The Geology, Carbonaceous Materials, and Origin of the Epigenetic Uranium Deposits in the Tertiary Sespe Formation in Ventura County, California

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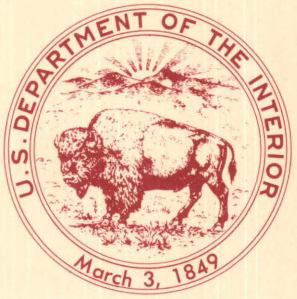

The Geology, Carbonaceous Materials, and Origin of the Epigenetic Uranium Deposits in the Tertiary Sespe Formation in Ventura County, California

By KENDELL A. DICKINSON and JOEL S. LEVENTHAL

A description of and model for a group of Tertiary epigenetic uranium deposits the formation of which was controlled by humate deposition at the fresh water–marine water interface in the coastal subsurface of California

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The Geology, Carbonaceous Materials, and Origin of the Epigenetic Uranium Deposits in the Tertiary Sespe Formation in Ventura County, California

By Kendell A. Dickinson *and* Joel S. Leventhal

Abstract

Uranium deposits of potentially commercial tonnage and grade have been known in western Ventura County, California, since about 1959. These epigenetic uranium deposits are mainly in the lower part of the upper Eocene to lower Miocene, predominantly nonmarine Sespe Formation. Uranium-bearing rocks are exposed in a faulted anticline on Superior Ridge. The uranium is associated with carbonaceous material, vanadium, and probably molybdenum, in mineralized rock, which is defined here as rock containing more than 10 ppm uranium.

At least part of the carbonaceous material and uranium was deposited in veins from aqueous solution. Later alteration added quartz, which is disseminated in the veins, and jarosite and clay minerals that were deposited in central voids in the carbonaceous veins. The carbonaceous material is partly soluble in sodium bicarbonate, and has a pyrolysis–gas chromatography signature similar to that of terrestrial carbonaceous material rather than to those of marine organic material or oil. Carbon isotope values from the Sespe carbon are generally lighter than those of oil from the same general area. The carbonaceous material was most likely derived from terrestrial humate.

The source of the uranium for these deposits was probably the Sespe Formation itself. The Sespe consists of arkosic sedimentary rock that contains much felsic-volcanic and granitic clastic material. High thorium-to-uranium ratios suggest that uranium leaching occurred in an alkaline, oxidizing environment during semi-arid climatic conditions, during or after deposition of the middle and upper parts of the Sespe. The uranium-host sandstone was formed from sediment deposited in streams that flowed directly into the ocean or into a westward-flowing trunk stream. The sandstone-filled paleochannels served as ground-water conduits that carried uranium-bearing solutions to the depositional site. The uranium mineralization took place when the humate was deposited or perhaps shortly thereafter. The humate may have been deposited in a zone of mixing between terrestrial and marine water.

INTRODUCTION

Epigenetic uranium deposits of potentially commercial value have been found in the lower part of the upper Eocene to lower Miocene Sespe Formation near Ojai, in Ventura County, Calif. This report discusses the geological and geochemical setting of these deposits and postulates a model for their origin.

Several uranium deposits are located on Superior Ridge, a topographic high about 3 mi long that is located just south of White Ledge Peak and from 6 to 9 mi west of Ojai, Calif. A single deposit on Laguna Ridge is located about 3 mi south of Superior Ridge, and was included with the Superior Ridge deposits in what Bowes and Myerson (1957) called the White Ledge Peak district. A few small deposits are located near the Hartman Ranch on upper Sespe Creek (fig. 1).

Most of the uranium exploration and development activity in Ventura County took place between 1954 and 1960. Airborne radiometric surveys and hand-held geiger counters were the primary exploration tools. Trenches dug by hand or by bulldozer were used to expose the deposits. Exploration reached the drilling stage only on Superior Ridge where about 30 holes were drilled. The deepest hole was drilled to 380 ft.

A preliminary model for uranium mineralization in the Sespe was presented by Dickinson (1982). He postulated, as we do here, that the organic material necessary for concentrating the uranium by chemical reduction or precipitation originated as terrestrial humic acid or humate. Because of the importance of the chemical nature of the organic material to the genesis of the deposit, a study of the material was carried out and is presented here as a separate section.

Mineralized samples of host rocks, nonmineralized samples of potential host rocks, and samples of some possible source rocks were collected (fig. 1). All samples were analyzed for uranium and thorium by the

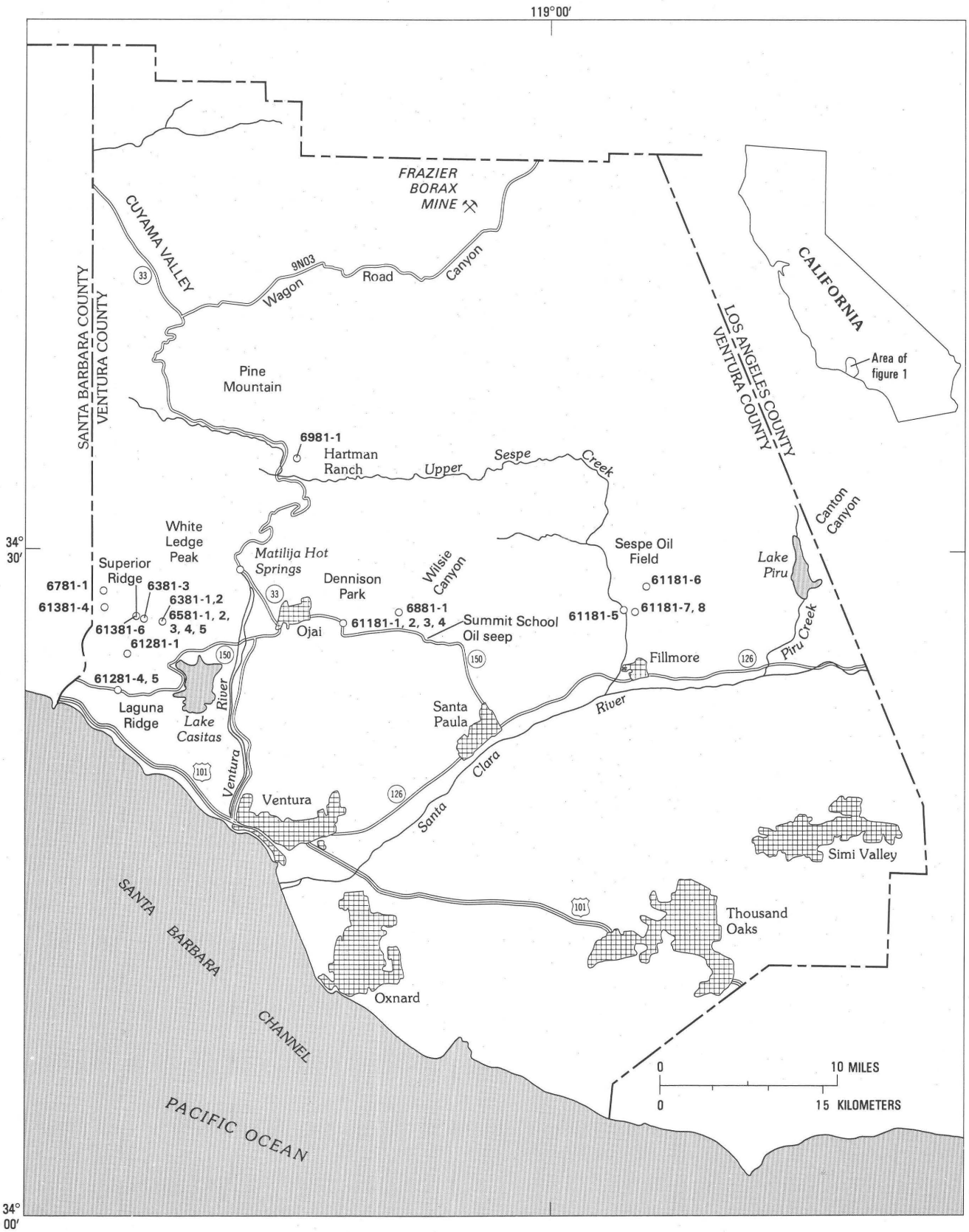

Figure 1. Area of the report and sample localities, Ventura County, Calif.

delayed-neutron method (Millard, 1976). Mineralogy of the samples was studied mainly by X-ray diffraction. Chemical analyses were made by six-step semiquantitative emission spectroscopy or by inductively coupled plasma spectroscopy (ICP) (Crock and others, 1983) of both mineralized and nonmineralized host rocks (Dickinson and others, 1984).

ACKNOWLEDGMENTS

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GEOLOGY

The uranium occurrences described in this report are located in a folded and faulted area north of the Ventura basin along the southern flanks of the Santa Ynez Mountains, which are a part of the east-west-trending Transverse Ranges of southern California. A sequence of largely marine sedimentary rocks underlies the area. The oldest exposed rocks in the area are Upper Cretaceous. These rocks are overlain by an Eocene sequence that comprises, in ascending order, the Juncal Formation, the Matilija Sandstone, the Cozy Dell Shale and the Coldwater Sandstone (Page and others, 1951). The Eocene sequence began with deep-ocean sedimentation during deposition of the Juncal and Matilija Formations and ended with shallow-water sedimentation during deposition of the Coldwater Sandstone. The mostly terrestrial Oligocene Sespe Formation, which is an exception to the otherwise marine character of the sequence, overlies the Coldwater Sandstone. The Sespe is the host rock for the uranium deposits. Marine sedimentation followed deposition of the Sespe and continued until the Pleistocene in the Ventura River Valley. Formations involved are the Oligocene and Miocene Vaqueros, the Miocene Rincon, Monterey, and Santa Margarita, and the Pliocene Pico Formations (fig. 2). According to Dickinson and Lowe (1966), the Rincon Shale is missing in an otherwise similar sequence in the upper Sespe Creek area to the northwest, but mapping by Moser and Frizzell (1982) indicates its presence there.

The geology of the Superior Ridge and Ojai area has been compiled by Moser and Frizzell (1982). The general stratigraphic sequence in two areas of Ventura County is shown in figure 2.

Sespe Formation

The Sespe Formation was named in the Sespe Creek area 6 mi north of Fillmore by Watts (1897), who called it the "Sespe Brownstone." The formation was later revised by Kew (1924), who extended the term throughout the depositional basin. The Sespe rests on the Eocene Coldwater Sandstone with apparent conformity in most areas, but in a few areas the contact is a disconformity or a slight angular unconformity. The upper contact of the Sespe with the Oligocene and Miocene Vaqueros Formation is conformable in most areas, but a slight disconformity or angular unconformity is found in others.

Bailey (1947) reported a maximum thickness of the Sespe Formation of 7,500 ft, but in most of the Ventura basin, it ranges from 3,000 to 5,000 ft in thickness. The Sespe generally thins westward. The late Eocene to early Miocene age of the Sespe Formation is based mainly on its stratigraphic position, although it contains some vertebrate fossils (Reinhart, 1928; Page and others, 1951). The lower part of the Sespe may be predominantly late Eocene.

The Sespe Formation is a thick red-bed sequence consisting mostly of arkosic shale, sandstone, and conglomerate. The ratio of plagioclase to orthoclase in the Sespe generally exceeds 1.0, based on whole-rock X-ray analyses. The ratio increases to the east, where a more mafic igneous provenance was demonstrated by Bohannon (1976). Total feldspar exceeds quartz in most of the samples. The lower part of the Sespe is more conglomeratic than the upper part, which contains more red beds. In the Superior Ridge area, the lower part consists mainly of yellowish-brown or pinkish-gray, medium- to coarse-grained, poorly sorted to well-sorted arkosic sandstone that exhibits plane bedding as well as crossbedding. The predominant clay mineral in the uranium host rocks at Superior Ridge is montmorillonite (Bowes and Myerson, 1957), but the clay suite also includes chlorite, and possibly mixed-layer chlorite-montmorillonite and illite.

A basal conglomeratic member of the Sespe Formation was recognized by Dickinson and Lowe (1966) in the area of upper Sespe Creek. This basal member is apparently limited in areal extent to the western margin of the Sespe depositional basin. Bowes and Myerson (1957) recognized a lower member of the Sespe in the Superior Ridge area that was interpreted to be transitional with the underlying Coldwater Sandstone and that is apparently below the main conglomeratic facies included in the basal member of the Sespe by Dickinson and Lowe (1966). In the remainder of this report, the lower member of Bowes and Myerson (1957) will be referred to as the

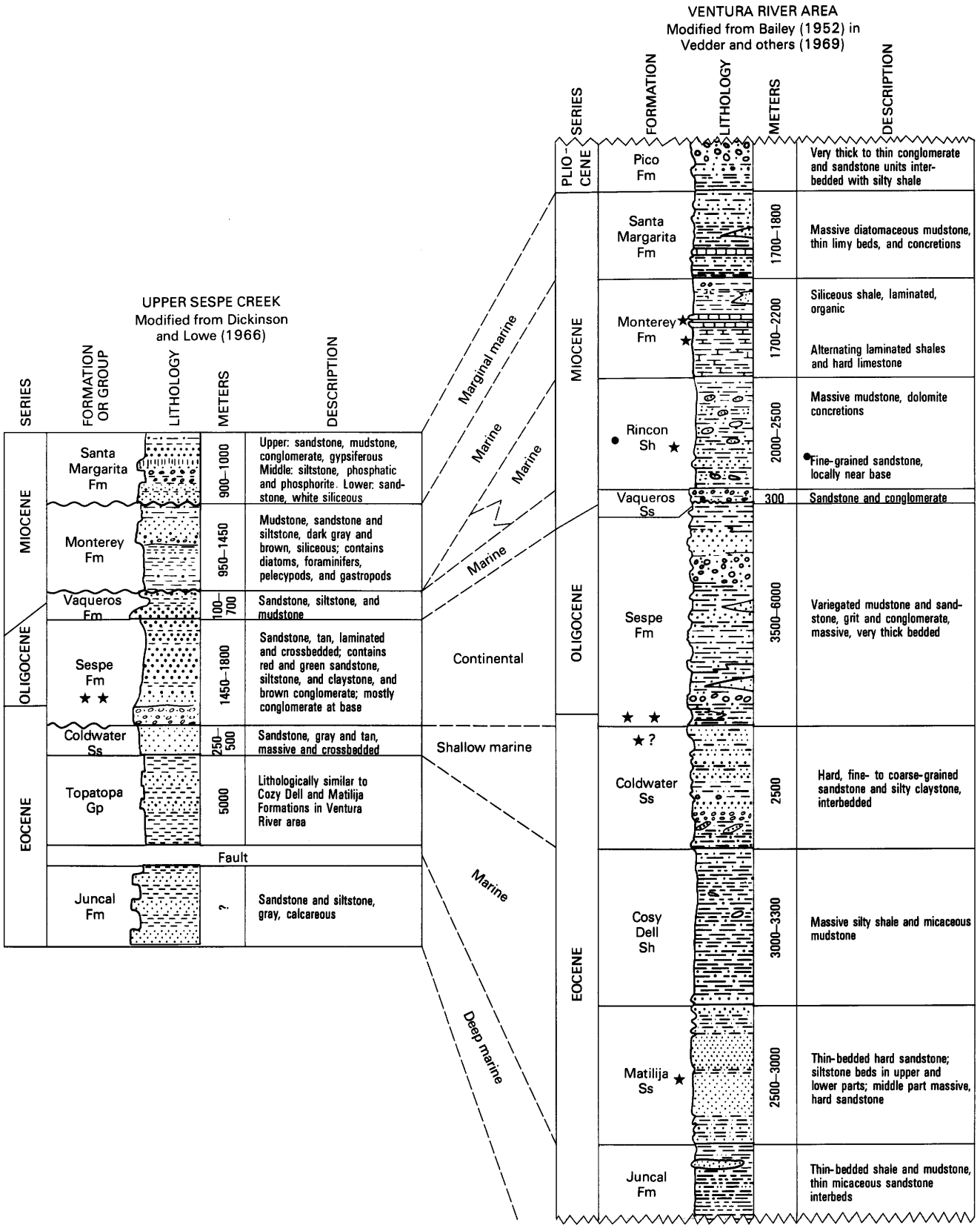


Figure 2. Stratigraphic columns showing uranium occurrences (★★, >0.1 percent U_3O_8; ★, >0.001 percent <0.01 percent U_3O_8). Thicknesses and correlations approximate.

lower transitional Sespe. The lower transitional Sespe is nonmarine, but it intertongues with the underlying marine Coldwater Sandstone (Moser and Frizzell, 1982), and is the main uranium host rock at Superior Ridge. The lower transitional Sespe ranges from 225 to 450 ft in thickness. Additional stratigraphic details of the lower transitional Sespe are shown in figure 3, which was originally published by Bowes and Myerson (1957).

On the basis of paleocurrent work by Bohannon (1976), the sediment source of the Sespe in the upper Sespe Creek area was from the west, northwest, and north; farther east in the Canton Canyon area (fig. 1), the source was from the north, northeast, and east. These data are not corrected for tectonic rotation as proposed by Luyendyk and others (1980). The conglomerate clasts in the Sespe Creek area are mainly volcanic rock of rhyodacitic composition, granitic rock, and sandstone. In the Canton Canyon area to the east, the main clast types are granite, syenite, anorthosite, and gabbro (Bohannon, 1976).

The Sespe Formation was deposited in a dominantly fluvial environment (Reed, 1929; Reinhart, 1928; Bailey, 1947; Dickinson and Lowe, 1966). Bohannon (1976) described fining-upward sequences in the upper Sespe Creek area that he attributed to meandering and braided streams on a flood plain. In the Canton Canyon area, Bohannon (1976) suggested deposition in a broad alluvial fan. Some possible lacustrine beds have been reported (Reed, 1929, p. 503). At Dennison Park east of Ojai, laminated beds containing gypsum indicate that minor amounts of the Sespe were deposited in evaporitic lakes.

Bailey (1947) suggested that a major stream flowed westward through the Sespe depositional basin with tributaries entering from both the north and the south. The paleocurrent data of Bohannon (1976) and McCracken (1969a) generally support this hypothesis. McCracken (1969a) hypothesized that a trunk stream existed in the approximate position of the modern Santa Clara River and that it reached the present coast near Point Rincon.

Structure

The structural evolution important to the history of uranium mineralization began with the end of the Eocene uplift that created the nonmarine basin in which the Sespe Formation was deposited. Minor folding may have occurred in the Miocene as evidenced locally by a slight disconformity between the Sespe Formation and overlying units and perhaps also by conglomeratic lenses within the Sespe. These movements were relatively small and are difficult to measure or map because of the large-scale folding and faulting that occurred later. However, they may have affected uranium mineralization because of their effect on paleohydrology. The greatest orogeny occurred during the Pleistocene prior to deposition of the Santa Barbara Formation (Weber and others, 1973; Jackson and Yeats, 1982). This orogeny produced the Superior anticline and related faults, as well as the overturned anticlines both east and west of the Superior anticline. It probably modified existing uranium deposits and uplifted and subsequently exposed the uranium deposits along Superior and Laguna Ridges.

URANIUM DEPOSITS

Superior Ridge

The Superior Ridge deposits, the largest and most extensive known uranium occurrences in Ventura County, were first discovered during 1954 by using aerial radiometrics (Bowes and Myerson, 1957). During 1954 and 1955 many claims were filed in an area about 5 mi long by ½ mi wide (fig. 4). These claims included Gamma Queen, Coyote, Chismahoo, Payoff (later consolidated into the Payore), Lamar, and Beer Can (fig. 1, table 1). All the Superior Ridge deposits (White Ledge Peak deposits of Bowes and Myerson, 1957) are in the lower transitional Sespe Formation (figs. 4, 5).

The Superior Ridge uranium deposits are located along the crest and on both flanks of a faulted anticline (figs. 4, 5). The fault parallels the Arroyo-Parida fault to the south and the Santa Ynez fault about 3 mi to the north. Whereas it is tempting to suggest that mineralization is related to these Pleistocene structural features, the uranium occurrences probably were more widespread in the lower transitional Sespe at an earlier age, and the anticline only served to expose a mineralized area to erosion and other modification.

The most common uranium mineral in the Superior Ridge deposits is carnotite [$K(UO_2)_2(VO_4)_2 \cdot 3H_2O$)]. Becquerelite [$CaU_6O_{19} \cdot 11H_2O$], autunite [$Ca(UO_2)(PO_4)_2 \cdot 10\text{–}12H_2O$], and a black uranium oxide (possibly pitchblende) are also present. These uranium-bearing minerals are found in lenses and concretions, most commonly associated with carbonaceous material. Bowes and Myerson (1957) described an occurrence at the Payore claim as follows: "The concretions, along with irregular carbonaceous streaks and disseminations, form local lenticular clusters of ore-grade material along bedding of a size approximating 10 by 10 by 2 feet." At the Beer Can #12 deposit, we found uranium associated with an irregular 7×4 ft pod of altered sandstone containing siliceous carbonaceous veins. The carbonaceous vein material, which resembles lignite in hand specimens, is anomalously high in both uranium and vanadium. The veins are present along the bedding plane for about 50 ft.

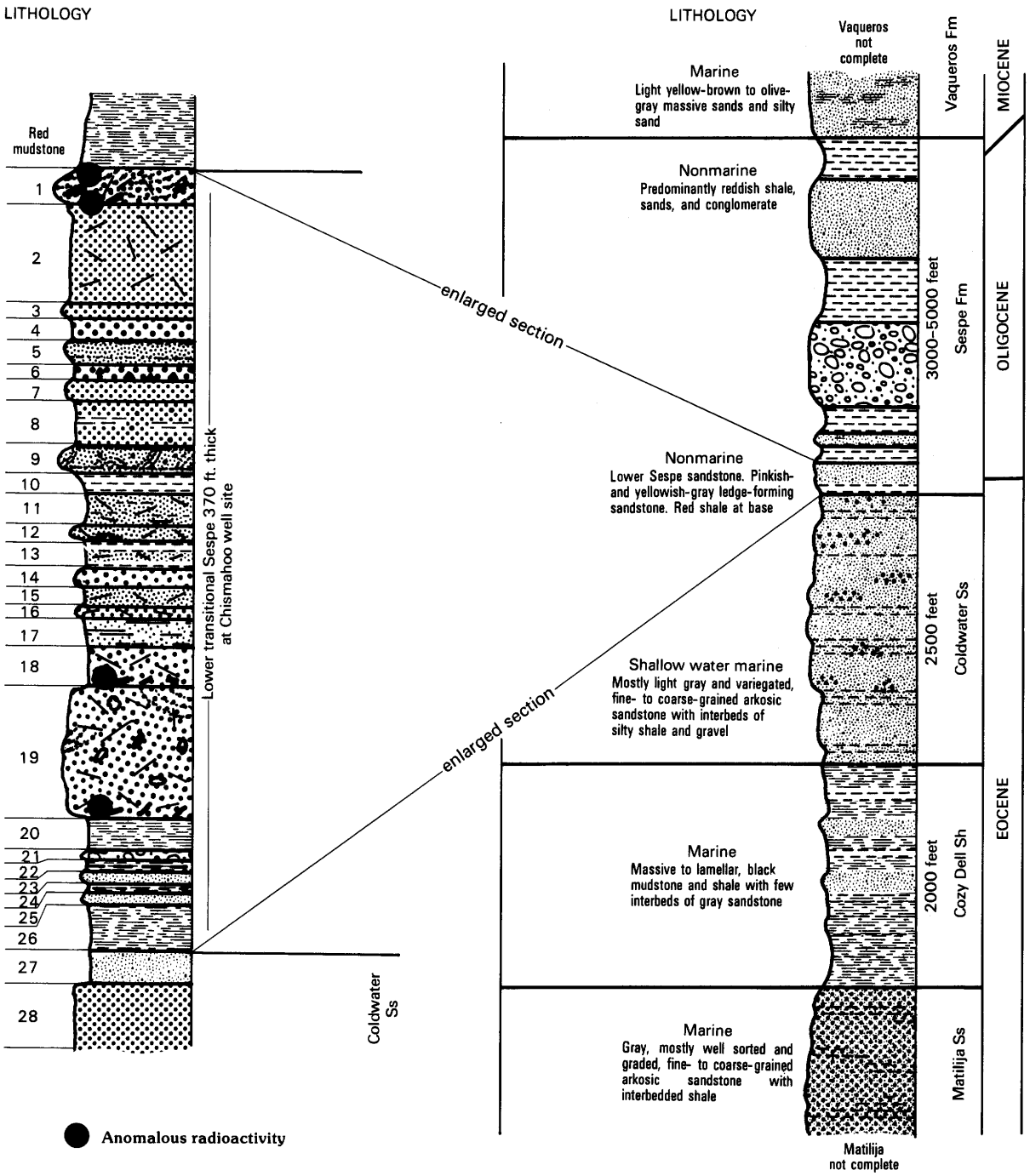


Figure 3 (above and facing page). Stratigraphic section of the lower transitional Sespe Formation in the Superior Ridge area (modified from Bowes and Myerson, 1957).

The carbonaceous material in the veins probably was precipitated from humate-bearing ground water as discussed later.

Nine holes drilled on the Payore claims near the east end of Superior Ridge encountered discontinuous ore horizons at a depth of between 320 and 380 ft. Homestake mining Company estimated undiluted reserves of 57,167 lb U_3O_8 based on data obtained from the claim owners. These data consisted of eU_3O_8 measurements from drill holes.

Laguna Ridge

One claim, the Hoot Mon (fig. 4, table 1), was filed on Laguna Ridge, about 3 mi south of Superior Ridge. The Hoot Mon deposit is also in the lower transitional

EXPLANATION

1 Sandstone, arkosic, light-pinkish-gray, coarse- to very coarse grained, crossbedded; containing radioactive orange-pink iron-rich concretions and carbon trash
2 Sandstone, arkosic, gray-yellow, medium-grained, micaceous, irregularly iron oxide stained
3 Sandstone, yellow-gray, medium-grained
4 Sandstone, arkosic, yellow-gray, coarse-grained
5 Sandstone, gray to yellow, thick-bedded
6 Sandstone, brown, very coarse grained to conglomeratic; contains chert pebbles
7 Sandstone, pale-yellow-orange, medium-grained
8 Sandstone, arkosic, friable, medium- to coarse-grained; locally contains thin to medium beds of brown shale
9 Sandstone, quartzose, light-yellow-gray, coarse-grained, thick-bedded, locally crossbedded, iron-oxide-stained
10 Shale, brown-gray
11 Sandstone, arkosic, gray-orange, medium-grained, locally shaly
12 Sandstone, coarse-grained, thick-bedded, iron-oxide-stained
13 Shale, brown-gray; interbedded with yellow-gray medium-grained arkosic sandstone
14 Sandstone, light-yellow-gray, coarse-grained
15 Sandstone, arkosic, yellow-gray, medium-grained, friable
16 Sandstone, arkosic, yellow-orange, coarse-grained
17 Shale, brown-gray, sandy; interbedded with fine-grained shaly sandstone
18 Sandstone, arkosic, micaceous, pale-yellow-orange, coarse-grained; lower part is radioactive and locally contains carbon trash
19 Conglomerate, light-pinkish-gray, crossbedded, thick-bedded; coarse- to very coarse grained arkosic sandstone; and iron-rich concretions. Locally unit is stained with orange-pink iron oxide, is radioactive, and contains carbon trash
20 Mudstone, red and brown-gray
21 Sandstone, brown, conglomeratic
22 Shale, brown-gray, silty
23 Sandstone, yellow-gray, iron-oxide-stained
24 Shale, red, silty
25 Sandstone, yellow-gray
26 Mudstone, red and brown-gray
27 Siltstone, brown-gray
28 Sandstone, gray

Sespe, which is exposed where it is thrust to the surface along the Arroyo-Parida fault. According to Bowes and Myerson (written commun., 1956), this deposit, which was not sampled for this study, contains carnotite associated with carbon trash and is similar in occurrence to the Superior Ridge deposits.

Upper Sespe Creek

Two uranium claims, Bertram Lode and Lucky Saddle #1, were staked on upper Sespe Creek near Hartman Ranch near State Highway 33 (table 1). These deposits were not located during the present study, but samples with weak uranium mineralization were collected in the area (table 2). The host rock is micaceous arkosic sandstone of the lower part of the Sespe Formation. The lower transitional Sespe has not been recognized in this area (Dickinson and Lowe, 1969). Sandstone samples from the Lucky Saddle #1 contained as much as 0.1 percent U_3O_8, and carbonaceous samples from this deposit contained as much as 0.8 percent U_3O_8 (uranium contents were chemically determined). Radioactivity of the Bertram Lode was associated with iron-stained concretions (Dickinson, 1982). Such isolated occurrences are probably common in Eocene through Miocene sedimentary rock in Ventura County. They may have resulted from redeposition of minor amounts of uranium during modification of other deposits and they are believed to be commercially insignificant.

ELEMENTAL ASSOCIATIONS

For weakly mineralized rocks, uranium content alone is not sufficient criterion for determining which rocks have been mineralized and which have not. However, a significant correlation exists between uranium and vanadium and probably between uranium and molybdenum in rocks that have been mineralized (table 2). For this reason, higher vanadium and molybdenum values in a particular sample are used as evidence that it has been mineralized. In addition, the Th:U ratio is low for mineralized rocks, and generally only an upper limit for thorium can be determined (Millard, 1976). Examination of the data in table 2 suggests that samples containing more than 10 ppm uranium have been mineralized, although some samples containing 5–10 ppm uranium may have also been slightly mineralized.

The linear correlation coefficient between uranium and vanadium contents in samples containing more than 10 ppm uranium is +0.86, placing the correlation above the 99-percent confidence level for 10 samples (table 2). The correlation between uranium and vanadium in samples containing less than 10 ppm uranium is –0.03, which is not significant for 25 samples. An apparent correlation also exists between uranium and molybdenum. Molybdenum was undetectable in only one sample with more than 10 ppm uranium and was detectable in only one sample with less than 10 ppm uranium. The correlation between both uranium and vanadium and uranium and molybdenum is common in some epigenetic uranium deposits (Shoemaker and others, 1959).

Table 1. Summary of uranium claims
[NA, not available]

Area and claim Sec./T. N./R. W.	Maximum uranium values (pct. eU_3O_8)	Uranium minerals	Percent V_2O_5	Petrology of host rock	Stratigraphy	Strike/dip
Superior Ridge:						
Beer Can #12 2 4 24	0.19	Carnotite	0.67	Sandstone, gray, light-brown, arkosic, crossbedded, fluvial; contains black carbonaceous veins.	Lower transitional Sespe Formation.	Dip 40° S.
Payoff[1] 10 4 24	2.18	Carnotite	NA	Sandstone, gray, light-brown, micaceous, poorly sorted, fluvial; contains carbonaceous trash.	---do----------	Strike northeast.
Chismahoo East #1 10 4 24	.23	Carnotite	NA	Sandstone, gray to light-brown, poorly sorted; contains conglomerate lenses and carbonized wood.	---do----------	N. 70° E.; 40° N.
Coyote #1 4 4 24	.16	Carnotite	NA	Sandstone, gray, coarse-grained, micaceous, fluvial.	---do----------	N. 45°–70° E.; 30°–40° S.
Gamma Queen 4 4 24	.07	Autunite	.09	Sandstone, buff-colored, fine-grained, micaceous; contains pockets of carbonaceous material and interbedded conglomerate, siltstone, and red and green shale.	---do----------	N. 85° W.; 45°–50° SW.
Lamar 7 4 24	.03	NA	NA	Sandstone; contains carbon trash	---do----------	NA
Laguna Ranch:						
Hoot Mon #4 2 4 24	NA	Carnotite	NA	Sandstone, buff-colored to light-gray, fluvial; contains carbon trash.	---do----------	NA
Sespe Creek area:						
Bertram lode 2 5 23	.64	NA	NA	Sandstone; contains uraniferous concretions and interbedded shale.	Upper Eocene----	N. 60°–70° E.; 30° S.
Lucky Saddle 31 6 22	.51	NA	NA	Sandstone, gray, micaceous, fluvial; contains carbonaceous material along bedding planes.	Lower Sespe Formation.	

[1]Later included in the Payore claims.

CARBONACEOUS MATERIALS

Analytical Techniques

The pyrolysis-gas chromatography method was described by Leventhal (1981) and is summarized here. A powdered sample (≈2 mg) is placed in a 2 mm×2.3 cm quartz tube which is put in the spiral of the Chemical Data Systems pyroprobe[1]. The sample is then heated for 10 s at 750 or 900 °C. The pyrolysis products are separated on a 2 m×1 mm stainless steel gas-chromatography column packed with Supelcoport coated with OV-101. The separated compounds are detected by a flame ionization detector.

Rock-Eval pyrolysis is described by Tissot and Welte (1978). It consists of continuous heating of a powdered sample from 225 °C to 550 °C at 25 °C/min and measurement of evolved CO_2 and hydrocarbons (HC). Volatiles released at temperatures below ≈300 °C are called S_1 (mg HC/g sample). Pyrolysis products released above ≈300 °C are called S_2 (mg HC/g sample). The quantity S_2/percent org C is the hydrogen index (HI) which is similar to H:C ratio. Carbon dioxide released up to 390 °C is S_3; S_3/percent org C is the oxygen

[1]Any use of trade names and trademarks in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

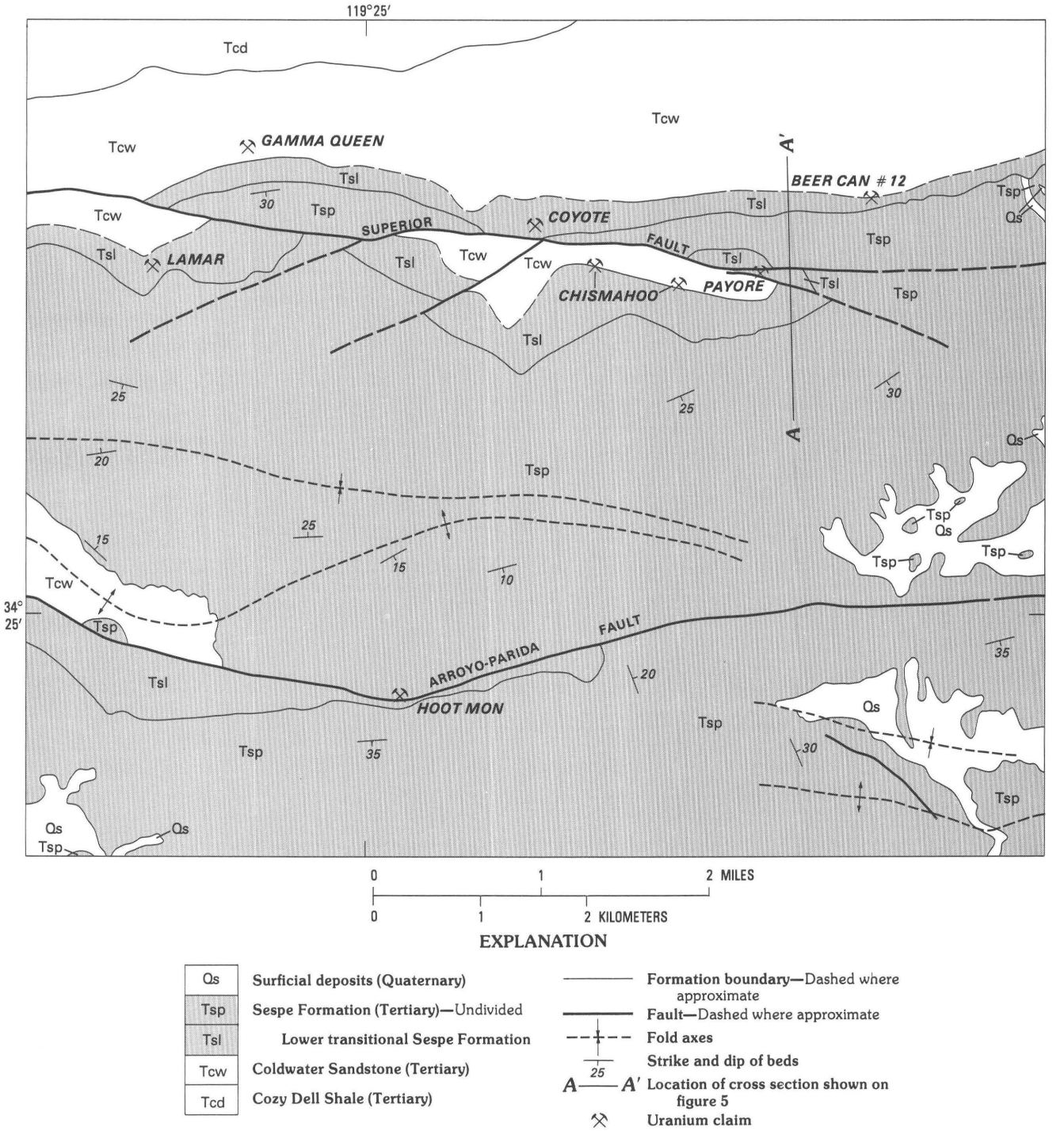


Figure 4. Geologic map of Superior Ridge and Laguna Ridge areas. Geology modified from Bowes and Myerson (1957) and Moser and Frizzell (1982).

index (OI) and is similar to the O:C ratio. The temperature at which S_2 is a maximum is called T_{max} and relates to thermal maturity. Temperatures below 420 °C indicate that the sample is thermally immature with respect to petroleum generation, whereas T_{max} above 460 °C indicates rocks that are thermally overmature and have already yielded petroleum. The results are displayed on a plot of HI vs. OI which is similar to a van Krevelen plot of H:C vs. O:C.

In addition to these techniques, the carbon-rich materials were studied by scanning electron microscopy-X-ray energy spectrometry (SEM-XES), X-ray diffraction,

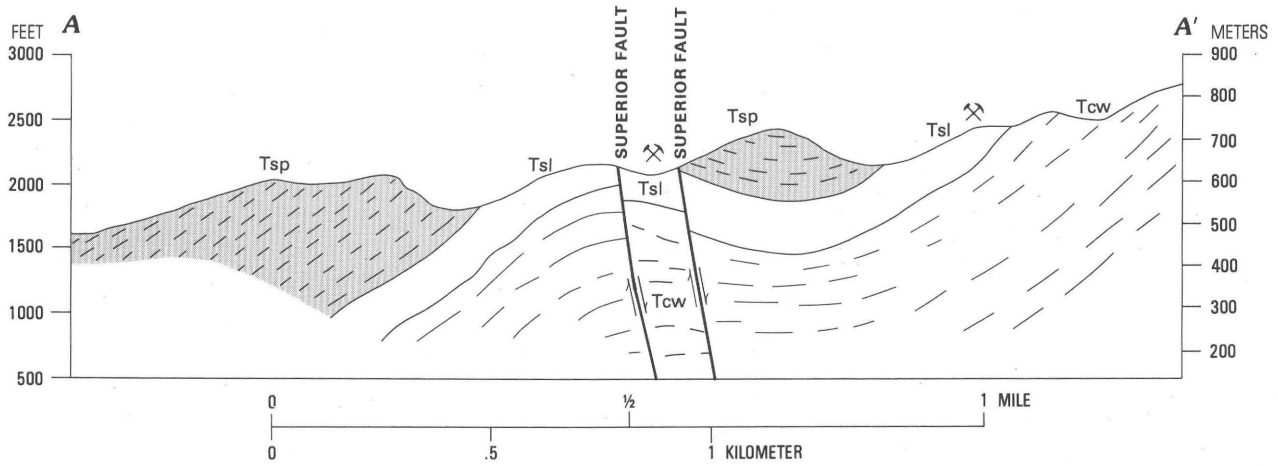


Figure 5. Cross section along Superior Ridge; viewer is looking west. **Tcw**, Coldwater Sandstone; **Tsp**, Sespe Formation; **Tsl**, lower transitional Sespe Formation (fig. 4). Locations of uranium occurrences (crossed pick and hammer) are projected at right angles to plane of cross section (fig. 4). Modified from Bowes and Myerson, 1957.

chemical analysis by ICP, and microscopy of thin and polished sections.

Results and Discussion of Organic Matter Analyses

In order to test for soluble organic matter, a small portion of sample was crushed and added to two test tubes, one with sodium bicarbonate and another with a mixture of toluene and methanol. Organic material that is soluble in sodium carbonate solution (alkaline pH) is humic (Schnitzer and Kahn, 1972), whereas material soluble in the organic solvent mixture is bitumen. The uranium-related samples show mainly humic material and only slight bitumen. A portion of the Beer Can #12 alkaline extract was transferred to another tube and acidified to pH 2; it gave a flocculant precipitate (humic acid), leaving a nearly clear solution (fulvic acid). Thus the Beer Can #12 extract is mainly humic-acid-type material and contains only a small amount of fulvic acid, which is characteristic of very recent organic matter.

Pyrolysis–gas chromatography was used to fingerprint the largely insoluble organic matter from the suite of samples (table 3). The Beer Can #12 (fresh and weathered), east outlier, west outlier, and Payore samples all give very similar results; the pyrograms for these samples give the same retention time and relative intensities for the 25 pyrolysis products that are observed. The irregular spacing of the peaks (lower trace, fig. 6) is *not* typical for bitumen or marine organic matter. These results can be contrasted with the pyrolysis–gas chromatography results of the Summit School oil seep (upper trace, fig. 6) with a predominance of evenly spaced *n*-alkanes (nC_{15-25}) that are typical of petroleum.

The extremely high organic carbon content (table 3) of these uranium-enriched samples is quite anomalous compared to many uranium deposits where the organic carbon is in the range of 0.5–3 percent. The Rock-Eval pyrolysis shows this organic matter to be type III (terrestrial) that has been partly oxidized (as shown by the high oxygen index values); such organic matter is typical of uranium deposits (Landais and others, 1984; Leventhal and others, 1986). The Rock-Eval results reported here are similar to those of Frizzell and Claypool (1983) from nearby unmineralized organic material.

Although the T_{max} and low HI (table 3) indicate that this uranium-rich organic material is in the oil-generating window, it is still capable of yielding additional pyrolysis products. The $\delta^{13}C$ value (table 3) for the organic carbon in these uranium-rich samples is typical of Tertiary to Holocene terrestrial organic matter (Degens, 1969).

The oil seep sample gives a carbon isotope value slightly heavier than the uranium-related organic matter and typical of oil from the Monterey Formation and related oils (Sofer, 1984). The oil seep shows a low T_{max} and high HI as expected.

Another unusual aspect of these samples is their high sulfur content. The iron content of the Beer Can #12 sample is relatively low, based on the ICP analysis (table 4). No pyrite was identified in the SEM–XES or optical petrography observations. Thus approximately half of the sulfur may be present as organic sulfur. The non-pyrite sulfur content is not far from the 0.7 percent reported in Holocene Florida humate (Swanson and Palacas, 1965, p. B21) and is within the range for modern humic substances (Schnitzer and Kahn, 1972, p. 31).

The analyses of the uranium-enriched samples show high organic carbon (table 1), not typical of normal soil

Table 2. Sample data from the Sespe Formation

[N, not detected; L, detected but below limit of determination; detection limit for molybdenum 3 ppm, for vanadium 7 ppm (Millard, 1976)]

Locality	Sample[1] No.	Uranium (ppm)	Thorium (ppm)	Th:U	Proximity to mineralization[3]	Vanadium (ppm)	Molybdenum (ppm)	Field description	Mineralogy as determined by whole-rock X-ray diffraction[4]
Superior Ridge ----	6381-1A	162.0	<27.0	([2])	M	1500	30	Sandstone, light-yellow-brown, medium-grained; contains carbonaceous fragments.	Q, P, O, S, I.
	6381-1C	84.5	<16.0		M	1000	30	Sandstone, light-yellow-brown, medium-grained ----------	No data
	6381-1E	93.8	<17.0		M	500	50	-----do----------	No data
	6381-2	8.8	13.2	1.5	P	50	N	Sandstone, pink, fine- to medium-grained, friable --------	No data
	6381-3	2.8	6.2	2.2	P	30	N	Sandstone, light-yellow-brown, fine-grained, hard, slightly calcareous.	Q, P, O, S, I, ch.
	6581-1	10.7	<3.9		M	50	N	Sandstone, gray, fine- to coarse-grained, conglomeratic, crossbedded.	Q, P, O, S, I, ch.
	6581-2	6.4	<3.2		M?	50	N	Siltstone, light-yellow-brown, hard ----------	Q, P, O, S(?), I, ch.
	6581-3	2870.0	<640.0		M	5000	50	Sandstone, light-yellow-brown, medium- to coarse-grained; contains carbonaceous fragments.	Q, O, P, S(?), I, ch.
	6581-4	6.2	8.2	1.3	P	30	N	Sandstone, light-yellow-brown, medium- to coarse-grained, thin-bedded.	Q, O, P, S(?), I, ch.
	6581-5	5.2	<2.7		M?	70	N	Sandstone, tan, medium- to coarse-grained, poorly sorted, calcareous.	Q, C, P, S.
	61381-3	1.8	7.3	4.0	R	30	N	Conglomerate, reddish-brown, argillaceous; contains seashell fragments.	C, Q, P, ch, S.
	61381-4	1.0	3.9	3.9	R	30	N	Sandstone, red, coarse-grained, conglomeratic, crumbly	Q, P, O, ch, S.
	61381-6	19.2	<5.3		M	70	L	Sandstone, buff-colored, medium-grained, hard; contains contorted bedding.	Q, O, P, I, S.
Wilsie Canyon ----	6881-1	7.9	10.9	1.4	P?	20	N	Sandstone, reddish-brown, conglomeratic, weathered.	Q, O, P, S.
Hartman Ranch ---	6982-2A	15.7	<6.1		M	50	N	Sandstone, reddish-gray, medium-grained; contains carbonaceous fragments.	O, P, Q, I, ch.
	6982-1B	3.9	13.0	3.4	R	30	N	-----do ----------	Q, P, O, S, I.
Dennison Park ----	61181-1	2.3	9.2	3.9	R	70	N	Siltstone and very fine grained sandstone, red, laminated, calcareous.	Q, P, O, G, S, I.
	61181-2	1.5	5.3	3.6	R	30	N	Sandstone, pink, evenly bedded, calcareous, micaceous.	Q, P, O, G, S, ch.
	61181-3	2.0	8.4	4.2	R	30	L	Sandstone, red, medium-grained, medium- to thick-bedded.	Q, P, O, C.
	61181-4	2.5	9.5	3.7	R	70	N	Sandstone, reddish-brown to buff, fine- to medium-grained, crossbedded.	Q, P, O, I, ch.
Sespe Oil Field area.	61181-5	1.8	10.8	6.1	R	30	N	Sandstone, red, fine- to medium-grained, medium-bedded, conglomeratic.	Q, P, O, I, ch.
	61181-6	2.1	9.0	4.3	R	50	N	Sandstone, buff-colored, fine-grained, silty, non-calcareous.	Q, P, O, I, S.
	61181-7	3.3	14.0	4.3	R	70	N	Sandstone, gray to brown, weathered, very fine to fine-grained, banded.	Q, P, O, ch, S, I.
	61181-8	1.8	8.7	4.8	R	30	N	Sandstone, red, hard, medium-grained, micaceous --------	Q, P, O, S, I.
Laguna Ridge -----	61281-1	1.7	9.1	5.4	R	50	N	Sandstone, light-tan, hard, evenly thin- to thick-bedded.	Q, P, O, S.
West Casitas Pass.	61281-4	2.6	11.0	4.2	R	30	N	Sandstone, buff-colored, medium-grained, evenly layered, thin- to thick-bedded.	Q, P, O, S, I.
	61281-5	2.1	8.1	3.9	R	50	N	Sandstone, light-reddish-brown, evenly layered, thin- to thick-bedded.	Q, P, O, S, ch, I.

[1]See figure 1.
[2]If blank: ratios not computed if thorium is less-than value.
[3]R, remote; P, proximal; M, mineralized. Queried where uncertain.
[4]In general order of decreasing proportion. Q, quartz; P, plagioclase; O, orthoclase; S, smectite; I, illite or mica; ch, chlorite; G, gypsum; C, calcite. Queried where uncertain.

organic matter. The zones of enriched organic carbon suggest that the carbon was mobilized and redeposited. Based on the solubility, pyrolysis–gas chromatography, and Rock-Eval results, this organic matter apparently is of humic origin and was reprecipitated as a humate.

The organic material at Beer Can #12 was originally described by Bowes and Myerson (1957) as follows: "Radioactivity is associated with an irregular 7-by–4-foot pod of black carbonaceous lignite-like material that occurs in veinlets near its margin. Similar material is found in irregular narrow streaks along the bedding plane for 50 feet." The pod of black carbonaceous lignite-like material was not found, but a pod of altered sandstone about 7× 4 ft (fig. 7*A*) was found on the outcrop. This pod contained veins of shiny black material that range from 1/2 to 1 inch in width and from a few inches to about 3 ft in length (fig. 7*B*). The veins lack plant cell structure but have a banded structure similar to inorganic veins, with corresponding bands on opposite sides. A central void is found in places along these veins (fig. 7*C*). Reflected light microscopy confirmed that the material was not lignite, vitrinite, or coal (Neely Bostick, oral commun., 1985). As shown by our autoradiograph studies, bands of radioactive material (uranium) in the veins are nearly coincident with the mineral bands (fig. 7*D*). In addition, transversely oriented veinlets are present in some of the bands.

Table 3. Organic carbon and related analyses

[Parentheses indicate anomalous data resulting from instrumental limitations. Rock-Eval analysis was done by Ted Daws, sulfur analyses by Mark Stanton; and carbon isotopes by April Vuletich; leaders (---), no data]

Sample	Gamma counts/second at site	Organic carbon percent	T_{max}	Rock-Eval HI	OI	Sulfur percent	^{13}Corg permil
Beer Can #12 carbon veins hand picked sample (primary occurrence).	>10,000	35.5	446	95	72	0.72	---
Beer Can #12 carbon veins (weathered) (primary occurrence).	>10,000	68.4	458	50	26	1.11	-23.5
Beer Can #12 carbon veins (fresh) (primary occurrence).	>10,000	70.4	445	82	20	0.96	-24.5
Beer Can #12 carbon veins (30 ft east of primary occurrence).	2,500	63.6	(501)	14	40	0.50	-24.3
Beer Can #12 carbon clasts (30 ft west of primary occurrence).	1,500	11.3	---	4	76	0.05	-23.5
Beer Can #12 clay clasts (30 ft west of primary occurrence).	230	0.24	---	(<4)	(650)	<.02	-24.0
Beer Can #12, shale layer approximately 30 ft below uranium deposit.	230	0.01	---	(<4)	(700)	<.02	---
Payore claims, carbonaceous fragments.	7,500	58.3	473	16	64	0.45	-22.9
Summit School oil seep black heavy oil.	120	75.4	(421)	634	8	1.51	-22.9

The black material making up the veins contains as much as 70 percent organic carbon (table 3). Most of the remaining material is quartz. Only quartz was identifiable in X-ray diffractograms of the black vein material. An ashed sample of the black material also showed quartz and a trace of a clay mineral, probably smectite. Material from the central void of the vein was identified, using X-ray diffraction, as jarosite and clay minerals (fig. 7*E*, *F*). Jarosite was previously identified in some of the other deposits (Bowes and Myerson, 1957). The mineralogy of the veinlets was not determined, but, based on XES, they contain silicon, vanadium, potassium, aluminum, iron, and uranium, generally in that order. In addition, tiny inclusions of silica-rich material are diffused through the organic matter (fig. 7*E*).

In general the paragenetic sequence of the veins is as follows: (1) Veins of organic matter and uranium are deposited from humic-acid-bearing ground water in fractures of already lithified or partly lithified Sespe Formation. Some if not all of the uranium entered in aqueous solution with the organic matter as suggested by the banding as mentioned previously. (2) Various elements (Si, V, K, Al, and Fe) and minerals, most notably quartz, were deposited penecontemporaneously in the veins. (3) Clay minerals, jarosite, and probably iron oxide were deposited in the voids.

MODEL FOR URANIUM MINERALIZATION IN THE SESPE FORMATION

The model for uranium mineralization in the Sespe Formation consists of several elements. These elements are source of uranium, leaching, paleohydrology, host rock, and reductant, and are discussed herein. Hypothesized physical aspects of the model are shown in figure 8.

Source of Uranium

Much of the clastic material in the Sespe was derived from volcanic and granitic rock from uplands that surrounded the depositional basin (Bohannon, 1976; McCracken, 1969a; Reed, 1929). This clastic material apparently was leached by surface and ground water to provide the uranium for deposits in the Sespe (fig. 8).

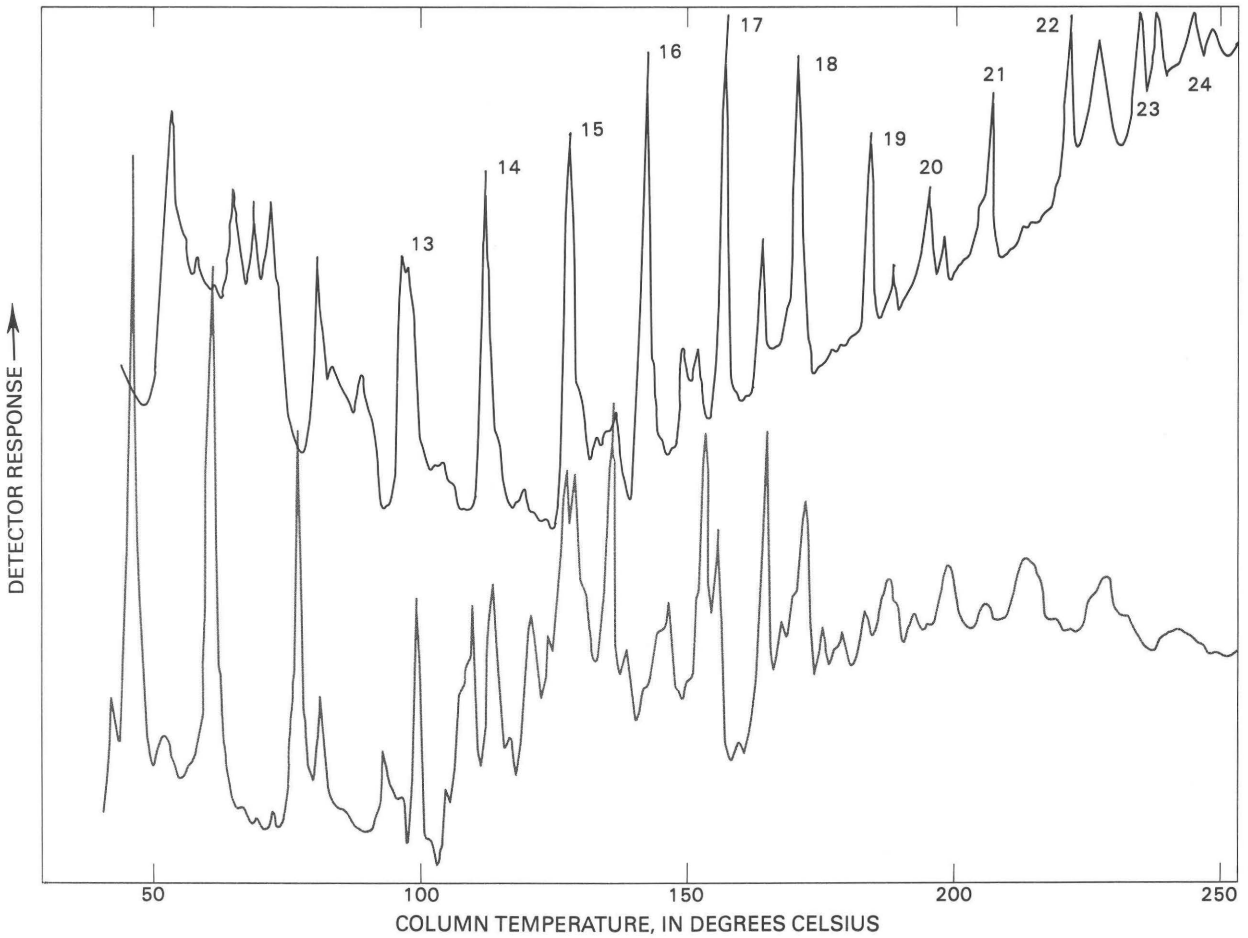


Figure 6. Examples of pyrolysis–gas chromatograms of mineralized organic carbon veins from the Beer Can #12 uranium occurrence (lower trace) and the Summit School oil seep (upper trace). Numbers are *n*-alkanes in oil seep (upper trace).

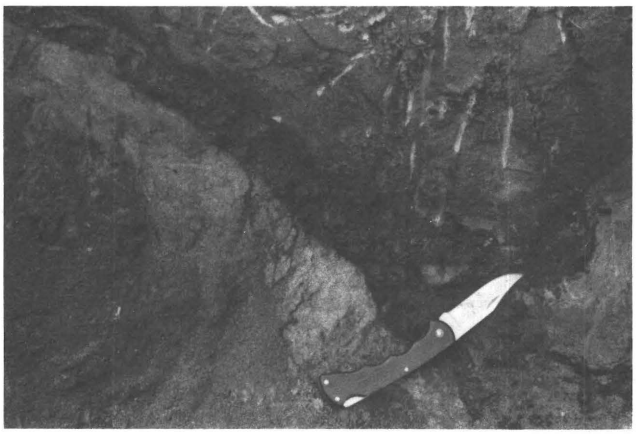
Table 4. Comparison between ICP analyses of organic carbon-rich samples and surrounding altered sandstone

[All values, average of two samples. Elements not determined or reported only as less-than values were omitted. These include Ag, Au, B, Be, Bi, Cd, Eu, Ge, Ho, Sn, Ta, W, and Zr]

	Carbonaceous veins (hand-picked samples)	Altered sandstone from near carbonaceous veins
	In percent	
Al	0.21	6.0
Ca	.08	0.9
Fe	.46	1.6
K	.08	2.5
Mg	.05	.47
Na	.03	1.8
P	.008	.25
Ti	.008	.20
	In parts per million	
Mn	24	220
As	140	<10
Ba	18	790
Ce	32	55

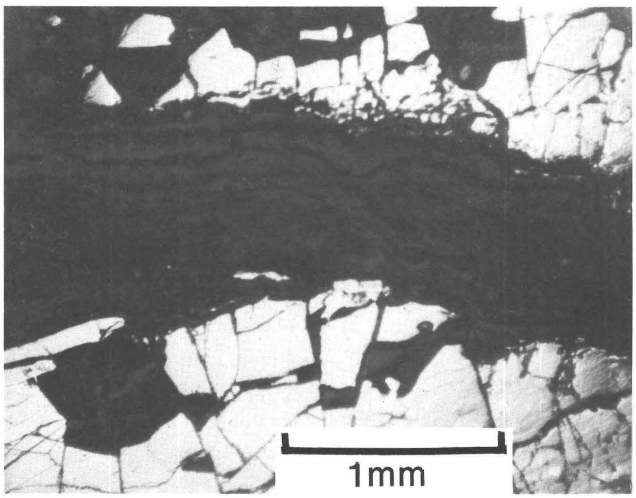
Table 4. Comparison of analyses—Continued

	Carbonaceous veins (hand-picked samples)	Altered sandstone from near carbonaceous veins
	In parts per million—continued	
Co	5	6
Cr	22	83
Cu	7	5
Ga	<4	15
La	8	30
Li	60	18
Mo	100	25
Nb	4	25
Nd	27	23
Ni	11	18
Pb	28	19
Sc	<2	6
Sr	15	210
Th	<4	6
U	1850	<100
V	2700	154
Y	44	17
Yb	2	2
Zn	5	24

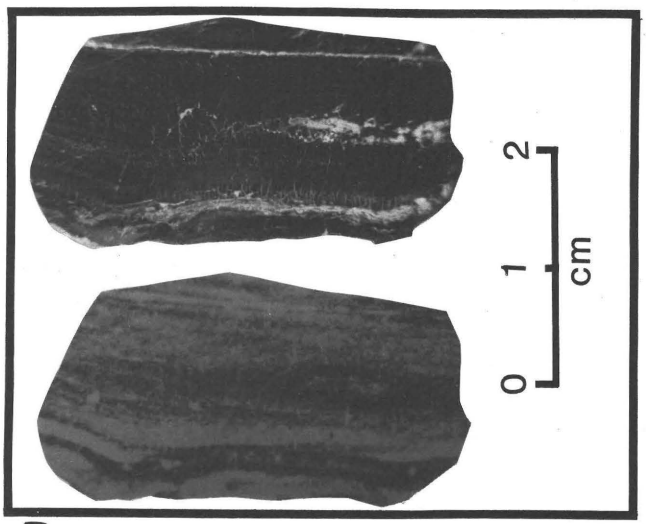


A

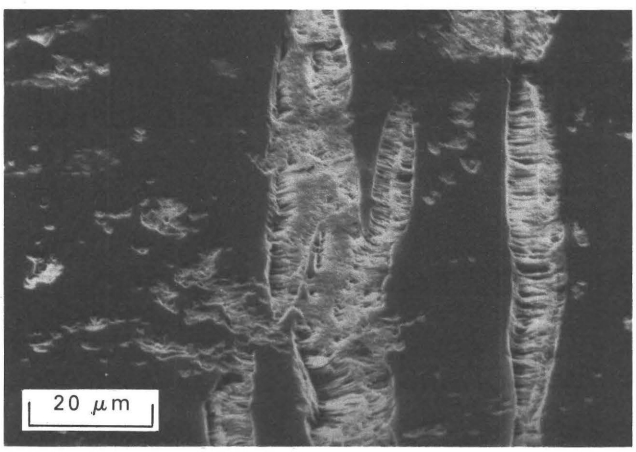
B



C



D



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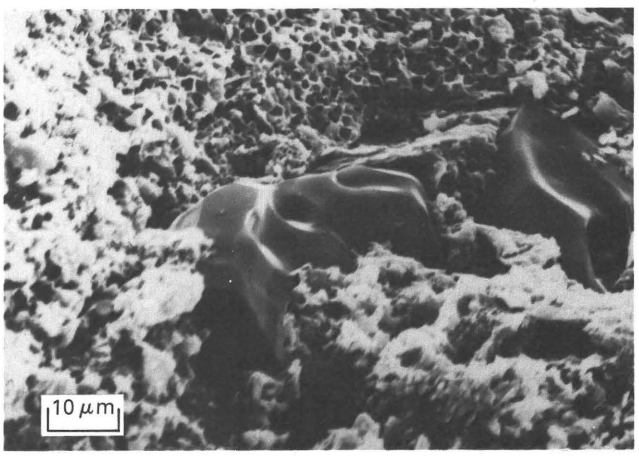

F

Samples of the Sespe are divided into two groups. The first is taken from localities or stratigraphic positions that are remote from mineralization. The second group is in the lower transitional Sespe proximal to, but not within, areas of mineralization. The Th:U ratio for the proximal group averages about 1.6 and for the remote group it averages about 4.1. This relationship suggests that the part of the Sespe represented by the remote-group samples has lost uranium through leaching and could be the source of uranium for the deposits.

Most of the samples designated in the remote group on table 2 (14 samples) are reddish brown, and, based on color, are more highly oxidized than the proximal group. These samples average 9.1 ppm thorium and 2.2 ppm uranium. Two of these samples, 61381-3 and 61381-4, were collected near the uranium deposits on Superior Ridge, but their color suggests that they were oxidized and probably leached.

The hypothesis suggested here is that the proximal group of samples represents rock that was neither leached nor enriched in uranium; thus these samples provide a baseline for comparisons. Only four samples were included in this group (table 2), which averages 6.4 ppm uranium and 9.6 ppm thorium. Three of the four samples in this group are light yellowish brown. Chemically reducing conditions apparently prevailed in parts of the Sespe, not only where uranium mineralization occurred, but also in the surrounding areas represented by the proximal samples.

Figure 7 (facing page). Carbonaceous veins in lower transitional Sespe Formation at Beer Can #12 uranium claim. *A*, Photograph of vein of carbonaceous material in the altered sandstone shown in *B*. Light streaks above knife are pick marks. Knife 7.5 in. long. *B*, Photograph of pod of altered fluvial arkosic sandstone containing veins of carbonaceous material. Hammer (lower center) 13 in. long. *C*, Photomicrograph (reflected light) of central part of polished section from vein (*D*) showing jarosite and clay minerals. Lighter areas showing fractured fragments are carbonaceous material. *D*, Photograph (upper) of vein fragment consisting primarily of carbonaceous material. Banding represents matching depositional layers on opposing sides of vein. Light-colored layers are siliceous. Void in central part was filled with jarosite, $KFe(SO_4)_3(OH)_6$; quartz, SiO_2; and clay minerals. Autoradiograph (lower) of sample shown in upper part. Notice similarity between banding shown in photograph (upper) and lighter colored bands showing high radioactivity in autoradiograph (lower). *E*, Electron micrograph of polished carbonaceous vein material showing transverse veinlets. Veinlets contain silica, vanadium, potassium, aluminum, iron, and uranium, in decreasing order. Note also numerous tiny inclusions(?) of silica-rich material. *F*, Electron micrograph of central part of carbonaceous vein (*E*) showing porous texture of jarosite and clay minerals. Smooth grain in central part of picture is a molybdenum mineral.

Neither felsic tuff nor alkaline granite, generally the most favorable uranium source rocks, is present in great abundance near any of the uranium deposits in Ventura County. Late Tertiary volcanic rock in the Ventura basin and Western Transverse Range area is mostly basaltic (Moser and Frizzell, 1982), and such rocks are not a rich source of uranium. A Miocene felsic tuff is found near the Frazier Borax Mine in Cuddy Valley, and Pliocene felsic rocks in the Wagon Road Canyon area have been evaluated as potential source rocks by Dickinson (1982). Although these rocks contain significant amounts of uranium, their location is probably outside the Sespe depositional basin and they are therefore ruled out as potential sources. Volcanic ash is a strong component of phosphatic sediments of the Santa Margarita Formation in the upper Sespe Creek area (Lowe, 1969), and samples of these sediments from near Pine Mountain collected by T. Vercoutere (written commun., 1983) averaged about 30 ppm uranium. The possibility that this uranium played a role in the Sespe mineralization cannot be eliminated, but the distant location is not favorable for the Superior Ridge and Laguna Ridge deposits.

Leaching

Uranium is mobilized from source rock in its oxidized valence state (+6) and commonly travels in solution as a di- or tricarbonate anion complex. For this reason, uranium leaching commonly occurs under oxidizing and alkaline environments. Such environments are favored by arid or semi-arid climatic conditions (which preserve the abundance of relatively soluble alkalies) and by the presence of volcanic glass that tends to release alkaline metals upon hydration. Reed (1929) suggested that the Sespe was deposited under humid or subhumid conditions because of the commonness of red beds in the sequence. However, the red color apparently resulted from diagenetic alteration of ferromagnesium minerals to hematite (McCracken, 1969b). Therefore, it is likely that the Sespe was deposited under semi-arid conditions as suggested by Reinhart (1928), who based his opinion on freshness of the feldspar. In addition, the upper part of the Sespe contains gypsum and lacustrine limestone, indicators of an arid climate.

Paleohydrology

A certain amount of structural warping may have occurred during the deposition of the Sespe Formation. As a result, accurate knowledge about the paleohydrology during the main period of mineralization, which is believed to be the Oligocene, is not available. The best assumption, however, is that the hydrologic head was

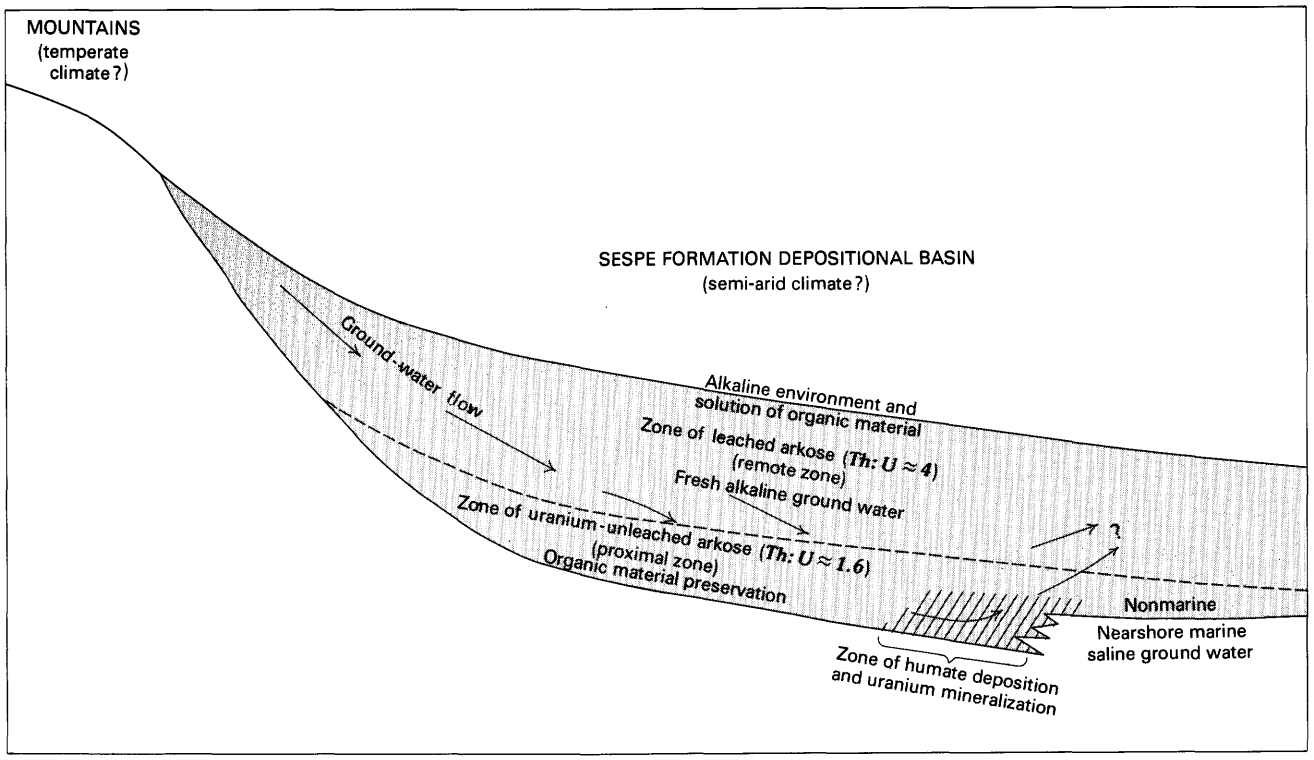

Figure 8. Hypothesized conditions for solution of uranium and humic material, transportation in ground water, and resulting uranium mineralization in lower transitional Sespe Formation (Dickinson, 1982).

generally parallel to streamflow (Butler, 1969). Bailey (1947) suggested that a major westward-flowing river was draining the Sespe depositional basin and that tributaries entered this stream from both the north and south. Paleocurrent directions determined in the upper Sespe Creek area by McCracken (1969a) and by Bohannon (1976) confirm this pattern. The Superior Ridge deposits probably result from uranium deposition in sandstone-filled paleochannels formed by streams flowing south to the main river or southwest to the seacoast. South-flowing paleostreams in the upper Sespe Creek area (Bohannon, 1976) deposited sandstone bodies that may have also served as conduits for uranium-bearing ground water and that now contain uranium.

In the Superior Ridge area, ancestral ground-water flow in the lower transitional Sespe was probably southward or southwestward inasmuch as this area lies north of Bailey's (1947) major stream and the seacoast was to the west. The uranium host rock in this area was deposited close to the beach as indicated by marine shells found in lower Sespe gravels. Ground-water movement in these sediments would have been sluggish shortly after deposition because of the low hydrologic head near sea level. This sluggishness may have contributed to establishment or preservation of the reducing environment in these rocks.

Host Rock

The main host rocks for uranium deposition are beds of yellowish- or pinkish-gray, poorly sorted to well-sorted medium- to coarse-grained arkosic sandstone of the lower transitional Sespe Formation. These lower beds, deposited in south- to southwest-trending fluvial channels, laterally intertongue with nearshore marine sandstone beds of the underlying Coldwater Sandstone. No porosity or permeability measurements were made on the uranium host rocks, but they are locally well sorted fluvial sandstones and, as such, probably had high initial permeability.

Reductant

Bowes and Myerson (1957) pointed out that uranium in the Sespe Formation is associated with carbonaceous material. This led to the conclusion that carbonaceous material provided the reductant that concentrated the uranium. At most of the uranium occurrences, the carbonaceous material was reported as carbonized wood or carbon trash. An exception is the Beer Can #12, where the organic matter occurred in veins. An additional exception is one sample of organic matter

from the Payore claims (table 3) that does not appear to have originated as carbonized wood. In addition, carbonaceous material from some deposits not examined may have been in a form other than carbonized wood. In a preliminary hypothesis, Dickinson (1982) suggested that the veins were derived from humate deposited by ground water in a manner similar to that of the Holocene Florida humates, which formed when humic-acid-bearing stream or ground water came into contact with marine water (Swanson and Palacas, 1965). The analyses presented herein are in general agreement with this hypothesis.

CONCLUSIONS

1. The uranium host rock is arkosic sandstone deposited in channels occupied by south- and southwest-flowing streams emptying directly into the sea or into a west-flowing trunk stream near the marine coast.
2. The source of the uranium was predominantly granitic and volcanic clasts that make up much of the Sespe Formation.
3. The sandstone bodies that provided conduits for uranium and humic-acid-bearing ground water maintained approximately the same structural attitude that existed at the time of sand deposition. Considering the stratigraphic distribution of the uranium occurrences (at the base of the Sespe), these sandstone bodies could not have functioned as conduits for ore-bearing solutions after Pleistocene tectonism.
4. Carbonaceous material, vanadium, and molybdenum are associated with uranium in the uranium-mineralized rocks in the Sespe and were probably transported penecontemporaneously in the uranium-mineralizing or related fluids.
5. Much, if not all, of the carbonaceous material that is associated with the uranium was formed by the precipitation of humate from humic-acid-bearing ground water in a chemically reducing zone where subsurface waters of terrestrial and marine origin intermingled.

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