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Geology and Origin of the Death Valley Uranium Deposit, Seward Peninsula, Alaska

KENDELL A. DICKINSON,

U. S. Geological Survey, Box 25046, Mail Stop 939, Federal Center, Denver, Colorado 80225

KENNETH D. CUNNINGHAM,

Tenneco Mineral Company, 300 Union Boulevard Lakewood, Colorado 80227

AND THOMAS A. AGER

U. S. Geological Survey, National Center, Mail Stop 970, 12201 Sunrise Valley Drive, Reston, Virginia 22092

Abstract

A uranium deposit discovered in 1977 in western Alaska, by means of airborne radiometric data, is the largest known in Alaska on the basis of industry reserve estimates. At about latitude 65° N, it is the most northerly known sandstone-type uranium deposit in the world. The deposit lies in Eocene continental sandstone near the eastern end of the Seward Peninsula, in the southern end of a graben that extends northward into the Death Valley depositional basin.

The deposit is apparently of epigenetic and supergene origin. The uranium was derived from the Cretaceous granite of the Darby pluton that forms part of the western side of Death Valley. Uranium from primary mineralization is in the subsurface in a marginal facies of the Tertiary sedimentary basin where nearshore coarse clastic rocks are interbedded with coal and lacustrine clay. Primary mineralization occurred when uranium-bearing oxidizing ground water moved downdip from the pluton eastward through transmissive clastic beds or on the surface. Uranium was deposited where the coal or other carbonaceous material produced a reducing environment in arkosic host rocks. The supergene enrichment is related to a soil horizon at the present ground surface. The most common uranium mineral is meta-autunite, but coffinite has been identified in the primary deposits. The host rocks for the primary deposits were partly covered by basalt flows that issued from nearby vents. Some of the basalt is highly altered, and some basalt float from the supergene zone has alteration rinds that are enriched in uranium.

Extensive exploratory drilling took place from 1979 to 1981. The average grade of the potential ore is 0.27 percent U_3O_8 and the average thickness is 3 m. The calculated reserves are 1,000,000 lbs U_3O_8; additional drilling would probably add to this figure.

Introduction

THE Death Valley uranium deposit was discovered by means of an airborne radiometric survey in 1977 near the eastern end of the Seward Peninsula in western Alaska (Figs. 1 and 2). The primary uranium deposit is in Tertiary continental sandstone that was deposited in a southern extension of the Death Valley depositional basin, called the Boulder Creek basin by industry geologists.

Initial field work was done by industry personnel during the summer of 1978. Core drilling programs were carried out during the summers of 1979, 1980, and 1981. Samples collected by the U. S. Geological Survey during 1982 and 1983 from shallow discovery pits yielded as much as 11 percent U_3O_8.

Reserves are about 1,000,000 lbs U_3O_8, based on average grade of 0.27 percent U_3O_8 and an average thickness of 3 m calculated from within a 30-m radius of holes drilled in an area of about 90 by 900 m in the vicinity of the original discovery pits. These reserves do not include uranium from a much smaller, but related, secondary surficial deposit. They make the Death Valley uranium deposit the largest known in Alaska, about 20 percent larger than the Bokan Mountain deposit in igneous rocks on Prince of Wales Island in southeastern Alaska (Staatz et al., 1980). Drilling at the Death Valley deposit, however, did not completely define the boundaries of the potential ore and the reserves reported here are a minimum estimate.

The initial drilling program in 1979 included 21 holes on about 30-m centers in an area of about 122 by 152 m near the original discovery pits along Boulder Creek (Fig. 2). These holes, most of which reached bedrock, averaged 36 m in depth. In 1980, 25 holes were drilled, averaging 65 m in depth.

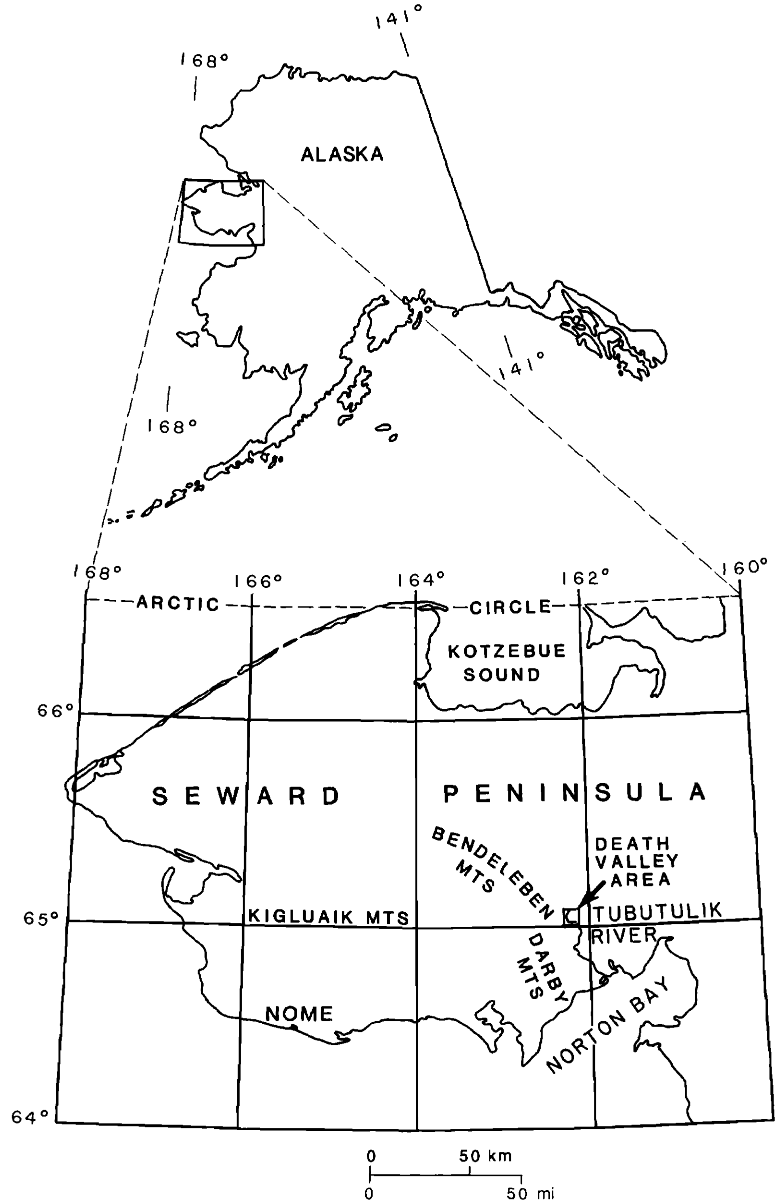

FIG. 1. General location of the Death Valley, Alaska, area.

Thirteen of the holes drilled in 1980 penetrated the entire sedimentary section and entered basement rocks. Four separate areas were drilled: (1) near or within the discovery area, (2) about 180 m south, (3) about 430 m north, and (4) between 600 and 1,100 m north. Six holes were drilled during 1981. They were scattered northwest and southeast of the discovery area.

Previous work

Only a brief description of the Death Valley uranium deposit has been previously published (Dickinson and Cunningham, 1984). However, much study of the geology pertinent to the Death Valley uranium deposit has been done. A geologic map of the Seward Peninsula was published by Hudson (1977). A geologic map of the Bendeleben quadrangle was published at a scale of 1:250,000 by Sainsbury (1974). C. C. Hawley and Associates (1978) published a version of Sainsbury's (1974) map (fig. VI 1.1) and a geologic map of part of the Bendeleben A-1 quadrangle (fig. VI-1A-1) for the U. S. Department of Energy's National Uranium Resource Evaluation (NURE) program. The geology of the

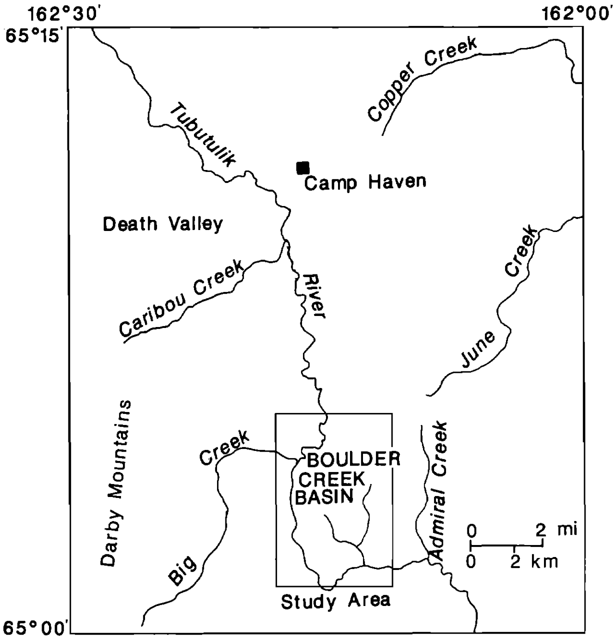

FIG. 2. Map of Bendeleben A-1 quadrangle showing study area.

southeastern part of the Bendeleben quadrangle, which contains the Death Valley uranium deposit, was mapped by Miller et al. (1972) and by Miller and Bunker (1976). The geology of the area of the Death Valley uranium deposit was mapped by Houston International Minerals Company (Fig. 3). A new geologic map was compiled by Till et al. (1986). Aeromagnetic maps have been published for the Bendeleben quadrangle (Cady, 1977; Decker and Karl, 1977). A Bouguer gravity map of the Seward Peninsula was published by Barnes and Hudson (1977).

Stream-sediment and water analysis data for the Bendeleben quadrangle were collected for the NURE program by Sharp and Hill (figs. 6 and 11, 1978). The coal associated with the uranium has been studied by Stricker and Affolter (1987).

Methods of study

Rock samples were collected from the surface in and near the initial discovery pits, and additional samples were split from cores. Cores were available for study from only about one-half of the drill holes. Most of the missing cores were from the most intensely mineralized area, thus, limiting the study in that area. Uranium and thorium were determined by neutron activation analysis (NAA) (Millard, 1976). Other elements were analyzed by energy dispersive X-ray fluorescence and semiquantitative spectroscopy (Myers et al., 1961). Additional data, obtained by similar techniques, and by closed can gamma-ray spectroscopy was acquired from industry sources. Petrologic studies included whole-rock and clay mineral X-ray diffraction, scanning electron microscope, thin sections, and autoradiographs. Correlation coefficients given in Tables 1 and 2 and mentioned in text are for linear correlations.

Seven core samples were processed for palynological study by the U.S. Geological Survey at Reston, Virginia, using standard maceration techniques. Three of the seven samples were barren of palynomorphs. Three additional samples from the core were prepared for the Survey by a private micropaleontological consulting firm and were found to contain palynomorphs. Thus palynomorph assemblages were examined from core depths of 141, 146, 146.7, 151, 378, 402.8, and 409 ft in drill hole DV-30. Analysis of the palynomorph flora was conducted by T. A. Ager. Most of the samples of lacustrine mudstone yielded well-preserved, abundant palynomorphs. Samples from coal and carbonaceous clay were either barren of palynomorphs or contained relatively sparse assemblages of low diversity.

Geology

The bedrock in the area of the Death Valley uranium deposit consists mostly of Precambrian(?) and Paleozoic metamorphic rocks that were intruded by a Late Cretaceous granitic pluton, the Darby pluton (Sainsbury, 1974; Till et al., 1986). Faulting after pluton emplacement formed a graben, which contains the Tertiary Boulder Creek basin. The Darby pluton (Fig. 3) (Miller and Bunker, 1976; Johnson et al., 1979) forms most of the western side of the graben and is the primary basement rock under the graben. Metamorphic rocks form the eastern side of the graben (Fig. 3). During and after subsidence of the graben, it was filled with interbedded sedimentary rocks and basalt flows that are mostly early Eocene in age. Younger basalt flows and sediments were deposited unconformably over the older basalt flows and sedimentary rocks. The primary uranium deposit is in the early Eocene sedimentary rocks that partly fill the Boulder Creek basin.

Igneous rocks

The late Cretaceous plutonic rock consists of orthoclase, plagioclase, quartz, biotite, and chlorite, in decreasing order of abundance. It was classified as quartz monzonite by Miller and Bunker (1976) and as granite by Johnson et al. (1979). It is coarse grained, and some orthoclase grains are as

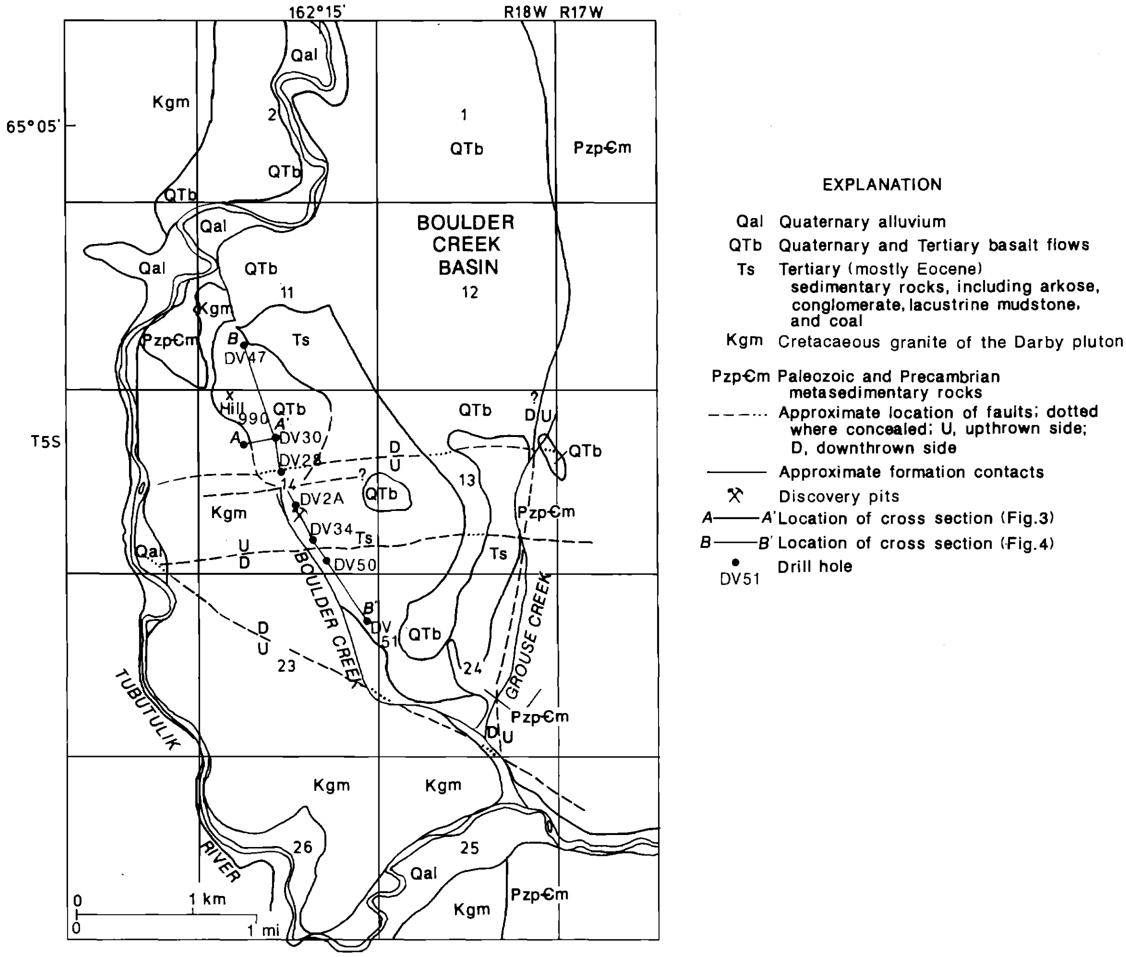

FIG. 3. Geologic map of the area of the Death Valley uranium deposit, Alaska. Modified from Houston International Minerals Corporation, unpublished annual report, 1981.

large as 1.5 cm. Aplite dikes less than 0.3 m wide cut the granite in some areas. The granite is deeply weathered and is covered by as much as 30 m of saprolite in the subsurface. In the weathered granite most plagioclase has been altered to clay that is primarily montmorillonite but includes some small amounts of illite.

The flow rocks are predominantly black aphanitic basalt containing phenocrysts of olivine, magnetite, and plagioclase. They can be divided into two groups based on probable age: the Eocene or older group, based on pollen data presented below, and the late Cenozoic group, based on an assumed correlation with flows in the Imuruk basin (about 200 mi north) and the Koyuk River valley (about 100 mi northeast) and on the apparently modern character of some of the topographic expressions. Four different flows or multiple flow units have been recognized in the late Tertiary or Quaternary basalt sequence: (1) black aphanitic basalt containing phenocrysts of olivine and magnetite, (2) lithic tuffaceous basalt containing phenocrysts of olivine and amphibole, (3) scoriaceous basalt, and (4) basalt containing glomeroporphyritic clusters of amphibole or xenocrysts of quartz and K-feldspar. Both the older and younger flows entered the Boulder Creek basin. The older flows dammed the ancestral Tubutulik River valley and a lake was formed. The younger basaltic lava flowed northward along the ancestral Tubutulik River valley and apparently diverted the river's course. The younger flows, and possibly the older flows, were extruded from a vent near hill 990 (Hopkins, 1963), which may have been controlled by east-west-trending faults (Fig. 3).

The lower basalt flows, which were unreported in the literature, are interbedded with sedimentary rocks dated as Eocene using pollen analyses. In addition, the Eocene beds overlie the Late Cretaceous pluton. The older flows occupy the deeper parts of the Boulder Creek basin.

Metamorphic rocks

The eastern side of the Boulder Creek basin is bounded by Precambrian and Paleozoic metasedimentary rocks. These rocks consist of calc-silicate schist, biotite-quartz schist, marble, black slate, and a minor amount of greenstone. In general, the metamorphic rocks strike northeast and dip steeply to the southeast. Locally the metamorphic rocks contain tight vertical folds (Till et al., 1986).

Sedimentary rocks

The major sedimentary rock types in the Boulder Creek basin include conglomerate, sandstone, mudstone, and coal (Figs. 4 and 5). Generally, the most abundant mineral in these rocks is quartz followed in descending order of abundance by K-feldspar, kaolinite, montmorillonite, illite, and mica. In addition, most of the clastic rocks contain carbonized plant material. The most abundant and perhaps the only autochthonous constituent is siderite ($FeCO_3$), which is in the lacustrine-mudstone central basin facies (Dickinson, in press). The conglomerate and sandstone were deposited in basin margin areas where deposition occurred by alluvial, fluvial, mass movement, or residual processes. They are characterized by poor sorting and general angularity of clasts. Some of the clay in the coarse-grained rocks probably resulted from alteration of plagioclase clasts. Most of the clasts were derived from the granite especially near the base of the stratigraphic section. Indeed, the transition from granite to overlying sandstone is gradational. Yet plagioclase, which is common in the granite, is uncommon in the sediment. Much of the later sediment probably entered the basin by fluvial transport from distant provenance areas or from the metamorphic areas to the east. The occurrence of kaolinite as the most common clay mineral in the sedimentary rocks and its scarcity in the altered quartz monzonite and basalt suggests that it was derived by authigenesis or from a different sediment source.

The mineralogy of the mudstone, which is predominantly of lacustrine origin, resembles that of the coarser clastic rocks except for a greater proportion of clay and the presence of fine-grained siderite in profundal samples. Some of the lacustrine mudstone is varved, and some contains intraclasts or disrupted bedding believed to have resulted from turbidity currents. The varves together with a lack of lacustrine biota suggest a meromictic lake (Dickinson, in prep.). One of the few modern lakes containing laminated siderite is Lake of the Clouds in northern Minnesota (Jones and Bowser, p. 216, 1978). Lake of the Clouds is a permanently stratified stagnant (meromictic) lake with chemically reducing alkaline bottom water (a monimolimnion) (Anthony, 1977). In an area just south of lake basin at Boulder Creek the granitic saprolite is cemented with calcite. The occurrence of calcite seems to be local and may be related to fractures or veins. Abundant calcium in the lake water would have prevented the formation of siderite.

The coal, which was studied by Stricker and Affolter (1987), is generally bituminous and low in sulfur. It occurs in beds more than 30 m thick in the central part of the Boulder Creek basin (Figs. 3 and 4). The thick sequences of coal were deposited prior to the entrance of early Eocene lava in this part of the basin. According to Stricker and Affolter (1987), the grade of the coal increases near its upper contact with the basalt.

The sedimentary rocks in the Boulder Creek basin generally are fine grained upward and probably represent a lower source terrane. The initial sediments were granitic saprolite that developed from deep weathering of the granitic surface. As the basin began to deepen, fluvial and alluvial sedimentation predominated and the resulting sandstone and conglomerate became better sorted. The facies pattern that formed next included a swamp in the central part of the basin surrounded by fluvial and alluvial deposits. Eocene basaltic lava then flowed into the basin, filling the deeper parts and damming the major stream drainage. This dam, together with additional subsidence, formed an ancestral lake in the central part of the basin. Lacustrine sediments reached thicknesses of more than 30 m. Knowledge of the sedimentary sequences was limited by drilling to the western littoral and profundal areas of the lake. During lacustrine sedimentation organic material continued to be deposited in swampy onshore areas where it was interbedded with alluvial and fluvial sediments.

Structure

The Boulder Creek basin is apparently a graben (Fig. 3) that formed in the north-south Kugruk fault zone (Till et al., 1986). Faults are difficult to recognize in this area, however, because active soil creep or solifluction has disturbed the modern surface. In addition to the graben-bounding faults, east-west-trending faults were suggested by lineaments on aerial photographs. East-west-trending faults that displaced rocks downward to the south apparently account for the deep southern part of the basin (Fig. 5). Rotated fault blocks resulted in dips as great as 50° but more commonly from 10° to 30°, formed after the deposition of the Eocene sediments. The faulting probably occurred before the roughly horizontal younger volcanic flows and Quaternary sediments were deposited as shown in Figures 4 and 5, but this conclusion remains somewhat uncertain because of poor exposures. The faulting does not

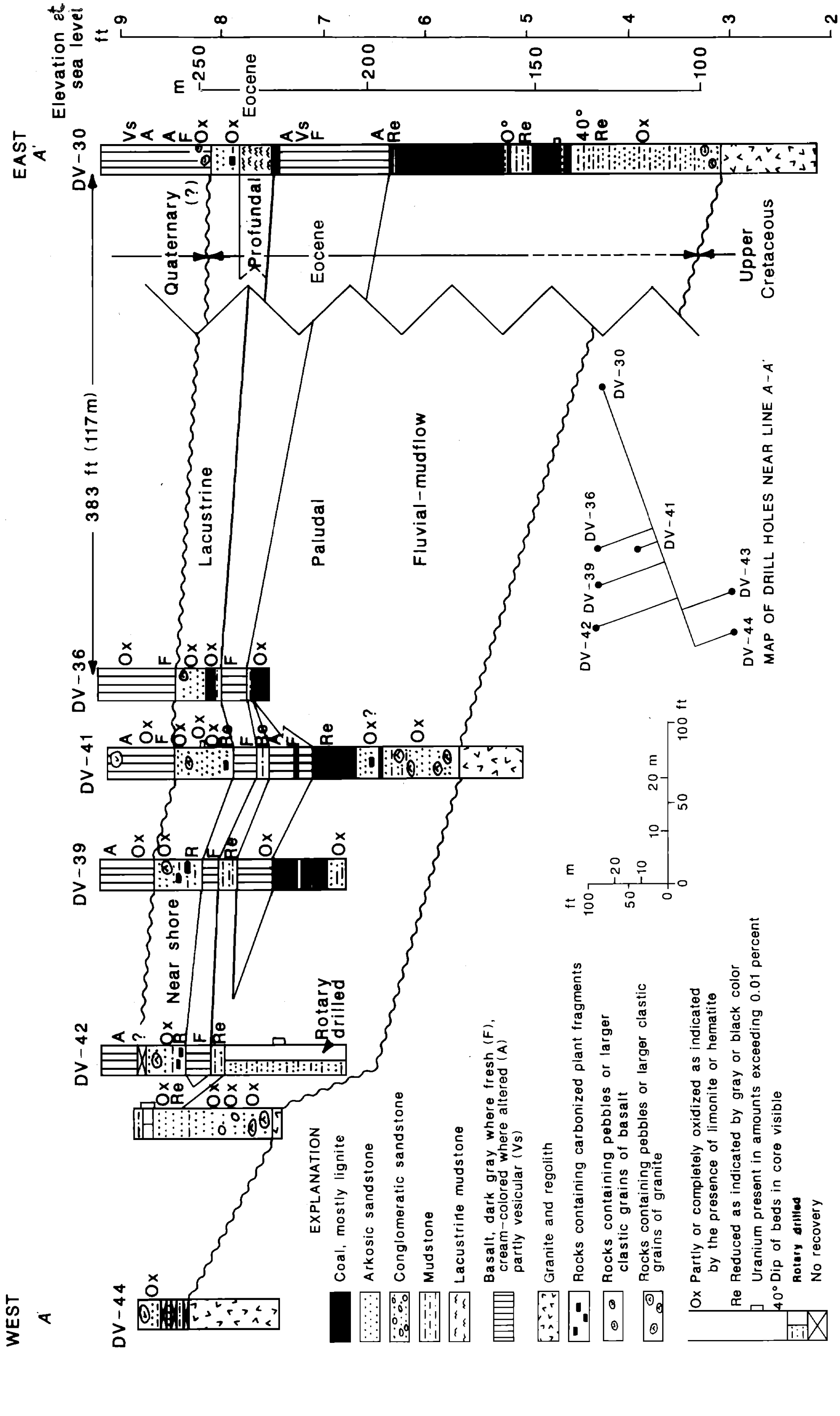

FIG. 4. Line of sections (A-A', Fig. 3) extending from the margin of the Boulder Creek basin (west) to an offshore area (east). Sections are based primarily on drill core descriptions.

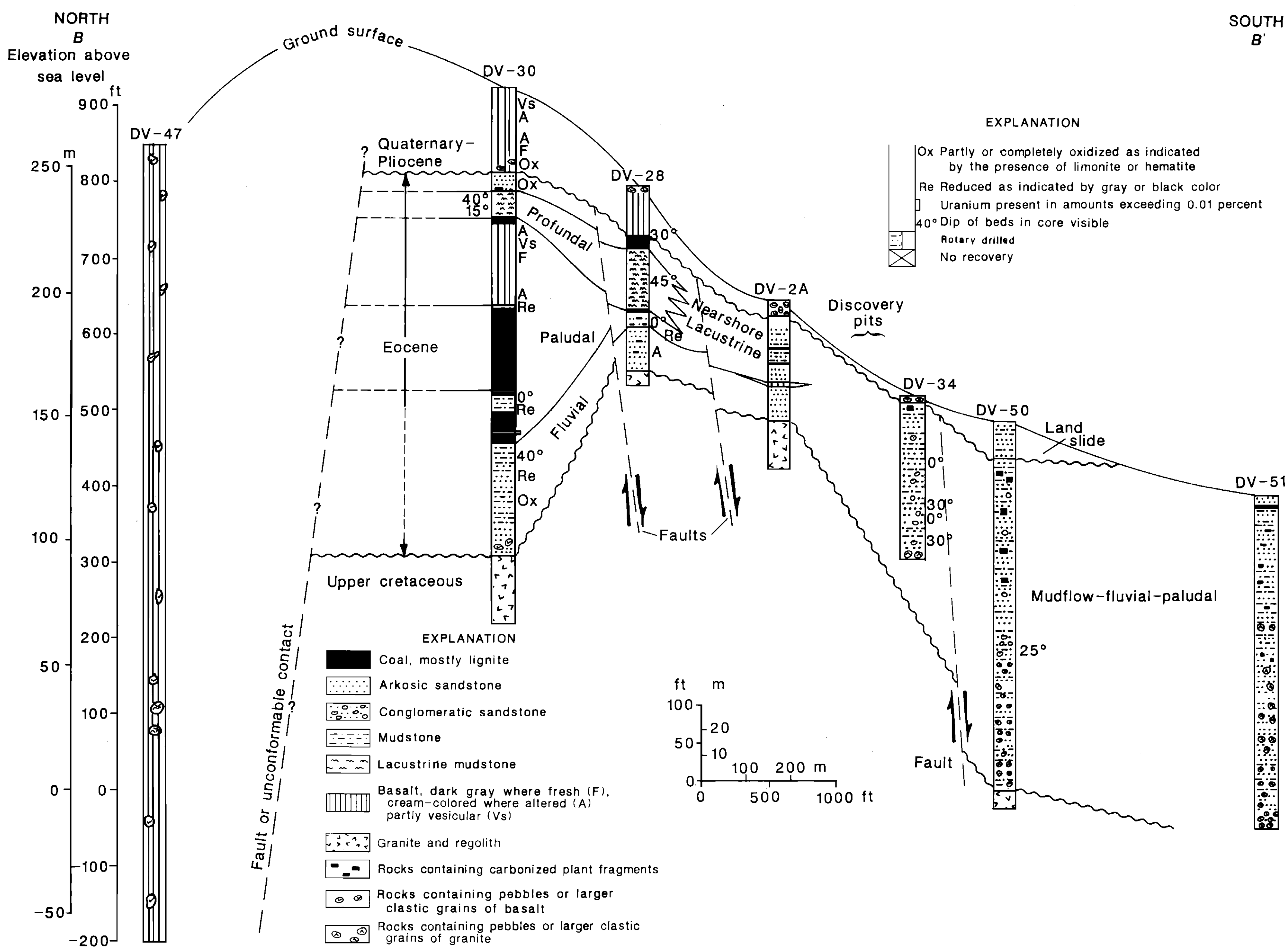

FIG. 5. Line of sections (B-B', Fig. 3) extending from the north to the south through the Boulder Creek basin. Sections are based primarily on drill core descriptions.

seem to have upset the regional facies patterns. Some tectonic activity may have occurred during lacustrine deposition as suggested by slump and turbidite sediments.

Palynology

Age

Palynological evidence for an early Eocene age of sediments underlying late Cenozoic basalts in Death Valley was found in core from drill hole DV-30. Palynomorph assemblages from the core samples include the following pollen types: *Platycarya, Plicatopollis, Carya, Castanea* type, *Ulmus* type, *Alnus, Betula, Paraalnipollenites confusus,* Sapotaceae, *Momipites,* Ericales, and many other angiosperms, some of unknown taxonomic affinity. Gymnosperms are not abundant in most samples, but include taxa such as *Larix* type, Taxodiaceae (probably *Metasequoia* and/or *Glyptostrobus*), and several conifers with basaccate type pollen. A diverse fungal spore assemblage is present in some samples and includes a useful biostratigraphic marker, *Pesavis tagluensis.*

The early Eocene age assignment of these deposits between core depths of 141 and 409 ft is based primarily upon the restricted age ranges of several palynomorphs known from other areas of Alaska, arctic Canada, and elsewhere in North America. *Platycarya* is a well-known indicator of early to middle Eocene age in North America (Rouse et al., 1970; Hickey et al., 1983; Wing, 1984; Wing and Hickey, 1984; McIntyre, 1985, 1986). Plant macrofossils of *Platycarya* are known from the gulf of Alaska region, and until recently, were considered to be of middle Eocene age (Wolfe, 1977). Recent evidence, however, suggests that *Platycarya* is actually of early Eocene age (Wolfe and Poore, 1982). The fungal spore *Pesavis tagluensis* appears to be restricted to rocks of mid-Paleocene to mid-Eocene age in arctic North America (Rouse, 1977). *Paraalnipollenites confusus* is commonly found in Paleocene rocks of arctic Canada (Rouse, 1977) but has recently been discovered in rocks of early Eocene age in southern California (N. O. Frederiksen, pers. commun., 1986), and in the Natsek E-5 well in the Beaufort Sea (McIntyre, 1985, 1986). Indigenous specimens are unknown from rocks younger than early Eocene, however. The overlapping biostratigraphic ranges of these taxa suggest that the sampled core interval is most likely to be of early Eocene age. The sedimentary rock below a depth of 409 ft in hole DV-30 was not analyzed for pollen and could be older than Eocene, although it must be younger than the underlying Upper Cretaceous granite.

Eocene pollen and spore floras from Alaska are as yet poorly known and have been reported from only a few localities in the state (Adkison and Newman, 1973; Yeend, 1977; Ager et al., 1985). Eocene floras are also known from recent investigations in arctic Canada, however, and have been described in greater detail (Rouse, 1977; Choi, 1983; McIntyre, 1985; Norris, 1986).

Climate

The pollen and spore assemblages from the Death Valley core provide a basis for interpreting the early Eocene climate of Seward Peninsula. Interpretations of paleoclimates based on palynological evidence alone must be limited to broad generalizations because of the uncertainties about the precise taxonomic relationships between some of the fossil and modern genera. The biostratigraphic ranges and climatic tolerances of modern genera provide some basis for reconstructing the climate of the past if fossils assignable to the same genera are found. However, it is considered likely that the climatic tolerances of many taxa have changed through time, so modern analogs must be used cautiously as a means of approximating past climates (Wolfe, 1979). Studies of plant megafossils in other regions, however, have shown that the warmest global climates of the Tertiary occurred during the early Eocene (Wolfe and Poore, 1982).

With these caveats in mind we offer an interpretation of the paleoclimate. The palynomorph assemblages of core from drill hole DV-30 contain many genera that are now restricted to regions of the world where climates are temperate to subtropical. Thus, it is clear that the early Eocene climate of Seward Peninsula was significantly warmer than the present arctic to transitional-arctic climate in the region. But how much warmer was it? To refine the interpretations of paleoclimate further, one can examine evidence from fossil leaf floras from southern Alaska. Wolfe (1977, 1979) used taxonomic affinities and morphologies of fossil leaf assemblages to interpret past climates and vegetation. In the Gulf of Alaska, Eocene leaf floras (Wolfe, 1977; Wolfe and Poore, 1982) suggest that the climate in the Gulf of Alaska was paratropical. Paratropical climate is characterized by mean annual temperatures (MAT) in the range of 20° to 25°C, abundant precipitation year around, little seasonal change in temperatures, and a probable lack of frost at low elevations (Wolfe, 1977). The modern mean annual temperature of the Gulf of Alaska at sea level is about 5°C. Early Eocene vegetation of the Gulf of Alaska was broad-leaved evergreen forest (Wolfe, 1977), whereas the modern vegetation of the region is coastal Sitka spruce (*Picea sitchensis*)-hemlock (*Tsuga* spp.) forest.

In contrast, the modern climate of the Seward Peninsula is significantly colder due to its close proximity to cold seas and to the arctic air mass. Present-day mean annual temperature on the Seward Peninsula is about −5°C (about 10°C colder than the Gulf of Alaska coast). Modern vegetation of the Seward Peninsula is mostly tundra, with boreal spruce (*Picea*) forest reaching its western limit on the southeastern quarter of the peninsula.

During early Eocene time the vegetation of the Seward Peninsula appears to have been mixed broad-leaved deciduous and broad-leaved evergreen forest with some conifers. Thus vegetation differences existed between the two regions in early Eocene time as they do today, due to latitudinal and other geographic influences. Based upon the inferred forest type found on the Seward Peninsula during the early Eocene we interpret the climate of the peninsula to have been at least as warm as warm temperate (mean annual temperature in range of 11°–13°C) and perhaps to have been subtropical (mean annual temperature about 13°–18°C) (Wolfe, 1977, 1979). The climate was probably moist with significantly higher precipitation than occurs today in the region (modern mean annual precipitation is ca. 250–500 mm over most of the peninsula). During early Eocene time the mean annual precipitation may have been on the order of 800 to 2,000 mm per year.

Significance of Latitude

Sandstone-type uranium orebodies have been thought to be only in sediments that were deposited at latitudes of less than 50° (IAEA, 1983). The paleolatitude of the Seward Peninsula during the Tertiary was as high or higher than its present 64° (Dott and Batten, 1981). According to the North American reference pole for the Paleocene (Diehl et al., 1983), the present position of the Seward Peninsula is about 8° lower in latitude than it was during the Eocene. The occurrence of the Death Valley uranium deposit at 64° north latitude and of sandstone-type uranium deposits nearly as far north in the Healy Creek area (Dickson, 1982), is ample evidence that a high-latitude limitation for this kind of deposit has not been established; exploration for sandstone-type deposits in high latitudes should not be curtailed for this reason.

There is apparently no special significance in terms of mineralization processes at the latitude of Death Valley, especially considering that the climate there was much warmer during the early Eocene than now and that the Death Valley deposit resembles basal deposits in other areas at much lower latitudes.

Geochemistry

Insufficient chemical data are presently available to distinguish between the two ages and modes of mineralization clearly. Nevertheless, certain inferences about the chemical nature of the mineralization can be made. Two groups of samples were analyzed by the six-step semiquantitative spectroscopy method. One group consists of samples that were collected for this study and were analyzed in the laboratories of the U. S. Geological Survey. The other group was collected by industry geologists and analyzed by a commercial laboratory (Table 1). The two groups of samples are discussed separately because more information is available for the Survey samples and because detection limits were different.

Strontium, barium, phosphorus, arsenic, and molybdenum are apparently positively correlated with uranium in samples of rock mineralized during the primary or secondary mineralization (Tables 1 and 2). G. A. Stricker and R. A. Affolter (in prep.) found an enrichment of uranium (as much as 37 ppm) and tungsten (as much as 360 ppm) near the base of the thick coal in drill hole DV-30 (Figs. 4 and 5). Vanadium and manganese may be negatively correlated with uranium in the samples. Judging from the low sulfur coal and from the dearth of sulfides in the deposit, it is also low in sulfur.

Strontium and barium are positively correlated with uranium in both groups of samples. This relationship suggests that strontium and barium were involved in the mineralizing processes, especially in the supergene enrichment. The barium zeolite harmotome [$(K_2Ba)Al_2Si_5O_{14} \cdot 5H_2O$], a mineral of the phillipsite group, and phillipsite [(K_2Ca)-$Al_2Si_4O_{12} \cdot 4\frac{1}{2}H_2O$] were found in veins in the younger basalt. Both strontium and barium are alkaline earth metals, and they may have been carried in solution in alkaline ground water, together with uranium, as carbonates. Caliche soil profiles in south Texas contain both strontium and barium associated with uranium (Dickinson, 1977).

The correlation between U and P is fairly certain even though the U.S.G.S. sample set contains insufficient data. The relationship between U and P is easily explained because much of the uranium mineral is a phosphate, autunite [$Ca(UO_2)(PO_4) \cdot 10$–$12H_2O$], or a variety of autunite. Arsenic also probably correlates with uranium, but there is insufficient data to calculate the correlation coefficient. However, the three samples containing As in excess of the detection limit are the three containing the

TABLE 1. Trace Element Composition of Uranium-bearing Sedimentary Rock from the Death Valley Uranium Deposit

Sample number	Depth in feet	U	V	Be	Sr	Ba	As	P	Mo	Mn	Pb	Cu	Ni
A. Samples analyzed by the U. S. Geological Survey													
Surficial sandstone													
8382-1	0	50,700	N	15	1,500	1,500	1,000	1,500	30	70	300	7	N
8382-2	0	117,000	50	15	1,500	2,500	2,000	3,000	20	70	300	15	500
8382-6	0	3,280	30	7	300	700	N	300	15	300	70	7	5
8382-7	0	6,730	15	30	700	700	N	3,000	7	300	150	3	N
Sandstone core samples													
21-106	106	65	30	7	200	700	N	N	70	1,500	150	7	30
21-132	132	8	30	15	150	700	N	N	N	1,500	150	7	3
22-19	19	81	150	7	300	1,500	N	N	30	70	150	70	30
22-27	27	54	30	7	300	1,500	N	N	N	150	70	3	7
30-493	493	15	300	2	300	1,500	N	N	15	300	50	70	30
38-108	108	25	70	15	300	500	N	N	7	200	500	30	15
Mudstone core samples													
28-102	102	8	150	3	150	500	N	N	N	1,000	150	100	70
28-159	159	2	15	2	15	150	N	N	N	15,000	N	10	7
29-176	176	10	150	7	70	500	N	N	7	10,000	100	70	30
30-159	159	9	150	3	70	300	N	N	7	1,500	70	70	70
34-48	48	4	150	10	150	500	N	N	10	150	150	50	30
34-166	166	4,700	150	15	300	500	N	N	7	300	150	70	30
Lower detection limit			7	1.5	5	2	1,000	200	3	1	10	1	5
B. Samples analyzed by private laboratory													
25764	109	470	70	7	100	200	N	1,000	70	300	150	50	30
25775	40	7,600	30	15	300	500	500	7,000	700	30	150	10	10
25776	115	120	100	7	100	300	N	1,000	20	300	50	30	50
25777	39	150	70	7	100	500	N	500	15	200	50	30	30
25783	46	290	20	10	100	100	N	1,000	N	70	70	10	15
25789	44	81	100	15	50	200	N	500	70	500	30	30	50
25809	39	1,900	30	7	100	300	N	1,000	300	70	70	7	15
25810	42	50	70	7	100	300	N	1,000	15	500	70	30	50
25811	23	230	70	10	100	300	N	500	200	150	20	5	30
25823	25	120	30	7	100	150	N	1,000	N	700	20	3	10
Lower detection limit			30	7	100	150	200	1,000	5	10	20	5	5

All values are in ppm, N = not detected, L = detected but not determined

most uranium (Table 1). This correlation may result from the geochemical similarity of arsenic and phosphorus or the affinity of arsenic for the iron disulfide minerals, marcasite and pyrite, which are associated with the carbonaceous material. Lead is positively correlated with uranium in both data sets, but the correlation coefficient is above the 90 percent confidence level only in the commercial data set and is, therefore, uncertain. Lead was also found by energy dispersive XRF in a uranium-enriched sample (Fig. 6). The two sample sets show opposite correlations for Mo and Ni.

Both data sets show negative correlation coefficients for vanadium and manganese, but these coefficients are below the 90 percent confidence level and are not confirmed. In some uranium deposits where the common uranium mineral is a vanadate, such as carnotite, uranium is correlated with vanadium. This correlation is positive, for instance, in Jurassic uranium ores in the western conterminous United States (Shoemaker et al., 1959). Vanadium is an ore element in these deposits and its content reaches more than 1 percent V. In the Death Valley, Alaska, deposits, four uranium-enriched samples averaged less than 0.003 percent V.

Manganese is high in the nonmineralized mudstones compared to the average composition for igneous rocks (Table 2). This relationship could

TABLE 2. Summary Statistics for Trace Elements of the Death Valley Uranium Deposit

	U	V	Be	Sr	Ba	As	P	Mo	Mn	Pb	Cu	Ni
A. U.S.G.S. sample set												
Average values (in ppm)[1]												
Surficial sandstone, highly mineralized (4 samples)	44,400	24	17	1,000	1,225	—[2]	1,950	18	185	205	8	—
Subsurface sandstone, slightly mineralized (6 samples)	53	101	9	258	1,070	—	—	21	620	178	31	19
Subsurface mudstone, nonmineralized to mineralized (6 samples)	794	128	7	126	408	—	—	6	4,660	103	62	40
All samples	11,425	90	10	394	859	—	—	—	2,026	157	37	54
Linear correlation coefficients between uranium and other elements (number of valid pairs in parentheses)												
All samples		−0.18 (15)	0.29 (16)	0.88 (16)[3]	0.64 (16)[3]	—	—	0.08 (12)	−0.18 (16)	0.41 (15)	−0.27 (16)	0.98 (14)[3]
Samples containing over 10 ppm U		−0.19 (9)	0.18 (10)	0.88 (10)[3]	0.64 (10)[4]	—	—	0.01 (9)	−0.29 (10)	0.37 (10)	−0.26 (10)	1.0 (8)[3]
B. Privately analyzed sample set												
	U	V	Be	Sr	Ba	As	P	Mo	Mn	Pb	Cu	Ni
Average values (in ppm)[1]												
Subsurface samples of lignite, lignitic sandstone, and lignitic mudstones	1,101	59	9	—	285	—	—	—	282	68	—	29
Linear correlation coefficients between uranium and other elements (number of valid pairs in parentheses)												
All samples		−0.43 (10)	0.55 (10)	0.97 (10)[3]	0.56 (10)[4]	—	0.97 (7)[3]	0.96 (8)[3]	−0.49 (10)	0.64 (10)[5]	−0.38 (9)	−0.49 (10)
Average composition of igneous rock (Wedepohl, 1971)	3.5	95	2	290	590	1.7	810	1	690	15	30	44

[1] For calculating averages, 0.7 × lower detection limit is used for values below lower detection limit (Miesch, 1947, p. 26)

[2] — = insufficient data

[3] Correlation valid at 99 percent confidence level

[4] Correlation valid at 90 percent confidence level

[5] Correlation valid at 95 percent confidence level

create a negative correlation coefficient between U and Mn even if the Mn was at normal levels in the uranium-mineralized sandstone. Other elements found in uranium-mineralized surficial sandstone using energy dispersive XRF are copper and zinc (Fig. 6). For comparison, the Blizzard deposit is enriched in Zn, Ni, Co, and Mo.

The Uranium Deposit

The uranium deposit, excluding the part produced by supergene enrichment, is of the epigenetic sandstone type. It is probably a roll-type deposit, but it is difficult to classify because the shape of the uranium-enriched body is complex and not accurately known. On the basis of sedimentary environments, the deposit would be classified as a basal-type deposit because the host rocks lie directly on igneous and metamorphic terrane (Finch and Davis, 1985). In the classification scheme of Nash et al. (1981), the deposit would be of single-solution origin, whereby uranium-bearing ground water was filtered through the host rocks, and the uranium was precipitated at a redox interface by a biogenic or nonbiogenic mechanism related to carbonaceous material and chemical reduction.

The primary uranium deposit at Death Valley resembles several of the basalt-type deposits listed by Boyle (1985). These include the Ningyo-toge deposit on Honshu Island, Japan (Katayama, 1985; Sakamaki, 1985), the Blizzard and Tyee deposits in southern British Columbia, Canada (Boyle, 1982), and the Sherwood deposit in Stevens County, Washington (Milne, 1979). The Ningyo-toge deposit on Honshu Island is characterized by Cretaceous granitic bedrocks, conglomeratic host rocks, lacustrine sedimentary rocks, and overlying basalts. A volcanic source rock rather than a granitic one was proposed for the Sherwood occurrence. The Blizzard deposit is characterized by uranium mineralization in unconsolidated conglomeratic Tertiary rock deposited in faulted paleovalleys formed on granitic intrusive bedrock. Although there are many similarities between this British Columbia deposit and the Death Valley deposit, including a basaltic cap rock, there are geochemical and mineralogical differences.

Mineralization

Uranium for the Death Valley deposit was apparently dissolved from the Darby pluton, carried eastward in oxidizing ground water, and precipitated in a chemically reducing environment in Tertiary sedimentary rocks that contain abundant carbonaceous material. Although mineralization may have been intermittent through the Tertiary and continued until the present, two general ages or modes of mineralization are probably represented by the present deposits. These are an earlier Eocene(?) primary epigenetic mineralization (Figs. 4, 5, 7) and a later Holocene secondary supergene enrichment (Fig. 8).

The primary mineralization occurred in Eocene sedimentary rocks in the Boulder Creek basin. The

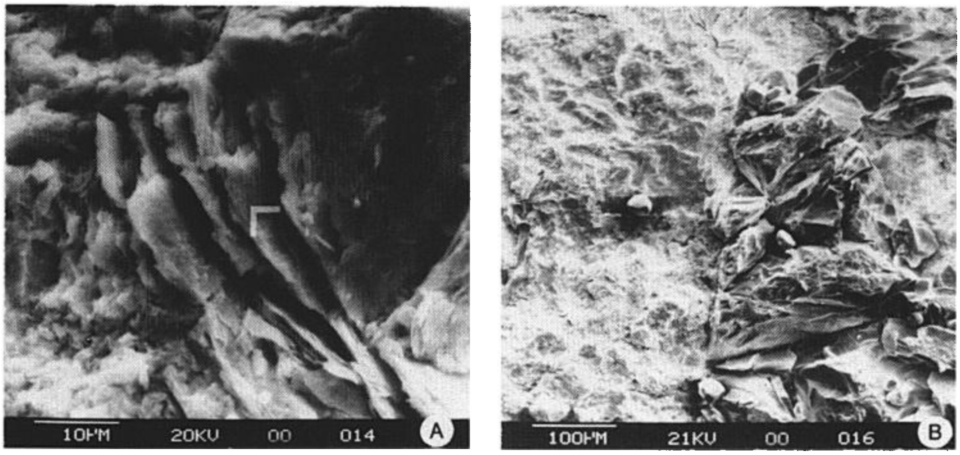

FIG. 6. Electron micrographs of a highly altered uraniferous (12% U_3O_8) arkosic sandstone surface sample. A. Tabular orthorhombic crystals of the mineral autunite $[Ca(UO_2)_2(PO_4) \cdot 10H_2O]$. A partial analysis by energy dispersive XRF of spot near marker indicated: U_3O_8, 69 percent; P_2O_5, 16 percent; K_2O, 4 percent; and CaO, 3 percent, together with 2 percent or less of CuO, Al_2O_3, Fe_2O_3, SiO_2, ZnO, and NiO. B. Approximately the right half of the micrograph is metamict quartz, and the left half is altered material. A partial analysis by energy dispersive XRF of a spot on the left half indicated: Fe_2O_3, 32 percent; U_3O_8, 18 percent; SiO_2, 17 percent; CuO, 16 percent; and ZnO, 11 percent. Small subhedral grains are sphalerite (ZnS).

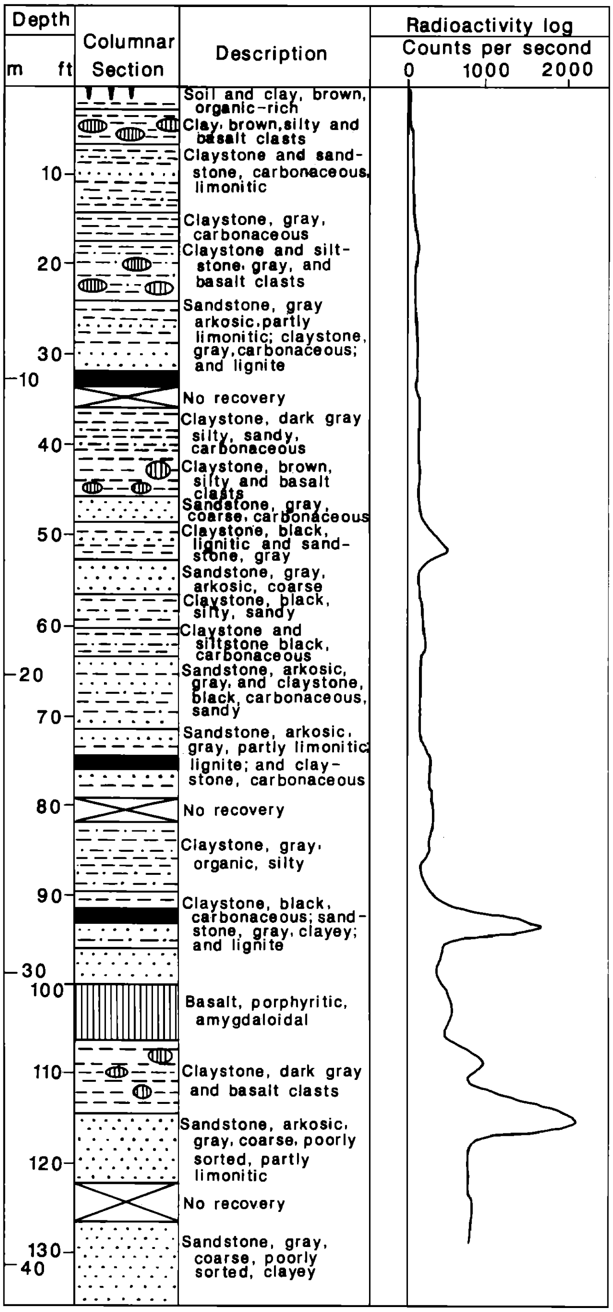

FIG. 7. Lithologic and radiometric logs of hole DV-21 located near drill hole DV-2A (Fig. 3), in the area of the primary uranium mineralization. Data were provided by D. Hedderly-Smith (writ. commun., 1984).

mineralized rocks are fairly widespread in the subsurface where they are present at stratigraphic positions both below and above the Eocene basalt and lacustrine rocks. Mineralized rocks extend to depths of about 91 m (Fig. 3). The primary mineralization is found in an area of about 3,000 by 120 m. The only uranium mineral identified by XRD in the reduced zone is coffinite $[U(SiO_4)_{1-x}(OH)_{4x}]$. The uranium is associated with carbonaceous material and in a few places with pyrite, although pyrite is not common. Where the primary uranium has been oxidized, autunite is the only uranium mineral identified.

The secondary uranium mineralization (or supergene enrichment) is apparently related to the present surface and is more accurately classified as a surficial deposit. Uranium minerals identified by XRD from the secondarily enriched samples are meta-autunite I, $Ca(UO_2)_2(PO_4)_2 \cdot 8\text{–}10H_2O$, meta-autunite II, $Ca(UO_2)_2(PO_4)_2 \cdot 0\text{–}6H_2O$, and lead meta-autunite, $Pb(UO_2)_2(PO_4)_2 \cdot 8H_2O$.

Neither the surface nor the subsurface uranium-enriched body is in radioactive equilibrium. The low-grade material, containing less than about 0.1 percent U_3O_8, has a surplus of daughter products and the high-grade material has a deficiency of daughter products (Fig. 9). This disequilibrium pattern is typical for many deposits of this kind and was attributed by Santos (1975) to a continuous redistribution of daughter products, mainly ^{226}RA.

The primary uranium mineralization occurred

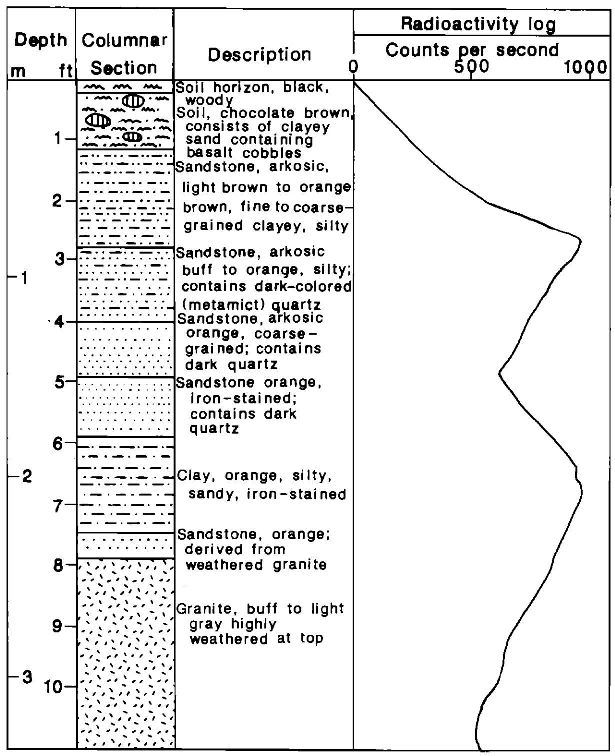

FIG. 8. Lithologic and radiometric logs through near-surface sediments where supergene enrichment has occurred. Core was taken from a locality about 100 m northwest of the discovery pit (Fig. 3).

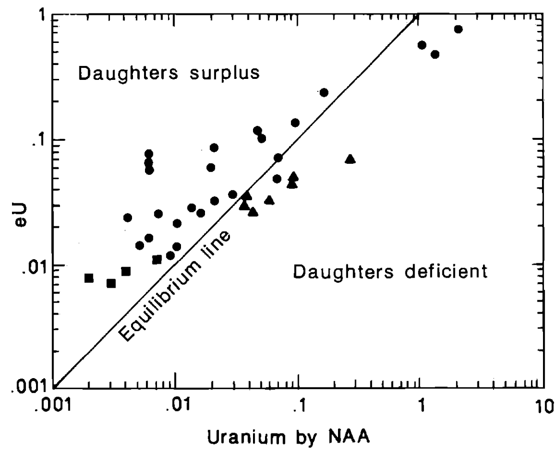

FIG. 9. Scatterplot showing uranium equilibrium relations for primarily enriched samples from drill hole DV-31 (●) and for secondarily enriched samples from shallow holes DVS-7 (■) and DVS-10 (▲).

some time after the early Eocene (age of the host sediment deposition); the secondary mineralization occurred in the Holocene. Some evidence suggests that the primary mineralization took place shortly after host-rock deposition. First, the Late Cretaceous granite source rocks probably would have supplied uranium to ground water at a greater rate during the time of high relief when the graben was formed. This high relief is suggested by sediments that appear to have been deposited by mass movement, such as slumps or mudflows and lacustrine turbidites. Second, a warmer climate may have been more favorable to the uranium-leaching process. Third, the mineralization seems to have occurred before the post-Eocene faulting. Indeed, this faulting would have disrupted uraniferous groundwater movement in the more permeable basinward-dipping beds.

The supergene enrichment is related to the present surface. It is probably modern, and for that matter, its formation could be still in progress. The involvement of the recent surficial mudflows and soil formation in the uranium enrichment process indicates a recent age.

Source rocks

The Darby pluton is considered the most likely uranium source rock for the deposit because of its relatively high uranium content, the higher variability of the uranium with respect to the thorium in the samples, and the proximity of the pluton to the Boulder Creek basin. The pluton was recognized as part of a uranium province by Miller and Bunker (1976) who reported averages of 11.2 ppm uranium and 58.7 ppm thorium for 13 samples. The average Th/U ratio, 5.2, is high relative to an average of 3 to 4 for most granitic rocks (Rogers and Adams, 1978). The coefficient of variation calculated from Miller and Bunker's (1976) data is higher for uranium (38%) than it is for thorium (19%) suggests that uranium was mobilized in the oxidizing surficial water. Some of the mobilized uranium was apparently removed from the outcrop samples of the pluton and the original uranium content was apparently higher. The Th/U ratio in soils developed on plutonic rocks in the area surrounding Death Valley (the Bendeleben A-1 quadrangle) averages 10, nearly twice the value found by Miller and Bunker (1976) for rocks of the Darby pluton (Table 3). The possibility that the Darby pluton is part of a uranium province was also suggested by West (1953) on the basis of high uranium contents in panned stream-sediment concentrates. The other major rock types in the Boulder Creek basin area, basalts and metasedimentary rocks, are an unlikely source of uranium.

Paleohydrology

The uranium-bearing waters traveled from the source rocks to the host rocks at the surface or in transmissive subsurface zones. The mineralization may have taken place at the top of a stagnant water table in the manner suggested for the Ningyo-toge deposits (Katayama, 1958). If so, then two general water tables were present, one related to the ancestral Tubutulik River that resulted in mineralization before deposition of the Eocene basalt in the river channel, and one related to the level after the lake formed behind the basalt dam.

Host rocks

The host rocks for the primary uranium deposition are poorly sorted arkosic sandstone and conglomerate containing abundant carbonized wood and minor amounts of coal (Fig. 3). The host rock for the secondary uranium enrichment is a surficial

TABLE 3. Soil Data from Plutonic Rock in the Bendeleben A-1 Quadrangle

Sample number	Rock type[1]	Uranium	Thorium	Th/U
10	PQ	2	30	15
20A	PG	16	85	5
30	PQ	15	150	10
39A	PG	20	260	13
39B	PG	13	160	12
40	PG	9	30	3
41	PQ	12	140	12
42A	PG	8	100	13
Average		12	119	10

Data from NURE (C. C. Hawley and Assoc., 1978)
[1] PQ = plutonic quartz monzonite, PG = plutonic granite

layer generally less than 6 m thick made up of soil and weathered bedrock that can be divided into three zones (Fig. 4). The upper zone is about 30 cm of organic-rich clay and sand containing basalt cobbles that may been deposited in a mudflow. The intermediate zone, as much as 3 m in thickness, is mostly buff to orange arkosic sand containing scattered carbonaceous material. The lower zone consists of granitic grus or semiconsolidated arkosic sandstone and mudstone. Uranium enrichment is variable in all three soil zones, but it is generally greater in the middle zone. Arkosic sandstone fragments, some containing more than 11 percent U_3O_8, are the highest grade samples in the section. Some fragments of basalt float from the soil have uraniferous rinds (Fig. 10).

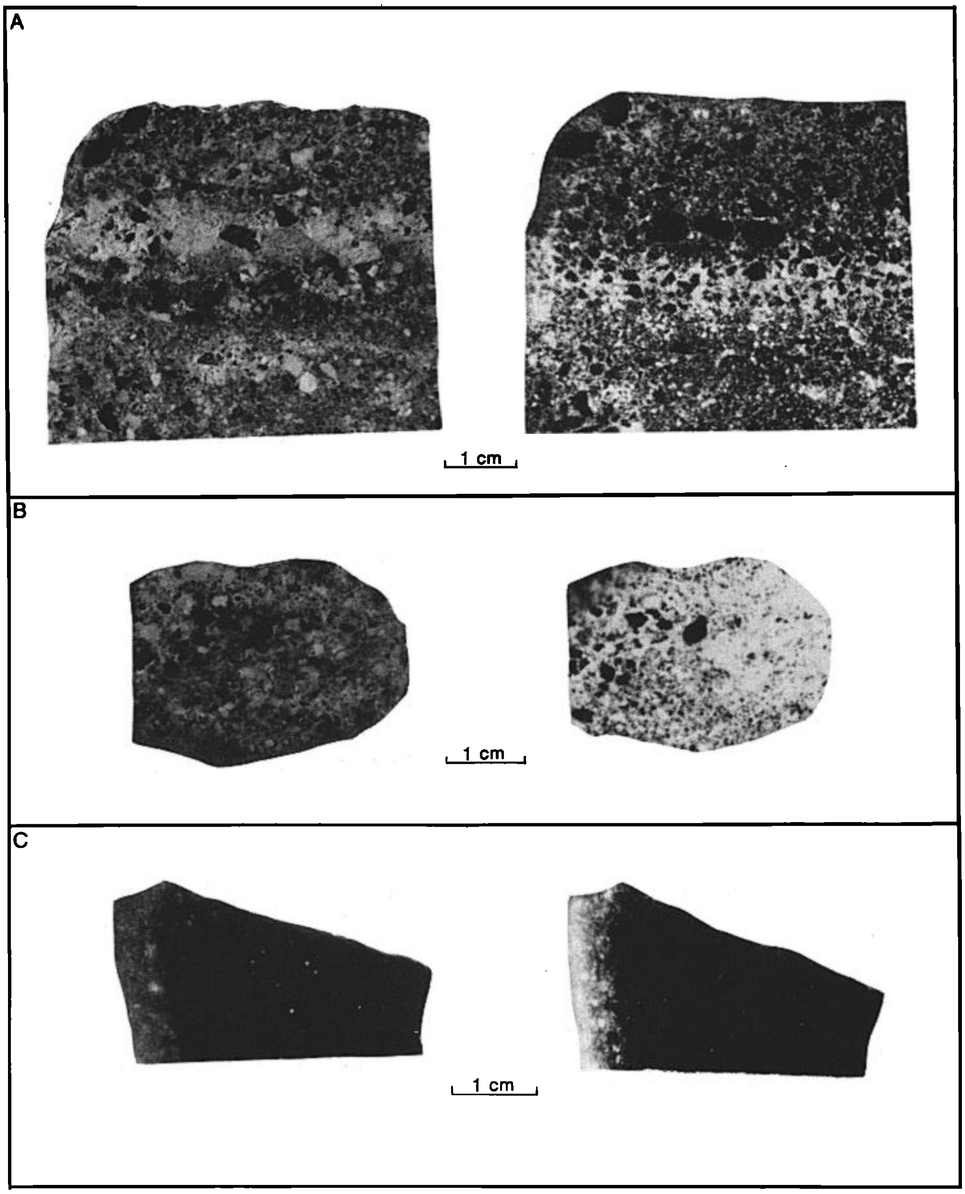

FIG. 10. Autoradiographs (right) and photographs (left) of uranium-enriched samples from zone of supergene enrichment. A. Arkosic sandstone showing coincidence of uraniferous layer and iron-stained porous layer. B. Arkosic sandstone fragment containing about 12 percent U_3O_8. Black grains in autoradiograph are metamict quartz and feldspar. Unaltered feldspar is white on photograph and black on autoradiograph. Nearly all interstitial material and many altered grains are white (radioactive) on the autoradiograph. C. Basalt fragment showing altered uraniferous (radioactive) rind.

Summary and Conclusions

The Death Valley uranium deposit, although the most northern known of its type, is fairly typical of many epigenetic basal-type deposits in the conterminous United States and other parts of the world. It is the only potentially commercial epigenetic deposit known in Alaska. The deposit is in a carbonaceous arkosic sandstone host rock that was deposited during the early Eocene in a small graben-formed basin on granitic bedrock. The host sandstone, which is fluvial or colluvial in origin, is interbedded with basalt, coal, and lacustrine sediments. Basalt flows of two different ages, early Eocene and late Tertiary or Quaternary, entered the depositional basin. The older flow apparently dammed the river valley and produced a lake basin. The lacustrine sediments include turbidites and laminated sideritic mudstone deposited in littoral and profundal facies of a meromictic lake that formed in the basin.

The uranium-enriched rock is interbedded with lacustrine mudstone that yields an early Eocene pollen assemblage. The pollen flora suggests that the paleoclimate was temperate to subtropical despite a paleolatitude about 8° higher than the present 64° north.

The uranium deposit is relatively enriched in Sr, Ba, P, and As and it is relatively depleted in V, S, and possibly Mn. It may also be slightly enriched in other elements, such as Mo, Ni, Pb, Cu, and Zn, but available data are insufficient for a determination.

The uranium was leached from the granite of the Darby pluton and transported in ground water through transmissive beds or in surface water to the site of deposition. The uranium was precipitated in response to a strongly reducing chemical environment brought about, for the most part, by a large component of carbonaceous material in the host rock. In one area supergene enrichment occurred at the present surface, only a short distance from the primary deposits.

The location of the Death Valley uranium deposit suggests new areas to explore for uranium in early Eocene sedimentary rocks in the Death Valley area and in other Tertiary basins, which are numerous on the Seward Peninsula and elsewhere in Alaska. A high-latitude limitation on the occurrence of epigenetic sandstone-type uranium deposits has not been proven. A warm climate during the early Eocene may have been favorable for the formation of this uranium deposit.

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October 30, 1985; January 28, 1987

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