secondary copper minerals. Mine dumps showed radioactivity up to 0.06 mr/hr.

Cachiyuyo mines

The Cachiyuyo group of mines is located 5 kilometers west of Carrera Pinto, near the northeast corner of the Copiapó area. Radioactivity was detected in a north-trending vein in diorite at the San Samuel mine which at depth contains quartz, chalcopyrite, pyrite and hematite. A maximum reading of 0.01 mr/hr was measured in the mine. The mine dumps showed radioactivity up to 0.04 mr/hr.

Flor de Puquios mine

The Flor de Puquios mine is located about 5 kilometers east of Carrera Pinto on a persistent vein structure, trending N. 45° W. in a metamorphosed border pendant of fine-grained, sericitized, arkosic sandstone. Secondary arsenic and copper minerals, pyrite, chalcopyrite, quartz and calcite have been observed in breccia at vein intersections. The secondary minerals were presumably deposited from ground waters pervading fissures that registered radioactivity up to 0.2 mr/hr. The average radioactivity of the vein and host rock in the mine was only 0.02 to 0.03 mr/hr.

Cardones mine

Torbernite associated with gypsum was reportedly found in a vein exposed at this abandoned copper mine, which is located about 4 kilometers east of Carrizal Alto.
San Francisco mine

This abandoned copper mine is located 10 kilometers east of Carrizal Alto. The host rocks are metamorphosed porphyritic volcanics lying in contact with diorite. Radioactivity, up to 0.3 mr/hr, is associated with an irregular and discontinuous zone of veinlets in the mine.

Ore controls

Zoning, alteration and oxidation

In the Carrizal Alto district radioactivity is most persistent in the veins nearest the contact between diorite host rock and the intruded border rocks. In the Pampa Larga district uranium apparently has been localized at vein intersections and is associated with silver-arsenic-antimony ores in the Descubridora and Alacran mines. The proximate relationship of ore to the contact between diorite and metavolcanics in this district is well illustrated at the Maria Catalina mine.

Radioactive minerals have also been localized in breccia pipes at prominent vein intersections in the Cabeza de Vaca district. The outer margins of these pipes show the highest levels of radioactivity.

Carbonaceous layers consisting of decayed organic material had an apparent localizing influence on copper and uranium distribution at the La Piadosa deposit.

Indications of intense hydrothermal alteration have been observed in breccia pipes in the Cabeza de Vaca district and at the Candelaria mine. Silicification, kaolinization and sericitization of the fractured host granodiorite are most pronounced. Prominent bleaching and intense kaolinization and sericitization of wall rocks are also evident in mineral veins in the Pampa Larga district. On the other hand, weak silicification and pyritization are characteristic of wall rocks adjacent to vein in the Coast Range.

Oxidation within the Copiapó area generally ranges in depth from 20 meters (Carrizal Alto and Cabeza de Vaca districts) to 50 or 60 meters (El Roble-Algarrobo, Carrizal Alto and Cabeza de Vaca districts). The best showings of uranium lie beneath the oxidized zones and are associated with primary ores.

Oxidation and leaching seem to have affected distribution of uranium in many of the deposits. In the Cabeza de Vaca, El Roble and Pampa Larga districts radioactivity of the vein outcrops was approximately one-fourth to one-third the magnitude detected in the primary ore at depth. Weathering, however, has not completely removed radioactivity in the surface exposures of these deposits. For example, measurements on the outcrop of the Descubridora vein in the Pampa Larga district showed 0.2 mr/hr, and at the Maria Catalina vein, within the mineralized sector, 0.25 mr/hr. The radioactivity at the
Maria Catalina mine was first detected by a scintillation counter at a distance of 100 meters from the vein outcrop. In these cases the vein outcrops were reasonably clear of any contaminating debris brought up in mining operations. From indications in the primary zones, however, there has been little or no apparent enrichment of uranium due to supergene processes.

**Regional controls**

A zonal arrangement of metalliferous deposits is apparent eastward from the coast across the Copiapó area. The mineral zones from belts which traverse the area from north to south and are consistent with lithologic, topographic and structural trends. The following metal distribution is illustrated in a cross section of deposits that extends from the coast through Copiapó and the Quebrada de Cerrillos-Quebrada San Miguel:

1. Copper associated with uranium in deposits in the coast-range batholith (Carrizal Alto, El Roble-Algarrobo);
2. Iron and gold deposits at the batholith's eastern margin (Cerro Iman iron area, Cerro Bramador gold area);
3. Copper deposits in a variety of host rocks (Flor de Puquios, Dulcinea, El Venado, Manto Verde) and silver deposits associated with calcareous sediments (Garin deposits, Checo de Plata, Ladrillos, Elisa de Bordos, Chañarcillo);
4. Silver, arsenic, antimony, uranium (Pampa Larga district) and mercury deposits (Cerro Fraile area to the south);
5. Copper deposits containing uranium in breccia pipes of the Cabeza de Vaca pluton (Cabeza de Vaca district and Candelaria mine) and local lead deposits (Mineral de los Plomos).
6. Silver deposits (Lomas Bayas, San Antonio, Retamos) and local lead deposits (Anaconda, Tricolor).

Copper seems almost universally present in these zones although it is not always predominant. It is particularly persistent and abundant in the coast-range batholith and east of the iron-gold zone at the east margin of the batholith. The low-temperature mineral deposits appear to be confined largely to intruded rocks bordering the Cabeza de Vaca pluton, particularly within the synclinal structure on the western margin of the pluton.

**District-wide and local controls**

**Carrizal Alto and El Roble-Algarrobo districts**

Metal deposits within the coast-range batholith show no evidence of zonal relationships favoring abundant uranium accumulation. Copper is ubiquitous and usually present in major quantities, but uranium has been
observed only in minor amounts. In both the Carrizal Alto and the El Roble-Algarrobodistricts uranium is best developed in the minable copper ore bodies. In the Carrizal Alto district uranium is somewhat concentrated in the western sector of the vein, where copper showings are relatively narrow (1 to 2 meters) although of good grade. This sector of the vein is also nearest the contact (within 1 to 3 kilometers) between diorite and intruded metamorphic rocks.

The western extensions of veins in the Carrizal Alto district were explored by CORFO engineers, particularly where they cross the diorite contact into adjacent rocks. It was observed that the veins rapidly disappear and display no increase in radioactivity after crossing the contact. All outlying mineralized areas were also explored (Cardones, San Francisco, etc.), but the radioactivity observed there was lower and the veins less well developed than at Carrizal Alto.

In the El Roble-Algarrobo district uranium is best developed in copper ore bodies in the southernmost Algarrobo system of veins, from which the highest production of copper in the district was realized.

From these relationships it is possible to conclude that proximity to the contact between diorite and adjacent rocks may have a bearing on uranium distribution in metalliferous deposits in these districts, and this relationship, therefore, might merit further consideration in any planning for future geologic studies.

**Pampa Larga and Cabeza de Vaca districts**

Low-temperature mineral deposits are apparently distributed in a zonal pattern around the Cabeza de Vaca pluton. These deposits are most numerous within the synclinal trough to the west of the pluton. As the pluton itself contains hydrothermally mineralized breccia pipes and is generally more radioactive than other facies of the Andean diorite, it is presumed to be a late intrusive phase which gave rise to the metalliferous deposits in the adjacent rocks. The presence of uranium both in the high-temperature veins within the pluton and the adjacent formations, 5 to 10 kilometers to the west of the pipes, is an indication that all the mineralizing solutions may have been derived from this one source.

**Genesis of uranium deposits**

All occurrences of uranium in bedrock in the Copiapo area are believed to be related to metallization connected with the widespread and probably prolonged intrusion of the Andean diorite complex of Late Cretaceous to early Tertiary age. As indicated by Flores (1938), introduction of gold and copper in the Copiapo area may have taken place during the Late Cretaceous. Hydrothermal activity following intrusion of the Andean diorite is probably responsible for most of the important copper, iron, silver and gold deposits in this as well as in other areas in Chile.
As previously suggested, uranium deposits in the Pampa Larga and Cabeza de Vaca districts are thought to be related to a single or similar source which under different conditions contributed to the formation of both low- and high-temperature mineral deposits.

The La Piadosa prospect is especially interesting, for it represents a completely different type and age of uranium mineralization which apparently is not directly related to hydrothermal emplacement. The deposit is believed to have been formed from ground-water solutions and, to some extent, this hypothesis is supported by hydrogeochemical data. The emplacement of uranium and copper is still in progress and is undoubtedly due to the reducing effect of organic matter in the clastic host rock on solutions containing both copper and uranium, which may have been derived initially from thermal waters of volcanic origin. From experience gained in the United States it would be reasonable to predict the favorableness of this environment for uranium deposition, and similar geologic terrain elsewhere in the Copiapó area might also be potentially uranium bearing.

Radioactivity measurements

Radioactivity levels of individual rock units and of mineralized structures within these units are tabulated below and are also included in figure 2.
<table>
<thead>
<tr>
<th></th>
<th>Range of background radioactivity (mr/hr)</th>
<th>Range of radioactivity of mineralized zones or structures (mr/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvium</td>
<td>0.008 0.015</td>
<td></td>
</tr>
<tr>
<td>Terrace gravels</td>
<td>0.008 0.015</td>
<td>0.10 0.8</td>
</tr>
<tr>
<td>Rhyolite dikes and necks</td>
<td>0.02 0.03</td>
<td></td>
</tr>
<tr>
<td>Andean diorite complex:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pampa Larga pluton</td>
<td>0.01 0.02</td>
<td>0.01 2.0</td>
</tr>
<tr>
<td>Cabeza de Vaca pluton</td>
<td>0.025 0.05</td>
<td>0.05 1.5</td>
</tr>
<tr>
<td>Easternmost pluton</td>
<td>0.025 0.045</td>
<td></td>
</tr>
<tr>
<td>Coast-range batholith</td>
<td>0.015 0.03</td>
<td>0.015 0.2</td>
</tr>
<tr>
<td>Pre-Triassic granite and leucosyenite</td>
<td>0.018 0.03</td>
<td></td>
</tr>
<tr>
<td>Triassic(?) sediments</td>
<td>0.015 0.035</td>
<td></td>
</tr>
<tr>
<td>Jurassic sediments</td>
<td>0.01 0.025</td>
<td>0.02 0.03</td>
</tr>
<tr>
<td>Jurassic volcanics</td>
<td>0.008 0.015</td>
<td>0.01 0.03</td>
</tr>
<tr>
<td>Lower Cretaceous sediments</td>
<td>0.01 0.03</td>
<td>0.015 0.025</td>
</tr>
<tr>
<td>Lower Cretaceous volcanics</td>
<td>0.01 0.02</td>
<td>0.01 0.02</td>
</tr>
<tr>
<td>Upper Cretaceous sediments</td>
<td>0.008 0.02</td>
<td>0.01 0.025</td>
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<td>Upper Cretaceous volcanics (tuff)</td>
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<td>0.007 0.01</td>
</tr>
<tr>
<td>Tertiary volcanics</td>
<td>0.015 0.03</td>
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</tr>
<tr>
<td>Pre-Triassic metamorphic rocks</td>
<td>0.01 0.035</td>
<td>0.006 5.0</td>
</tr>
</tbody>
</table>

The Cabeza de Vaca pluton has the highest measured level of radioactivity encountered in the Copiapó area. Mineralized structures within the pluton also exhibited relatively high activity.
CONCLUSIONS

No minable deposit of uranium ore has been discovered or indicated in the Copiapó area from the reconnaissance undertaken by the authors or by previous exploration.

The base- and precious-metal deposits of the Copiapó area that are related to hydrothermal emplacement do not appear to offer much potential for commercial uranium concentrations; nevertheless, the possibility of finding such uranium deposits cannot be ruled out completely. The probability for developing uranium deposits would seem to be greater, however, peripheral to the intensely mineralized areas, inasmuch as uranium may have a tendency to accumulate in latent hydrothermal solutions and dissipate in ground-water solutions, from which it may be precipitated in favorable sedimentary environments (Nininger et al., 1960). This geochemical evolution is suggested in the Pampa Larga district where the uranium content of the ores is highest relative to the total metal content in the low-temperature deposits, and in the La Piadosa region where ground-water solutions apparently were responsible for uranium emplacement in the sediments.

Geologic studies in both the Front Range and the San Juan Mountains in Colorado, USA, have disclosed that commercial vein-type or fracture-controlled pitchblende deposits are developed largely at the periphery of base- and precious-metal mining districts, although many of the latter do, however, contain noncommercial quantities of uranium with the ore minerals. Zonal relationships in these areas indicate that uranium is not abundantly associated with ores of other metals. Geologic observations by the authors suggest that this also may be true of the Copiapó area.

To the extent that sedimentary formations adjacent to hydrothermally mineralized areas in the plutons offer geochemically favorable environments for uranium depositions, they also offer further possibilities for finding uranium.

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Figure 2. Geologic sketch of the Copiapó area, Province of Atacama, Chile

Figura 2. Bosquejo geológico del área de Copiapó, Provincia de Atacama, Chile