Anderson mine, Arizona, which occurs in tuffaceous lacustrine sediments (Sherborne et al., 1979). Behavior of uranium in distal volcaniclastic rocks, as at Pēna Blanca, Maureen, or the Anderson mine, is transitional to reactions in tuffaceous sandstone environments, reviewed in the next section.

Deposits in Sandstone

General statement

Sandstone-type deposits, probably limited to rocks less than about 400 m.y. old, are currently the most important single type of uranium deposit. Deposits in this group occur within sandstones and related rocks but do not include calcretes, quartz-pebble conglomerates, or veins. Although they constitute only 41 percent of the western world's resources, they make up more than 95 percent of the United States' uranium resources. Judging from the Soviet literature on these deposits, they must also constitute significant resources in the Soviet Union.

Economic deposits of this type are present throughout the world. They occur in Permian rocks in southern and eastern Europe, Mississippian to Triassic rocks in South America and South Africa, Mesozoic rocks in eastern Europe and on the Colorado Plateau (Fig. 25) of the western United States, and in Tertiary rocks of Australia, the Soviet Union, India, Japan, and in the northern Rocky Mountains Province and Texas Gulf coastal plain of the United States.

Broadly speaking, host rocks for sandstone-type deposits are fluvio-lacustrine molasselike sequences that accumulated within intermontane basins and across broad intracratonic piedmonts and marginal marine plains. The smaller basins can be as little as a few tens of kilometers across, but the larger plains extended for hundreds of kilometers. The ore-bearing parts of these sequences are generally diagenetically reduced, fluvial sandstones containing intercalated overbank and lecustrine mudstone lenses. Provenance for the epiclastic sandstones can commonly be attributed to granite-cored mountain ranges, but volcanic, metamorphic, and multiple-cycle sedimentary rocks may also contribute.

The rock sequences that host sandstone-type deposits typically contain both diagenetically reduced and oxidized facies (Rackley, 1976). With few exceptions, the uranium deposits are found in reduced

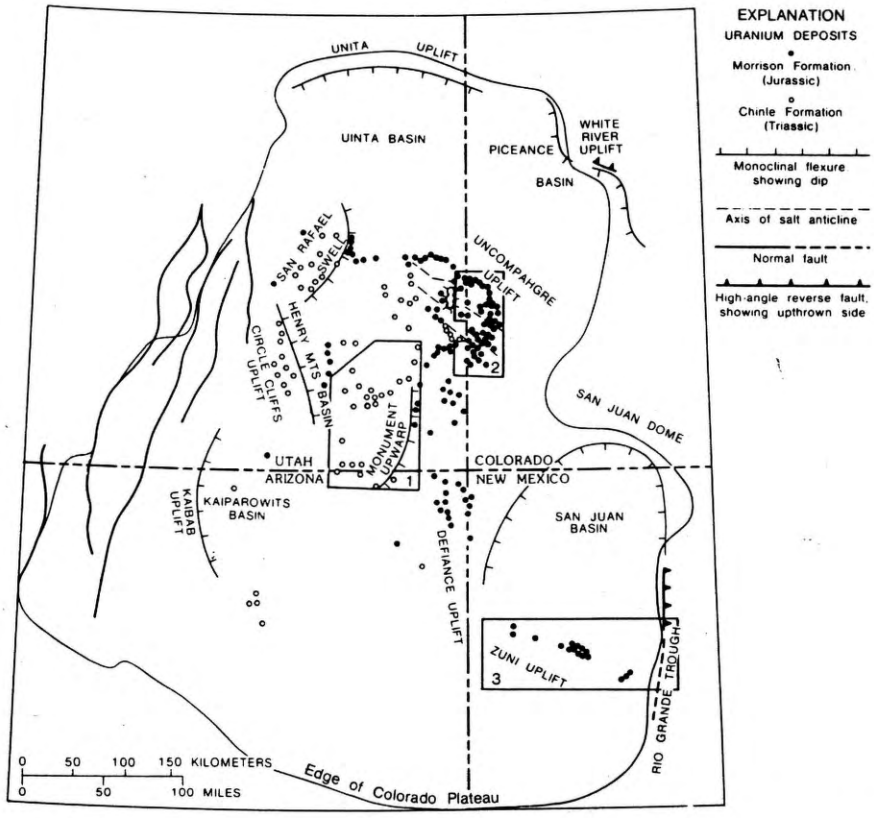

FIG. 25. Principal uranium deposits and major structural features in the Colorado Plateau region. Blocks show approximate areas covered by the following districts: 1, Monument Valley-White Canyon; 2, Uravan mineral belt; 3, Grants mineral belt (modified from Fischer, 1968).

facies which are typically light gray or drab to nearly white. Fossil wood, if present, is generally coalified, reflecting early burial and preservation under anaerobic conditions below the ground-water table. The anaerobic conditions are necessary both for coalification and for a microbiological, sulfate-reducing environment in which iron minerals were at least partly pyritized. The oxidized facies may be relatively insignificant or even missing in the vicinity of the ore deposits, but the reduced facies is almost invariably present.

Oxidized facies are red, light buff, or tan, reflecting the creation of iron oxide minerals through early aerobic deposition and preservation under oxidizing conditions both above and below the local ground-water table. Clays may be coated with a hematitic film; magnetite and other iron-bearing minerals are partly oxidized; and fossil wood, if not missing, is generally silicified.

Host rocks were generally deposited as permeable fluvial channel and bar sandstones and typically have mean grain sizes that range from fine through medium, and compositions ranging from arkosic to quartzose. The percentage of feldspar seems to have no direct relation to favorability for uranium deposition. The permeabilities of many host sandstones are now somewhat restricted by cements and alteration products, but the hydrologic conductivities were probably much higher during ore deposition, permitting the passage of large volumes of ore-forming fluids during mineralization.

These are essentially stratabound deposits in which the orebodies are typically, but not invariably, localized within parts of individual depositional units. Most of them are tabular or mantolike in shape and are peneconcordant with the bedding. Sharply crosscutting features called rolls are, however, common in some types, and these features in some instances constitute the principal orebodies. Margins of the ore against barren country rock are extremely sharp and continuous in some varieties but are highly irregular and diffuse in others.

The most important physical and geochemical factors controlling ore localization seem to be related to (1) permeability, (2) adsorptive agents such as coalified wood, other humic materials, and Ti-oxides, and (3) reducing agents such as carbonaceous matter and sulfur species related to biogenic sulfate reduction, to "sour" natural gas, or to limited oxidative destruction of pyrite-marcasite.

In most deposits reduction seems to be a key factor in localizing uranium (Rackley, 1976). The most important ore minerals are principally composed of reduced uranium, U(IV). These consist of uraninite (var. pitchblende), coffinite, and uraniferous organic matter, either singly or combined in various deposits. In some deposits where reductants are absent, adsorption of U(VI) by uraniferous iron oxides, zeolites, clays, or titanium oxides appears to have been an important localizing mechanism.

Zoning of concentrations of associated elements, such as Se, Mo, and V, is common in several varieties of sandstone-type uranium deposits. These deposits are commonly tabular varieties that are either peneconcordant with the stratification or roll abruptly across it, and have relatively sharp contacts with barren country rock. The zoning is attributed to the effect of deposition across a geochemical gradient produced either at the interface between two differing solutions (Shawe, 1956) or in a single solution that is changing in response to reactions within the country rock (Rackley et al., 1968; Granger and Warren, 1969). Varieties of deposits in which no zoning of associated ore elements has been reported typically have more diffuse boundaries and more poorly defined shapes.

Evidence such as isotopic age dating (Miller and Kulp, 1963; Berglof, 1970; Lee and Brookins, 1978; Ludwig, 1978, 1979), structural and sedimentary features (Nash and Kerr, 1966; Moench and Schlee, 1967), and aspects of geochemistry—particularly organic geochemistry—suggests that sandstone-type deposits were generally formed soon after (in geologic terms) sedimentation of the host rocks. More recent alteration and modifications of the deposits may be evident, but most commonly these caused partial distruction rather than enrichment of ores.

The source of the uranium in these deposits has been a controversial subject for several decades. The principal alternatives consist of sources related to: (1) both magmatic and meteoric hydrothermal solutions (Waters and Granger, 1953; Gabelman, 1970; Kerr, 1958; Gabelman and Krusiewski, 1964); (2) leaching of the host rocks (Shawe, 1956, Melin, 1964; Rackley et al., 1968; Rapaport, 1963); (3) leaching of devitrifying volcanic ash in tuffaceous mudstones associated with the host rocks (Denson and Gill, 1956; Waters and Granger, 1953; Granger and Warren, 1978); and (4) leaching of granitic rocks in the area of host-rock provenance (Rosholt and Bartel, 1969; Stuckless et al., 1977). In such places as the Colorado Plateau, strata closely underlying the host rocks commonly contain red-bed facies that are interpreted to have been deposited under highly saline, evaporative conditions (sabkha- or playalike). The possibility that brines or saline solutions from these units may have been the mineralizing solutions has not been thoroughly investigated.

Judging from the current literature, hydrothermal solutions (certainly those from a magmatic source) are now rarely advocated and host-rock leaching is no longer a widely supported concept. Ash (tuff) leaching and granite leaching, however, are still being argued and, in our opinion, each may be valid sources in certain instances. Both sources may be involved in some

places according to Harshman (1972). The various concepts of source of the uranium in sandstone-type deposits of the United States have been summarized by Rackley (1976).

For the purposes of this paper the uranium deposits in sandstone are divided into two major groups, based on the role we perceive organic matter to have played in their genesis. In the first group organic matter is generally detectable both visually and chemically in typical samples of ore, and it is believed that the organics played a direct role in localizing the ore. In the second group organic matter is either missing in many or all ore samples, or the part played by organics is believed to have been indirect. It is evident that most sandstone host rocks were prepared, initially, by reduction in an organic-rich environment, but organic matter may not invariably have been directly responsible for later localization of ore. Subdivisions of each group are then based on perceived differences in shape, geologic relations, and, particularly, geochemical history and genesis. This grouping provides a convenient and provocative division of deposits for purposes of this discussion but is not necessarily presented as a basis for classification.

Within this outline, we now summarize the most conspicuous and unique characteristics of the several varieties of sandstone-type uranium deposits.

Deposits localized by syngenetic detrital organic matter

Host rocks for this group of deposits are principally aggradational fluvial channel or bar sandstones and conglomerate lenses that commonly occupy shallow degradational paleochannels cut into underlying rocks (Fig. 26). It can usually be inferred that the original channel filling was more permeable than the enclosing rocks, but subsequent alteration and authigenic cementation processes commonly have reduced the original permeability by one or more orders of magnitude.

Ore-bearing parts of the host sandstones invariably contain coalified fossil plant fragments ranging in size from finely comminuted debris to entire logs. Cores of the larger fragments may be silicified, but the abundance of coaly material indicates that wood was incorporated with channel sands, buried, and preserved below the water table.

Intercalated and overlying rocks almost invariably

Sandstone-Type Uranium Deposits

- I. Deposits with organic matter serving as adsorbant-reductant
  - A. Uranium deposition in an organic-rich matrix
    - 1. With syngenetic detrital organic matter
      - a. Examples
        - (1) Niger deposits (Bigotte and Obellianne, 1968; Robertson, 1970)
        - (2) Permian sandstones, Europe (Herbosch, 1974; Mittempergher, 1974; Pluskal, 1970; Barthel, 1974; Petrascheck et al., 1974)
        - (3) Karoo sandstones, South Africa (von Backstrom, 1974; Toens and le Roux, 1979)
        - (4) Sandstone of Chinle Formation, Arizona-Utah (Hawley et al., 1968; Isachsen and Evensen, 1956; Young, 1964)
        - (5) Tallahassee Creek Conglomerate, Colorado (Chenoweth, 1980; Shapiro and Heinrich, 1961)
        - (6) Basal deposits, Japan (Ishihara et al., 1969; Katayama et al., 1974; Katayama and Kimyama, 1977; Doi et al., 1975)
    - 2. With epigenetic-authigenic organic matter
      - a. Examples
        - (1) Permian sandstone (epigenetically enriched), Europe (J. Geffroy, C.E.A., France; oral commun., 1974)
        - (2) Temple Mountain, Utah (Hawley et al., 1968; Kelley and Kerr, 1958)
        - (3) Grants mineral belt, New Mexico (Granger et al., 1961; Moench and Schlee, 1967; Granger, 1968; Nash, 1968; Hilpert, 1969; Kelley, 1963)
- II. Deposits with nonessential organic material
  - A. Uranium deposition at a chemical solution gradient (host rock-solution reaction)
    - 1. Redox gradient in a single solution—(geo)chemical cell, roll-type deposit, roll-front deposits
      - a. Bordered on one side by oxidized rock
        - (1) Examples
          - (a) Primary roll-type deposits (Harshman, 1972; Rackley et al., 1968; Rackley, 1976; Granger and Warren, 1969; Goldhaber and Reynolds, 1979; Eargle et al., 1975)
          - (b) Secondary roll-type deposits (redistributed) (Gould et al., 1963; Shawe and Granger, 1965; Saucier, 1979)
    - 2. Chemical gradient between two solutions (intersolution reaction)
      - a. Bordered on both sides by reduced rock
        - (1) Examples
          - (a) Uravan mineral belt (Fischer, 1968, 1970, 1974; Shawe, 1956, 1976; Shawe et al., 1959; Garrels and Larsen, 1959)
          - (b) Entrada belt (Fischer, 1960; Fischer et al., 1947)
  - B. Deposition by adsorption of uranium-(VI) from infiltrating solution
    - 1. Involving iron hydroxides and oxyhydroxides
      - a. Examples
        - (1) Cutler Formation (Campbell and Steele-Mallory, 1979)
    - 2. Involving zeolites or clays
      - a. Examples
        - (1) Basal deposits, Japan (Ishihara et al., 1969; Katayama et al., 1974; Katayama and Kimayama, 1977; Doi et al., 1975)

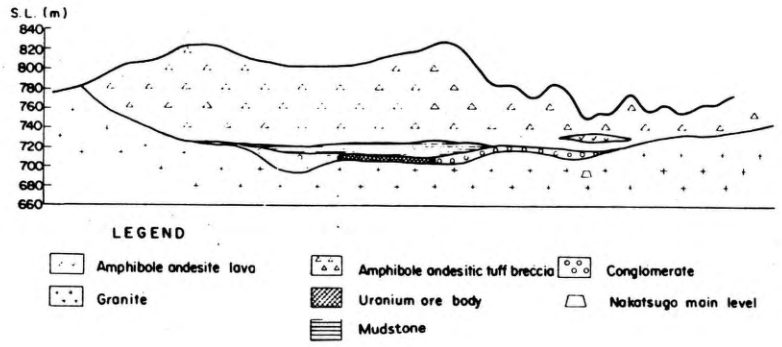

FIG. 26. Cross section of a paleochannel containing a basal uranium deposit. The Nakatsuga-south orebody, Ningyo-toge mine, Japan. Fine particles of carbonaceous matter are disseminated throughout the ore-bearing conglomerate (modified from Katayama and Kamiyama, 1977).

contain units rich in pyroclastic components ranging from fresh ash and tuffaceous sandstone to thoroughly devitrified tuffs and montmorillonitic mudstone. Fine-grained organic debris may locally darken these rocks to a darker gray but, ordinarily, they are light to moderate greenish gray or yellowish gray where fresh.

In these deposits uranium is invariably closely associated with fossil fragments of detrital organic matter and orebodies generally do not form sharp boundaries against barren rock. Reduced uranium minerals are commonly found both within the organic fragments, where coffinite and pitchblende locally replace parts of the cell structure, and interstitially within the enclosing sandstones. Structureless uraniferous organic matter may occur in addition to pitchblende and coffinite. Pyrite is invariably present and, similarly to uranium, can occur both disseminated in the sandstone and closely associated with organic matter. Elements such as selenium, molybdenum, vanadium, and copper may also be present but are generally less abundant than uranium. (Note, however, that so-called "red-bed" copper deposits may also contain uranium and are found in the same or similar host rocks.)

Ore localization is generally attributed both to the adsorptive properties of the organic matter and the reducing properties of both organic matter and biogenically derived H_2S. By this concept U(VI) was extracted from the ore-bearing solutions as they percolated through organic-rich zones. Some U(VI) was adsorbed on and in solid organic matter and subsequently reduced. Some of the uranium may have been reduced and precipitated directly (as pitchblende or coffinite) from solution by either aqueous humic acids derived from the degrading plant debris or dissolved hydrogen sulfide generated by sulfate-reducing bacteria.

Where these deposits are contained within thick sequences of sedimentary rocks, directly associated with tuffaceous sediments, it seems likely that the uranium was derived from devitrifying volcanic ash. Where the host sandstones either rest directly on, or are derived from, debris from nearby uraniferous granites or other rocks, and there are no associated volcanics, it is certainly permissible to speculate that the uranium was derived by leaching of these rocks (Doi et al., 1975). Reconstruction of ground-water movement during the earliest stages of ore deposition could be of considerable help in determining the source(s) of uranium (Fig. 27).

Several lines of evidence suggest that primary ore deposition, although epigenetic, occurred early in the history of the host rocks. Berglof (1970), for example,

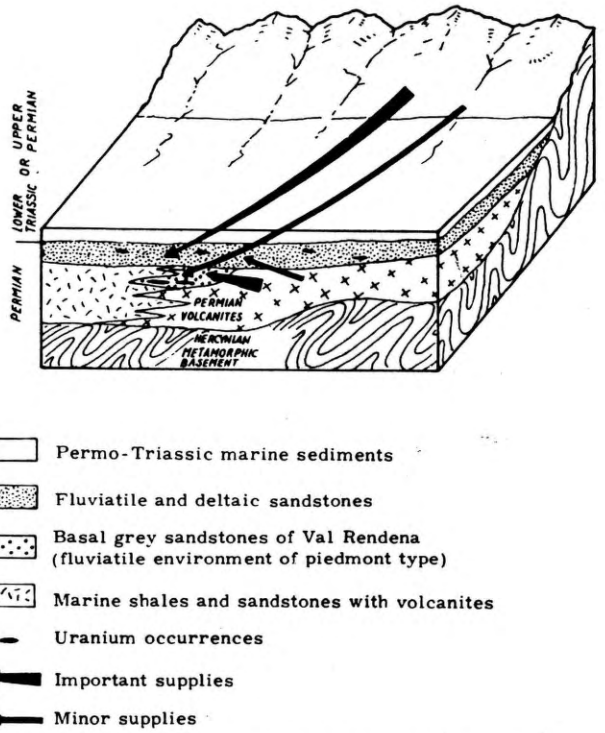

FIG. 27. Diagram showing geologic setting and sources of uranium in Permian sandstones along the eastern slope of the Lombard Basin, northern Italy (modified from Mittempergher, 1974).

showed that some reasonably concordant Pb-U ages for ores in the Triassic Chinle Formation (Fig. 25) are approximately the estimated ages of the Chinle. Primary ore deposition in this group of deposits almost invariably preceded any significant fracturing or faulting, suggesting that they were deposited soon after the host sandstones. Speculation regarding the source of uranium generally narrows down either to rocks that provided the host-rock components or to devitrifying volcanic constituents of associated rocks. Either of these concepts is most reasonable if mineralization was completed not long after host-rock deposition. Degrading plant matter is much more effective as a bacterial nutrient and chemical reagent soon after deposition. This period of time is comparable to peat and lignite stages of coalification and tends to diminish when fossil organic matter approaches bituminous coal stages.

The story of primary ore deposition has commonly been obscured by processes such as structural deformation and redistribution of uranium in this group of deposits. In fact, we were reluctant to include all of the many, and somewhat varied, deposits in Permian sandstones of Europe in this category but have done so for simplicity. Locally, for example, primary ore has been remobilized (by encroaching oxidized solutions?), redistributed, and enriched in fractured host rocks of the Permian Autuniene beds in the Lodève region, southern France (M. J. Geffroy, oral commun., 1974). Folding and metamorphism have seemingly obscured a Permian paleochannel-controlled deposit at Zirovski Vrh, Yugoslavia. Also, deposits in the conglomeratic Triassic Shinarump Member of the Chinle Formation at Temple Mountain, Utah, have been partly remobilized and redistributed by processes that have not yet been completely elucidated. In each of these deposits, however, primary uranium deposition appears to have been localized in detrital organic-carbon-bearing fluvial (or fluvio-lacustrine) sandstone units.

Deposits with epigenetic/authigenic organic matter (uraniferous humate)

Deposits in this group are principally found in the Jurassic Morrison Formation of the Grants mineral belt along the southern edge of the San Juan Basin in northwest New Mexico (Figs. 25 and 28). Here, the primary accumulations of uranium are coextensive with layers of authigenic organic matter which impregnates the sandstone. Although rare on a worldwide scale, these deposits contain slightly more than 50 percent of the U. S. uranium resources. Epigenetic and authigenic organic matter makes up a part of the uranium-bearing material in various other types of sandstone deposits (Hawley et al., 1968) but represents only a minor redistributed phase in most instances. As noted above, in some parts of the Lodève district of southern France uraniferous organic matter in Permian sandstone deposits has been mobilized, seemingly by the encroachment of oxidizing conditions into low-grade uraniferous organic-rich sandstones and siltstones, and moved into fractures and pore spaces in adjacent reduced rocks (J. Geffroy, C.E.A., France, oral commun., 1974). Locally this process has enriched the original lower grade deposits and produced economic ores.

The ores in the Grants mineral belt, northwestern New Mexico (Hilpert, 1969), occur in feldspathic to arkosic sandstone units deposited principally by braided streams which flowed across a broad alluvial plain in the southern part of the San Juan Basin. In ascending order the Morrison Formation consists of (1) the Recapture Creek Member, sandstones and siltstones deposited in a fluvio-sabkha environment; (2) the Westwater Canyon Member, sandstones and intercalated mudstones deposited in a fluvio-lacustrine environment; and (3) the Brushy Basin Member, dominantly a montmorillonitic mudstone deposited in an overbank and fluvio-lacustrine environment. The mudstones are composed principally of montmorillonite-type clays and were derived from volcanic ash. Some very thin bentonitic layers within the mudstones appear to have been derived from air-fall ash (T. Bell, Univ. California, oral commun., 1980), but the bulk of the mudstone was probably deposited either by streams that were overloaded with fine volcanic debris or from lakes fed by these streams. Ores occur both within the Westwater Member and in sandstone units within the Brush Basin, particularly a large continuous channel sandstone unit informally called the Jackpile sandstone, at the top of the Brushy Basin and near the east end of the mineral belt.

The source, aqueous transport, and localization of organic matter is a major problem in understanding the localization of these deposits (Granger, 1968). The presence of coalified fossil wood, disseminated pyrite, and bleached (reduced) appearance indicates that much of the sandstone was quickly buried and preserved under anaerobic conditions below the water table.

The primary uranium is coextensive with sharply bordered undulating tabular layers of authigenic organic matter suspended in the reduced sandstones (Fig. 29). This organic matter (Granger et al., 1961; Moench and Schlee, 1967), presumably derived by precipitation of a humic or fulvic acid as a humate, generally forms layers from about 0.3 to 2.0 m thick, although much greater thicknesses occur locally.

The uraniferous organic matter within the tabular zone layers, coats sand grains, fills interstices, fills fractures and cavities in partly altered mineral grains, and, locally, partly replaces sand grains. X-ray analysis indicates that coffinite and, rarely, pitchblende are

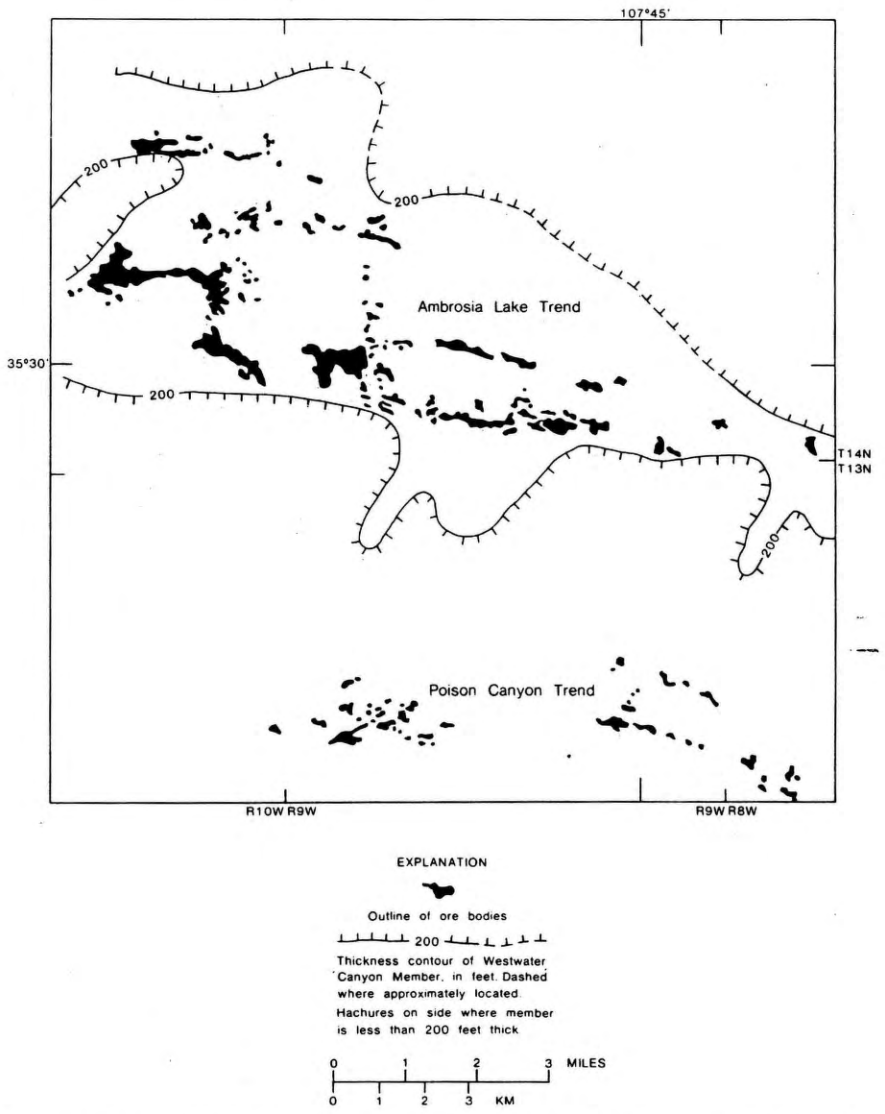

FIG. 28. Map of ore deposits in the Morrison Formation, Ambrosia Lake area, New Mexico. Deposits are dominantly uraniferous humate and a few redistributed roll type (modified from Santos, 1963).

present in the organic matter, but metallurgical tests suggest that a significant proportion of the uranium occurs in unidentified form, perhaps a urano-organic compound (Kittel, 1963; Rhett, 1979). Proposed sources for the humate consist of: (1) post-Jurassic paludal environments resting on truncated edges of the host rocks not far from the ore deposits; (2) contemporaneous decaying plant matter along the courses of the depositing streams; (3) diagenetically coalifying plant debris deposited with the host sandstones; and (4) organic matter deposited with lacustrine mudstones and epigenetically expelled into the sandstones by compaction.

The fairly uniform, peneconcordant layers of humate suggest that they were deposited by reactions at an interface between two solutions, one which contained the dissolved humic materials and another in which these organic substances were insoluble. Some uranium could have been deposited simultaneously with the humates but more probably was deposited subsequently by adsorption followed by reduction and partial crystallization as coffinite. The deposits are related to areally extensive alteration of ilmenite and magnetite and, locally, to silicate mineral authigenesis (Adams et al., 1978). Isotopic ages, structural relations (Moench and Schlee, 1967), and rip-up clasts of ore in basal Cretaceous rocks (Nash and Kerr, 1966) all indicate that alteration occurred and the

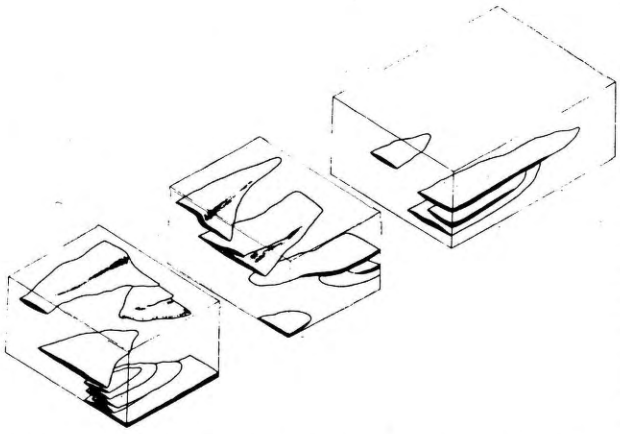

FIG. 29. Idealized exploded block diagram showing typical relationships of uraniferous humate orebodies, Ambrosia Lake district, New Mexico. The orebodies are elongate, lens-shaped masses arranged singly or en echelon vertically and horizontally (from Granger et al., 1961).

uraniferous humate was emplaced prior to deposition of immediately overlying formations.

Sources of the uranium have not been established. Precambrian granitic rocks that are exposed in the general direction of provenance of some of the Morrison sandstones appear to have been leached of some of their uranium (Ludwig and Silver, 1977). Tuffaceous materials incorporated in the Morrison mudstones are thoroughly devitrified and possibly lost some uranium during the devitrification. Either the provenance granites or tuffaceous materials, which we prefer, could have provided the uranium, but no reliable studies have yet been made.

The uranium of many of the primary uraniferous-humate deposits was mobilized and redistributed, throughout a large part of the main mineral belt, by the enroachment of either Early Cretaceous or Tertiary oxidation that extended far below the present water table. Uranium in some of the original deposits has been oxidized and swept ahead of the leading edges of the oxidized zone where it was reduced and redeposited by processes related to roll-type ore formation, described in the following section. Most of the organic matter was removed but not redeposited during the remobilization process and the redistributed, roll-type ores typically contain coffinite with minor pitchblende but little or no organic carbon.

Uranium deposited at a redox interface (single solution)

Deposits in this group are principally found in Tertiary fluvial sandstones although similar deposits occur in Mesozoic fluvial sandstones and in Tertiary marginal-marine strandline sandstones. In the United States these have been called both roll-type deposits and (geo)chemical cell deposits; in the Soviet Union they have also been referred to by such terms as infiltrational deposits that are associated with a limonitization wedge-out or pinch-out.

These deposits are found in sandstone units that either contain diagenetic disseminated coalified fossil plant fragments and pyrite or were epigenetically reduced and sulfidized by infiltrating sour (H_2S-rich) natural gas. Large stratabound tongue-shaped zones (Fig. 30) of red, buff, or nearly white oxidized sandstone are developed in the dominantly reduced sandstones where meteorically derived recharge waters gained access along truncated and exposed surfaces of structurally tilted parts of the host rocks. These recharge zones typically occur along the edges of depositional basins and the oxidized tongues may extend downdip for as much as about 30 km.

Uranium orebodies may occur as thin layers in reduced sandstone bordering the upper and lower surfaces of the oxidized tongues (limb ore) or, more im-

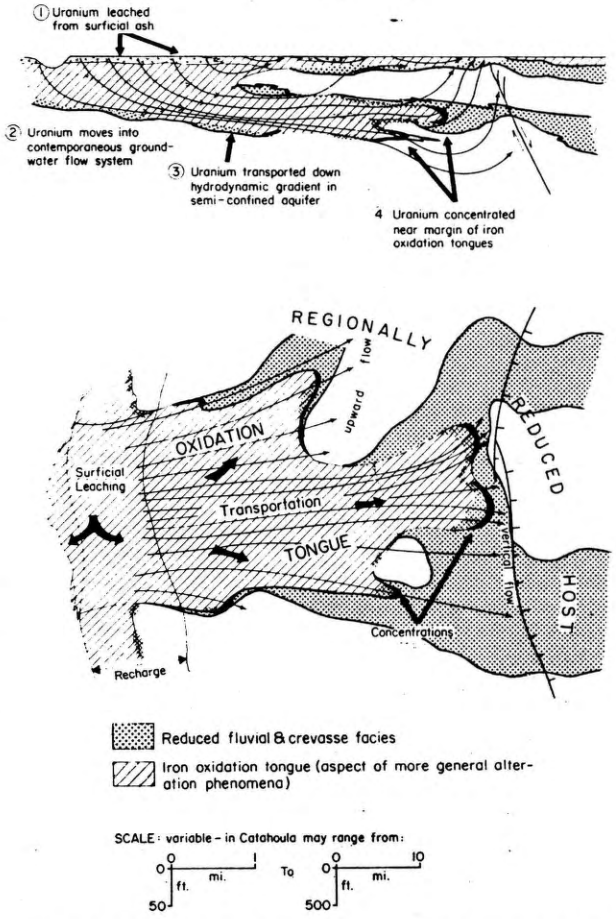

FIG. 30. Diagrammatic representation of the genesis of roll-type deposits in the Catahoula Tuff, Texas. Faults are commonly missing near roll-type deposits formed elsewhere (from Galloway, 1978).

portant, as thicker bodies that wrap around the distal and lateral margins of the tongues (roll ore).

Two principal models have been proposed to explain the genetic geochemistry of ore localization. Both concepts agree that oxidized tongues developed by expanding through the reduced pyrite-bearing sandstones at a rate far slower than the flow rates of the oxidizing ground waters. The first concept (Rackley et al., 1968) utilizes the biogenic processes of two different genera of bacteria: one to oxidize the pyrite at the roll front and the other to reduce the resulting sulfate to H_2S. Uranium is introduced through the oxidized tongue by the oxidizing ground waters and is precipitated within the H_2S-rich environment. As the oxidized tongue expands, the uranium deposit is continually oxidized along the encroaching margin of the tongue and redeposited in the immediately following H_2S zone along with pyrite-marcasite. Deposits, therefore, form best where the ore solutions flow through the orebodies along distal edges of the oxidized tongue.

The second concept (Granger and Warren, 1969) proposes that biogenic processes are unnecessary and that, in such an environment where dissolved oxygen is being supplied at a rate controlled by ground-water flow, pyrite-marcasite oxidizes to soluble metastable sulfur species intermediate between sulfide and sulfate. These metastable forms of sulfur then spontaneously disproportionate (or split) into stable sulfate, which is kinetically inert to further redox reactions, plus even more reduced species such as H_2S, which impose strong reducing conditions. Localization processes affecting the uranium are essentially identical under both concepts: soluble oxidized uranium is reduced to insoluble U(IV) species in the reducing environment bordering the oxidized tongue. Recent studies (Goldhaber and Reynolds, 1979) suggest that the biogenic concept is applicable to sandstones that contain fossil organic matter—a nutrient for the heterotrophic bacteria—but that the abiotic concept is applicable to deposits in organic-free sandstones that contain disseminated pyrite-marcasite derived from the sulfidizing action of infiltrating sour natural gas.

Three principal sources of uranium have been proposed for the primary ores: (1) the host sandstones, themselves; (2) granitic rocks from which the host sandstones were at least partly derived; and (3) overlying tuffaceous strata (Fig. 30). The preponderance of evidence makes (1) unlikely in most places because the oxidized tongue generally contains more uranium than the reduced rock in advance of the roll fronts. In addition, selenium, which is commonly associated with roll-type deposits, can be more than an order of magnitude richer in the oxidized tongue than in unmineralized reduced rock. In some instances roll-type bodies can also form from redistribution of pre-existing deposits. In the Grants mineral belt, New Mexico, numerous secondary roll-type deposits have resulted from redistribution of the primary deposits by encroachment of large oxidized tongues.

Whether granitic or tuffaceous rocks provided the uranium for most deposits is a moot question. Much of the ore-bearing host rock in Wyoming was derived from an abnormally uraniferous granitic upland (the Granite Mountains) that has been shown to have been leached of a thousand times as much uranium as has been found in the ore deposits (Rosholt and Bartel, 1969). However, nearly all deposits are also within a few hundred meters below a truncated surface on which rests middle or upper Tertiary tuffaceous strata. Oxygenated meteoric solutions could easily have leached the devitrifying tuffs and percolated downward and laterally through the uranium host rocks. Ages of the deposits are generally compatible with a source from the tuffs but do not rule out granitic sources. Several deposits along the Texas Gulf coastal plain, however, occur in the tuffaceous sandstones of the Oligocene-Miocene Catahoula Tuff, derived largely from nongranitic, volcanic-rich terranes.

Uranium deposited at a chemical interface (two solutions)

Deposits in this group are principally found in Jurassic rocks in the Uravan mineral belt, Colorado and Utah. The principal host rock is the Salt Wash Member of the Morrison Formation, a unit now believed (Ethridge et al., 1980) to have been deposited largely by meandering streams traversing a broad fan-like alluvial plain. The host sandstones for many of the orebodies, therefore, are point bar deposits (Noel Tyler, Colorado State University, oral commun., 1979).

Although largely peneconcordant tabular-shaped deposits with relatively sharp borders, the layers of ore commonly roll sharply across the bedding (Fig. 31). An excellent description of these roll orebodies is given by Shawe (1956). Rolls range from minor undulations in dominantly tabular ore layers to C-shaped forms that double back on themselves. Mirror image C-shaped rolls can look like flattened tubes in cross section.

Nothing now present in the rocks seems to explain the shapes of the ore layers—their rolling, undulating, and crosscutting relations to bedding. Investigators (Fischer, 1947; Shawe, 1956; Granger, 1976) have, therefore, attributed localization of the ores to reactions at the interfaces between relatively stagnant pore solutions and extrinsic(?) infiltrating solutions. Ore solutions must have flowed parallel to the ore layers and did not flow through the deposits, as was the case with roll-type deposits formed at redox interfaces.

Commonly called uranium-vanadium deposits, the

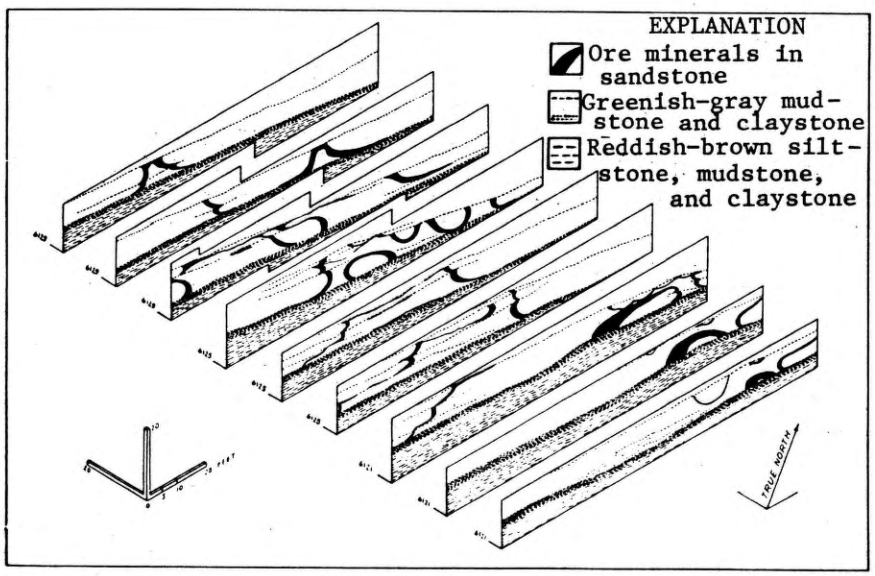

FIG. 31. Sections showing discordant "roll" features in sandstone-type orebodies near the south end of the Uravan mineral belt, southwest Colorado. These are common but not abundant shapes in a district containing principally tabular and lenticular ore layers (from Shawe et al., 1959).

ores ordinarily contain more vanadium than uranium. Coalified fossil plant fragments within the ore layers can be extremely rich in both uranium and vanadium but essentially barren where they occur outside ore. Organic material does not seem to be directly essential to ore formation, and many ore samples contain no more organic matter than ordinary sandstones (<0.1% organic C).

Vanadium in the primary ores occurs both as V(III) and V(IV) minerals. V(III) minerals consist of the vanadium mica, roscoelite, and the vanadium oxide, montroseite (Weeks et al., 1959). V(IV) minerals include vanadium mica-montmorillonites, chlorite, and vanadium oxides such as paramontroseite, doloresite, and duttonite. Uranium minerals include both pitchblende and coffinite. These minerals are principally interstitial to sand grains in the ore layers, but where best developed they—particularly the V-micas and V-clays—replace the sand grains.

Weathered and oxidized deposits of this group commonly retain much of their original grade and shape because the oxidized uranium and vanadium tend to combine as the nearly insoluble minerals carnotite and tyuyamunite. In addition, the primary vanadium clays and micas are very resistant to weathering and oxidation. Until exploration had exposed these deposits in unoxidized environments below the water table, they had been referred to for many years as carnotite deposits, and it was assumed by many geologists that carnotite was the primary mineral.

Most investigators have emphasized the relationship of high-grade ore to fossil plant trash and have assumed that ore deposition was somehow related to reduction of both uranium and vanadium by organic matter and H_2S. Granger and Warren (1981) suggest, however, that V(III) derived through destruction of detrital magnetites and carried as an organic complex in diagenetic pore solutions may also have reduced uranium introduced by separate, extrinsic groundwater solutions. Ore layers were formed at the interfaces between the two solutions. Because silica and alumina can also be transported as organic complexes, this model better explains the abundance of vanadium clays and micas in the ores than do simple reduction models.

The source of uranium in these ores has not been established. Perhaps the most popular speculations center around leaching during devitrification of tuffaceous components of the now-montmorillonitic Brushy Basin Member which directly overlies the ore-bearing member. Other proposed sources include hydrothermal solutions from Tertiary intrusives (unlikely, based on age determinations) and solutions expelled downward by compaction of overlying Cretaceous marine shales (Shawe, 1976).

Uranium deposited by adsorption

Deposits in this group are generally not large, high grade, nor thoroughly investigated but are included for completeness. The occurrences given in the table shown earlier in this section are among the few examples known where sorption of uranium (VI) by iron hydroxides, zeolites, or clays is reported to have formed ore. Where organic matter is also present in these rocks the uranium may have been reduced to uranium (IV), but some of these deposits evidently contain neither organic matter nor reduced uranium.

Although sorption of uranyl ion by $Ti(OH)_4$ is also

well known (Davies et al., 1964) and has been recognized as a subsidiary secondary process in many ore deposits (Reynolds et al., 1977; Ferris and Ruud, 1971), it has never been identified as the principal process in localization of an ore deposit.

The sorbent minerals were principally formed by in situ or authigenic minerals. Sources of the uranium in the zeolitic or clay-rich deposits in Japan is generally attributed to leaching of the immediately underlying granites.

Other Deposits

Olympic Dam

An exciting new environment is indicated by the recent discovery of a huge copper-uranium orebody at Olympic Dam (Roxby Downs), South Australia. Early estimates from 20 drill holes indicate that ore-grade mineralization extends over an area of more than 1.5 by 0.5 km, and that thicknesses exceed 170 m. The orebody is totally buried, covered by 350 m of unmineralized rock, but is characterized by strong gravity and magnetic anomalies (Haynes, 1979). It reportedly contains thick zones of about 0.05 to 0.1 wt percent U_3O_8 and 1 to 2 wt percent Cu, with estimated reserves of roughly 600,000 short tons U_3O_8 and 11,000,000 short tons of Cu (World Mining, 1979).

Preliminary descriptions of the deposit indicate that it occurs on the Stuart shelf, a platform adjacent to the upper Proterozoic Adelaidean geosyncline in South Australia. The deposit is within a sequence that includes volcanics, fine-grained clastic sediments, and hematitic granitic breccias (Haynes, 1979; Western Mining Corporation, 1979). The mineralized zones are apparently tabular and occur along the margins of multiple hematite breccia zones within granite breccia, but the nature and origin of the breccias is unclear. Copper occurs as sulfides, which in one core hole on public display appear zoned vertically from chalcopyrite at depth to bornite and chalcocite in the higher zones (Western Mining Corporation, 1979). Magnetite and pyrite are present in the deeper zones, and the latter is reportedly partly replaced by copper sulfides. Brannerite has been identified as a uranium-bearing phase. The geological setting and genesis of this and a recently discovered neighboring deposit are uncertain, although they bear some geological similarities to equally perplexing U-Cu deposits in the Mt. Painter region of South Australia (Youles, 1975, 1978) which occur in hematitic granite breccia, arkose, and tillite.

Yeelirrie and calcrete deposits

Another important recent development in uranium geology has been the identification and description of uranium enrichment in calcrete drainages of Western Australia, South-West Africa (Namibia), and Somalia (Butt et al., 1977; Mann and Deutscher, 1978; Carlisle, 1978). The host rocks are lenticular bodies of alluvium, soil, or detritus cemented by carbonate and other minerals. Uranium, nearly always as carnotite, occurs in voids and fractures in calcrete and disseminated in underlying clay-quartz regolith. A similar variety of uranium occurs in sediments in salt lakes. At Yeelirrie, Western Australia, 50,000 short tons U_3O_8, half grading more than 0.36 percent U_3O_8, has been delineated, and deposits at Langer Heinrich and Tumas River, Namibia, appear to be significant (von Backstrom and Jacob, 1979).

Calcrete and associated late Pleistocene to Holocene sediments of Western Australia contain numerous uranium occurrences and deposits in three geomorphic settings (Butt et al., 1977): (1) trunk valleys, (2) playa lakes, and (3) dissected calcrete terraces. Valley calcrete, such as that containing the Yeelirrie deposit, occupies trunk valleys of major drainages which can be as much as 5 km wide and 100 km long. The calcrete zone generally is 5 to 10 m thick. Because they are part of internal drainages the trunk valleys commonly lead to playa lakes where they form chemical deltas which can form uranium deposits (Mann and Deutscher, 1978). The Australian calcrete deposits occur in Quaternary or modern playa lakes or trunk calcretes in an area of internal drainage where evaporation exceeds rainfall. Evaporation is important to concentrate potassium, and also increasing uranyl ions actively as carbonate complexes are weakened by common ion effects and decreased pH (Mann and Deutscher, 1978). Hydrologically, the best carnotite development is in large internal drainages underlain by granitic rock that yields uranium to ground water. The carnotite is most effectively precipitated where the ground water is constricted by barriers and caused to move upward, becoming oxidized or mixing with deeper ground waters carrying vanadium (Fig. 32). Vanadium is best transported in deeper ground waters as V(IV) and carnotite precipitates where vanadium is oxidized to V(V) and/or mixed with a solution carrying U(VI) (Mann and Deutscher, 1978).

Uranium deposits occur in calcrete and gypcrete in Namibia that differ from the Western Australia deposits in several aspects (Carlisle, 1978; von Backstrom and Jacob, 1979). The calcrete-gypcrete forms in coarse fluvial detritus, contains increasing amounts of authigenic gypsum toward the Atlantic Ocean, and is of late Tertiary age. The Langer Heinrich deposit is the best known, and probably is economic; other deposits occur in the area. At Langer Heinrich the host is a calcreted conglomerate; the coarse clasts are only slightly weathered, angular granitic detritus of local derivation. The cementing carbonate is a coarse-grained mosaic that encompasses clastic grains. Gypsum constitutes about 2 percent of the cement, less than in other deposits closer to the ocean. Opaline silica cement is not seen. The channel gradient is much