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GEOLOGICAL FACTORS AFFECTING THE
GRADE AND TONNAGE OF
SANDSTONE URANIUM DEPOSITS

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CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
2. DISTRIBUTION OF URANIUM IN THE EARTH'S CRUST	2
3. URANIUM DEPOSITS	4
3.1 Distribution of Uranium Deposits of the World	4
3.2 Classification of Uranium Deposits	5
4. SANDSTONE URANIUM DEPOSITS	8
4.1 Distribution of Sandstone Uranium Deposits	8
4.2 Types of Sandstone Uranium Deposits	9
4.3 Sources for Sandstone Uranium Deposits	13
5. GEOCHEMISTRY OF URANIUM	15
5.1 Crystal Chemistry of Uranium	15
5.2 Mineral Chemistry of Uranium	15
5.3 Chemistry of Uranium in Low Temperature Aqueous Solutions	18
5.4 Fixation of Uranium	23
6. SANDSTONES	29
6.1 Definition of Sandstones	29
6.2 Classification of Sandstones	29
6.3 Factors Affecting Sandstone Generation	35
6.3.1 Source	36
6.3.2 Climate	36
6.3.3 Tectonics	38
6.3.4 Environment	40
6.3.4.1 Sand Deposition in the Alluvial Environment	41

	<u>Page</u>
6.4 Factors Affecting the Potential of a Sandstone as a Uranium Host	63
6.4.1 Composition of the Sandstone	63
6.4.2 Porosity and Permeability	67
6.4.3 Diagenesis	78
7. FACTORS CONTROLLING THE GRADE AND TONNAGE OF SANDSTONE URANIUM DEPOSITS	88
7.1 Factors controlling Grade	88
7.2 Factors controlling Tonnage	93
8. CONCLUSION - PREDICTION OF SAND BODIES AND CONTAINED MINERALIZATION	102
9. ACKNOWLEDGEMENTS	114
10. REFERENCES	115

1.

INTRODUCTION

The largest known reserves of uranium are found in sandstone deposits, in the form of roll-front, peneconcordant and stacked types.

Drilling on spacings of between 50 m and 5 m centres is the current method of attempting to delineate such ore bodies but because of the apparent random distribution of the mineralization there is a large degree of uncertainty in these predictions. Even on drilling grids of 3,5 m centres the uncertainty in predicting the distribution of stringer ore in roll front mineralization is still 100 per cent. (Sandefur & Grant 1980).

Because of escalating costs it is becoming increasingly less economically feasible to delineate bodies of this nature in this manner and much more reliance will have to be placed on the geologist's interpretation of ore distribution when calculating ore reserves. The grade and tonnage of a sandstone uranium deposit can only be calculated with some degree of confidence if the processes forming the ore body are fully understood.

The aim of this review is to examine the factors governing the formation and geometry of a sandstone body, the mobility and fixation of uranium and to establish criteria which will enable a more confident prediction to be made of the distribution of sand bodies and the distribution of the mineralization within them.

2. DISTRIBUTION OF URANIUM IN THE EARTH'S CRUST

The relative abundance of various elements in the continental crust is shown in Figure 1. Uranium is considered to exist in crustal rocks at a level of approximately 2-4 parts per million. Thus while

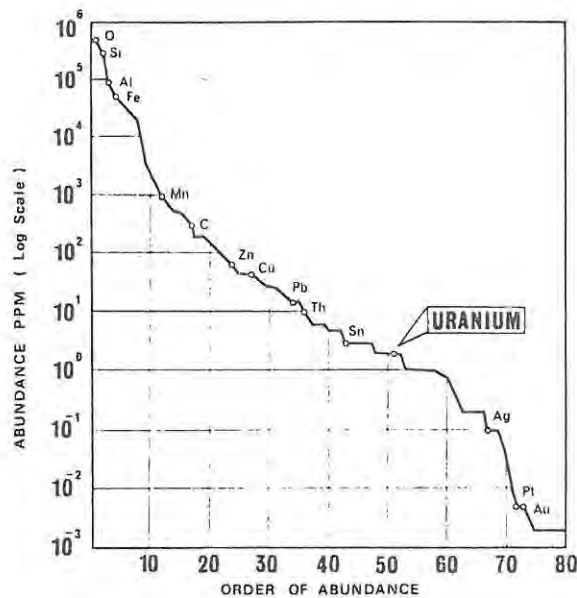


FIG. 1. Relative abundance of uranium.

(after Robertson et al, 1978)

uranium is broadly distributed in crustal rocks it is not an abundant element. Concentrations of uranium are rare and are distinctly time bound as shown in Figure 2.

There appear to be identifiable geological factors which explain these time-related concentrations and in the case of the sandstone deposits the physical and chemical environments of formation are the overriding factors. A rather controversial theory at present suggests that the marked change that took place in the atmospheric conditions of the world around 2,200 million years ago resulted in the level of oxygen availability being reached where the uranium minerals became extremely soluble. (Robertson et al, 1978) This period therefore marks the division between the detrital uranium-bearing conglomerates and the chemical-bearing sandstone deposits. It is significant that all but a few deposits of the latter occur in rocks

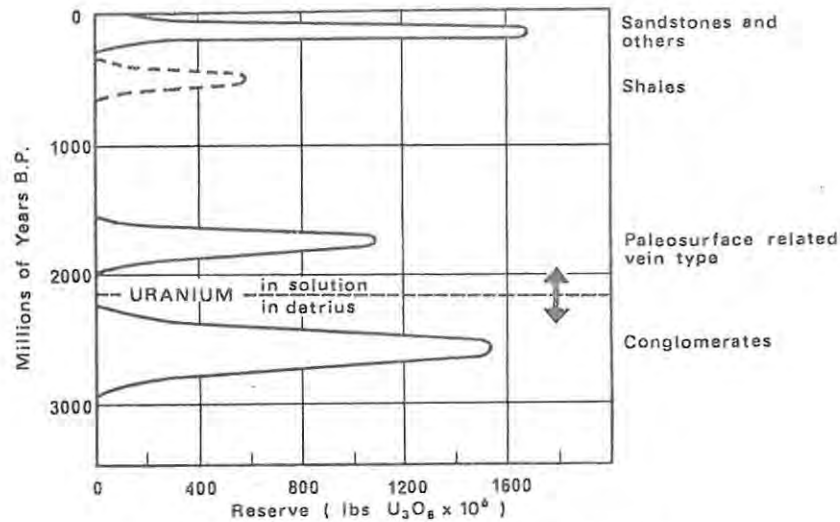


Fig. 2. Time-bound character of uranium deposits.

(after Robertson et al., 1978)

of Permian age or younger, thus placing a distinct time boundary on the deposits.

Age dating of uranium deposits has shown a number of deposits to be very recent which implies that a continuing process of concentration and redistribution is probably still taking place.

Ore deposits of this type are associated with continental sediments and there are no economically viable concentrations found in sediments of marine origin. Sedimentary basins in which drainage is relatively closed seem particularly favourable. Basins with open drainage to the sea have not generally been found to contain uranium mineralization of mineable proportions though many small prospects are located in such environments. One exception to this is the deposit of South Texas on the open Gulf Coast where grades though low, attain economic proportions.

3.

URANIUM DEPOSITS

3.1 DISTRIBUTION OF URANIUM DEPOSITS OF THE WORLD

The world's supply of uranium comes from several sources of which vein-type, uranium in sandstone and uranium in conglomerates contribute a large proportion. The major provinces of Colorado-Wyoming; Witwatersrand; Northern Territory, Australia; South Australia; and Northern Saskatchewan were discovered by 1950 and they constitute 60 per cent of the western world's reserves (Bowie 1979). The most important uranium provinces discovered since 1950 have been the Blind-River - Elliot Lake field of Ontario; the Agadès basin, Niger; and Rössing, South West Africa. Figure 3 shows the major uranium deposits and provinces of the western world.

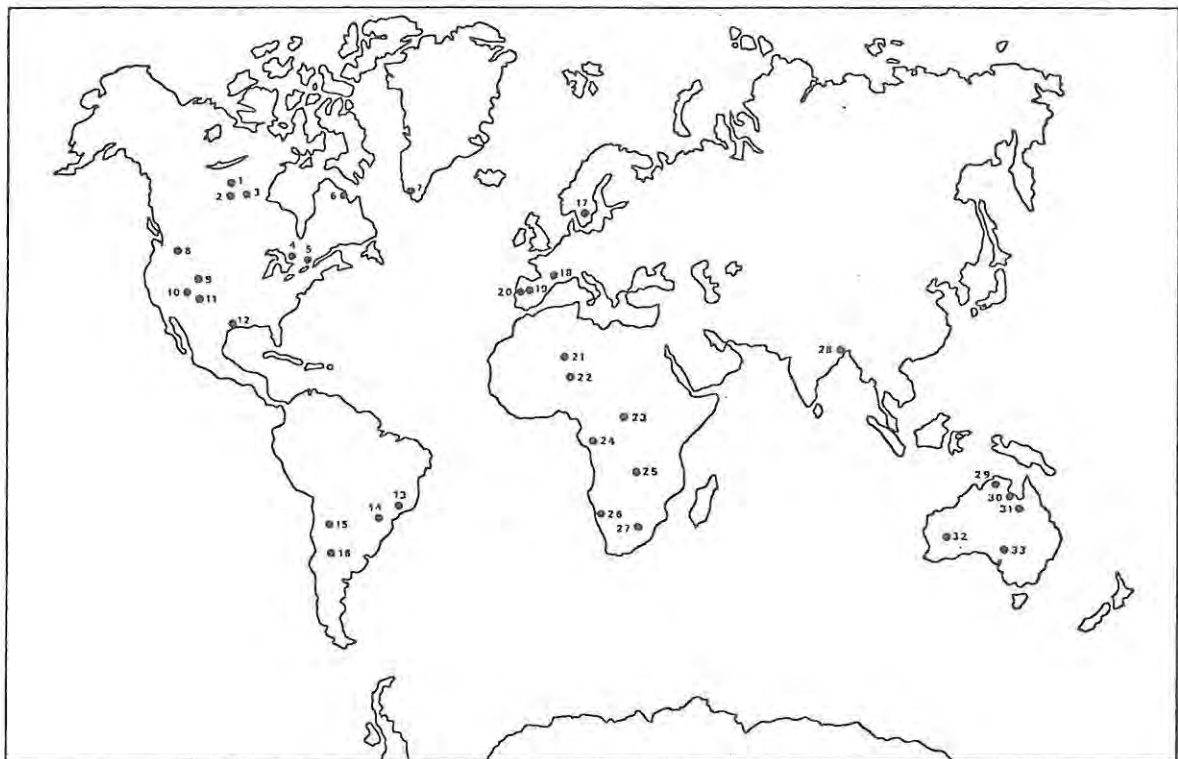


FIGURE 3. Major uranium deposits and provinces (non-Communist countries): 1, Beaverlodge; 2, Cluff Lake; 3, Wollaston belt; 4, Elliot Lake/Agnew Lake; 5, Bancroft; 6, Makkovik; 7, Ilímaussaq; 8, Spokane; 9, Wyoming basins; 10, Uravan; 11, Grants; 12, Texas; 13, Poços de Caldos; 14, Figueira; 15, Salta; 16, Malargue; 17, Ranstad; 18, Massif Central; 19, Salamanca; 20, Urgeiriça; 21, Hoggar; 22, Agadès; 23, Bakouma; 24, Mounana; 25, Shinkolobwe; 26, Rössing; 27, Witwatersrand; 28, Singhbhum; 29, Alligator Rivers; 30, Westmoreland; 31, Mary Kathleen; 32, Yeclirrie; 33, Frome/Yarramba.

(after Bowie, 1979)

3.2 CLASSIFICATION OF URANIUM DEPOSITS

Uranium deposits have very varied origins and for this reason are difficult to place within the artificial boundaries of classification. As a result there are many types of classifications.

Maucher (1962) lists the more important ones in his book while more recent studies have been published by Ruzicka (1971) and Ziegler (1974). During the last decade the discovery of several new types of uranium deposits has led to more revised classifications of uranium deposits.

Bailey and Childers (1977) classify the uranium deposits according to the principal controls of mineralization which are strata-controlled, structure-controlled and intrusive-controlled. This emphasizes observable, important differences and similarities with genetic implications and is therefore a useful classification.

Dahlkamp (1978a) presents a general classification of recognized types of uranium mineralization by the time stratigraphic relationship of host rock to ore emplacement. This comprises sedimentary, intrusive, metamorphic, contact metasomatic and supergene deposits. A modification of this classification incorporates the prevalent geological processes associated with their formation. This results in subdivisions of the previous classification into endogenic, exogenic or a combination of both processes.

The majority of classifications differ widely in their choice of subdivisions but most of them appear to be in agreement when classifying the sandstone uranium deposits. Morton (1979) has suggested several classifications including one based on the relationship of the various uranium deposits to age of unconformities. However, his simpler classification based on the principal controls of mineralization will suffice to place sandstone uranium deposits in context with the other type of uranium deposits and will be used here.

A. A CLASSIFICATION OF THE PRINCIPAL URANIUM ASSOCIATIONS (after Morton 1979)

1. SEDIMENTARY-HOSTED U DEPOSITS

- 1(i) Placer and modified-placer deposits (Σ, Δ)
- 1(ii) Sandstone-, conglomerate- and siltstone-hosted deposits (E, Δ)
- 1(iii) Pelite-hosted deposits (Σ, Δ)
- 1(iv) Phosphorite-hosted deposits (Σ, Δ)
- 1(v) Limestone-hosted deposits (E, Δ)
- 1(vi) Duricrust-hosted deposits (Σ)
- 1(vii) Lignite-, coal- and carbonaceous-pelite-hosted deposits (Σ, Δ, E)
- 1(viii) Diatremic deposits in sedimentary sequences (E)

2. IGNEOUS-/VOLCANIC-HOSTED U DEPOSITS

- 2(i) Plutonic segretation deposits of disseminated, pegmatitic, diatremic or vein character (Σ, E)
- 2(ii) Volcanogenic-exhalative deposits of disseminated- or vein-character (Σ, E)
- 2(iii) Supergene or deuteric deposits within plutonic or effusive suites (E)

3. METAMORPHIC-HOSTED AND METAMORPHIC U DEPOSITS

- 3(i) Disseminated- and vein-deposits in regionally metamorphosed sediments or in volcanic sequence (Σ, E)
- 3(ii) Metatect pegmatitic deposits (Σ, E)
- 3(iii) Anatectic granitoid deposits (Σ, E)
- 3(iv) Diatremic deposits in metamorphic terrains (E)
- 3(v) Contact metamorphic/metasomatic deposits (Σ, E)
- 3(vi) Jabiluka type deposits of sub- and supra-unconformity types (E)

Δ = Diagenetic
 Σ = Syngenetic
 E = Epigenetic



Fig. 4. Areas with uranium deposits in sandstones. (after Ruzicka, 1976: Potential for uranium discoveries in the world, AIF, Geneva)

(from OECD 1980)

4.

SANDSTONE URANIUM DEPOSITS

4.1 DISTRIBUTION OF SANDSTONE URANIUM DEPOSITS

Uranium deposits in sandstone are the most important source of uranium as they contain 34 per cent of known reserves (Bowie 1979). The majority of the uranium occurs in the Colorado-Wyoming province of the U.S.A. but other significant deposits are those in Niger and South Australia. Reserves in the order of 200,000 t U_3O_8 could be proved in the Agadès basin which already contains the Arlit deposit. The Frome Embayment province of south Australia has features similar to the Colorado-Wyoming deposits. Uranium deposits also occur in sandstones at Figueira (Brazil), Sierra Pintada (Argentina), Nagalia Basin (Australia), Ningyo-Toge and Kurayoshi (Japan), Val Rendena (Italy), Zirovski Vrh (Yugoslavia) and Forstau (Austria), the Gulf Coastal Plain (U.S.A.), and others as shown in Figure 4.

TYPE OF DEPOSIT	SYMBOL	AVERAGE U-GRADE in %	TOTAL U - POTENTIAL (MINED + RESERVE) ≤ 5 t p lb		MINED AS	
			Individual Deposit in t U	Uranium District up to max t U	Main Product	Secondary Product
CONGLOMERATE - TYPE		0,025 - 0,15	15000 - 100000	200000	1 U 2 Au	- U
SANDSTONE - TYPE		0,2	5000 - 25000	150000	U	Cu, V, Mo, Se
VEINLIKE TYPE		0,2 - 2	10000 - 250000	450000	U	Ni
HYDROTHERMAL VEINS		0,1 - 1	100 - 25000	50000	1 U 2 Co, Ni, Ag, Br	U
INTRAINTRUSIVE TYPE		0,04	10000 ± 100000	100000	1 U 2 Cu	U
CALCRETE - TYPE		0,1 - 0,2	40000	40000	U	V
BLACK SHALE + PHOSPHORITE - TYPE		0,02 - 0,08	10000 - 70000	300000	1 U 2 P	U

Fig. 5. Uranium Grade and Potential of Types of Deposits

(after Dahlkamp 1978a)

Dahlkamp (1978a) presents a summary of grades and contents of the various types of deposits. (Figure 5) A cumulation of the total reserves Figure 6 serves to highlight the potential of sandstone type deposits.

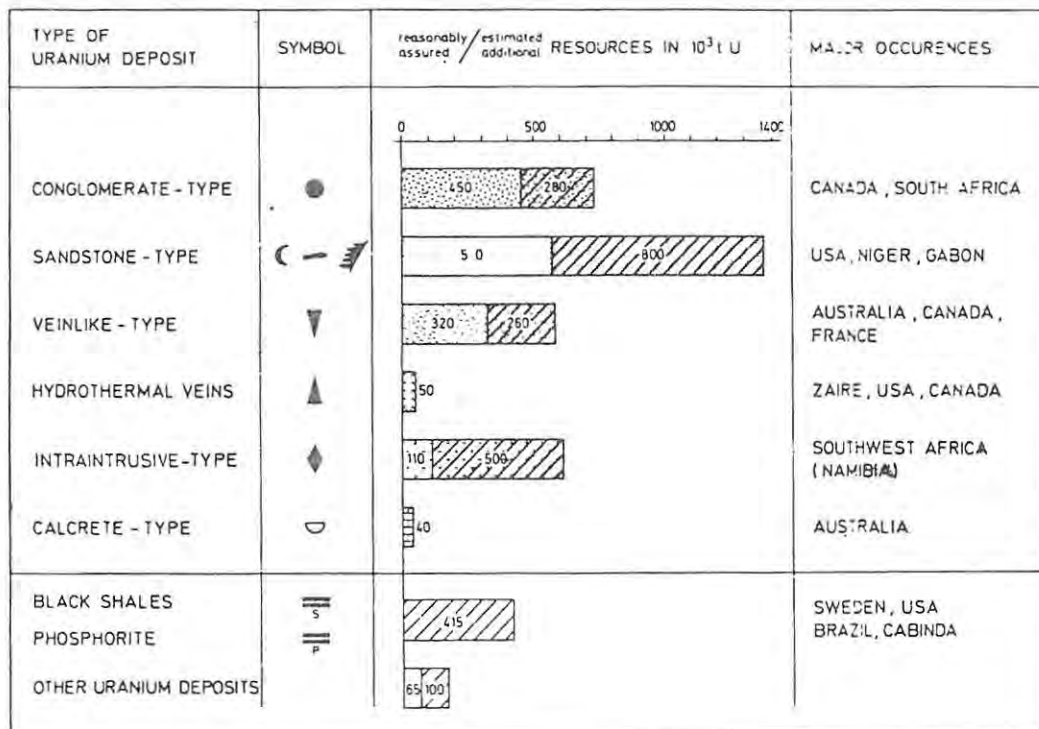


Fig. 6. Free World Uranium Resources by Type of Deposit
(after Dahlkamp 1978a)

4.2 TYPES OF SANDSTONE URANIM DEPOSITS

Most classifications are in agreement in subdividing sandstone-type deposits into peneconcordant (trend) deposits, roll-front deposits and stack deposits. The diffuse nature and small scale of these types of uranium ore deposits contrasts markedly with base metal deposits. 99 per cent of the known sandstone deposits of the U.S.A. individually contain less than one million tons of ore with less than 3 million pounds of U_3O_8 .

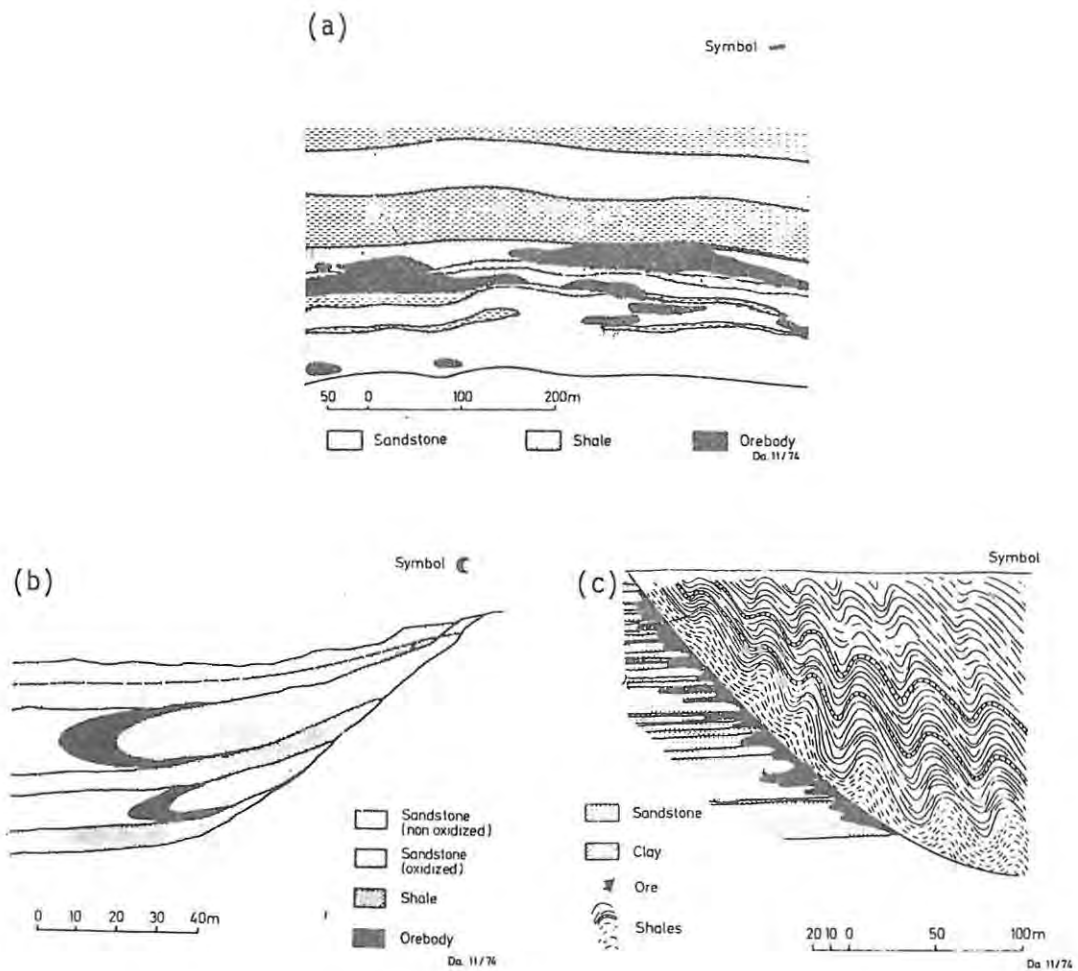


Fig. 7. Types of Sandstone Uranium Deposits

- (a) Peneconcordant-type (idealised, after Grutt Jr. 1972, Clary et al.)
 - (b) Roll-front (idealized)
 - (c) Stack-type (idealized, after Gangloff 1970)
- (after Dahlkamp 1978a)

4.2.1 Peneconcordant (Trend) Deposits

These deposits as shown in Figure 7(a) are epigenetic and controlled by lithology. The bodies are flat lying or gently dipping bodies and occur mostly parallel with the enclosing strata. Ore deposits are best developed in cross-stratified medium to coarse-grained arkoses and sandstones. The depositional environments of the host rocks are mainly fluvial-stream

channels, flood plains and fluvial enclosed alluvial bars but may be of a deltaic or lagoonal origin. The mineralization must have closely followed sedimentation and can therefore be thought of as an early diagenetic phenomenon (Morton 1979). Once the uranium has been precipitated it is "locked" into the host rock. A very characteristic feature is the proximity of ore bodies to unconformities. This type of deposit is characterized by its significant pyrite content, the presence of vegetal organic matter and of amorphous organic substances. The vanadium concentrates are often such that in the U.S.A. they can be mined exclusive of the uranium.

The dominant ore minerals occurring in the reduced zone are pitchblende and coffinite which are associated to some extent with vanadium oxide minerals. The important uranium minerals within the oxidized zone are carnotite, tyuyamunite or francevillite all of which are uranyl vanadates. Accessory elements include Mo, Se, Cu.

This type of uranium deposit is found mainly in host rocks of Tertiary, Jurassic, Triassic and Carboniferous age. The main ore districts are the Colorado Plateau, the Paguate-Grants-Church-rock District in the U.S.A., the Agadès region in Niger, the sub-Andean zone of Argentina, and the Lake Frome embayment in South Australia. Mineralization of this type is also found in the Karoo in South Africa.

The average uranium content varies between 0,15 per cent and 0,4 per cent U_3O_8 . In plan the ore bodies appear as amoeboid to lenticular-shaped with a lateral extension of several tens to several thousands of metres across trend. Thicknesses vary between one and 5 metres and may be as much as fifteen metres.

4.2.2 Roll-Type Deposits

Roll-type deposits have lithologies and host rock provenances similar to those of the peneconcordant type. The ore bodies are epigenetic and their formation was controlled by lithology and physicochemical processes.

Uranium mineralization is located along the contact between oxidized

and non-oxidized sandstone. This boundary is regarded as the furthest downdip or outer penetration front of oxidizing ground water. A characteristic is the interbedding of the mineralized permeable layers in impermeable horizons of mudstone and siltstones. In contrast to trend-type deposits, the host rocks appear to maintain their permeability after the initial fixation of uranium. This is evidenced by the apparent continuing process of roll-front generation to present time.

The ore bodies differ from the peneconcordant-type in that they cross-cut the stratification of the host rock and are thus discordant to the strata. In cross section, the form of the ore bodies resembles a crescent while the plan view of the form is sinuous.

The main ore minerals are pitchblende and coffinite while selenium in the form of ferroselite (FeSe_2) is found enriched on the convex side of the roll-front. In addition arsenic, phosphorous and copper seem to occur coincidentally with uranium.

Stratigraphically, the roll-front deposits are mainly hosted by rocks which are Tertiary, (Paleocene, Eocene in Wyoming; Eocene & Miocene in Texas) but they also occur in the Uravan Mineral Belt in Utah & Colorado in Jurassic strata.

The main uranium districts of this type are found in the intra-cratonic sedimentary basins of Wyoming (Powder River, Shirley Basin and Gas Hills) and the Texas Gulf Coast, U.S.A.

Average uranium contents vary between 0,1 per cent and 0,5 per cent U_3O_8 . The dimensions of the ore fronts in the apex zones are up to 15 metres; the widths vary from a few centimetres to several hundred metres, and the strike lengths can be in the order of several kilometres.

4.2.3 Stack Deposits

Such deposits are tectonically, lithologically controlled epigenetic deposits which occur in rocks of the same type as the peneconcordant and roll-front deposits.

The diagnostic characteristic of stack deposits is the uranium concentration that is in or along fault zones with impregnation of the adjacent clastic sediments.

It is generally thought that stacked ore bodies, which appear to be less than ten million years old have been formed by the destruction of older (> 100 million years) trend-type ore bodies .

The main ore minerals in the reduced zone are pitchblende with subordinate coffinite. In the oxidized zone uranyl vanadates are present.

The host rocks are of Triassic and Jurassic age and some are of Lower to Middle Proterozoic.

Main deposits are found in the Ambrosia Lake/Grants District, New Mexico and in the Franceville Basin of Gabon. The average uranium contents vary between 0,1 and 0,4 per cent U_3O_8 . The dimensions of the bodies vary between a few tens of centimetres to tens of metres in thickness by hundreds of metres in length.

4.3 SOURCES OF URANIUM FOR SANDSTONE TYPE DEPOSITS

There are at least three possible external sources of uranium for sandstone-type deposits. They are :

- (1) Magmatic-Hydrothermal Sources
- (2) Leaching of exposed pre-sediment granites and/or
- (3) Leaching of tuffaceous volcanic rocks

Although the source of uranium for sandstone-types may vary from basin to basin depending on the geology of the basin rims, this has no bearing on the character of the sandstone deposit. The source of uranium in sandstone-type deposits of the U.S. can be explained by any of the sources listed above. (Adler 1974)

There is also the possibility that the uranium was derived from the sediments themselves. From studies of Cainozoic Red beds, Walker (1975)

suggests that a source for uranium associated with Red beds could be unstable detrital silicate minerals such as hornblende, augite, and plagioclase which have undergone extensive intrastratal alteration. The minerals are potentially important carriers of trace amounts of uranium and because they are sufficiently abundant, the cumulative effects of their breakdown could result in the release of significant amounts of uranium. Walker suggests that similar conditions of intrastratal alteration and release of uranium would have occurred during the history of most of the ancient first cycle non-marine Red beds. Diagenetic alteration in these ancient Red beds provides intrastratal sources of uranium which would be more than adequate to explain the origin of the uranium in associated ores. It is therefore inferred (by Walker 1975, p 925) that "although extraneous provenance areas provide additional sources they are not pre-requisites of ore-grade concentrations in Red beds."

5.

GEOCHEMISTRY OF URANIUM

Uranium with its atomic number of 92 is one of the actinide group of elements (those with atomic numbers of 89 and above). Of the naturally occurring elements actinium, thorium, proactinium, plutonium and uranium, only thorium and uranium occur in appreciable quantities in nature. (Mc Kelvey et al., 1955)

5.1 CRYSTAL CHEMISTRY

The oxyphile and lithophile behaviour of uranium in geologic processes is governed by its chemical characteristics, particularly its outer electron structure. The electronic configuration of neutral gaseous uranium is (Rn) $5f^3$, $6d$, $7s^2$, and the common ionic species are U^{3+} , U^{4+} , U^{5+} , and U^{6+} . The $5f$ electrons are those principally involved in chemical bonding and in the formation of aqueous ions. In addition to the four outermost electrons in the uranium atom the two electrons in the inner unfilled $5f$ electron shell can also be valence electrons. Uranium therefore also has the possibility of either a pentavalent or hexavalent state. Until recently the pentavalent state was thought to be like the trivalent state of uranium and only obtained under laboratory conditions. (Seaborg & Katz 1954) The hexavalent state of uranium is very stable and is found in over two-thirds of the hundred or more minerals in which uranium is a major (> 1 per cent) component.

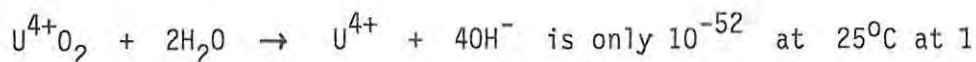
5.2 MINERAL CHEMISTRY OF URANIUM

The uranium atom, despite its 92 electrons has a radius of 1,38A which is essentially the same as tungsten and molybdenum. Its ionic size is 1.05A. U^{4+} which is the most abundant uranium species in nature has a radius of about 0.97A. The combination of the relatively large size and high charge probably accounts for its very limited substitution in the structures of the common rock-forming minerals.

The calcium ion with an ionic radius of 0,99A is the only abundant cation with a similar radius, so that U^{4+} does occur in some calcium-bearing minerals, notably sphene, apatite and fluorite. Its absence in other common calcium minerals - anorthite, calcite, and gypsum for example,

is probably due to the discrepancy in charge.

The U^{4+} oxide ($U^{4+}O_2$) is very slightly soluble in water. The dissociation constant for the reaction



atmosphere pressure and is not affected to any extent by increases in temperature up to $120^\circ C$. This great stability of $U^{4+}O_2$ under reducing conditions probably accounts for the preponderance of uraninite as the primary uranium ore mineral in the majority of uranium deposits.

U^{4+} also shows a limited amount of substitution for other tetravalent compounds such as zirconium, tungsten and molybdenum. The discrepancy in radius ($Zr = 0,79$; $W = 0,70$; $Mo = 0,70A$) is such that there is only a small percentage of uranium in minerals containing these elements. The only element with a tetravalent cation essentially identical to U^{4+} is thorium so that there is extensive isomorphism between uranium and thorium silicates. U^{4+} generally occurs in a whole series of complex tantalates, niobates, and various rare-earth oxides and phosphates where it may substitute for rare-earths, calcium, niobium or tantalum. In these cases the uranium amounts to up to 20 per cent of the mineral with the maximum uranium content being 40 per cent in brannerite $(U, Ca, Fe, Y, Th)_3(Ti, Si)_5O_{16}$.

Uraninite is easily oxidized and destroyed on weathering but most of the other U^{4+} minerals are not. Presumably, continued oxidation of the U^{4+} ion in fairly pure $U^{4+}O_2$ to the hexavalent state is permitted by the removal of friable and soluble oxidation products whereas in those compounds in which U^{4+} is a minor substituent it is protected from attack by the surrounding unoxidizable ions. In general, the U^{4+} tantalates, niobates and phosphates are durable and highly insoluble as well as resistant to oxidation, so that they are found in clastic sediments.

In systems where oxygen is a major component, hexavalent uranium is found to be closely associated with two oxygen ions forming the very stable divalent uranyl ion $(U^{6+}O_2)^{++}$ (McKelvey, et al., 1955)

The $(U^{6+}O_2)^{2+}$ ion is so stable that it can be considered a complex

ion like NH_4^+ and maintains its identity through various chemical transformations from solutions to solid and vice versa. (McKelvey et al., 1955). Unlike the spheroidal tetravalent uranium, the divalent uranyl group is "dumb-bell shaped" with the two oxygen ions on opposite sides of the uranium atom. (Figure 8)

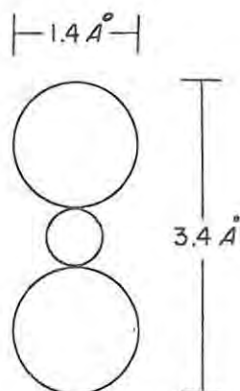
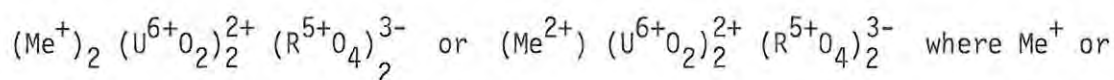


FIG. 8. The uranyl ion.

(after McKelvey et al., 1955)

It should be noted that the uranyl ion is an entirely different chemical species from tetravalent uranium. One of the most important differences being that uranyl compounds are much more soluble than the tetravalent compounds. Although most of the uranium minerals contain hexavalent uranium these are found in the zone of oxidation and it is most probable that most of the uranium in the crust occurs below the zone of oxidation in the tetravalent state.

In solids, the other atoms tend to arrange themselves around the uranyl structure so as to "key" the uranium into a layer structure. The compounds are of the general type :



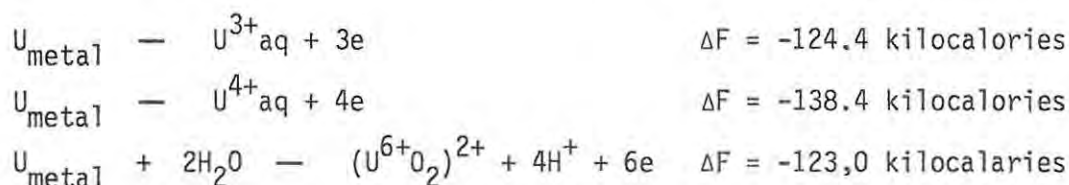
Me^{2+} are monovalent or divalent cations such as K^+ , Na^+ , Ca^{2+} , Mg^{2+} or Cu^{2+} . R^{5+} is either V^{5+} , As^{5+} , or P^{5+} . The stable group in the solid is the $((\text{U}^{6+}\text{O}_2) (\text{R}^{5+}\text{O}_4))^{-1}$ complex, which forms a continuous layer structure. The

Me^+ or Me^{2+} is much more loosely held so that it can be added or removed by a base exchange reaction without destroying the $((\text{U}^{6+}\text{O}_2)(\text{R}^{5+}\text{O}_4))^{-1}$ structure.

The uranyl ion does not bind strongly with most anions and hence forms few insoluble solids. Moreover, the few insoluble compounds that are formed are not combinations with the major rock-forming elements but with elements As, V and P which are not abundant in natural waters.

5.3 THE CHEMISTRY OF URANIUM IN AQUEOUS SOLUTIONS

Uranium's tendency to lose its valence electrons is indicated by the following ionization equations which give the energy released when uranium metal dissolves in water : (Mc Kelvey et al., 1955).

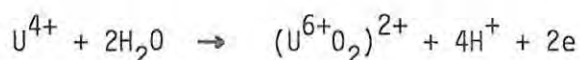


U^+ and U^{2+} are unknown in aqueous solution.

U^{3+} can be obtained in the laboratory but is extremely unstable with respect to the liberation of hydrogen from water it appears that the U^{3+} ion is unimportant in nature.

U^{4+} is stable under reducing conditions or in sedimentary environments in which organic material is preserved.

The U^{4+} ion in aqueous solution is oxidized easily to the uranyl ion $(\text{U}^{6+}\text{O}_2)^{2+}$ rather than to U^{6+} as shown in the reaction



The general relations between tetravalent uranium compounds and hexavalent compounds in aqueous solution are shown in Figure 9 where the stability fields of U^{4+} and U^{6+} oxides are plotted as a function of pH and oxidation potential.

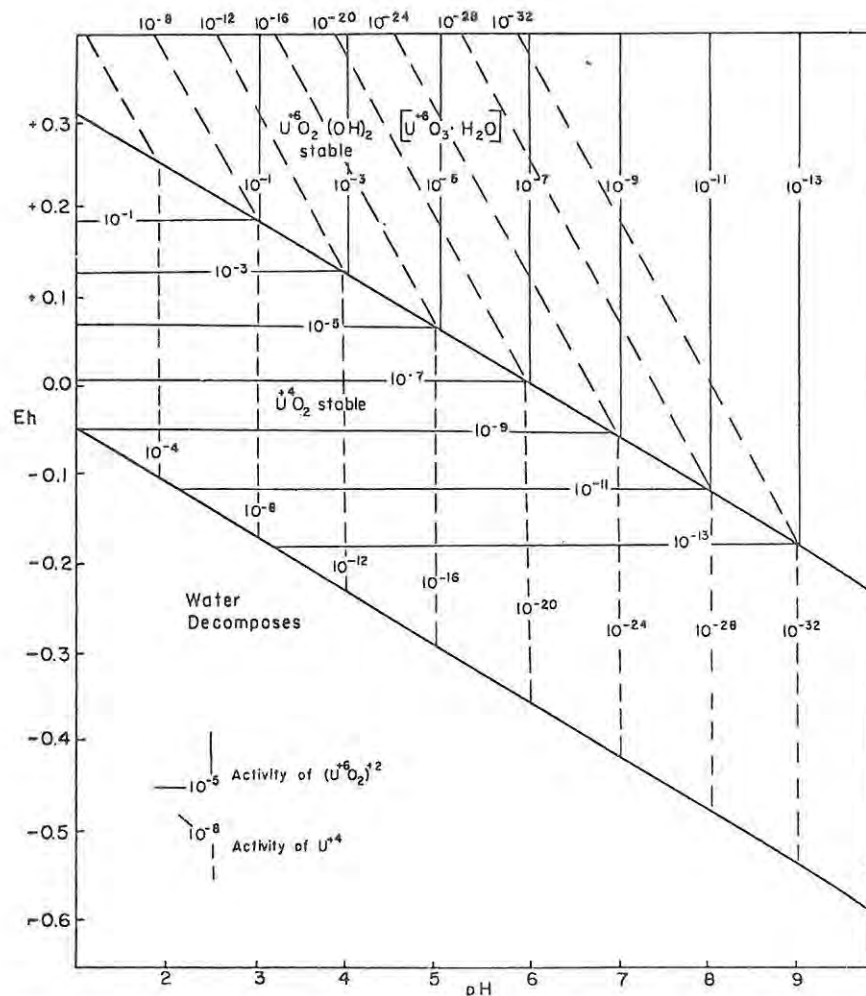


FIG. 9. Stability fields of UO_2 and $UO_2(OH)_2$. Superimposed contours show equilibrium activity of U^{4+} and $(UO_2)^{2+}$ ions.

(after McKelvey et al., 1955)

The activity of the U^{4+} ion, which is an approximate measure of the dissociation of uraninite, is extremely small even in solutions of pH 3. The activity of the $(UO_2)^{2+}$ ion on the other hand is appreciable ($> 10^{-5}$) at pH 5.

No effective complexes of U^{4+} are known so that the activity of the ion is probably an index of the stability of uraninite whereas the uranyl $(UO_2)^{2+}$ ion is strongly complexed by sulphate and carbonate and the activity shown is probably a small fraction of the total solubility. The sulphate complex is largely non-ionized $(UO_2)(SO_4)$ while the carbonate forms two complexes $[(U^{6+}O_2)(CO_3)_{-3}^{-4}]$ and $[(U^{6+}O_2)(CO_3)_2(H_2O)_2]^{-2}$.

In a closed chemical system the oxidation potential may vary with composition, temperature and pressure of that system. pH and oxidation potential (computed as Eh) have therefore been used to indicate the stability fields of uranium ore minerals (Miller 1958); Hostetler and Garrels 1962; Rich *et al.*, 1977). The most recent work is by Langmuir (1978), who studied the thermodynamic properties of dissolved uranium species and uranium minerals. Solution-mineral equilibria were computed and used to define the conditions under which uranium deposits are likely to form.

The application of the stability constant data shows that the uranium in natural waters is usually complexed not only with carbonate, which was generally accepted as the only complex but also with hydroxide, phosphate, fluoride, sulphate and perhaps silicate. These complexes greatly increase the solubility of uranium and the mobility of uranium in surface and ground waters.

The relative importance of these complexes has been examined by comparing the amounts in natural water that contain typical concentrations of the complexing ligands.

From the thermochemical data several diagrams of distribution of the various complexes versus pH have been constructed. Figure 10 indicates the wide range of pH conditions under which uranium can remain in solution

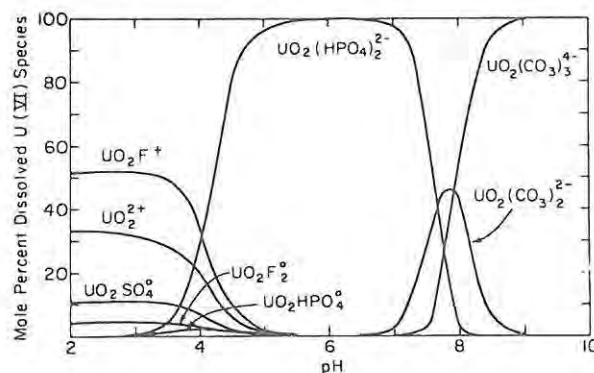


Fig. 10 Distribution of uranyl complexes vs pH for some typical ligand concentrations in ground waters of the Wind River Formation at 25 C. $P_{\text{CO}_2} = 10^{-2.5}$ atm, $\Sigma F = 0.3$ ppm, $\Sigma Cl = 10$ ppm, $\Sigma \text{SO}_4 = 100$ ppm, $\Sigma \text{PO}_4 = 0.1$ ppm, $\Sigma \text{SiO}_2 = 30$ ppm.

(after Langmuir 1978)

if complexed with either fluoride, phosphate or carbonate. Uranyl silicate complexes are unimportant.

The results show that in typical ground water concentrations fluoride complexing is dominant below pH4 while the most important uranyl complexes are formed with phosphate and carbonate under nearneutral and alkaline conditions respectively. The converse also applies in that the precipitation of the fluoride ion as fluorite can reduce the U^{4+} mobility and so lead to the precipitation of uranium or coffinite nearby.

Langmuir also shows that at a common ground water sulphate level of 100 ppm, UO_2SO_4 may be a significant species up to pH 7 (Figure 11).

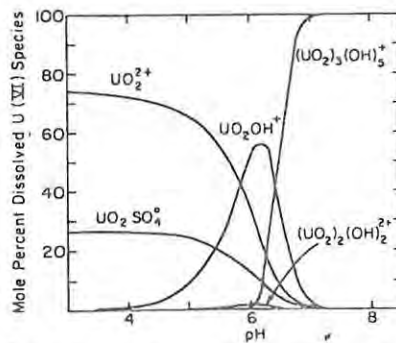


Fig.11 Distribution of uranyl-hydroxy and sulfate complexes vs pH at 25 C with $\Sigma U = 10^{-6}$ M, and $\Sigma SO_4 = 10^{-3}$ M (100 ppm).

(after Langmuir 1978)

There is controversy concerning the nature and stability of uranyl hydroxy complexes but the majority of workers show the significant species in hydrolysis reaction to be UO_2^{2+} , UO_2OH^+ , $(UO_2)_2(OH)_2^{2+}$ and $(UO_2)_3(OH)_5^+$. The amount of dissolved uranium present as well as temperature affects the importance of these complexes (Figure 12, p 22).

Figure 13 on page 22 shows that the uranyl carbonate complexes are the major species in pure water down to pH 8 under a ground water CO_2 pressure of 10^{-2} atmospheres and 25°C and down to pH 5.8 at $10^{-3.5}$ atmospheres. With increasing temperature, the carbonate complexes decrease in importance relative to the hydroxyl complexes to such an extent that the uranyl carbonate complexes are minor species at all pH's.

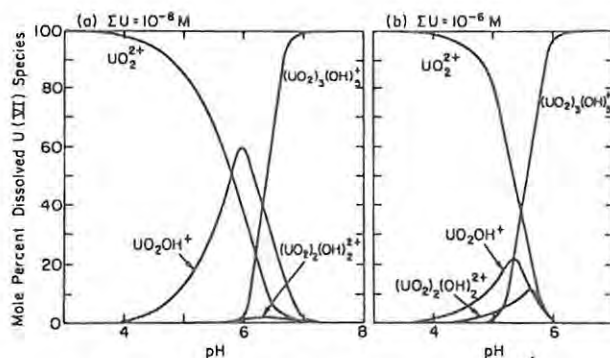
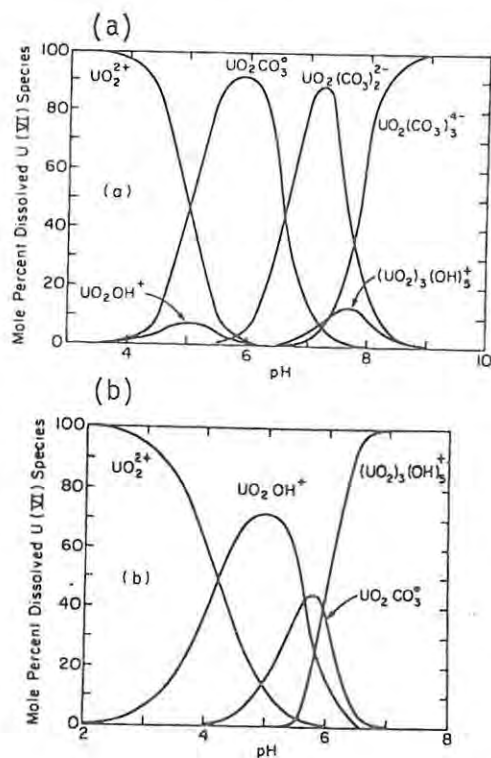


Fig. 12. Distribution of uranyl-hydroxy complexes vs pH in pure water at 25°C for $\Sigma U = 10^{-8} M$ (Fig. 12a), and for $\Sigma U = 10^{-6} M$ (Fig. 12b)

(after Langmuir 1978)

Fig. 13. Distribution of uranyl-hydroxy and carbonate complexes vs pH for $P_{CO_2} = 10^{-2} atm$ and $\Sigma U = 10^{-8} M$, at 25°C (Fig. 13a), and at 100°C (Fig. 13b)

(after Langmuir 1978)



5.4 FIXATION OF URANIUM

Studies of the chemistry of uranium in aqueous solution show that uranium is easily transported in various solutions under a range of pH conditions, but there is much that is not understood. The fixation of uranium is however even less well understood.

Although uranium is extremely mobile in the oxidized hexavalent state it can be precipitated as an arsenate, phosphate or vanadate (McKelvey *et al.*, 1955) in arid climates. Likewise, uranyl silicates, carbonates and sulphates form by dessication and are relatively stable at the surface. Uranium reduction and precipitation or uranous silicate or oxide requires an external agent, generally organic material.

Reduction by iron, sulphur oxidation in limestone and adsorption on clay are thought to be minor factors in the fixation of uranium. (Gabelman 1977), although, in the Beverley deposit of the Lake Frome Embayment, the uranium is reported to occur as finely divided uraninite thought to have been adsorbed on clay (OECD 1980).

The exact mechanisms of reduction and fixation by organic matter have been investigated (Moore 1954, Breger & Deul 1956) but are still not very well understood. Experiments were conducted to determine the relative ability of various types of carbonaceous material and other substances to remove uranium from solution. These are summarized in Figure 14 on page 24.

Furthermore, metamorphism of subbituminous coal to bituminous coal could destroy the organic compound important in extracting uranium. The anthracite and graphite are somewhat better extracting agents than bituminous coal and there is the possibility that the further metamorphism has created the ability to remove uranium by ionic absorption.

Lovering (1955) examined many uranium-bearing samples from localities in the western U.S.A. and concluded that the uranium is fixed by adsorption. The adsorption theory is supported by the fact that all of the materials found to be radioactive, are precipitated in a colloidal or very fine-grained state. Rankama and Sahama (1950) mention that soluble uranium compounds are strongly adsorbed on the hydroxide gels of iron, manganese,

aluminium and on silica gel.

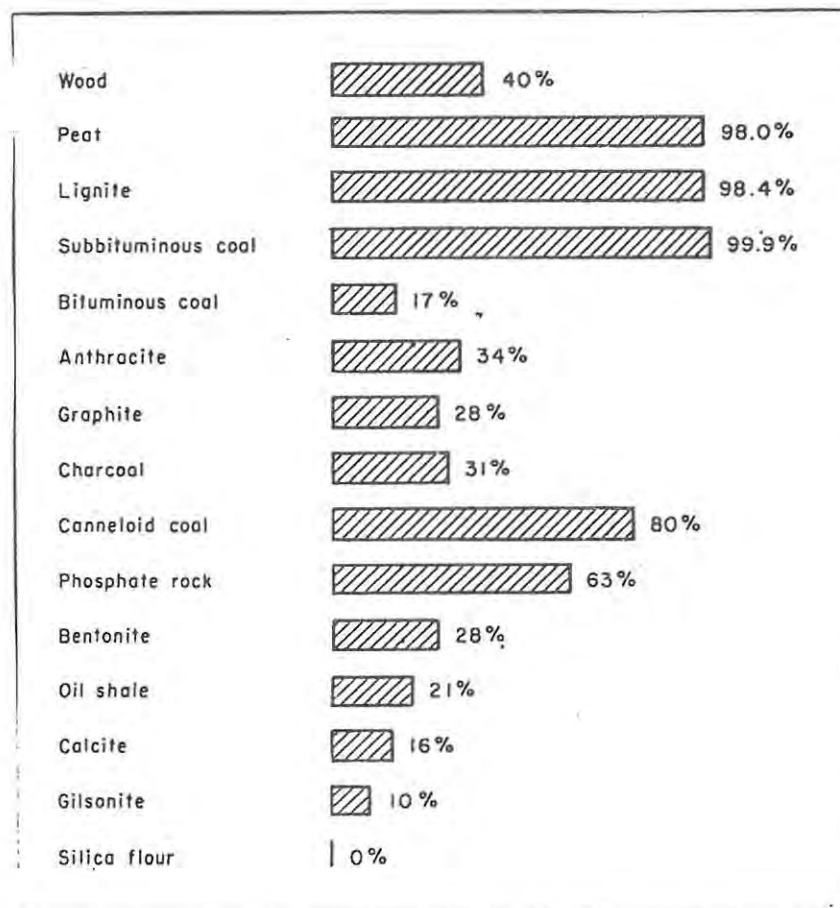


Fig. 14 Percent uranium extracted by coal and other materials from uranyl sulfate solutions containing 200 parts per million uranium

(after Moore 1954)

More evidence is emerging which suggests that a common mechanism of uranium concentration is by initial sorption of uranium complexes onto ferric oxyhydroxide, manganese oxyhydroxides, titanium oxyhydroxide, zeolites, clays, organics etc., followed by a latter reduction of U^{6+} to U^{4+} by mobile reductants such as H_2S , CH_4 , HS , H_2 . (van der Weijden and Langmuir 1976).

There are two groups of natural organic compounds found in rocks; the petroleum group and the humate group. The latter are derived by the breakdown of plant material and are very important in the capture or

precipitation or uranium from solution in both surface waters and underground aquifers. In some deposits such as the Ambrosia Lake District, New Mexico, the uranium in the deposits is insignificant in contrast to the amount of organic material present.

Humic materials and related organics could be important in the fixation of uranium in several different ways (Morton 1979). They could act as adsorbents or chelating agents in which case the effect would be a surface sorption or chelation of uraniferous ions onto humates etc. In the case where there is a direct reaction of the uranium salts with humic acids (HA) the following generalized process occurs.



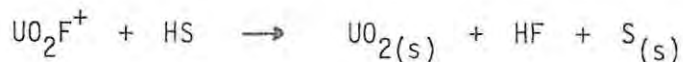
If the humic materials act as direct reductants the uranium salts could react in aqueous environments to precipitate uraninite as follows :



OR



In some cases the organics would act as indirect reductants by acting as nutrient for bacterial colonies. H_2S would be generated by the reduction of ground water sulphates which would initiate the precipitation of uraninite.



Humic acids have an extremely variable molecular weight (1000 - 10 000) composed of about 56 per cent Carbon, about 34 per cent Oxygen, about 6 per cent Hydrogen, about 3 per cent Nitrogen and 1 per cent Sulphur. They have a variety of organic complexes that can partake in electron sharing with water-borne ions such as UO_2^{2+} ; $\text{UO}_2(\text{OH})^+$; $\text{UO}_2(\text{CO}_3)_2\text{H}_2\text{O}^{2-}$ etc. The process of chelation or ion exchange will occur in this manner and will also be a function of pH.

Gruner (1956) proposed a multiple migration-accretion mechanism for the reconcentration of uranium in sandstone. This mechanism has become accepted as the mechanism by which unoxidized uranium concentrations migrate slowly down the palaeoslope by means of constantly repeated oxidation and reduction in favourable aquifers.

The concept developed by Gruner (1956) was supported by Stockey (1968). He recognized that uranium ore bodies in the Shirley basin, U.S.A. were on the margin of an extensive body of sandstone which was oxidized, whereas the ore bodies and the adjacent and equivalent sandstones were carbonaceous and pyritic. Stockey developed the "geochemical cell" concept described by Rackley (1972) for processes occurring as oxygenated water invaded the reduced, carbonaceous and pyritiferous sandstones. The term appears to have been accepted by most since it is very applicable to the dynamic system with advancing oxidizing fronts coupled with marked Eh, pH, mineralogical, chemical changes and micro-organisms.

Some workers (Granger and Warren 1969) have tried to find a process which does not rely on bacterial action to establish a reduction barrier but Rackley favours uranium precipitation reactions to be biochemically controlled as shown in Figure 15.

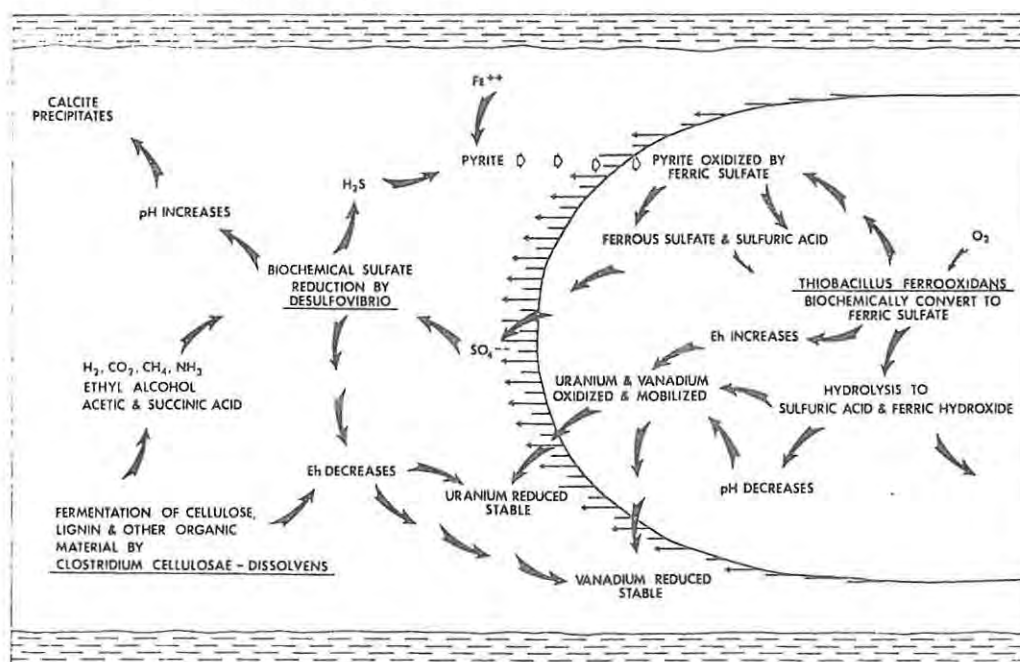


Fig. 15 - Some probable reactions in advancing geochemical cell. Cell moves from right to left. Left side is reducing, right side is oxidizing. Vertical and horizontal scales are relative to each other. Thickness range is 3-40 ft (1-12 m).

(after Rackley 1972)

A feature of the geochemical cell is the metal zonation that occurs. A knowledge of these relations can be useful in determining the configuration of an ore body from drill hole information. The characteristic zoning is shown as follows (Figure 16).

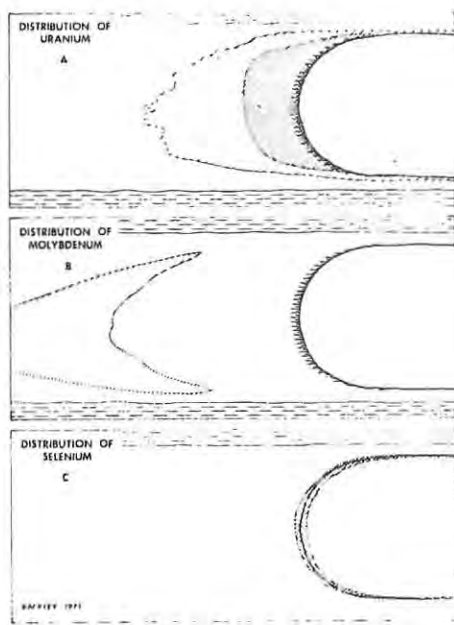


Fig. 16. Characteristic zoning of (A) uranium, (B) molybdenum, and (C) selenium in leading edge of geochemical cell. Intensity of hatching is relative indication of concentrations which may range from traces to a few percent on same front.

(after Rackley 1972)

Gabelman (1977) states that "there is little real evidence for significant migration of primary ores after their initial deposition" (p 76). Radiometric dating of some Wyoming "Roll-deposits" (Harshman 1972) suggests that emplacement and migration of the primary ores were not continuous processes. It appears that there is no real evidence of mineralization in the last 10 million years. Most deposits are on average in equilibrium which means that if migration is constant, the entire body must have moved as a closed system unit with no loss or gain of uranium to the surroundings. Gabelman therefore feels that the roll-front mechanism which is seen as a concentrating mechanism of uranium is not valid. He continues to quote further evidence for epochal rather than continuous migration by citing cases in Wyoming where "closed examination of the roll-fronts reveal no evidence contrary to an interpretation of exhausted motion or supply rather

than frozen motion. All these interpretations are permissive". (Gabelman 1977, p 76). Gabelman appears to be the only one who disputes Gruner's mechanism and his reasons for doing so appear to lack sufficient evidence.

Robertson *et al.*, (1978) feels that the effects of natural electrochemical phenomena may be of great significance in the concentration of uranium. They apply this mechanism to palaeosurface veinlike deposits but the mechanism could be applied to sandstone uranium deposits. It has been shown that uranium minerals are highly soluble in surficial and ground waters under oxidizing conditions. The uranium exists in the hexavalent form in solution with its positively charged ions constituting a weak electrolyte. Currents and potential differences have been observed where natural conductive features enable the high Eh conditions of the oxygenated environment to be linked to the low Eh conditions which exist at depth. It is suggested that natural electrochemical systems exist wherein precipitation of dissolved uranium will take place at locations where there is a coincidence of uranium-bearing solutions with appropriate natural electrodes. This situation is summarized in Figure 17 where the deposition of uranium occurs through a plating cell action. It is suggested that metal was extracted from source rock and transported in stream and ground water into the area of influence of a plating cell where concentration could take place.

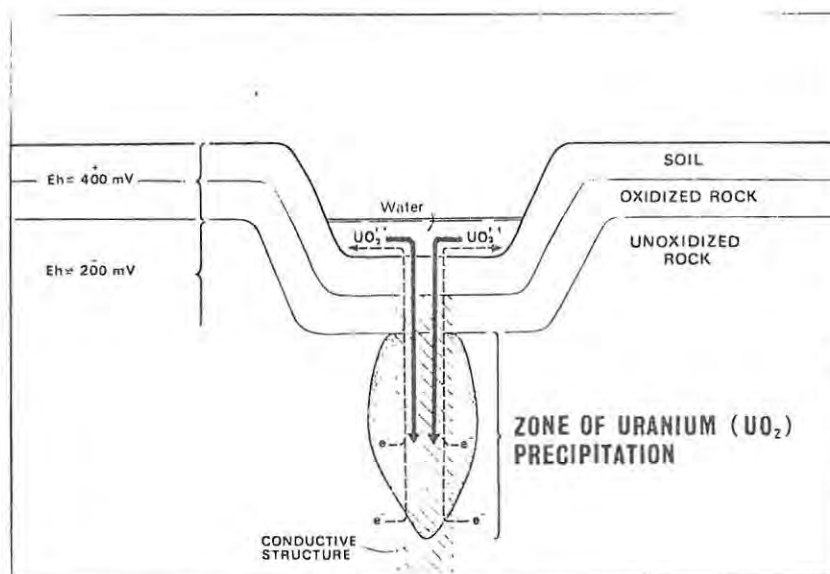


Fig. 17. Diagram of plating cell action.

(after Robertson *et al.*, 1978)

6. SANDSTONES

The formation of sandstone uranium deposits is closely related to processes forming the host rock. An in depth study of the generation of sandstone bodies is therefore necessary before discussing the factors directly affecting the grade and tonnage of a uranium deposit.

6.1 DEFINITION OF SANDSTONE

There are many ways of defining a sandstone but the most satisfactory defines sand as an unconsolidated sedimentary deposit of clastic particles that vary in size between 0,0625 mm and 2 mm and which are derived through mechanical or chemical weathering of source rocks. A sandstone is the consolidated rock equivalent of a sand (Chilingarian & Wolf 1975).

6.2 CLASSIFICATION OF SANDSTONES

For a classification of sedimentary rocks to have any practical use it should be based on easily observable, genetically significant variables that can be subjected to quantitative analysis (Pettijohn *et al.*, 1972). Generally, the composition and grain size are regarded as the most important criteria. There is a tendency for workers to use triangles to represent their classifications but there is no reason to limit the number of main variables to three and Pettijohn has developed the tetrahedron for classifying sedimentary rocks (Figure 18 on page 30).

In the case of the subdivision of sandstones, which have already been defined according to grain size, the important criterion is the end member mineral composition. Most of these classifications are based on that of Krynine (1948) and Pettijohn (1944) in which the major constituents are plotted at the apices of a triangle (Figure 19 on page 30). Figure 20 on page 31 shows four of the more widely used triangles.

One approach to the subject of classification much used for carbonate rocks but not normally used for sandstone, is factor analysis. (Blatt, Middleton and Murray 1980). This numerical technique identifies groups of variables and combines them into a few "factors" thereby

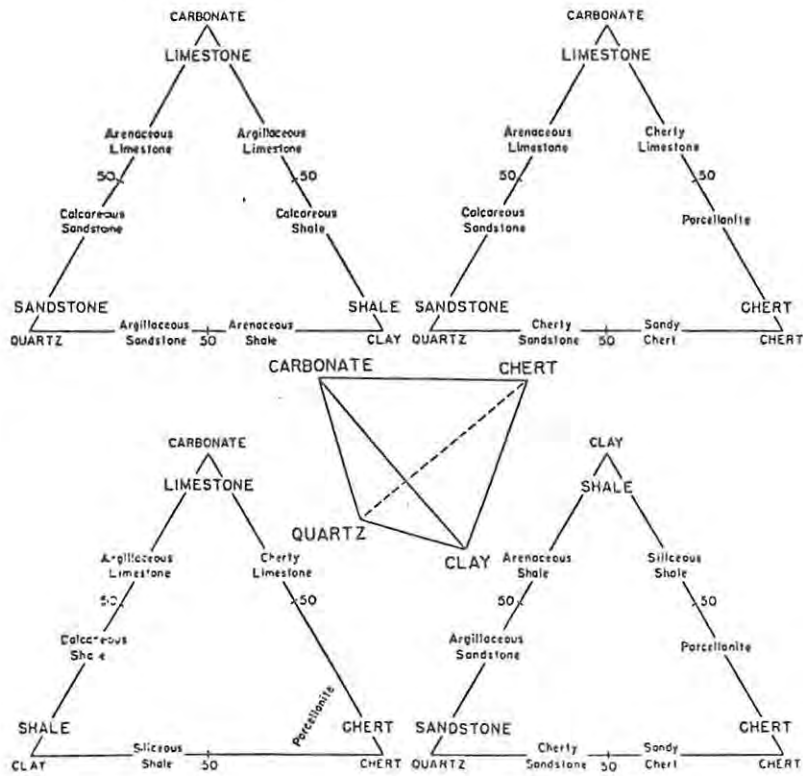
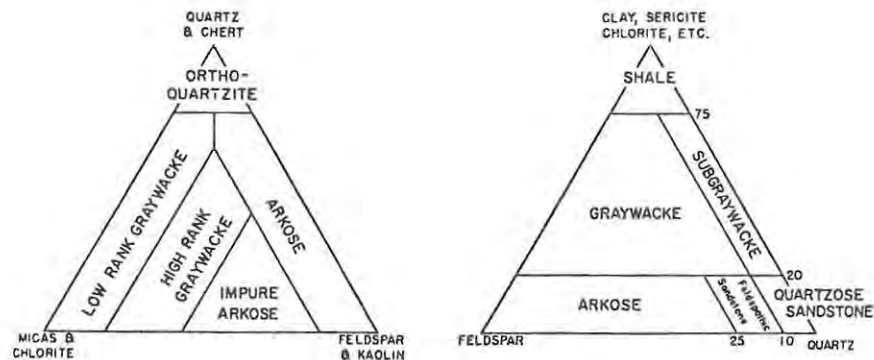


Fig. 18. Four faces of the tetrahedron for classifying rocks.

(after Krumbein & Sloss 1963)

Fig. 19. Triangular (three-end-member) classification of sandstone. ((Left) Krynine (1948); (Right) Pettijohn (unpublished chart, 1944).)

(after Krumbein & Sloss 1963)



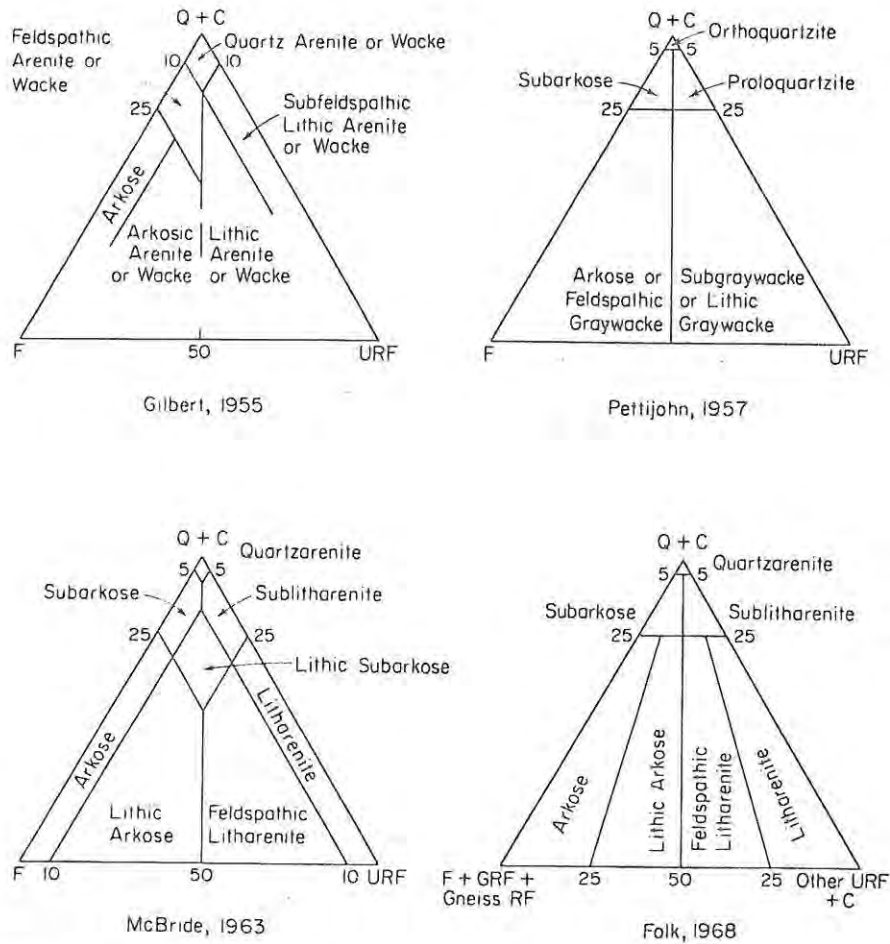


Fig. 20. Some triangles in common use for the classification of sandstones. The terms wacke or graywacke are used when the sandstone contains a significant amount of clay matrix, commonly 10 or 15 per cent.

(from Blatt, Middleton & Murray, 1980)

objectively identifying those "end members" most important for classification. This technique has been applied in an attempt to relate chemical composition of sandstones to the tectonic setting in which they are formed. Mathematical analysis led to the definition of the chemical "end members" shown in Figure 21. This subdivides sandstones as follows :

- (a) Eugeosynclinal sandstones (mostly greywackes)

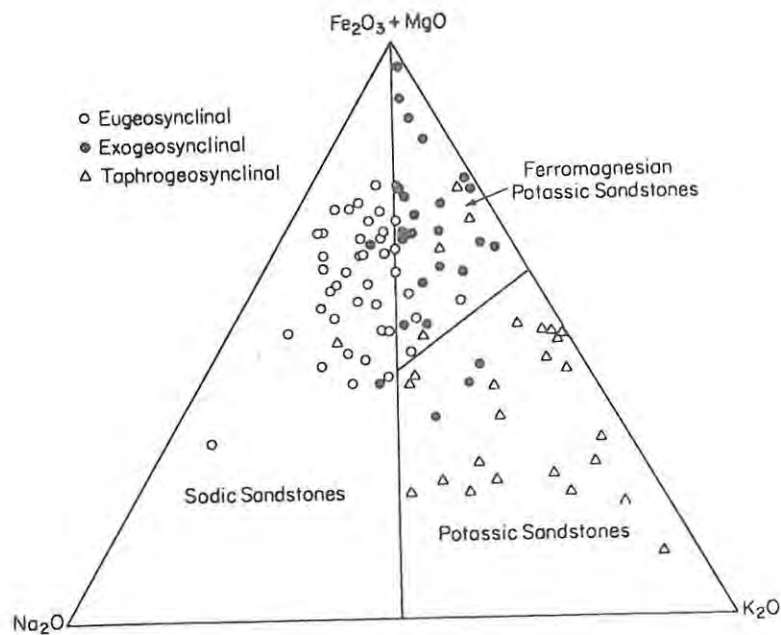


Fig. 21 Chemical composition of sandstones in relation to tectonic setting.

(after Blatt, Middleton & Murray 1980)

- (b) Taphrogeosynclinal sandstones - arkoses deposited in deep fault basins on the craton.
- (c) Exogeosynclinal sandstones - lithic sandstones forming part of the clastic wedges spread out over the edges of cratons from sources in peripheral folded mountains.

The arkoses are distinguished from lithic sandstones by their generally lower ratio of iron and magnesium to potash. Although this is partly related to diagenetic factors it is also related to source. Arkoses are usually derived from plutonic rocks of roughly granitic composition and these rocks are themselves relatively rich in potash and low in ferromagnesium components. Because of known transitions in mineralogy and tectonic setting there is a transition in chemical composition between arkoses and lithic sandstones.

Arkoses and greywackes are also clearly defined in this classification.

The former have less iron and magnesium reflecting the effect of source with most of the difference related to the ferrous rather than the ferric iron content.

A chemical classification of sandstones has been devised by Pettijohn *et al.*, (1972) in which the general geochemical behaviour of the elements is taken into account. It shows the relationship between elemental composition, mineralogy and rock type. The classification differentiates mature and immature sandstones by using the ratio of SiO_2 to Al_2O_3 rather than by using either of them individually. The mature quartz-rich sandstones therefore have high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio's by virtue of the absence of aluminosilicates, either clays or primary silicates.

The differences between alkali-metal rich and alkali-metal poor sandstones can almost equally well be taken as corresponding to a maturity index defined in chemical compositional terms, as shown in Figure 22.

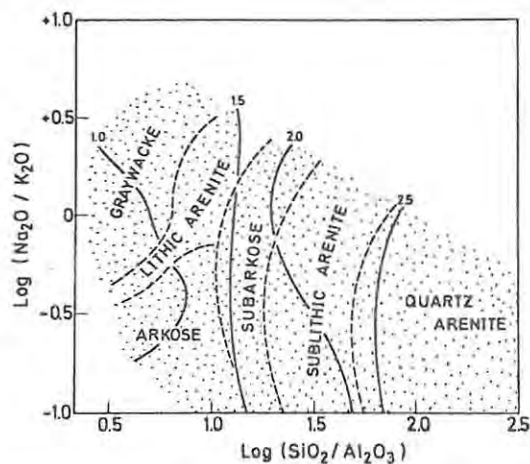


Fig. 22. $\text{SiO}_2/\text{Al}_2\text{O}_3$ versus $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of sandstones. Stipple outlines area of most analyses. Contours (heavy lines) show values of $\log [(\text{SiO}_2 + \text{Al}_2\text{O}_3)/(\text{Na}_2\text{O} + \text{K}_2\text{O})]$. Analyses drawn largely from Pettijohn (1963). (After Pettijohn *et al.*, 1972, p. 62)

Pettijohn *et al.*, (1972) suggest the need to discriminate between the original detrital components, those introduced as cements and those produced by post-depositional metamorphism or weathering. They classify

sands on the detrital composition into terrigenous, carbonate and pyroclastic. Terrigenous sands are those derived from outside the basin of deposition by erosion of pre-existing crystalline, volcanic and sedimentary rocks and are deposited mainly by water. Carbonate sands are virtually all deposited in marine waters and comprise mainly skeletal grains, oolites and detrital carbonate.

Pyroclastic sands are those derived directly from volcanic explosion such as ash, lapilli and bombs. They may be deposited on land or in water. In nature there are gradations between these three types of sands.

This review will concern itself with the terrigenous sands.

Pettijohn *et al.*, classify terrigenous sandstones as follows so that it is appropriate for both ancient and modern sands. They use the framework grains of quartz, feldspar and rock fragments of sand size and then incorporate the amount of matrix within the sand. Sands with less than 15 per cent matrix are termed arenites while those with more than 15 per cent matrix are termed wackes. A sand with less than 5 per cent matrix and 95 per cent quartz is termed a quartz arenite as shown in Figure 23.

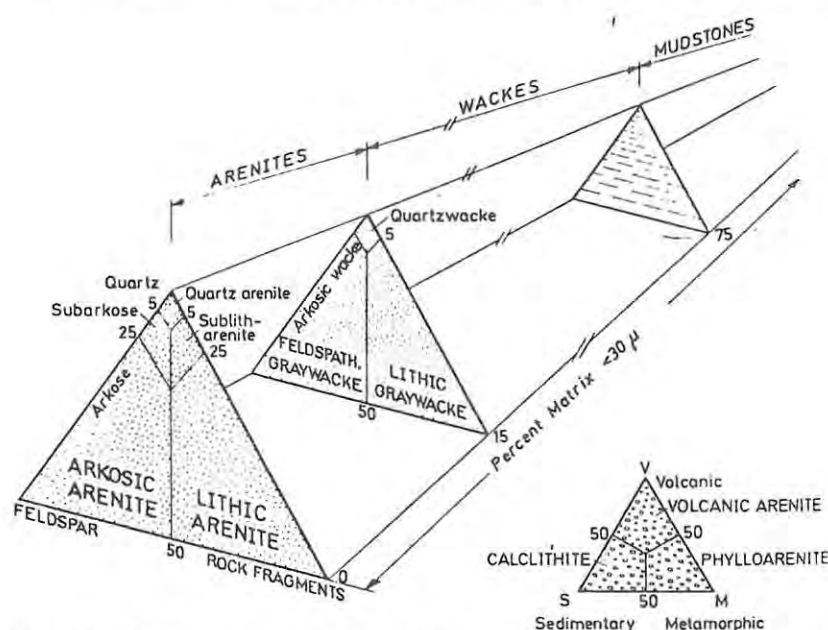


Fig. 23. Classification of terrigenous sandstones. (After Pettijohn *et al.*, 1972, fig. 5-3, p. 158; modified from Dott, 1964, fig. 3; courtesy of Springer-Verlag, New York.)

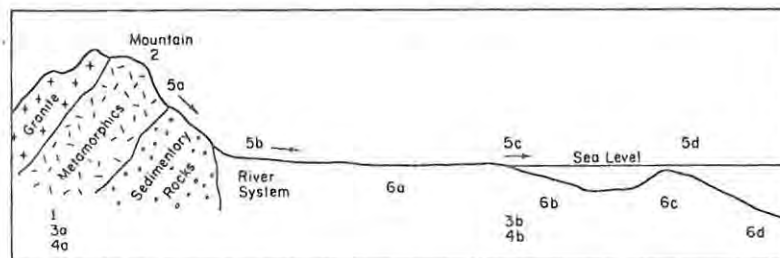
This classification of terrigenous sandstones is the most suitable for this review and terminology used in the text will be based on this classification.

6.3 FACTORS GOVERNING SANDSTONE GENERATION

The generation of a sandstone is the result of a complex interrelationship of four variables; source, climate, tectonics and depositional environment. (Figure 24)

1. Nature of source rock (igneous, metamorphic, and/or sedimentary).
2. Topographic expression and relief of source area (high or low, slope characteristics, etc.).
3. Distribution of tectonic elements over source and depositional area (platform versus geosynclinal).
4. Intensity of tectonism in each tectonic element (slow to rapid subsidence or uplift, or stable).
5. Geology agents which weather, transport, and distribute sediments (e.g., arid versus humid weathering; slow versus fast transportation in suspension and by saltation and traction; sorting; abrasion; and turbidite versus slide deposition).
6. Patterns of environmental elements in the depositional area (e.g., presence or absence of lagoons, shelf, and delta).

Example (numbers correspond to those above):



1 = plutonic, contact-metamorphic, and sedimentary source rocks; 2 = mountain; 3a = geanticline (= mountain source); 3b = geosyncline; 4a = very active uplift; 4b = very active subsidence; 5a = ice; 5b = water and wind; 5c = water waves, currents; 5d = slides and turbidity currents; 6a = coastal plain, with or without a delta; 6b = marine shelf; 6c = barrier reef or sand bar; and 6d = deep basin.

Fig. 24. Factors determining character of sedimentary rocks.
(after Chilingarian & Wolf 1976)

When other processes such as diagenesis interact, the evolution of a non-carbonate sandstone appears as follows : (Figure 25)

The stability and reactivity of the minerals of the source rocks determine which mineral will be modified by selective weathering.

The source will also affect the pH of the ground water which will affect the mobility of the elements.

6.3.2 Climate

Climate is indirectly involved in a variety of ways in sandstone generation. In addition to determining the type of weathering that the source rocks will undergo, climate plays an important role in channel morphology. The amount of rainfall will affect the discharge rate and the type of vegetation will govern the bank stability of the river. The marked effect of vegetation on bank stabilization has been shown by D. G. Smith (1976) where non-vegetated sediment can be 20,000 times less stable than banks containing 16 - 18 per cent by volume of plant roots.

The climate governs the type and amount of organic material that will be deposited within the sediments and also the mode of preservation of the organics. Under humid climatic conditions, chemical erosion is dominant. The high water table allows the preservation of organic material within the reducing ground waters, which results in upland bogs and fluvial marshes. During arid conditions however, the limited nature of biogenic activity will restrict the formation of reduced organic-rich fluvial sediments.

Climatic factors also have a strong control on the mobility of elements in ground waters, since mobility depends on the acidity and the ratio of oxidizing to reducing ground waters in the zone of weathering. (Figure 26, p 38).

Under humid conditions the metals will remain dispersed within the sediments as organometallic complexes and the high runoff will mean that a significant proportion of the ions liberated during chemical weathering will be transported by surface waters. During arid conditions the low nature of the ground water table enables significant leaching of uranium to occur within the oxidized zone.

RELATIVE MOBILITIES	ENVIRONMENTAL CONDITIONS			
	Oxidizing	Acid	Neutral to Alkaline	Reducing
VERY HIGH	Cl, I, Br S, B	Cl, I, Br S, B	Cl, I, Br S, B Mn, V, U, Se, Re	Cl, I, Br
HIGH	Mn, V, U, Se, Re Ca, Na, Mg, F, Sr, Ra Zn	Mn, V, U, Se, Re Ca, Na, Mg, F, Sr, Ra Zn Cu, Co, Ni, Hg, Ag, Au	Ca, Na, Mg, F, Sr, Ra	Ca, Na, Mg, F, Sr, Ra
MEDIUM	Cu, Co, Ni, Hg, Ag, Au As, Cd	As, Cd	As, Cd	
LOW	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl Fe, Mn	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl Fe, Mn	Si, P, K Fe, Mn
VERY LOW TO IMMOBILE	Fe, Mn Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, Rare Earths	Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, Rare Earths	Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, Rare Earths Zn Cu, Co, Ni, Hg, Ag, Au	Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, Rare Earths S, B Mn, V, U, Se, Re Zn Cu, Co, Ni, Hg, Ag, Au As, Cd Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl

Fig. 26 Relative mobilities of the elements in the secondary environment. From Andrews-Jones (1968).

(in Levinson 1980)

Climate determines the type of weathering to which the source rocks will be subjected and therefore affects the composition of the sandstone.

6.3.3 Tectonics

Tectonism is the primary control of sandstone petrography since without earth movements, sedimentation would cease. It also governs source, local climate and environment of deposition of a sand body. Tectonic uplift governs the relief and hence the rate and depth of erosion. This in turn

affects the volume and to some extent the kind of detritus transported to the site of deposition. Tectonism also indirectly controls which types of rocks will be subject to erosion. If erosion is only to a shallow level only sediments or perhaps extrusive volcanic rocks are likely to be exposed, whereas with deep erosion, coarse-grained feldspathic igneous or metamorphic rocks are made available. Tectonism therefore governs whether uraniferous source rocks will be exposed to weathering or not.

Tectonic uplift, if great enough, clearly modifies the climate in the source area, although it appears from several studies that climate does not really have an effect on the petrography of sandstones. Relief is probably more important than climate from the point of view of the weathering of source rocks, for with high relief mechanical rather than chemical weathering prevails. It has been shown that sediments of a hot humid climate can also be feldspathic and that relief rather than climate actually controls feldspar content. (Gibbs, 1967)

Uplift creates a gradient down which detritus moves but although it appears that transportation is only a minor factor in sandstone petrology, the action of high-gradient streams may impart a character to the texture and composition of the sands.

Although basin subsidence and tectonic uplift are not necessarily coupled together because in some cases the source area is far removed from the depositional basin, they do interact. The relationship of tectonism to sedimentation (sedimentary tectonics) is crucial since it is the ratio of sediment input to the basin capacity that broadly controls the depositional facies in the basin. An alluvial fill occurs when there is a large input into an area with inadequate subsidence. Minimal input produces a starved basin. The sands deposited in these differing environments will therefore be dissimilar in their structure and organization and to some extent unlike in their petrology.

Tectonism mainly determines the rate at which sedimentary particles pass through the depositional interface (Krumbein & Sloss, 1972). With rapid passage the particles are buried and protected from the environmental agents. A slow rate means that the particles lie at the depositional interface long enough to be thoroughly sorted and completely modified in

accordance with the physical and chemical processes of that environment.

The rate and conditions of deposition also control the porosity of the sediment and the state of preservation of trapped organic material.

Tectonics also plays a role on a smaller scale in governing the location and morphology of the depository and hence the sites for uranium mineralization. Depositional patterns in the Middle and Upper Jurassic rocks of northwestern New Mexico show that this area was affected by an increase in tectonic activity at the same time that the orogenic activity to the south and west produced the clastic fans of the Morrison Formation (Huffman & Lupe, 1977). During Morrison deposition the broad features such as basins were masked completely by the rapid influx of sediments. At the same time a number of smaller structures were quite active and these exerted a marked influence on the sedimentation.

When the uranium occurrences in this area are plotted they appear to be related to the linear thickness trends of isopach maps and it is thought that these trends represent persistent palaeostream channel systems and that the locations of the systems were controlled to some extent by the small anticlinal structures that were active at various times during the late Jurassic and re-activated during the Laramide orogeny.

6.3.4 Depositional Environment

The depositional environment has a direct bearing on the size, shape and thickness of the sand body. The environment also determines the regional distribution of the sandstones, the relationships with the bounding lithologies, the grain size distribution, and the mineralogical composition.

The sedimentary structures formed under the varying conditions also affect the permeability and porosity of the sandstone. The sedimentary environment will determine the biological activity and therefore the amount of organic material that will be trapped within the sediments. It will also determine the sites for accumulation of the material.

Sandstone uranium deposits are found developed in fluvial, deltaic

and lacustrine sand bodies but because the majority of deposits are found in fluvial sandstones, only the flow processes, sedimentary structures, and facies related to fluvial environments will be discussed.

6.3.4.1 Sand Deposition in the Alluvial Environment

The key to the understanding of most ancient alluvial deposits is the origin and physiography of the modern alluvial flood plain (Pettijohn et al., 1972).

The overriding factor in the generation of the flood plain morphology appears to be the variation in the hydraulic geometry of the river. In their paper on "River Channel Patterns", Leopold and Wolman (1957) conclude that any river contains straight, braided and meandering features over a very short distance and that each occurs in nature throughout a whole range of discharges. Their observations indicated that braids tend to occur in channels having certain combinations of values of flow factors and that meanders occur in different combinations. The straight channels can occur in either. Truly straight channels are not common in aggrading rivers and are therefore of little importance from a sedimentological point of view.

Eight or more variables are involved in the morphology of a stream channel. These are discharge, amount of sediment load, caliber of load, width, depth, velocity, slope and roughness. Each of these factors varies as a continuous function within certain limits so that there is a "continuum of natural stream channels having different characteristics that are reflected in combinations of values of the hydraulic factors", (Leopold & Wolman, 1957, p 73).

The factor having the largest range of values is discharge, for in natural channels it can vary from 0 to 10,000,000 c.f.s. Load which is expressed as concentration by weight varies from nearly 0 to about 500,00 ppm. Caliber of load expressed as median grain size may vary from a value near 0 to 3 m boulders. Width of natural channels varies between a few centimetres to 6 km, mean depth from 0 m to 30 m, mean velocity from near 0 to 7 m/sec., slope from near 0 to 1,0 and roughness expressed as the dimensionless Darcy-Weisbach number from 0,001 to 0,30.

Combinations observed in nature are far more restricted than the permutations of the values of the eight variables. Leopold and Wolman state that to their knowledge for example, rivers capable of discharging more than 1 million c.f.s. do not have slopes in excess of 0,0009 and usually less than 0,0002.

The magnitude and character of the runoff are functions of climate and lithologic factors all of which are independent of the channel system. The amount and distribution of rainfall is determined by the climate while the topographical and lithological character of the drainage basin help determine in conjunction with vegetation not only the characteristics of the runoff but also the load of debris delivered to the channel system. Both the quantity and nature of the load are directly related to geological factors.

Generally the shape and pattern of the channels are governed by the water and debris but the modifications to the channel are affected by processes within the channel itself.

Channel width which is primarily determined by discharge in conjunction with the resistance of bed and bank to scour, increases rapidly relative to other changes.

The roughness of any reach of a channel is controlled by the geological character of the bed material supplied by the drainage basin. Although abrasion and sorting may modify the material on the bed, the rock character partly determines the extent of such modification. The roughness may be primarily grain roughness. Alternatively, owing to the size distribution of the particles, the depth of the river and other factors, the roughness may be due to the configuration of the dunes, ripples or waves into which the particles on the bed arrange themselves.

Schumm (1972) found during his studies of the effect of the variation of discharge and sediment load on a stream's channel width, depth and sinuosity that as discharge (Q) increases, there are proportional increases in channel width (W), depth (D), meander wave length (l) and a decrease in channel gradient (S). This can be summarized as $Q \propto \frac{W D l}{S}$

Work by Schumm (1960) has shown that downstream changes in width and depth of a stream channel are greatly influenced by sediment type. A weighted mean percent silt - clay content (M) in the channel and banks of stable alluvial stream channels is used to describe the physical characteristics of the sediment. In this case, silt-clay is defined as alluvial material < 0,074 mm in size. As the percentage of silt and clay in the banks and channel increases, the shape of stream channels expressed as a width - depth ratio (F) varies according to the equation $F = 255 M^{-1.08}$. (Figure 27) Neither mean annual discharge nor the mean

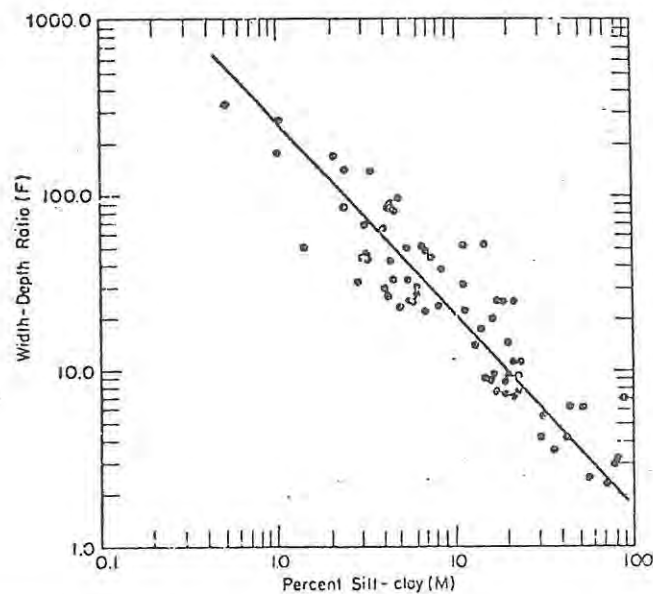


Fig. 27. Percent silt-clay in channel perimeter versus channel width-depth ratio. (after Schumm, 1960)

annual flood significantly affects this relation in spite of the importance of discharge to the absolute width and depth of a channel.

Schumm's conclusions were that as M increases downstream along a given river, the depth increases more rapidly and the width less rapidly with discharge than if M was constant. As a result width/depth ratio therefore decreases. Conversely as M decreases downstream, the depth

increases less rapidly and the width more rapidly with discharge than if M was constant. This results in an increase in the width/depth ratio. Unstable channels may be recognised by changes in width/depth ratio. In general, aggrading channels have a higher width/depth ratio than indicated by M; whereas degrading channels have a lower width/depth ratio than indicated by M.

M is calculated as follows :

$$M = \frac{S_c \times W + S_b \times 2D}{W \times 2D}$$

in which S_c is percentage of silt and clay in channel alluvium

D is channel depth

W is channel width

In a study of five semi-arid valleys Schumm (1972) shows the importance of the physical properties of the sediment in determining stream channel shape. A comparison of the data from each area demonstrated that in a drainage channel composed of fine-grained, highly cohesive sediment, deposition occurs on the sides of the channel as well as the channel floor. The result is a reduction in the channel width/depth ratio across an aggrading reach. Vegetation seems to aid deposition by its rapid growth on recently deposited fine alluvium, but it is not the initial cause of aggradation. Bank caving yields only small amounts of sediment and caved blocks are often nuclei for deposition along channel sides because of their resistance to disintegration.

Gradient shows an inverse relation to weighted mean percent silt-clay for small streams of low annual discharge.

It is suggested that the relation between channel shape and silt-clay can be used as a criterion of channel stability because aggrading channels generally plot well above the width/depth, silt-clay regression line, whereas degrading channels plot well below the line as shown in Figure 27.

Schumm also observed that the type of sediment in the load has a

marked effect on channel morphology. A significant increase in ratio of bed load to total sediment load (Q_s) increases the channel width, meander wave length and slope but decreases its depth and sinuosity (P) where P is the channel length/straight line distance between two points.

$$\text{In this case therefore } Q_s \propto \frac{W^1 s}{D P}$$

One can see from the above relationship that the width/depth ratio of the channel is an indication of the sediment load. Sand-carrying streams therefore have greater width/depth ratio's than those carrying predominantly silts and clays. Schumm estimates that for :

- (a) bedload streams $W/D > 40$
- (b) streams with 5 - 20 per cent silt & clay $W/D = 10 \text{ to } 40$
- (c) suspended load streams $W/D < 10$

These may be summarized in Figure 28, a diagram modified after Schumm by Long (1978).

Channel Type		Bedload	Mixed Load	Suspended Load
Single channel	Channel shape			
	width to depth ratio	60 : 1	25 : 1	8 : 1
	Channel pattern	 	 	
	SINUOSITY	1.0 1.1	1.4 1.7	2.5
Multiple channel	Patterns		  	
		alluvial fan	alluvial plain anastomosing	
Silt+clay in the channel perimeter		< 5%	5-20%	> 20%

Fig. 28 Morphology of principal river types, as a function of their sediment load (modified from Schumm, 1968).

(after Long 1978)

River Types

Knowledge of the characteristic morphological and sedimentary features of different river-types is necessary if one is to evaluate the uranium potential of a sand body. It is important to determine the river-type from the sediments so that the shape of the sand body and any extensions may be predicted. At the same time an idea of the porosity and permeability can be gained, a feature vital in the formation of uranium deposits.

Based on the work of both Leopold and Wolman (1957) and Schumm (1963, 1968), Miall (1977) had produced a classification of river types (Figure 29).

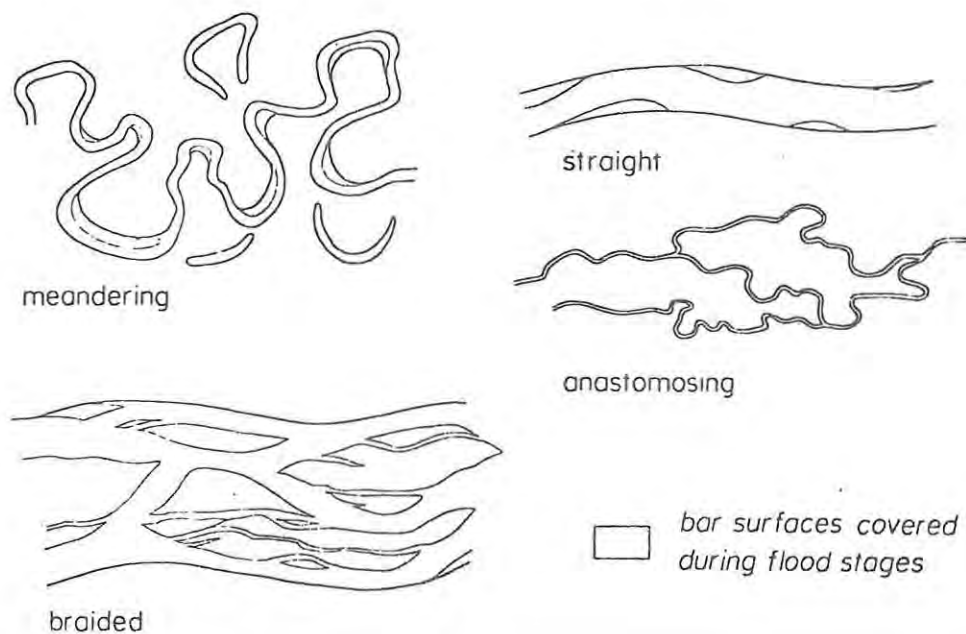


Fig. 29. Principal river types.

(Miall 1977)

Table 1 on page 47 shows the pertinent characteristics of the four river types.

The emphasis has been placed on two major types of rivers in the past; braided and meandering, but the observation of Leopold & Wolman (1957)

suggesting a continuum of stream types is now being accepted. Nevertheless, the majority of studies at present are related to these end members although the more recent papers are reporting examples of intermediate types of rivers.

TABLE I
Classification of river types

Type	Morphology	Sinuosity	Load type	Bedload percent (of total load)	Width/depth ratio	Erosive behaviour	Depositional behaviour
Meandering	single channels	> 1.3	suspension or mixed load	< 11	< 40	channel incision, meander widening	point-bar formation
Braided	two or more channels with bars and small islands	< 1.3	bedload	> 11	> 40	channel widening	channel aggradation, mid-channel bar formation
Straight	single channel with pools and riffles, meandering thalweg	< 1.5	suspension, mixed or bedload	< 11	< 40	minor channel widening and incision	side-channel bar formation
Anastomosing	two or more channels with large, stable islands	> 2.0	suspension load	< 3	< 10	slow meander widening	slow bank accretion

(after Miall 1977)

In support of the continuous spectrum of fluvial types, Miall (1977) quotes parts of the Donjek River in the Yukon as showing braided channels within the course of a meandering river. The Endrick River in Scotland is another example of a high sinuosity, bed-load stream which contains extensive gravel point bars (Bluck 1971). Vegetation has been shown to be effective in stabilizing banks (D. G. Smith 1976) so that where the banks are stable, the braided pattern is restricted. This factor could account for the features in the Donjek and Endrick Rivers.

Braided Rivers

Studies of the Donjek River (Williams & Rust 1969), the Platte River (N. D. Smith), the South Saskatchewan River (Cant & Walker 1976), the Kicking Horse River (N. D. Smith 1974) and others have revealed the following characteristic features of braided rivers. Studies by Doeglas (1962) and Williams & Rust (1969) are significant because they describe abandoned-channel deposits.

Braided rivers are characterized by a series of broad, shallow channels and bars formed under periods of variable discharge. They are characterized by high width/depth ratios (> 300), steep slopes and generally

low sinuosities. Leopold & Wolman (1957) showed empirically that braided and meandering streams can be distinguished on the basis of slope and discharge according to the equation (Figure 30) :

$$S = 0,06Q_b^{-0,44}$$

where S = slope

Q_b = bankfull discharge in m^3/sec

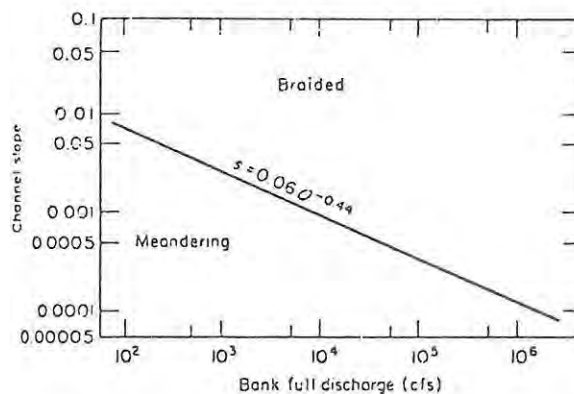


Fig. 30. Leopold and Wolman's (1957) plot of bank-full discharge and channel slope. Line separates field of braided patterns from meandering; straight channels occur on each side of line. (Schumm, 1977)

For a given discharge braided streams occur on slopes that are steeper than that in the equation while meandering rivers occur on flatter slopes.

Braided streams consist of a series of rapidly shifting channels and mid-channel bars. In some cases the stream bars may be stable enough for vegetation to become established and islands to form.

The deposits of braided streams are normally coarser than those deposited by other river types and contain mainly sand or gravel. In most examples a single dominant channel can generally be distinguished within the overall braided pattern, although in some sections there are several principal channels (Rust 1972).

There are three main types of bars found in a braided stream environment. They are :

- (a) longitudinal - comprising crudely bedded gravel sheets;
- (b) transverse to linguoid - consisting of sand or gravel; and
- (c) point or side-bars formed by bedform coalescence and chute and swale development in areas of low energy.

Figure 31 summarizes the principal bar types :

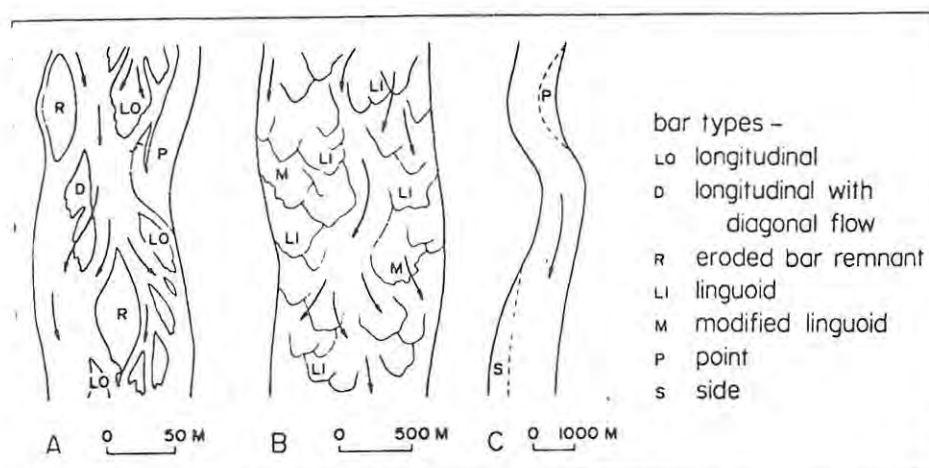


Fig. 31. Principal bar types.

(after Miall 1977)

Longitudinal bars are most commonly formed in gravel load streams (Rust 1972, N. D. Smith 1974) and develop as shown in Figure 32 on page 50. They are generally lozenge-shaped in plan, tapering off downstream, and are elongated parallel to flow direction. They are bounded by active channels on both sides and may therefore have eroded margins. Bar length may extend up to several hundred metres although these are thought to represent coalesced bars. The coarsest material is concentrated along the central bar axis (Boothroyd & Ashley 1975) and the grain size normally diminishes upwards and downstream (N. D. Smith 1974). The sedimentary structures within a bar comprise massive or poorly developed horizontal bedding (N. D. Smith 1970) possibly resulting from transportation in planar sheets in very high flow regimes.

Linguoid and transverse bars are most typical of sandy braided

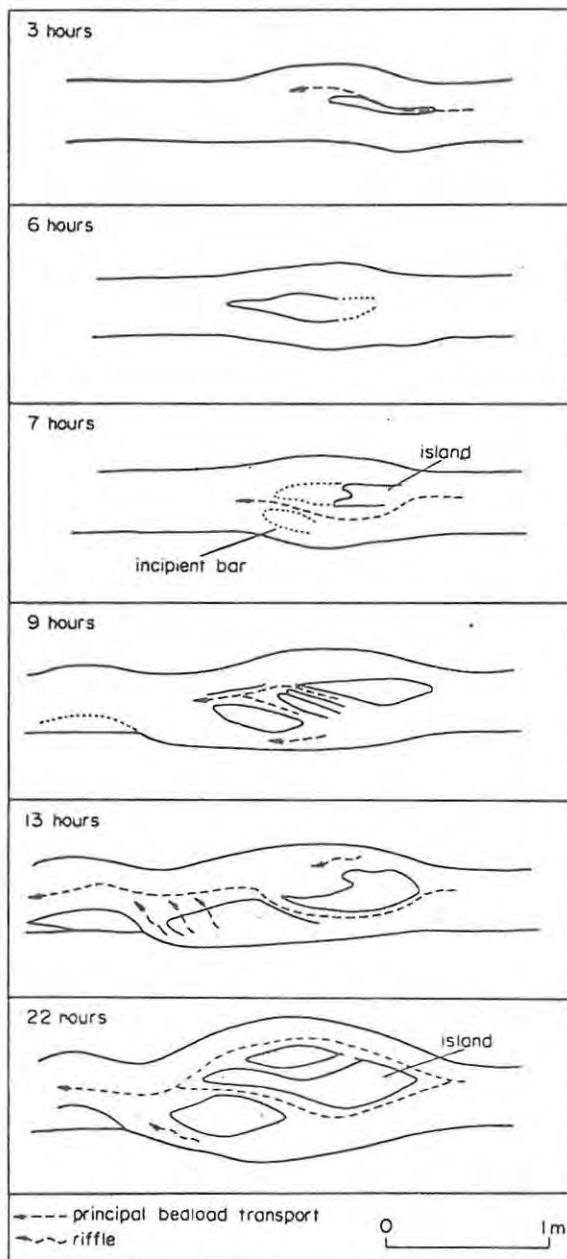


Fig. 32. The growth of longitudinal bars in a flume. Redrawn from Leopold & Wolman (1957).

(after Miall 1977)

ivers and have a characteristic rhombic or lobate shape. The upper surfaces dip gently upstream towards the preceding bar while the downstream surfaces terminate in sinuous avalanche-slopes. The bars vary in width from a few metres to 150 metres and have lengths of up to 300 metres. Linguoid bars generally occur in trains in an out-of-phase relationships with one another which results in the convex front of a bar tending to advance into

the space between the two preceeding bars. (Collinson 1978)

Descriptions of transverse bars (N. D. Smith 1971) indicate that they are generally similar to linguoid bars except that they have straighter crests. They may represent coalesced linguoid bars or solitary bars that extend completely across a channel or the space between obstructions such as trees or bushes (Miall 1977).

Point bars, side bars and lateral bars which are all genetically similar form in areas of relatively low fluvial energy. Examples of this type of setting would be the inside of a meander where the main current strength is diverted against the opposite outer bank. They also occur in braided streams such as the Kicking Horse River (N. D. Smith 1974) and the Endrick River (Bluck 1976). The details of point bar generation will be dealt with under meandering rivers since the point bar is a major characteristic of such rivers.

Braided Stream Facies

Many of the individual sedimentary features that occur in a braided stream environment also occur in other fluvial situations but the various combinations of facies are evidence of a braided stream environment. These are summarized in several type sections from various rivers. The lithofacies code (Miall 1978) includes the following shown in Table II on page 52.

Three main parameters affect the nature of braided river deposits, channel depth, bedload grain size and discharge (amount and variability). From the profiles that have been studied there appear to be four main ways in which these parameters combine to produce a given sedimentary succession. Various other type-profiles have been added to these four and more are expected if there is a spectrum between braided and meandering streams.

Each model has a hypothetical vertical sequence which appears to typify the interpreted depositional environment.

The Scott-type is characterized by small-scale gravel-sand cycles of waning-flood origin and represent proximal, gravelly rivers. (Figure 33)

TABLE II

LITHOFACIES AND SEDIMENTARY STRUCTURES OF
MODERN AND ANCIENT BRAIDED STREAM DEPOSITS

(Modified from Miall 1978 Table I)

FACIES CODE	LITHOFACIES	SEDIMENTARY STRUCTURES	INTREPRETATION
Gm	massive or crudely bedded gravel	horizontal bedding imbrication	longitudinal bars, log deposits, sieve deposits
Gt	gravel, stratified	trough crossbeds	minor channel fills
St	sand, medium to very coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	sand, medium to very coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (lower and upper flow regime)
Se	erosional scours with intraclasts	crude crossbedding	scour fills
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours including eta cross-stratification	scour fills
F1	sand, silt, mud	fine lamination, very small ripples	overbank or waning flood deposits

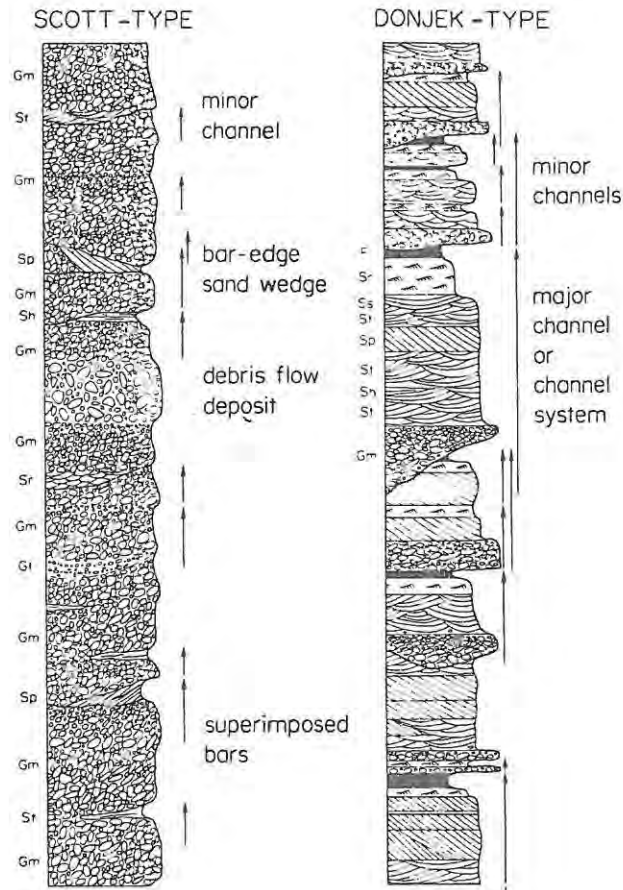


Fig. 33. Vertical profile models for braided stream deposits. Facies code to left of each column is given in Table II. Arrows show small-scale cyclic sequences. Conglomerate clasts are not shown to scale.

(after Miall 1978)

The Donjek type (after the Donjek River described by Williams & Rust 1969) contains various scales of fining upward cycles. The thicker cycles are thought to represent sedimentation at different topographic levels within the channel system or succession events of vertical aggradation followed by channel switching. It contains significant proportions of both sand and gravel and is therefore more distal than the Scott-type.

The Platte-type (after the Platte River described by N. D. Smith 1970, 1972) reflects sedimentation in very shallow rivers or those without well developed topographic differentiation. There is a lack of cyclicity and a dominance of planar cross bedding. (Figure 34)

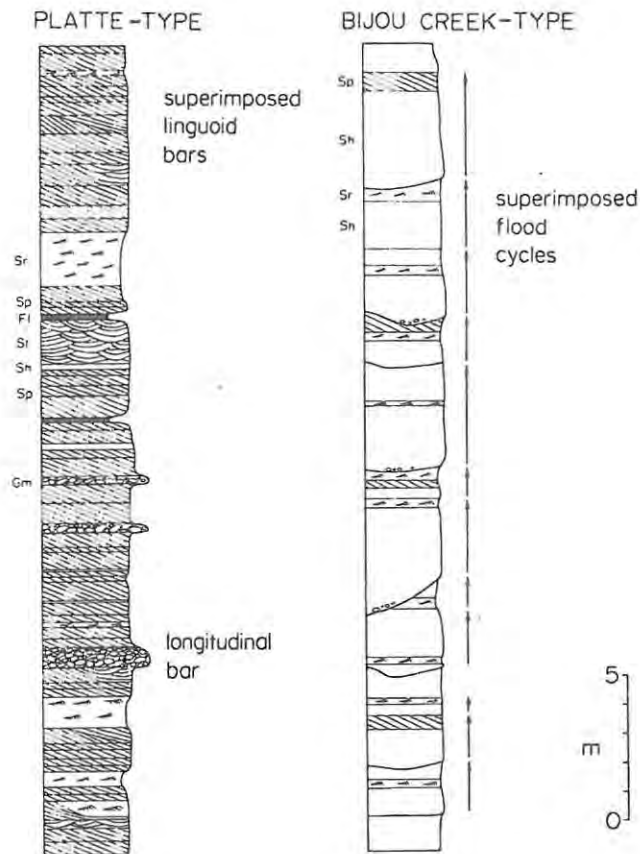


Fig. 34. Vertical profile models for braided stream deposits. facies code to left of each column is given in Table II. Arrows show small-scale cyclic sequences. Conglomerate clasts are not shown to scale. (after Miall 1978)

The Bijou Creek-type (McKee et al., 1967) represents the deposits of ephemeral streams characterized by catastrophic floods. A proximal sandy braided stream deposit occurring in areas that lack gravel supply. The most characteristic feature of the Bijou Creek model is the evidence it contains of high energy flow conditions, represented by dominantly planar stratified sand. Examples of this type of deposit are rare.

The Donjek model was evolved by Miall (1977) to include most types of cyclic gravel dominated braided river deposits but recent work by Cant (1978) and others show that sand-dominated cycles are equally common. The South Saskatchewan River (Cant & Walker 1976) is sufficiently well documented to be used as a model (Figure 35). Here, fining upward sequences are inferred to develop by aggradation of deep channels and multi-

storied "sand flats". Miall states that such sand-dominated cycles are common in the geological record.

S. SASKATCHEWAN-TYPE

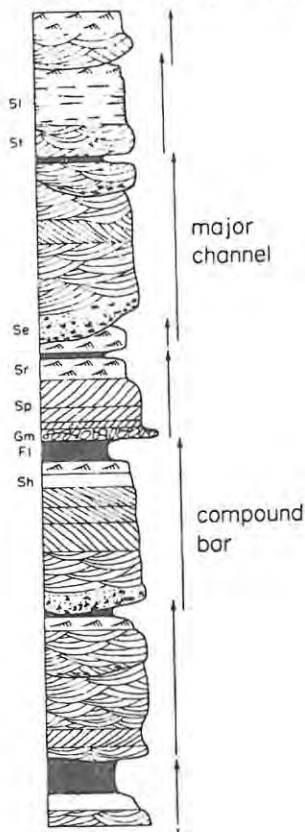


Fig. 35. Vertical profile models for braided stream deposits. Facies code to left of each column is given in Table II. Arrows show small-scale cyclic sequences. Conglomerate clasts are not shown to scale.

(after Miall 1978)

Ancient braided stream deposits have only been identified in a few cases of which the most convincing are in the Triassic of Nova Scotia (Klein 1962) and the Tuscarora Sandstone of Pennsylvania (N. D. Smith 1970). The deposits in the Witwatersrand Basin also represent braided stream environments (Pretorius 1975; Minter 1978).

In his description of the Durance River in France, Doeglas described the channel-fill deposits as coarse-grained, with channel or cross-bedded lamination in the upstream portions of abandoned channels and as fine-grained, silty and rippled in the downstream portions of abandoned channels.

Meandering Rivers

The sedimentology of the meandering river system has been investigated intensely with major contributions coming from studies of the Lower Mississippi (Fisk 1944, 1947), the Klarälven River, Sweden (Sundborg 1956), the Red River (Harms, Mackenzie & McCubbin 1963), the Brazos River (Bernard & Major et al., 1963), the River Endrick (Bluck 1971), the Lower Wabash River (Jackson 1976a, 1978) and more recently the Beatton River in British Columbia (Nanson 1980).

Meandering rivers generally occur in coastal - plain areas updip from deltas and downdip from braided streams. They are characterized by a single channel stream which is deeper than the multi-channel braided stream. Meandering streams usually have a wide range in discharge extending up to flood stages for a short time once or twice a year. The meandering channel is flanked by natural levees and point bars and migrates within a zone about 15 to 20 times the channel width.

The meandering stream is characterized by; the point bar, abandoned channel, natural levee and floodbasin. The nature of each of these and their interrelations are summarized in Figure 36 on page 57.

Only two main types of sand bodies are associated with a meandering stream: the point bar sands and the abandoned channel fills. The point bar sands which occur in the lower portion of the sequence constitute at least 75 per cent of the sand deposited by a meandering stream. Coalescing point-bar sands can actually form laterally extensive sand bodies interrupted only by the "clay plugs" found in parts of abandoned meander loops or in the last channel position of meander belts which have been abandoned abruptly. (LeBlanc 1972).

The flow processes involved in meandering streams have been reviewed extensively by Leopold et al., (1964) and Allen (1965). Since this work in which they deduced that the meandering form superimposes a non-uniform velocity pattern on the flow system (Figure 37), work by Bluck (1971), Sundborg (1956) and Jackson (1978) and others has shown a more complicated model.

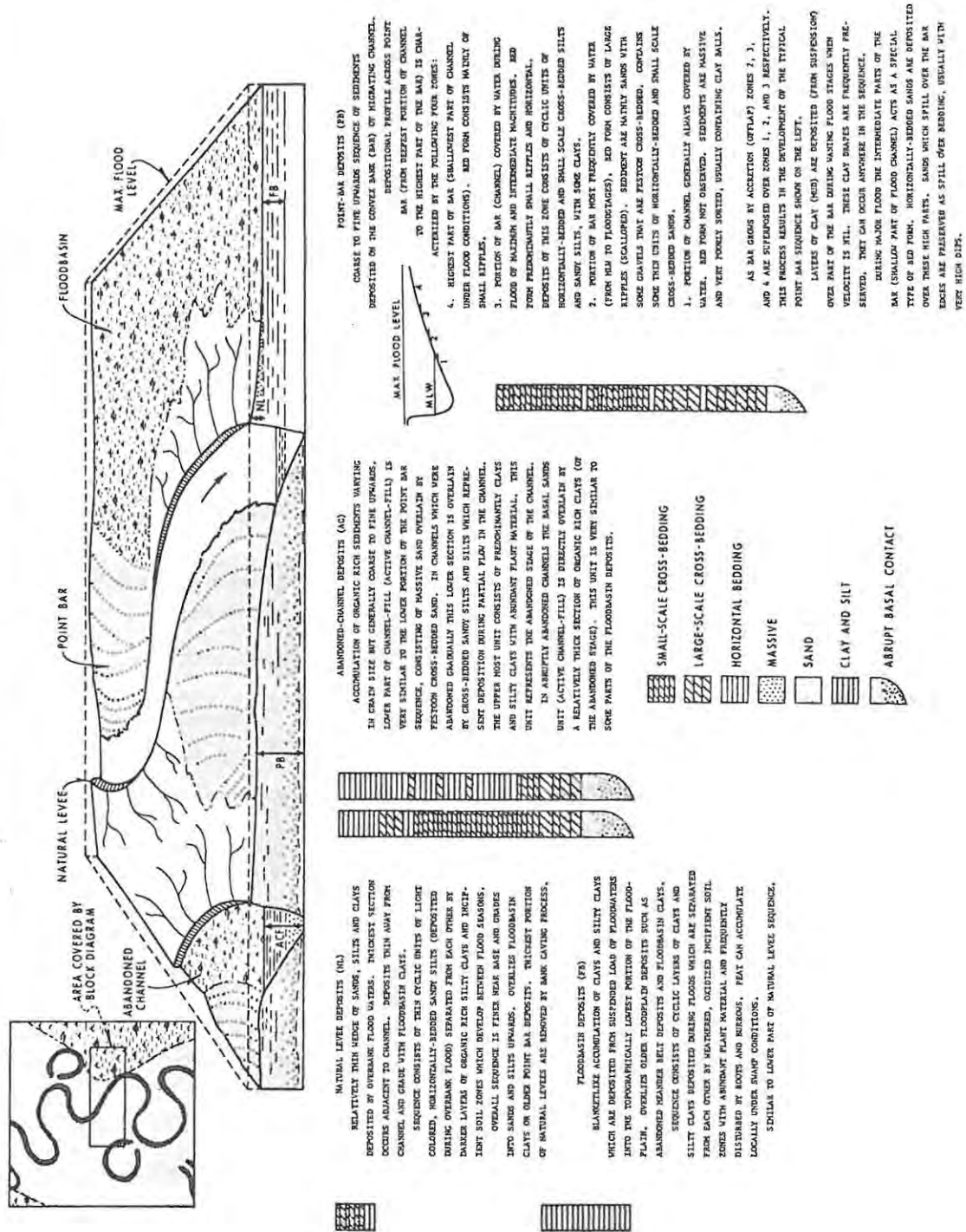


Fig. 36. Characteristics of meander-belt and floodplain deposits.

(after Potter 1967)

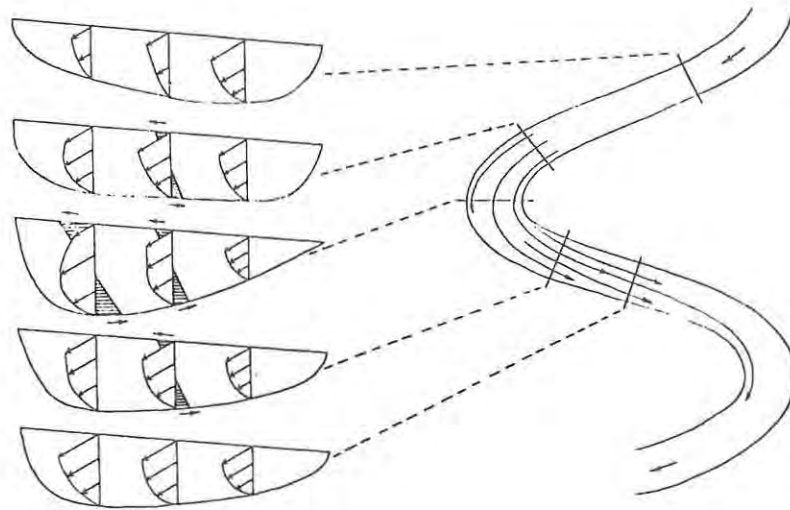


FIGURE 37. Flow pattern in a meandering river channel (From Allen, 1965; after Leopold et al., 1964).

In Allen's model the higher velocities of flow are confined to the thalweg of the channel while the lower velocities appear to be characteristic of point bar zones. The revised thinking shows that the flow velocity changes in a downstream direction from high to low and back to high, as a reference flow line through a deeper thalweg over a point bar and through the next thalweg downstream. This results in the direction of sediment transport following the flow lines of stream channel flow instead of laterally across the flow. The point bars in this situation build by elongation in a downstream direction similar to an enlarged longitudinal bar. (Figure 38, p 59) Lateral accretion as shown by Allen still occurs but now results in the accretion of a continuous series of longitudinal bars.

The most important processes in sedimentation in the meandering river are related to channel migration which occurs in response to bank caving and point bar accretion. The process of bank caving occurs most rapidly during falling flood stages when currents of maximum velocity are

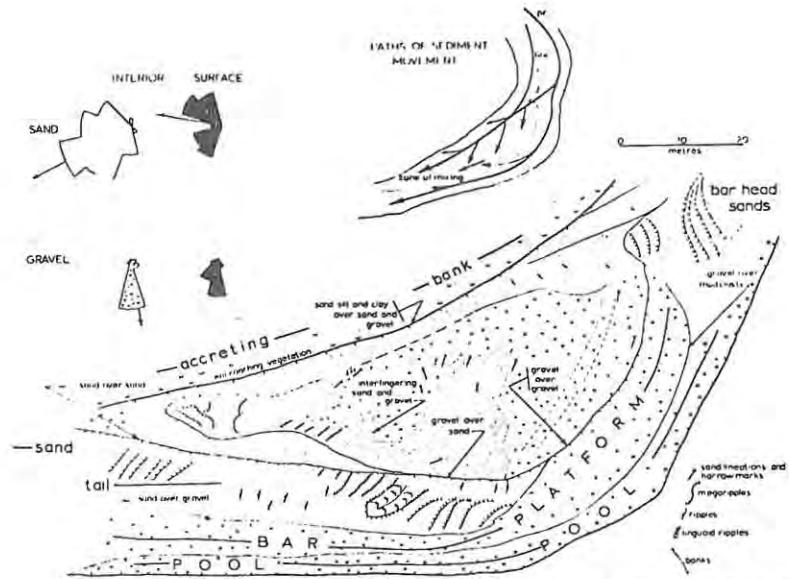


FIGURE 38. Bar head of typical point bar, River Endrick, Scotland, showing direction of sediment movement, and orientation of surface and internal directional structures (From Bluck, 1971).

directed against the concave bank. Bank caving occurs at maximum rates in bends where the bed and bank materials are very sandy. Deposition occurs on the inside portion of the bend at the same time as bank caving is taking place on the outside bend. (Figure 39)

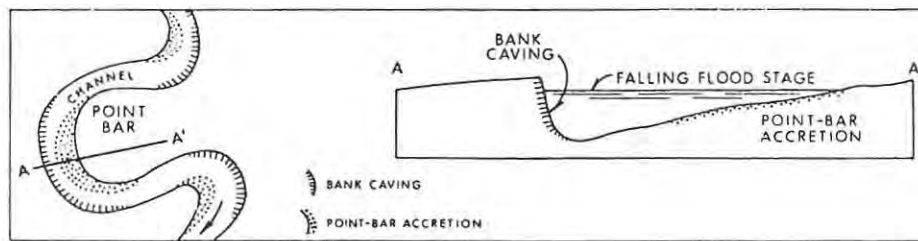
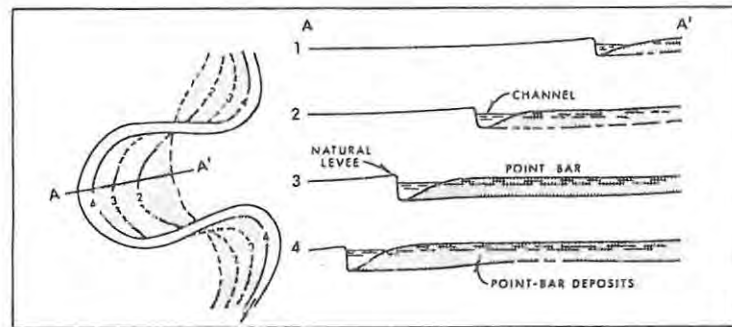


Fig. 39. --Areas of bank caving and point-bar accretion along a meandering channel.

(after LeBlanc 1972)

Bank caving and point-bar accretion result in channel migration and the development of the point-bar sequence of sediments. (Figure 40).



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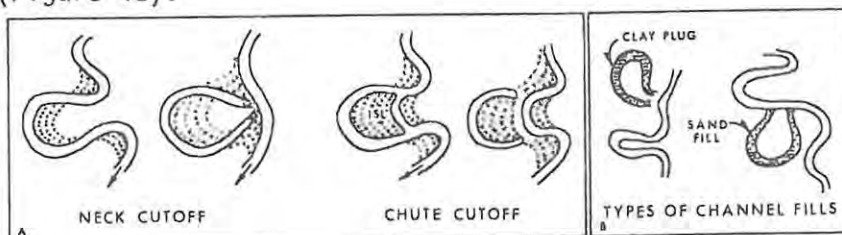
Fig. 40. —Development of point-bar sequence of sediments.

(after LeBlanc 1972)

The point-bar is probably the most common and easily identifiable environment of sand deposition. The thickness of this sequence is determined by the channel depth. LeBlanc quotes point-bar sequences along the Mississippi that are 45 m thick while medium-sized rivers such as the Brazos River of Texas has 15 metre thick point-bar sequences.

The process of channel diversion and channel abandonment is another characteristic feature of meandering streams. There are two types of diversion and abandonment; the neck or chute cutoff of a single meander loop; the abandonment of a long channel segment resulting from avulsion.

The abandoned meander loops become filled with sediments, the character of which depends on the orientation of the loop with respect to the direction of flow in the new channel. Meanders oriented with their cutoff ends pointing downwards are filled predominantly with clays whereas those oriented with cutoffs pointing upstream contain mainly sand and silts. (Figure 41).



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Fig. 41 —Channel diversion, abandonment, and filling as a result of neck and chute cutoffs. (after LeBlanc 1972)

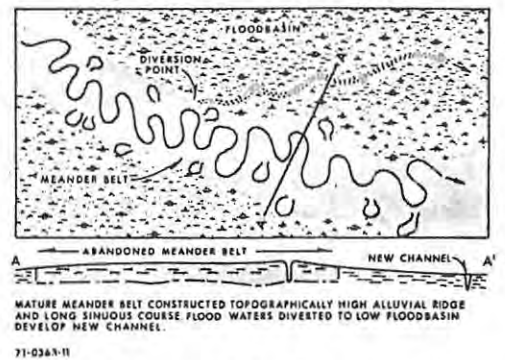


Fig. 42.—Major channel diversion and abandonment of a meander belt.
(after LeBlanc 1972)

The character of the sediments which fill long channel segments is governed by the manner of channel diversion. Abrupt abandonment during a single or few floods, results in the very rapid filling of only the upstream end of the old channel, thus creating a long sinuous lake. These long, abandoned channels fill very slowly with clays and silts transported by flood waters. (Figure 42)

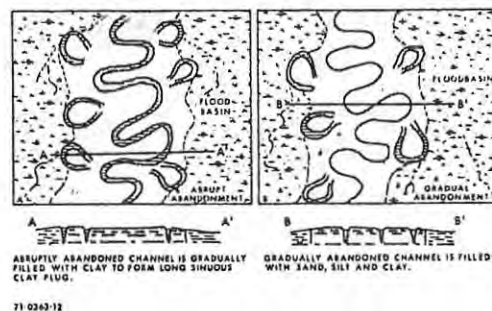


Fig. 43—Variations in character of abandoned channel fill typical of meander belts.

(after LeBlanc 1972)

If the channel abandonment takes place over a period of time a very gradual deterioration of the channel occurs. Diminishing flow therefore transports and deposits progressively smaller amounts of finer sand and silts. (Figure 43)

Meandering Stream Facies

The basic facies for meandering stream deposition is an upward fining sequence. (Figure 44)

In conclusion he states that only a few criteria may be broadly reliable in differentiating between meandering and non-meandering rivers :

- (a) Low palaeocurrent variance of imbrication of large pebbles and cobbles is expected in low sinuosity streams.
- (b) Exceedingly coarse gravel (> 0,5 m long axis) is diagnostic of a very proximal non-meandering stream.
- (c) Substantial mud content in coarse member, thick fine member and asymmetric channel fills with much mud are strongly indicative of a meandering stream.

Visher's idea of vertical profiles (1965) appear to have potential as a means of identifying facies and hence environments, but Jackson (1971) mentions that the major assumption made is the preservation of the complete sequence. He suggests that one should consider more thoroughly the style and potential of preservation of characteristic sedimentary features. The fact that not all of a vertical sequence will be preserved in nature and that deductions as to the nature of the sedimentary environment have to be made on the remnants of sequences is also stressed by Jackson.

6.4 FACTORS AFFECTING THE POTENTIAL OF A SANDSTONE AS A URANIUM HOST

In addition to the factors that interact in the generation of a sand body there are those factors which will determine whether (assuming the availability of uranium) a sand body has the potential for hosting uranium.

6.4.1 The Composition of Sandstones

The composition of the sandstones is important from several aspects with regard to its ability to host uranium. Sandstones which host uranium generally have an arkosic composition in which quartz, feldspar and rock fragments occur in roughly equal proportions. These are supplemented by clays, iron oxides, organics and sulphides which vary in content as well as origin.

The quartz content will determine the sand's response to compaction and hence affect the porosity of the sandstone. If the rock has a high quartz content its response to compaction will be minimal and the original porosity is likely to remain.

The feldspar content also governs the response of the rock to compaction. Both quartz and feldspar are susceptible to authigenesis and these new mineral overgrowths will reduce the porosity of the rock. The breakdown of feldspar under weathering conditions will result in clays which have different effects on the pore spaces of the rock. Depending on the type of rock fragments these will affect the porosity in much the same way as quartz and feldspar.

Because of the size and shape of clay minerals, they tend to occur interstitially between the larger grains and thus reduce the porosity. In addition to physically reducing the porosity, clay minerals could by virtue of their chemistry affect the permeability of the rock.

Fine grained clay which is found in sandstones as the essential constituent of matrix and argillaceous rock fragments includes all major groups of clays, i.e. the kaolin group (kaolinite, dickite, halloysite), the micas (muscovite, illite, glauconite), the montmorillonite or smectite group (monttronite, saponite etc.), the chlorite group and the mixed-layer group (corrensite etc.)(Grim 1968). The division of clay minerals into various groups is primarily on a structural rather than a compositional basis. The structures of these groups comprise units of alumina octahedra and silica tetrahedra, each of which forms sheets in the a - b crystallographic plane (Figure 45 on page 65).

The structure of the clay minerals is basic to the concept of ion exchange, whereby cations in the interlayer positions may equilibrate with the external environment, e.g. if a sodium montmorillonite is placed in a calcium-rich solution it will become a calcium montmorillonite. The extent of exchangeability is greatest for the montmorillonites, intermediate for the mixed layer illite and chlorite groups and lowest for the kaolinite group. Exchange takes place over long periods of time so during transport the clays will behave as stable detrital minerals but during processes taking millions of years such as diagenesis, all parts of the clay mineral

Mineral and Chemical Composition

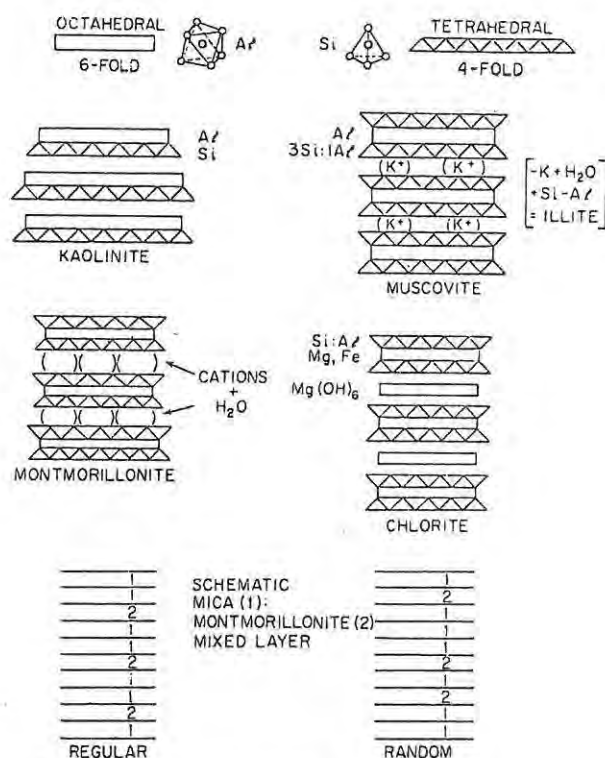


Fig. 45 Terminology and structure of clay minerals

(after Pettijohn et al., 1972)

structure may react with the environment.

Work by Schmidt - Coll rus (1976) and van der Weijden and Langmuir (1976) on the adsorption of uranium by various sorbents suggested that clays are relatively unimportant as concentrators of uranium. Some typical enrichment factors values (the weight of sorbent U per weight of sorbent plus U divided by the weight of dissolved U per weight of solution) are as follows :

amorphous Ti(OH)_4	:	8×10^4 - 8×10^6
amorphous Fe^{+++} oxyhydroxides	:	1.1×10^6 - 2.7×10^6
peat	:	10^4 - 10^6
fine-grained natural goethite	:	4×10^3

phosphorites	: 15
montmorillonite	: 6
kaolinite	: 2

Unfortunately not enough is known of the detailed mechanism of uranyl sorption from natural waters onto specific sorbents to allow accurate prediction of the role of sorption in low temperature sedimentary environments.

Although clay minerals show a low uranium enrichment capacity, they could by virtue of their chemistry retard the flow of cations through an aquifer allowing the uranium to react with other sorbents. A porous sandstone aquifer with a significant amount of argillaceous matrix would act as a semi-permeable membrane. Excessive negative charges on the surfaces of the clay particles are essential to produce the membrane effect, which increases with the increase in ion exchange capacity of the clay. Interaction between the cations in solution and negative sites on the clay platelets slows the transport of the cations through the aquifer. Uncharged molecules such as H_2O , H_4SiO_4 and H_2CO_3 however pass relatively easily through such membranes. In some cases silicates other than clay minerals can act as semi-permeable membranes. The vanadium-rich micas in some Colorado Plateau uranium deposits where there is little clay or organic material have set up an Eh front that had induced coffinite precipitation.

Pyrite is the most common sulphide found in sandstones. Most of it appears to be diagenetic though certain Precambrian deposits e.g. Witwatersrand gold and uranium deposits, contain detrital rounded pyrite grains. Pyrite is genetically related to one amorphous form of Fe S called mackinawite which is found in modern sediments under reducing conditions. Fe S forms first by the bacterial reduction of sulphate in sea water and during early diagenesis is converted to pyrite. Pyrite in sandstone is, if it is not detrital, indicative of at least local reducing conditions.

Because the pyrite that is formed diagenetically is commonly found in rounded aggregates it is not always easy to distinguish it from possible rounded detrital grains.

Oxidation of diagenetic pyrite within the sediments results in a steady supply of sulphate which can be reduced by sulphate-reducing bacteria that consume organic material trapped in the sediments as a source of energy.

Organic matter in sandstone is a biochemical product characteristic of the environment and has always been extensively altered by diagenesis. The varieties of organic matter in sandstone range from oil and gas to solid particles of high carbon content.

The organic compounds in sandstone are derived by the breakdown of plant and animal tissues in the sedimentary environments. Later the decomposition products may be dissolved, transported and reprecipitated during stages of diagenesis. The existence of organic matter is obviously the result of either high organic productivity in comparison to the oxidative breakdown of such organic material or to the presence of particular biological entities that are highly resistant to oxidation.

Sandstones in general are characterized by very small amounts of organic matter (< 0.1 per cent) as opposed to shales and limestones. The organic matter that is native to sandstones is dominantly detrital since the presence of oxygen and the high permeability of the sand promotes oxidation of much of the organic matter.

6.4.2 Porosity and Permeability

Two other factors which determine whether the sandstone will be a good host for uranium mineralization are the relative porosity and permeability of the sand body.

Absolute or total porosity is the percentage of all void space in a sand, whether the pores are connected or not, whereas effective porosity is the percentage of interconnected pore space. They are represented as follows :

$$P_t = \left(\frac{\text{bulk volume} - \text{solid volume}}{\text{solid volume}} \right) \times 100$$

and Effective Porosity as :

$$P_e = \left(\frac{\text{interconnected pore volume}}{\text{bulk volume}} \right) \times 100$$

Effective porosity is generally what is measured.

Studies have been carried out in order to approximate porosities found in granular materials but the abundance of grains of mixed sizes, non spherical framework grains, the filling of pores by cementation and interstitial clay, minimizes the significance of these studies. Compaction and cementation can reduce porosity from 50 per cent or more in modern sands to virtually zero in quartzites and other holocrystalline sandstones (Pettijohn et al., 1972). However, as cementation increases, particularly silica cementation, fracture porosity is likely to increase with respect to intergranular porosity, because the sandstone is more brittle and thus fractures more readily. Figure 46 shows the relationships of texture to

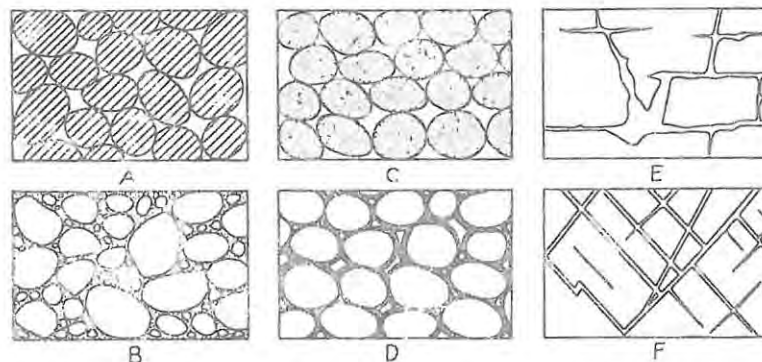


Fig. 46, Rock interstices and the relation of rock texture to porosity. Diagram showing several types of rock interstices and the relation of rock texture to porosity. A. Well-sorted sedimentary deposit having high porosity; B. poorly-sorted sedimentary deposit having low porosity; C. well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; D. well-sorted sedimentary deposit the porosity of which has been diminished by the deposition of mineral matter in the interstices; E. rock rendered porous by solution; F. rock rendered porous by fracturing. (After Meinzer, 1923, fig. 1; courtesy of U.S. Geol. Surv., Wash., in: Tolman, 1937, fig. 24, p. 98.)

(after Chilingarian & Wolf 1976)

porosity. The effects of depth compaction on porosity will be covered in a separate section. In work on relatively well sorted quartz sands and sandstones Maxwell (1976) concludes that reduction of initial porosity is also favoured by increasing overburden pressure, high temperature, greater age, moving formational water.

Experiments by Maxwell (1976) show that the porosity of sedimentary rocks tends to decrease with increasing age and depth of burial. Shales lose water and compact regularly and readily during burial but sandstones behave much less predictably particularly at shallow depths. Laboratory determinations of the crushing strength of quartz suggests that porosity might persist to very great depths.

Other experiments have shown that the solubility of quartz in water increases as temperature and pressure increases and that the crushing strength decreases greatly with rising temperatures in the presence of water solution. Natural sandstones should therefore compact and lose porosity with increasing depth and rising temperature.

Permeability

Permeability or hydraulic conductivity (K) is a measure of the ability of a sandstone to transmit fluids. It is defined as a constant of proportionality for the laminar flow of a particular fluid in a particular porous substance by Darcy's equation :

$$Q = KA \left(\frac{dp}{dl} \right)$$

where Q = volume of transmitted flow per unit time

A = cross sectional area

dp/dl is the dimensionless hydraulic gradient (change of pressure in flow direction l)

Thus the rate of flow is directly proportional to the cross-sectional area and the hydraulic gradient. This property is dependent on the fluid as well as the pore system and the direction of permeability measurement in the medium. It is therefore a vectorial property in contrast to porosity.

Specific permeability, k , is a measure of permeability depending only on the medium and is defined as :

$$Q = \frac{k a \gamma}{\mu} \frac{dp}{dl}$$

where γ is the specific weight of the fluid (weight per unit volume as opposed to density which is mass per unit volume)

μ is the viscosity.

Specific permeability is measured in darcies. It can be thought of as the characteristic pore area controlling flow.

Among the rock properties affecting permeability are grain size, sorting, orientation, packing of framework grains, cementation and bedding.

Orientation and packing of the framework grains of a sandstone appear to have a weak control on permeability in the plane of the bedding and a much stronger control in vertical sections parallel to sand transport direction (Mast & Potter 1963).

During deposition, framework sand grains accumulate with their long axes parallel to current flow and imbricated upcurrent 15° - 18° from the depositional interface. This imposes a form of anisotropy on the pore system in the plane of the bedding. Bedding also has the same effect as fabric though probably to a greater degree. There are slight pauses during the deposition of sand which are marked by thin mud laminations which inhibit flow in a vertical direction.

In modern sands permeability of 10 to more than 100 darcies have been reported but in most consolidated sandstones values of more than 1 or 2 are the exception.

Tsvetkova (1954) showed that the presence of clay greatly reduces the permeability of sandstones. This is especially true for montmorillonite clays where 2 per cent montmorillonite in coarse-grained sand lowers permeability 10-fold whereas 5 per cent montmorillonite clays lowers permeability 30-fold. Sandstones are particularly impermeable in the presence of 6-9 per cent montmorillonite clay while sandstone containing 2-15 per cent kaolinite clay can still remain quite permeable.

In some units however, jointing or microfaulting can increase permeability perpendicular to bedding by orders of magnitude.

The chief sedimentological variable affecting permeability in detrital rocks is pore throat size. With decreasing pore radius, the area of mineral surface over which the water must flow increases dramatically. The more contact between fluid and solid the greater the drag.

Poiseuille derived the following equation for the rate of laminar flow of liquid through a capillary as :

$$Q = \frac{\pi r^4 \Delta p}{8 \mu l}$$

where Q = fluid discharge (cc/s)

r = radius of a cylindrical capillary (cm)

Δp = pressure drop along the capillary (bars)

μ = viscosity (poises)

l = capillary length (cm)

Because of the tortuosity of a pore, the length of the capillary is longer than the length of rock traversed by the flow. See Figure 47 on page

If Darcy's law and Poiseuille's law are combined the flow through a capillary is expressed as :

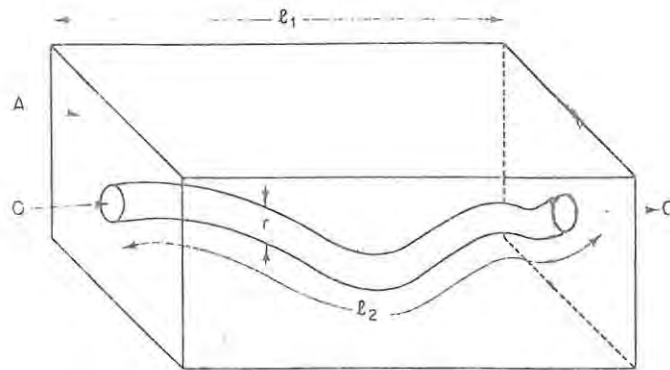


Fig. 47. Schematic diagram of a capillary pore channel in a sandstone.

(after Blatt, Middleton & Murray 1980)

$$Q = \frac{Ak \Delta p}{8\mu l_1} = \frac{\pi r^4 \Delta p}{8\mu l_2}$$

$$K = \frac{\pi r^2}{A} \cdot \frac{l_1}{l_2} \cdot \frac{r^2}{8} = \frac{(\text{porosity}) r^2}{(\text{tortuosity}) 8}$$

This shows that the permeability of the rock can be expected to decrease as the pore radius decreases. It also decreases as the volume of pores (porosity) decreases and the tortuosity increases. These features are affected mainly by diagenetic processes which will be dealt with later.

The effect of increased temperatures that accompany burial has been examined. Although there is a complex interrelationship between temperature and permeability, many sets of experimental data indicate that the permeability of sandstones to distilled water decreases as temperature increases. An explanation suggested by Blatt, Middleton & Murray is that mechanical stresses induced in the rock by thermal expansion of the mineral grains would constrict pore openings.

Interrelationship between porosity and permeability

Statistical distributions of permeability in oil reserves tend to be log normally distributed, whereas porosity typically has a normal distribution. Moreover, variance of permeability is much greater than that of porosity and can vary markedly vertically from centimetre to centimetre. (Figure 48).

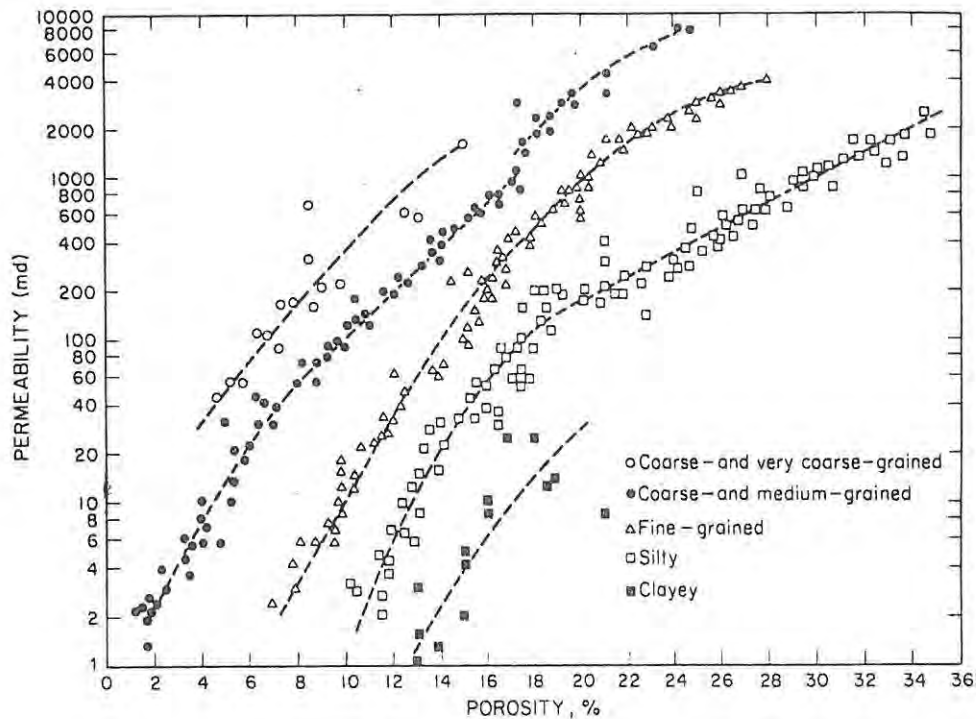


Fig. 48. Relationship between porosity and permeability of cores of very coarse, coarse, and medium-grained sands, silty sands, and clayey sands.

(from Blatt, Middleton & Murray 1980)

This relationship could be because porosity does not define the drag imparted to the fluid by the pore walls nor the path length of the capillary. Change in either of these would alter the permeability without affecting the porosity.

It has been found empirically that there is a relationship between the permeability and the specific surface area of a porous rock. This

relationship is known as the Kozeny equation and one form of it is :

$$K = \frac{10^8}{2t^2 S^2}$$

where k = permeability

ϕ = porosity

t = tortuosity

S = specific surface area (surface exposed to fluid per unit volume of solid)

This shows that as grain size decreases, specific surface increases and consequently so does resistance to flow.

Modification of the primary permeability by secondary processes will be dealt with later.

Reconstruction of palaeoporosity changes which might indicate potential as a uranium fluid conduit is not possible without the use of thin-sections, the electron microscope or other tools that permit visual examination of the interior of rocks.

In addition to the compositional factors, larger scale features such as bedding, cross-bedding, parting lineations and grooves will also affect the porosity and permeability of the sandstone. These structures which are generally formed in medium to coarse-grained sandstone generally have the sand grains orientated parallel to the current direction and therefore contribute to an increase in the horizontal permeability of sand bodies. Ripple marks, however, are generally developed in fine-grained sediments and exhibit thin laminations which act as barriers to flow.

Each depositional environment produces a diagnostic arrangement of fine-grained bounding lithologies around a sand body and as such makes the task easier for predicting their orderly subsurface arrangements.

The flow of ground water within a sand body, may not be uniform because the external shape of a trough cross-bedded unit, associated fine

clastics and irregular cementation will influence the flow (Roach & Thompson 1959).

Jobin (1962) in comparing the distribution of uranium deposits of the Colorado Plateau with the variations in transmissive characteristics observed several interesting relationships. Whereas permeability is the capacity of a substance to transmit fluids under a hydraulic gradient, the coefficient of transmissivity for a sediment at a given locality is equal to the product of its thickness and mean permeability.

The rocks of the Plateau may be grouped into three types, shales and mudstones; marine and aeolian siltstones and sandstones; fluvial sandstones and conglomerates.

The first group is relatively impermeable and because of their abundance and stratigraphic position they have played an important role in confining the pore solutions. The second group have a relatively high mean permeability and this fact coupled with its great thickness means that this type is the most transmissive of the rocks under consideration. The fluvial sandstones and conglomerates make up a small fraction of the total thickness of transmissive rocks. They have steep gradients in permeability and thickness, a moderate to low transmissive capacity and contain almost all the known uranium deposits.

It appears that the fluvial sandstones and conglomerates which are overlain by thick relatively non-transmissive rocks have yielded more than 92 per cent of recent uranium production and contain the large majority of known uranium deposits (Jobin 1962).

A comparison of the distribution of uranium deposits with the variation in transmissive characteristics in host rocks shows that the range of size of deposits tends to vary directly with the range in magnitude of the coefficient of horizontal transmissivity.

Figure 49 on page 76 shows the distribution of sandstones of the Morrison Formation and vertical and horizontal transmissivity. Those areas of high vertical transmissivity that coincide with areas of moderate but highly variable horizontal transmissive capacity are considered the most

likely to contain appreciable numbers of ore deposits of more than 1 000 tons U_3O_8 .

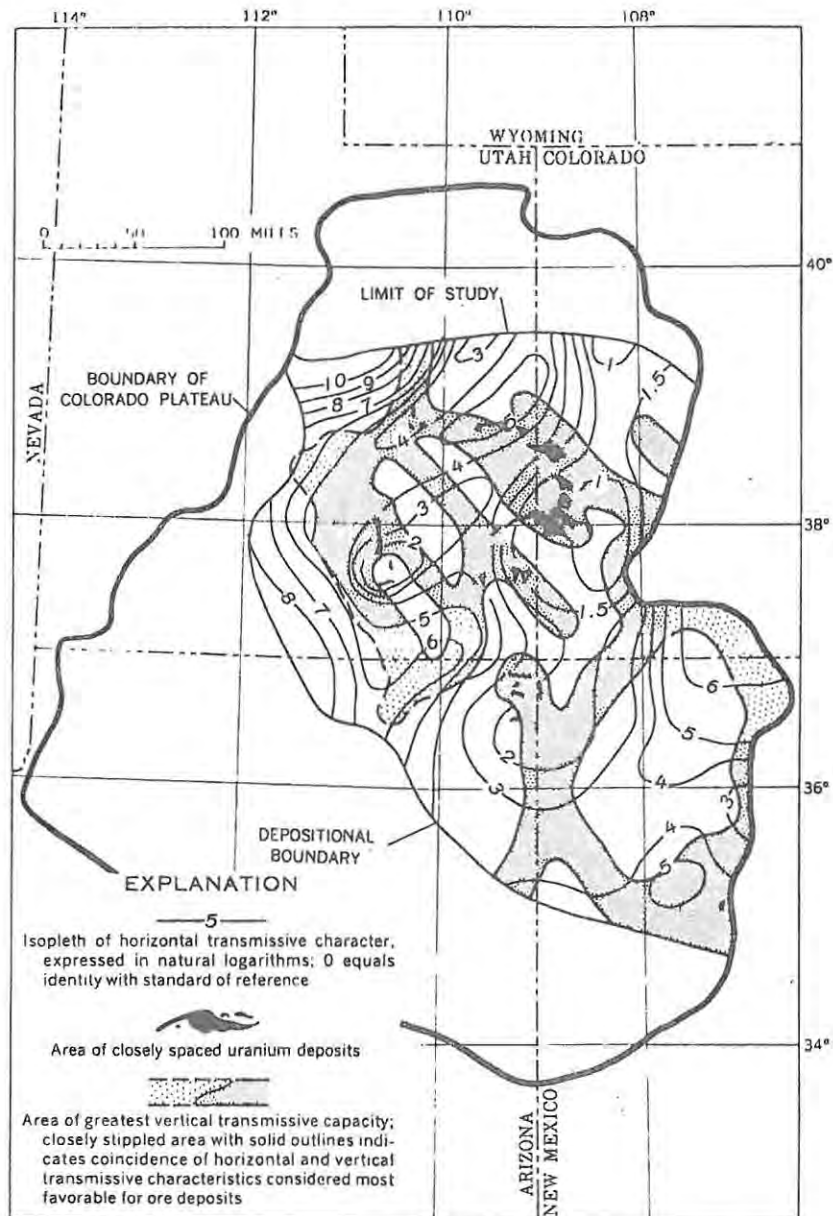


FIGURE 49 Sandstones of the Morrison formation classified as to similarity of horizontal and vertical transmissive character to average transmissive character of its most productive mining areas.

(after Jobin 1962)

The data quoted suggest that the major host rocks of uranium deposits have had a moderate to low transmissive capacity throughout their

history. (Jobin 1962). The selectivity of the movement of the uranium-bearing solutions and of the places of uranium deposition was controlled to a varying degree by the horizontal and vertical character of the host rock. The spatial relations between ore deposits within the stratigraphic section and relations to zones of high vertical transmissivity suggest a dominant control by aquicludes and regional structure which is probably of early Tertiary age. (Figure 50)

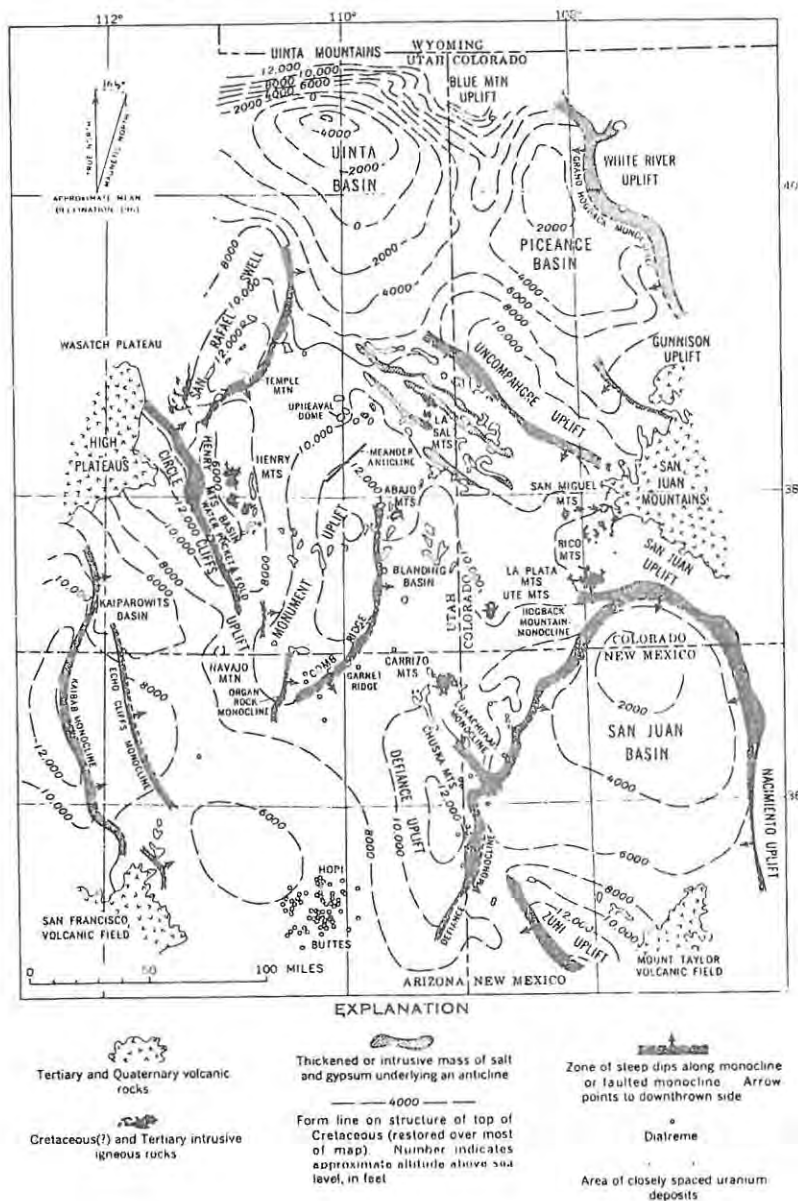


Fig. 50. Sketch map of the Colorado Plateau showing tectonic features and distribution of areas of closely spaced uranium deposits. Modified after Shoemaker (1954, pl. 1.)

(from Jobin 1962)

6.4.3 DIAGENESIS

The course of sandstone diagenesis in a given basin is dependent on the preburial, prediagenetic factors of provenance, depositional environments and tectonic setting. These interrelated factors influence the sand composition and texture which in turn govern fluid flow rates and mineral reactions. Diagenetic processes determine porosity in terms of origin, amount, subsurface distribution, pore-size distribution, pore-shape, surface area and permeability.

As a result diagenesis governs the potential of sandstone bodies for hosting uranium deposits and studies of this process will enable more accurate porosity predictions to be made in uranium exploration.

In general it is possible to subdivide the components that interact during the diagenetic processes into endogenic or exogenic components depending on whether the diagenetic materials were derived from within the sediment or without. The raw materials of diagenesis consist of organic and inorganic sediment, interstitial fluids and other components.

Diagenesis may express itself in a number of different ways such as changes in mineralogy, addition or removal of material, or modifications to texture or structure.

The process therefore includes all physicochemical, biochemical and physical processes modifying sediments between the stages of deposition and lithification at low temperatures and pressures characteristic of surface and near surface environments. (Chilingarian & Wolf 1976). The processes occur in response to continued burial and are therefore gradational.

Chilingarian & Wolf (1976) list the processes of diagenesis as follows :

(1) Physicochemical Processes :

Solution, corrosion, leaching, bleaching, oxidation, reduction, reprecipitation, recrystallization, cementation, decementation, authigenic

mineral genesis, crystal enlargement, replacements, chemical internal sedimentation and aggregation and accretion.

(2) Biochemical and Organic Processes :

Accretion and aggregation, particle-size reduction, corrosion, corrosion, mixing of sediments, boring, burrowing, gas bubbling, breaking down and synthesizing of organic and inorganic compounds.

(3) Physical Processes :

Compaction, dessication, shrinkage, penecontemporaneous internal deformation and corrosion and mechanical internal sedimentation within secondary cavities in the host rock.

Of these processes the following are regarded as more important :

(a) Authigenesis

The development of new minerals or overgrowths within a sediment. Secondary growth of quartz is a common example while authigenic feldspar may develop in sandstone or limestone.

(b) Cementation

This is the deposition of minerals in interstices among the grains of a sediment. It is one of the commonest forms of diagenesis and binds the particles together to form a rigid sediment. Cementation may occur either contemporaneously with sedimentation or the cement may be introduced at a later stage.

The most common cementing materials are calcite, dolomite, siderite and silica. The cementing material may either be endogenic or exogenic. When only one cement is present in a rock (e.g. sandstone) it is most commonly silica. If two or more cements are present the silica will be introduced first and either calcite or dolomite will follow. Pettijohn, Potter & Siever (1972) have investigated silica cementation and deduced that pressure solution and supersaturated pore water are the main mechanisms

causing silica cementation.

A study by Siever (1959) of cementation in sandstone demonstrates some of the relationships possible. (Figure 51).

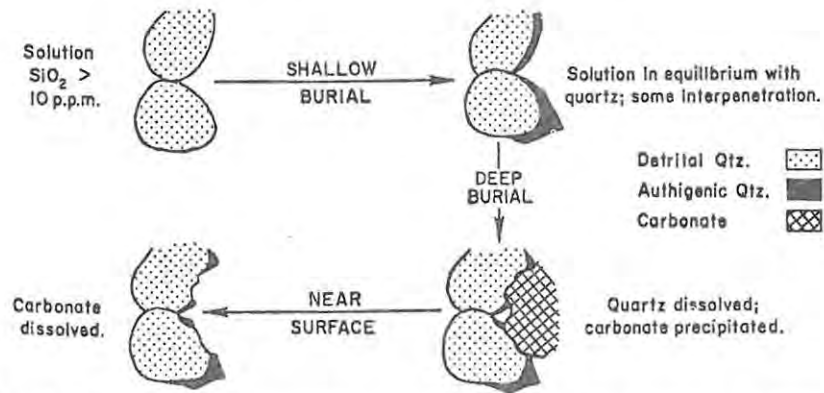


Fig. 51. Sequence of cementation and decementation in quartzose sandstone, from initial shallow burial, through deep burial, to subsequent near-surface conditions.

(after Siever 1959 and Pettijohn et al., 1972)

In the process of cementation and de-cementation in a quartzitic sandstone the initial sand may contain a very weak solution of silica in its pores. During shallow burial, this silica will develop overgrowths on the original quartz grains producing small euhedral faces. With deeper burial carbonate cement may be introduced into the remaining pores of the sandstone but if the process continues the carbonate will tend to replace the original silica or its overgrowths. If the rock is brought near surface by erosive agents the carbonate may be dissolved, leaving behind a partially de-cemented rock. (Carbonic acid is developed by the maturation of organics to produce CO_2 , which then reacts with the carbonate minerals.)

A somewhat different pattern results when the carbonate cement is siderite. This cementing material is introduced as small rhombs that form as attachments to the original detrital grains or their overgrowths. In some cases siderite might replace the quartz as shown in Figure 52 on page 81

With the advent of more sophisticated petrographic microscopes and the technique of cathodoluminescence, recent work has shown de-cementation (now called secondary porosity) to be more extensive than was previously envisaged. This will be discussed later.

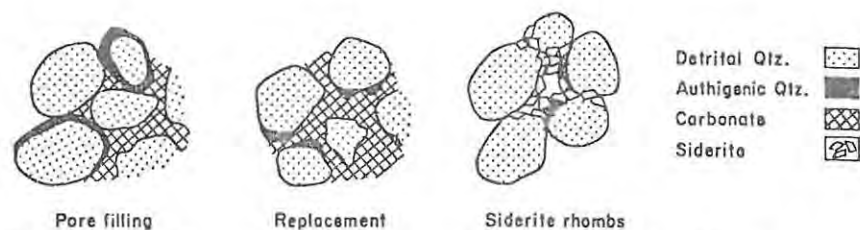


Fig. 52 Three aspects of sandstone cementation, involving pore-filling, replacement, and introduction of siderite rhombs. See the text for details.

(after Siever 1959 and Pettijohn et al., 1972)

(c) Compaction

Compaction is the reduction in bulk volume of sediment produced by increasing weight of overburden as sediment is buried. (Pettijohn et al., 1972).

The strongest effects are noted in fine-grained sediments where the interstitial water is forced out until the particles are in contact with one another. As compaction continues the grains may be rearranged and the fine clay minerals forced into interstices between more rigid particles. In this way, the porosity of the sediment may be virtually eliminated.

Sand shows much less compaction relative to mud for two reasons. Firstly, the porosity at the time of sand deposition is initially lower than that of fine-grained sediments. Secondly, the absence of abundant matrix material means that in a well sorted sand especially, the pore spaces between the rigid quartz grains will continue to remain relatively open.

(d) Diagenetic Differentiation

This is the redistribution of material within the sediments by solution and diffusion towards centres or nuclei where reprecipitation occurs.

Concretions in shale are an example of this process.

(e) Differential Solution

This is a selective solution process within the sediment, either of a particular constituent or along bedding planes.

(f) Recrystallization

This is a change in the sediment texture whereby the growth of small crystals or fragments form an aggregate of coarser crystals generally without a change in composition.

(g) Replacement

In replacement, new minerals are developed by the reactions between original constituents of sediments and exogenic materials. The new mineral develops in the space occupied by the original without a change in volume to form a pseudomorph. The alteration of mica to chlorite is an example.

Diagenetic Models

As knowledge on the subject of diagenesis has increased it has become clear that there are only a few dominating processes in operation (Krumbein & Sloss 1963).

The nature of the diagenetic environment and the rapidity of the postdepositional changes depend upon the medium of deposition and the kind of sediment being deposited. (Krumbein & Sloss 1963).

The depositional interface represents an important boundary condition that separates two different physicochemical regions. In diagenesis the basic relation seems to depend upon the position of the zero - value Eh surface with respect to the depositional interface. Figure 53 on page 83 shows three positions of the zero-value interface.

In a non-marine environment such as a sandy river bed, the zero-value

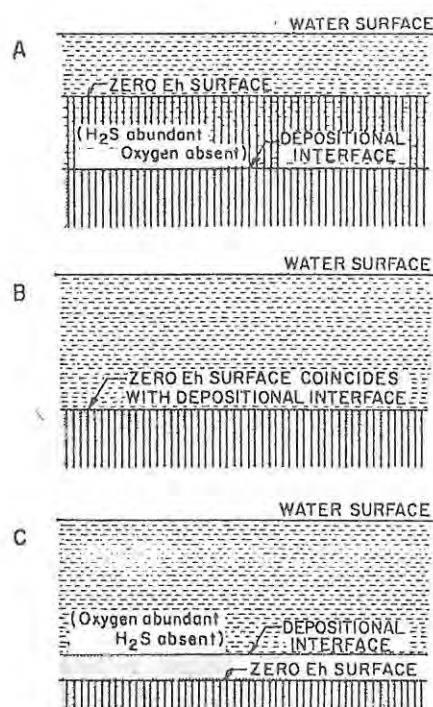


Fig. 53

Diagrams of relations between zero Eh surface and depositional interface for three conditions. Diagram A represents stagnant bottom-water conditions, B shows coincidence of the two surfaces, and C shows conditions when oxidizing conditions penetrate below the depositional interface. [After Krumbein and Garrels (1952). Copyright by the University of Chicago.]

(from Krumbein & Sloss 1963)

Eh surface may lie some distance below the depositional surface as shown in Figure 53C. This implies that depositional changes do not occur until the sediment has been buried to a depth sufficient to bring it below the zero-value Eh surface. These figures may imply that early diagenesis is most prominent where the zero Eh surface coincides with the depositional interface.

Pettijohn et al., (1972) offered a diagrammatic representation of six stages to which a sandstone is exposed during burial. (Figure 54 on page 84).

Dapples (1959) considered further simplification by considering

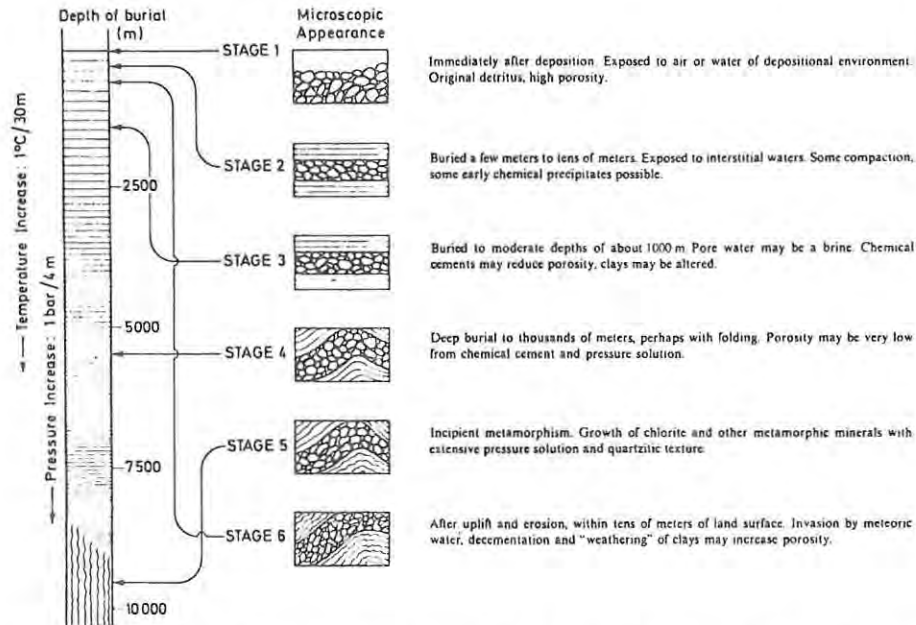


Fig. 54 . The stages of diagenesis in relation to depth of burial and increase of pressure and temperature. (After Pettijohn et al., 1972, fig. 10-1, p. 387; courtesy Springer, New York.)

diagenesis as occurring in three stages. The first involves changes in the sediment that occur during the course of its burial. In this stage the sedimentary grains are moved from the depositional interface to a position slightly below the interface as deposition takes place. The second includes the changes that occur in the early stages of moderate burial. The third stage is deep burial, sometimes associated with a long timespan.

Packham & Crook (1960) developed the concept of diagenetic facies. Each diagenetic facies is defined as including all sedimentary rocks which during diagenesis have developed a mineral assemblage related to a particular diagenetic environment expressed in terms of such environmental controls as pH, Eh, pressure, temperature, and materials present. Diagenesis is subdivided into alterations that might occur before or during deposition (halmyrolosis), immediately after burial (diagensis) and under deep-seated conditions (epigenesis). These facies are analagous to

metamorphic facies, starting at surface and passing down into the low-grade metamorphic facies.

The Role of Secondary Porosity in Diagenesis

As mentioned in the section on cementation (6.4.3 c) the subject of secondary porosity has received little alteration prior to 1975. It was recognised by Siever (1959) who used the term de-cementation to describe this feature.

The development of techniques such as cathodoluminescence and sophisticated instruments such as the electron micro-probe, has resulted in the identification of such secondary porosity that was previously misidentified as primary porosity (Hayes 1979; Schmidt & McDonald 1979 a & b). Cathodoluminescence and electron probe studies show that authigenic minerals are much lower in trace element content and show a lower luminescence than the detrital grains (Pettijohn et al., 1972).

The study of secondary sandstone porosity is very much in its infancy but it appears possible that secondary porosity is more abundant than primary porosity and is therefore of major geological significance.

Hayes (1979) in his studies of "holes in sandstones" states that primary intergranular porosity and permeability of sand are greatly reduced and subject to total destruction in the early stages of burial diagenesis. It is at this stage that the processes of compaction, cementation, recrystallization and replacement reduce the porosity of the sandstone. It is also noted that the rate of porosity loss with depth is related mainly to original sand composition. Secondary porosity is produced by later stages of diagenesis through processes such as the dissolution of detrital and authigenic minerals.

It has been found recently that secondary porosity must be formed before hydrocarbon migration if it is to serve as reservoir porosity and perhaps this applied in the case of uranium-bearing fluids/humates. Hayes notes that secondary porosity can be destroyed diagenetically but it will persist to greater depths than will primary porosity. (Figure 55)

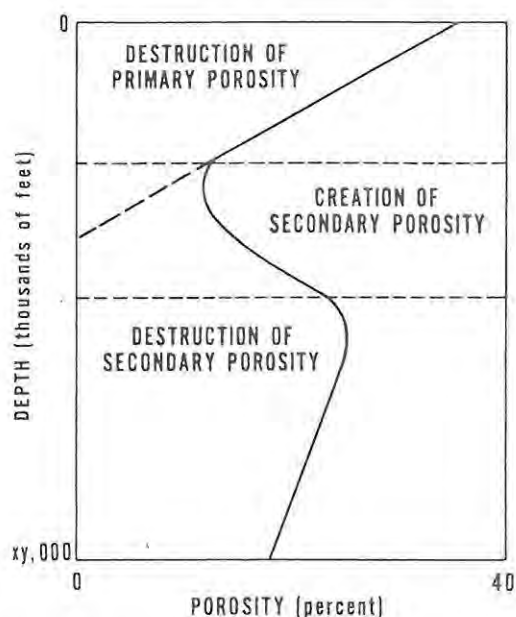


Fig. 55—Depth distribution and evolutionary sequence of primary and secondary porosity.
(after Hayes 1979)

Chemical diagenesis of sandstones is a kinetic process in which mineral matter is dissolved, transferred and precipitated by aqueous solutions moving through sandstones. The main source of water is from the dewatering of shales interbedded with sandstones. Reconstruction of the chemical evolution of moving water, of its flow paths through a basin and the time of migration are the keys to predicting subsurface distribution of sandstone porosity. Mathematical modelling of hydrodynamics and mineral reactions by means of computer simulation is a promising approach to porosity prediction (Hayes 1979).

Schmidt & McDonald 1979b recognize five principal classes of secondary sandstone porosity that can be differentiated according to processess of origin and fabric relationship. (Figure 56 on page 87).

They use a system of diagenetic regimes that Choquette & Pray (1970) formulated for porosity studies in carbonate rocks. They are eodiagenesis which is a regime at or near the surface of sedimentation where the chemistry of the interstitial water is mainly controlled by the surface environment

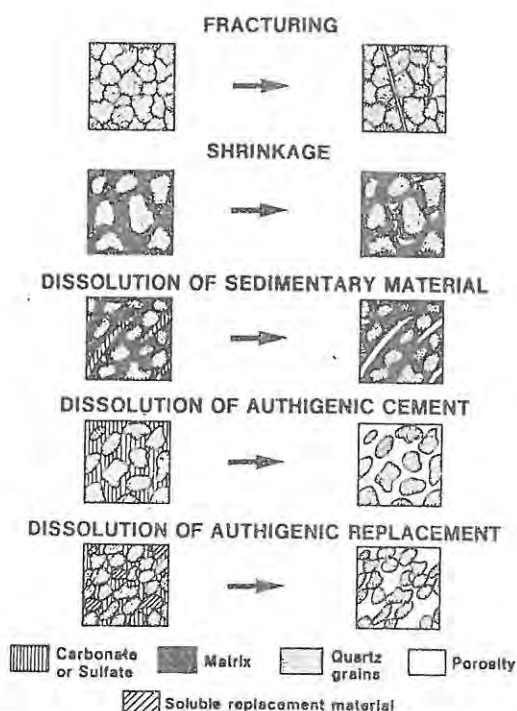


Fig. 56 —Textural origin of secondary sandstone porosity.

(after Schmidt & McDonald 1979b)

prior to effective burial. Mesodiagenesis is the subsurface regime during effective burial. Telodiagenesis represents the regime at or near the surface after effective burial. Only a minor portion of secondary porosity evolves during eodiagenesis or telodiagenesis and most is produced during mesodiagenesis. Most of this can be attributed to leaching of various carbonate cements.

Secondary pores in sandstones can be objectively described on the basis of their textural and genetic aspects and a very large number of porosity-types can be defined. Many of the textures of secondary porosity resemble those of primary porosity whereas other secondary textures are quite distinct. Schmidt & McDonald (1979b) have outlined the range of textures caused by secondary porosity and provided criteria by which they can be identified. In most instances simple petrographic criteria will suffice but more advanced analytical methods are required for some.

Studies of the secondary porosities of sandstones can therefore reveal features about the potential permeability of the rock and hence its potential as a host to uranium deposits.

7. FACTORS CONTROLLING THE GRADE AND TONNAGE OF
SANDSTONE URANIUM DEPOSITS

Having discussed the factors that indirectly affect the formation of sandstone uranium deposits (sections 5 and 6), those factors which have a direct bearing on the grade and tonnage of the deposits will be examined.

7.1 FACTORS CONTROLLING GRADE

Grade appears to be a rather loosely used term to describe that property of the rock which tells one the amount and quality of the potentially valuable minerals contained within it. In many cases the term 'grade' involves more than just an assay value since factors such as deleterious elements, grain size distribution, moisture content etc. have an effect on the value of the mineral element concerned. Grade is therefore a "vector of parameters" which when taken together indicate the amount and qualities of the described minerals or elements and can be used, along with information about the value of the mineral products, to assess the value of the rock in the ground. (Dixon 1979).

Several factors affect the grade of a sandstone uranium deposit, but before any of these is considered the essential pre-requisite is a large enough source of uranium that has been exposed to weathering processes. Tectonics would therefore be important in effecting these processes.

Assuming a large source of exposed uranium, the environment of deposition of the sand body would affect various factors which play an important role in uranium ore body formation.

The environment determines the grain size and sedimentary features of the sandstone which control the permeability. If the environment was dominated by braided-stream facies the tendency would be for a sand body with a high permeability to form, which would mean that the chances of uranium fixation and precipitation would be reduced. Also the chances of organics being present or being preserved in this alluvial environment are more limited than in the high sinuosity, meandering stream environment.

The environment determines the sequences of vertical lithologies

that will be deposited, which have a direct bearing on the permeability of that sequence. Interbedded units of shale and sandstone are the optimum hosts since solutions are confined and the constituents concentrated. This could result in an increase in grade, provided that there is sufficient adsorbent and reductant in the unit.

The environment also governs the composition of each sedimentary unit which affects the grade of a uranium deposit in the following ways. The control of composition over the grade depends on the content of the uranium fixers, such as organics and pyrite. The ratio of uplift to sedimentation in the region would affect the state of preservation of the organics and therefore the amount of uranium that would be fixed. If erosion was dominant, a minimal amount of organics would be preserved and no matter how much uranium passed by in solution only a small amount would be captured. A similar case applies to the sulphide content of the sandstone which is needed to create the mobile reductants responsible for the precipitation of the uranium.

The clay content of the sandstone would govern its permeability. This would be essential for reducing the flow of the aqueous solution so that the uranium would have time to be adsorbed onto the organics. If the permeability was too great, the uranium would be flushed away before it could be adsorbed. The clays could also be a uranium adsorbent though most workers feel that the clays play a limited role in this sphere.

The carbonate content of the host rock also has an effect on the grade of the deposit from a metallurgical point of view. Most methods of extracting uranium from the ore incorporate an acid leach. If the ore contains a high carbonate content then more acid than normal is used, thus increasing the cost of processing the ore and therefore indirectly lowering the grade of the ore. If the carbonate content of the ore is abnormally high, it might necessitate the use of an alkali leach method which in cases of ore with normal amounts of carbonate (2-5 per cent calcite), is more expensive than the acid leach method.

In some cases, elements like molybdenum and vanadium are extracted as by-products and their presence consequently increases the grade of the ore. However, over the years the specifications for yellow cake uranium concentrates have gradually become more restrictive. As a result elements

such as molybdenum, vanadium, phosphorus, sodium and also sulphate are regarded as contaminants. If the amounts of the elements are sufficiently high in the concentrate to warrant further treatment or payment of penalties then these elements would be regarded as deleterious products rather than by-products.

The composition of the sandstone will also govern its primary and secondary porosity which would affect the equilibrium of the proportions of the parent uranium isotope to its daughter products. Equilibrium is attained in a radioactive series when all the daughter products decay at the same rate as they are produced from the parent isotope. Thus, at equilibrium, each of these daughter products would be present in a constant to its parent isotope. Figure 57 shows the parent isotopes and decay

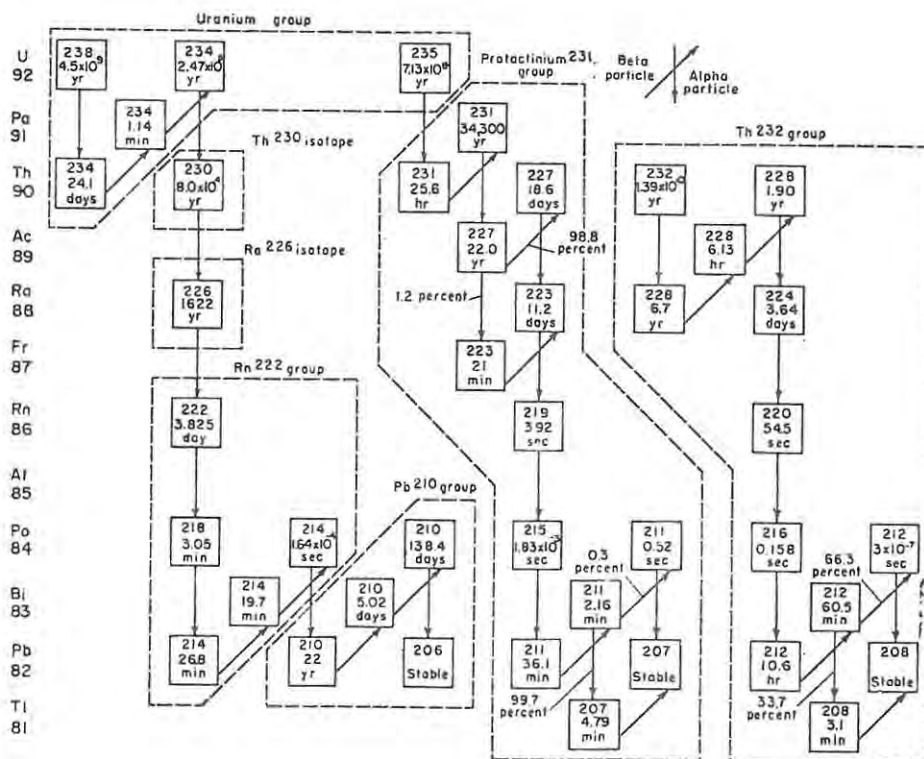


Fig. 57. Classification of natural radioisotopes into groups, showing atomic numbers, half-life periods, and modes of decay.

(after Rosholt 1959)

products of the three principal naturally occurring radioactive decay series; the ^{238}U , ^{235}U and ^{232}Th series. After a uranium deposit has been formed by precipitation from solution, it requires about 3×10^5 years to develop a complete chain of radionuclides, all of which have reached a steady state or equilibrium concentration. The loss or gain by geological processes of certain important isotopes during the more recent part of the existence of a mineral causes disequilibrium in the properties of the parent isotope to its daughter products. Where significant disruption of equilibrium occurs, the natural radioisotopes can be separated into the following major isotopes and groups of established equilibrium shown in Figure 57.

Approximately 98 per cent of the gamma emission is produced by the radium groups, particularly ^{214}Pb and ^{214}Bi . One of the methods of measuring the amount of uranium in the rock is the gamma-ray log. The gamma-ray log is a measure of the amount of ^{214}Pb and ^{214}Bi present in the ore. If the ore is not in equilibrium between ^{238}U and ^{214}Bi , calculations based on gamma-ray logs will be in error. The value calculated from a gamma-ray log is called eU_3O_8 or gamma-equivalent U_3O_8 . The calculated eU_3O_8 might be either higher or lower than the actual U_3O_8 content of the ore, depending on the nature of the disequilibrium.

Rosholt (1959) suggests that it is desirable when investigating radioactivity anomalies that analysis for ^{222}Rn and ^{210}Pb as well as for uranium be carried out to check the accuracy of the uranium and radioactivity analyses. Although it is common for the chemically determined uranium content of a sample to be compared with its equivalent uranium (eU) misinterpretations can be made. Radon loss is the most common anomaly and may present some misleading conclusions. In extreme cases high radon loss completely masks the presence of the long-lived daughters that are actually in greater amounts than uranium itself. The eU : U ratio would indicate major disequilibrium with deficient amounts of daughter products when in fact it is the amount of uranium that is deficient.

Similarly, a routine eU analysis will not indicate the presence of low energy alpha emitters when beta-emitting daughter products are not present in the sample. The large excess of ^{230}Th and ^{231}Pa is not indicated at all by the eU value because of the much lower ^{226}eRa and ^{222}eRn content.

Studies of the isotope - abundance ratios of samples showing significant uranium-series disequilibrium by Rosholt (1959) appear to be resolved into certain patterns. Rosholt contends that by analysing for the key isotopes ^{238}U , ^{235}U , ^{231}Pa , ^{230}Th , and ^{226}Ra one can classify nearly all disequilibrium samples into six categories represented in Figure 58.

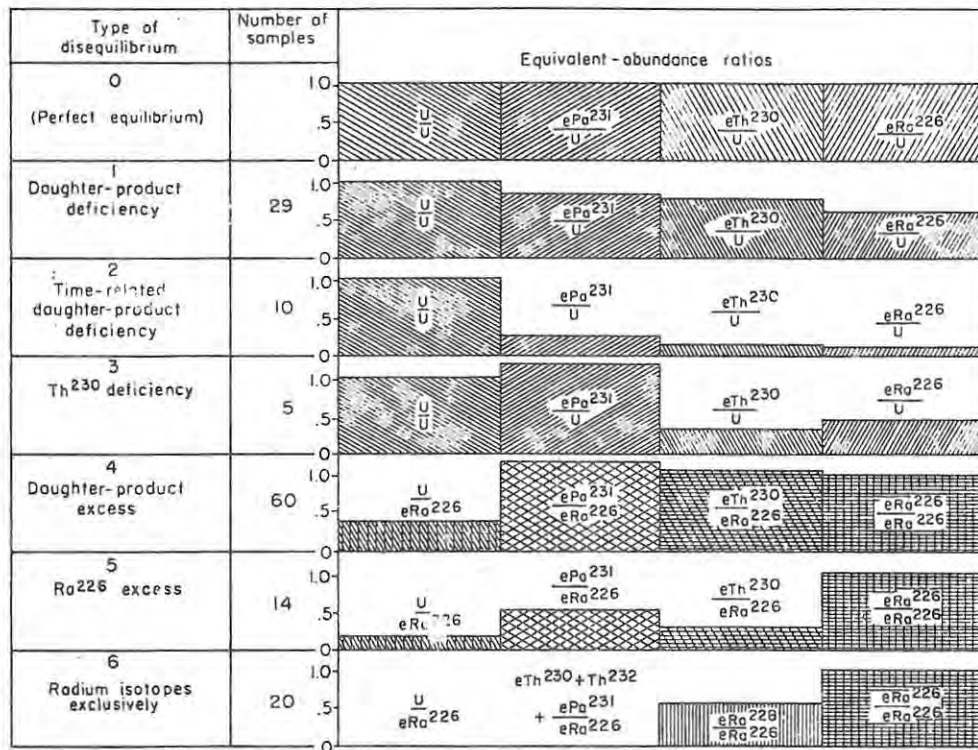


Fig. 58. The first four rows of equivalent - abundance ratios show the comparison of equivalent daughter - product content to uranium content where the $U : U$ ratio is automatically 1. The first three types of disequilibrium (rows 1 - 3) have values of U greater than ^{226}eRa . The last three types have values of ^{226}eRa in excess of U .

(after Rosholt 1959)

Types one and four appear to be the most common forms of disequilibrium. There are two explanations for the first case of disequilibrium. Uranium may have migrated to its present location at a time less than that required by its daughter products to reach approximate equilibrium (i.e. < 300,000 years ago). The alternative is that there has been preferentially greater

leaching of daughter products than of uranium. Type 4 disequilibrium which is found in samples taken from oxidized environments, is the result of the leaching of uranium. The alternative is that daughter products were added to the rock but this is unlikely.

These ratios are therefore be a means of determining the history of the deposit and the potential for the uranium to have remained in situ or dissolved from one part of the ore body when oxidizing ground water has passed through it, become reduced and been precipitated elsewhere.

Secondary porosity can therefore give an indication of the ease with which the oxidizing solutions could have moved through the rock and whether disequilibrium is likely to have occurred.

7.2 FACTORS CONTROLLING TONNAGE

Shape, continuity and size are the major parameters of tonnage. These parameters are controlled by the factors responsible for the generation of sand bodies but are also dependent on features such as a sufficient source of uranium and associated elements, a supply of carbonaceous material to trap the uranium, the correct ground water geochemical conditions for the transport of the uranium and adsorptive or reactive compounds in the aquifer which might capture the uranium.

Tectonism

Tectonism plays an important role in the distribution of sand bodies and therefore in the distribution of uranium deposits. In some cases the relationship is indirect as in the case of Colorado Plateau and Wyoming Tertiary deposits and the deposits of the Texas Gulf Coast, but the stack-type deposits of the Grant Mineral belt have a more direct association with structure.

In the case of the Wyoming Tertiary uranium deposits the effect of tectonics and the resulting sedimentation has the following control on the distribution of uranium mineralization. The four major uranium districts are in fluvial sandstones derived from the Precambrian granitic rock of the Sweetwater Arch. Each district is in a different basin with a different

relation to the source area. Each basin possessed special structural, tectonic and topographic differences which affected the sedimentary pattern and hence the localization of mineralization. Figure 59 shows the relation of arches and basins.

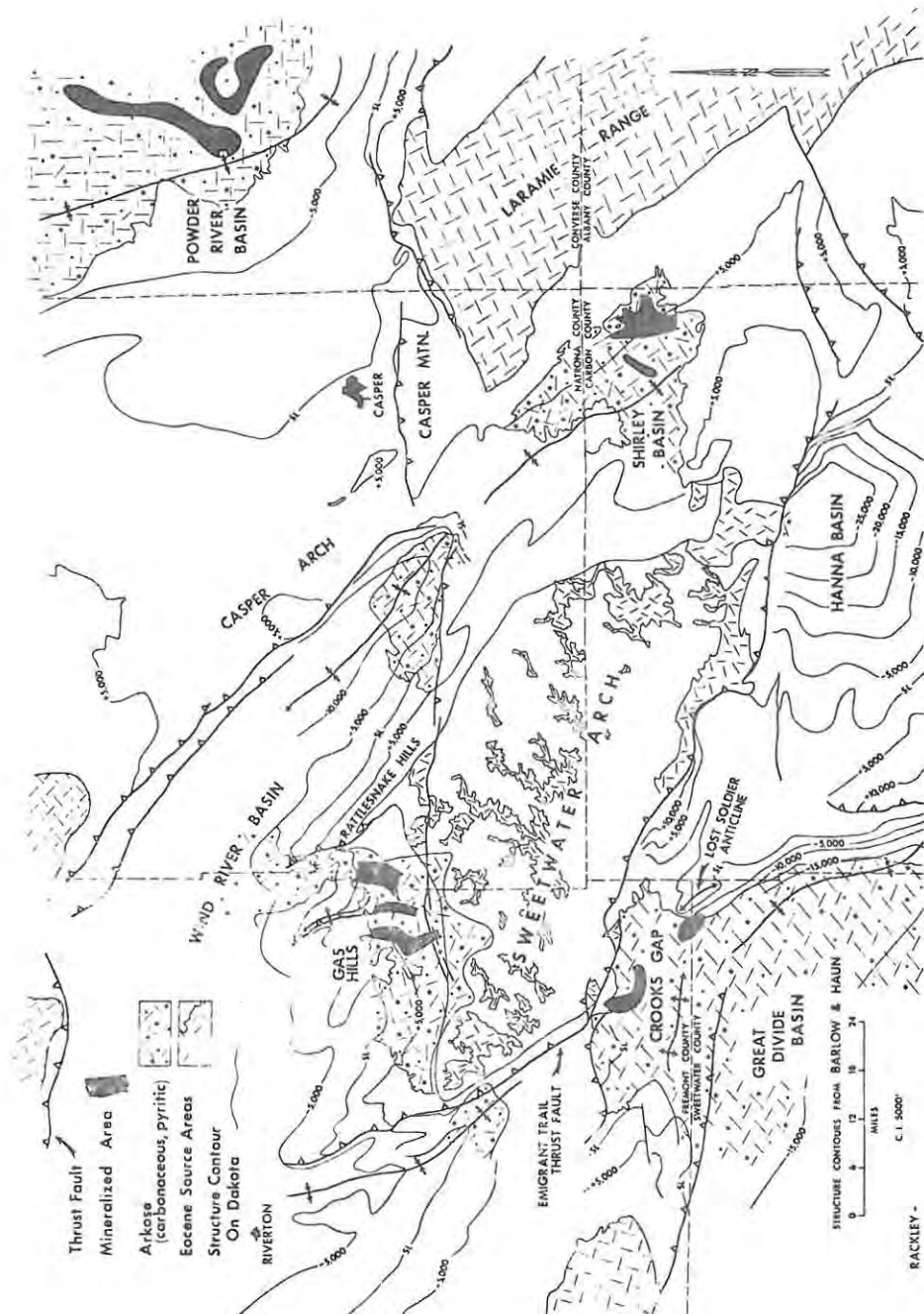


Fig. 59. Index and structure map of central Wyoming uranium province showing relation of Sweetwater arch, major source of sediment, and adjacent basins; distribution of favourable arkosic, carbonaceous facies; and mineralized areas. (after Rackley 1972)

Renewed uplift in Eocene times caused the production of sediment which was transported southward into the Great Divide basin and deposited as a set of alluvial fans. One of the major fans is near the Crooks Gap mining area and another is northwest of the Lost Soldier anticline. Here the sandstone changes into siltstone over a very short distance which suggests that the anticline was rising contemporaneously with deposition. The mineralization occurs in the sandstones of this interval west of the anticline.

Sedimentation in the Gas Hills area of the Wind River basin was on an alluvial fan in which ridges of older rock disrupted the normal development of the fan. The Wind River basin is located north and west of the Sweetwater arch and for much of the length of the arch the northern and southern flanks of the basin are identical. While uplift of the Sweetwater arch and sedimentation of the Wind River basin occurred, the Gas Hills area remained structurally and topographically above the level of these activities. Near the end of this period silts and muds were deposited in the Gas Hills area. During the Eocene period of uplift, these siltstones and mudstones were partially removed and followed by rapid deposition of the coarse arkose which hosts the Gas Hills uranium deposits. The arkose sequence is predominantly the alluvial fan from one major stream but ridges in the form of anticlines of resistant strata protruded through the fan and modified the movement of the streams and their pattern of deposition.

In the case of the Shirley basin, ridges also has a major influence on sedimentation and localization of uranium. The alluvial fan which was building out in response to Eocene tectonism did not therefore extend entirely across the basin but merged with channel and floodplain deposits on the east.

In the Powder River basin the initial influx of sediment onto the floodplain in response to the received uplift of the Sweetwater arch formed a wedge of sandstone in the western part of the basin. The subsequent meander belt of the stream was located along the structural axis of the basin possibly because of a slightly greater subsidence of that area. This produced a sequence of broad channel-deposited sandstones that host the uranium deposits in the southern part of the basin.

Braided streams predominated on the large alluvial fans where they shifted the sites about on the fan, adding sediment in radial bands. This interpretation has been obtained from studies of the predominantly coarser materials in simple lens-shaped channel fills. Ridges of older rock again disrupted the normal development of the alluvial fan causing the streams to deposit sediment and form local meanders. The deposition where meandering streams occurred was more complex than that of the braided streams. Flood-basin silt and clay are common in the eastern Shirley basin, the northern Shirley basin and in the Powder River basin.

The initial influx of sediments onto the floodplain from renewed uplift of the Sweetwater arch formed a wedge of sandstone in the western part of the basin. This resulted in a meander belt developing along the structural axis of the basin, thus forming a sequence of channel sandstones which host the uranium deposits. The major sandstone units were deposited as point-bar sands in cross-bedded sets. Clay-filled channels in sand as well as sand-filled channels in clay are common in both the Shirley basin and the Powder River basin. Flood basin deposits are found in the eastern Shirley basin, predominating in the northern Shirley basin and in the Powder River basin.

In the case of the Central Colorado Plateau uranium deposits Shoemaker (1956) suggests that although the majority of the deposits show no apparent relation to faults and joints, the regional structures in existence at the end of the Cretaceous may have influenced in a broad way the distribution of uranium deposits. This is suggested by the coincidence of the principal region of productive deposits in the Morrison Formation being within the region of salt anticlines.

Kelley (1956) contends that tectonic events as far back as the Permian may have had a bearing on the distribution of ore on the Colorado Plateau. The palaeohydrology would have been affected by past climates, ancient topography and therefore palaeotectonic events. Repeated changes in the direction of ground water flow could have resulted from orogenic movements and the disturbance of old structures by the intrusion of magma possibly in the form of dykes.

In his work on the transmissivity of uranium host rocks Jobin (1962) believed that the major tectonic features of the Colorado Plateau represented zones which were the loci of greatest vertical transmissivity. This will be shown to be an important factor in localizing uranium deposits. (See 6.4.2)

In the case of stack-type ore bodies in the Ambrosia Lake area, structure is one of the major ore controls. Ore layers commonly change thickness across joints or terminate against them (Figure 60).

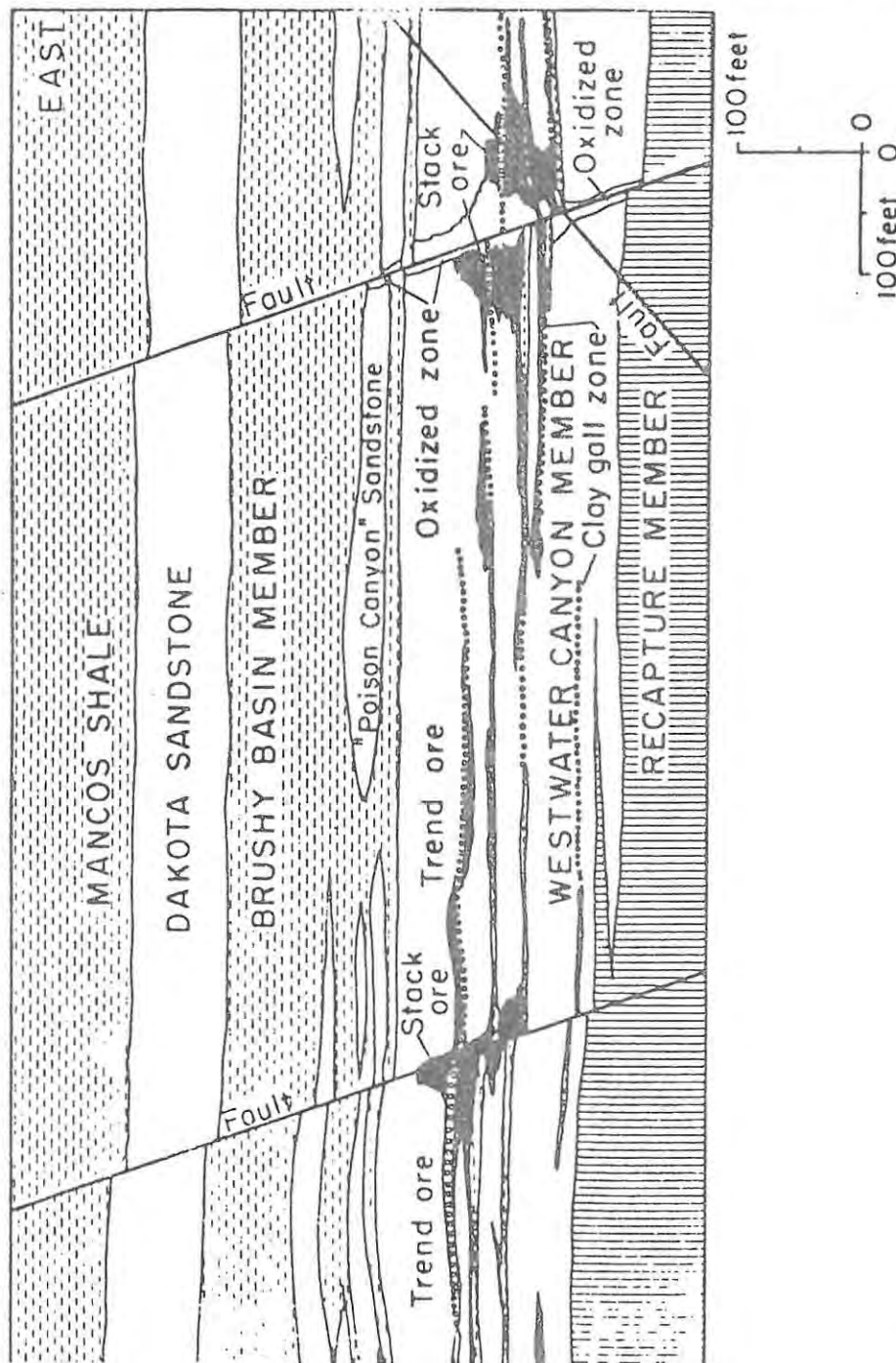


Fig. 60. Idealized long section through trend and stack ore showing the development of trend in porous fault zones and of stack ore in permeable carbonaceous sandstones away from the faults. (Ambrosia Lake, New Mexico). The uranium mineralisation commonly occurs marginal to central oxidized zones in the faults.

Two types of unoxidized ore have been classified in the Ambrosia Lake area (Granger et al., 1961); prefault and postfault in age. Prefault ore is displaced by Tertiary faults, is generally less than 5 metres thick and occurs in layered deposits which are primarily stratigraphically controlled. Most prefault ore appears to be in pods elongated in an east-southeasterly direction. Postfault ore is later than the Tertiary faulting and is structurally as well as stratigraphically controlled. These "stacked" deposits are often considerably thicker than 5 metres.

Clark and Havenstrite (1975) recognize 2 types of unoxidized post-fault ore in the Ambrosia Lake area. One type is associated with abundant carbonaceous material while the other contains very little carbonaceous matter but contains a relatively high proportion of vanadium. In the first case the uranium and the carbonaceous material apparently migrated together whereas in the second type the uranium migrated separately. The carbon-rich postfault ore is generally redistributed along northeast-striking fracture zones while the carbon-deficient type is controlled by north-striking fracture zones.

In the case of the Cliffside mine in the Ambrosia Lake area, the prefault ore pods are as high grade as the peneconcordant bodies which suggests that both types of deposits were enriched. In the stratigraphically controlled ore, the enriching solutions probably followed the same channels as the original solutions and as a result there was not a significant change to the shape of the ore body.

In the Marquez mine in the Ambrosia Lake area, the initial discovery was made by drilling along the trend of the Poison Canyon sandstone trend. The ore occurs in discontinuous lenses and pods and so it was thought that the ore was controlled by structures that could be projected from underground workings into areas where there was no information. In addition to disclosing unknown ore pods the structures could be used to reduce dilution during mining. Much of the ore occurs immediately below or within the Marquez disconformity.

The only uranium deposits that appear to be related to folding are those found in the Todilto Limestone, located between Ambrosia Lake and Grants. Few ore bodies in this area are related to faults. (McLaughlin 1975)

The broad regional faults of the area do not seem directly related to specific ore deposits. Gabelman (1956) noted that major clusters of deposits are located within broad, shallow synclines and interpreted the relationship as "indicating the accumulation of uraniferous solutions in structural sumps under the influence of gravity".(p. 396).

In the Catahoula Formation of the Texas Gulf Coastal Plain two fluvial systems are present which show distinctive fluvial channel-fill, flood plain and crevasse splay and lacustrine facies which tend to persist vertically through the sequence (Galloway 1978).

Growth faulting directly affected sediment distribution within the Catahoula Formation. Comparisons of sand isolith maps and fault distribution patterns show that areas of well-developed growth zones are characterized by complex sand distribution patterns. These assume an "almost reticulate" pattern of dip and strike oriented segments. In contrast, sand patterns are dominantly dip oriented in areas where adjacent growth faults are absent. It is thought that such a disruption of the trend and vertical distribution of channel-fill sand facies will affect the postdepositional ground water flow.

Galloway (1978) recognizes three ground water domains; an upper zone of circulating meteoric waters, a lower zone of upward flow of expelled pore waters, with a central zone of stagnation at the confluence of the two. The role of faults in changing the ground water flow pattern becomes increasingly marked as the recharge through the less permeable zones decreases. Faults serve as connecting zones between aquifers and can release excess overpressure within isolated aquifers by flow along the faults.

Growth faults are thought to have played a more direct role in the ore formation of the Texas deposits since the faults are regarded as the channelways upwhich reducing H_2S permeated and reacted with the uranium-bearing solutions. Faulting also produced facies changes, modified the trends of the sands and modified the flow directions of the uranium-bearing fluid, which in turn affected the geometry of the mineralization.

As mentioned earlier permeability is an index of possible flow

governed by the hydraulic gradient and the cross-sectional area through which the flow occurs. The orientation of permeable elements will also affect the ground water flux and hence the location of uranium deposits. Highly permeable conduits that trend down the regional hydrodynamic gradient will effectively transmit more water into the subsurface than will permeable elements oriented at a high angle to the regional gradient.

The flow through a permeable system may be limited by several factors. The rate of recharge into the aquifer is determined by a number of variables including slope of the shallow water table relative to the regional hydrodynamic gradient, permeability of the overlying unsaturated material, and climate. If individual permeable members are isolated by members of a very low permeability this may be a limiting factor unless structural breaks allow vertical flow to occur.

The gross aquifer permeability is greatest at the time of deposition and decreases progressively thereafter, while recharge between less permeable zones is most effective during the early postdepositional phase. The orientation of the potential aquifers is also important with the most effective result parallel to the regional hydrodynamic gradient. The volume of water that moves through a particular zone depends on the hydraulic conductivity, the hydrodynamic gradient or excess head and the time involved. The latter two factors have a one to one relationship so that the aquifer with a high excess head needs less time to transmit the same quantity of water. The flow volume is inversely proportional to the length of the flow path.

Mast and Potter (1963) in permeability experiments conducted on core deduced that minor textural inhomogeneities in the plane of the bedding become the dominant factor affecting the permeability variations in the plane of the bedding. Fabrics perpendicular to bedding are much better defined because there are stonger constraints on grain orientation perpendicular to bedding than in a plane parallel to it. If tectonic features such as faults have been subjected to secondary cementation, they could in fact also impede the flow of solutions thereby changing the permeability of that aquifer.

Another parameter of tonnage is the specific gravity of the rock that is mined. Depending on the composition of the host and its resultant

porosity the specific gravity will vary accordingly. If sufficient care has not been taken in establishing whether there is a variation of specific gravities throughout an ore body or what the specific gravities of the host rock are at all, the results could lead to incorrect ore reserves being calculated.

Undervaluation of the tonnage of the deposit is however not as serious as overvaluation which would result in unfulfilled contracts and a shortening of the life of the mine.

In the case of semi-consolidated rocks hosting roll-front deposits the variation in specific gravity between the oxidized and reduced portions of the front could be quite significant. It would therefore be advantageous to be able to predict the trends of the areas of different specific gravities using the minimum amount of drilling possible.

CONCLUSION

8. PREDICTION OF SAND BODIES AND CONTAINED MINERALIZATION

A study of the geological factors affecting the grade and tonnage of a sandstone uranium deposit reveals that there are certain features of the host and mineralization which could assist in producing realistic ore reserve estimates.

Various geophysical methods have been developed to aid in the location of mineralization both in a local or regional setting, but often the results are inconclusive or ambiguous and the programme needs to be confirmed by drilling. Besides gamma logging, geophysics appears to have a limited use in ore reserve estimation. Because narrow elongate sandstone bodies in a shale section usually produce a compactional distortion in the adjacent shales, small density contrasts between the shale and sandstone may be sufficient for gravity methods to identify, at shallow depths, the position of the sandstone.

Geostatistical methods have been in vogue in recent years to aid in ore reserve estimations. Hand contouring of grade thickness values produces erratic trends on such maps and a Kriging method has been derived to produce smoother contours while still highlighting the trends. However, if no geological interpretation is included both in the data input stage and the interpretive stage, the exercise is meaningless.

Sandstones possess a feature which is termed stationarity by statisticians and which means that variograms inferred from the data are representative of the orebody as a whole. However, for these results to have any value the geological input is essential. This means that overall it is the geological criteria that will be relied on to predict the shape of the sand body and the distribution of the mineralization within it.

There are only a limited number of techniques for locating new sandstone bodies but these may be applied both on a regional and a local scale. They are fairly obvious techniques and entail very detailed surface mapping of the outcrop to ascertain features such as grain size, vertical sequences indicating facies types, secondary porosity, and directional structures. These should then be supplemented with subsurface data in the form of drill core so that permeability tests can be carried out on the

relevant sections. Both structure and palaeotopography may be used since these have an effect on fluvial distribution. Facies models seem to have the most potential for locating sand bodies. However, as Jackson (1977) points out, only portions of the vertical sequences survive erosion which makes facies prediction very tentative. As more descriptions of various facies models are published, computer simulation of sandstone distribution within a basin would seem to be the next step in the development of the facies-model concept for sands.

The work by Leopold & Wolman (1957) and Schumm (1960) to quantify channel morphology is an aid both to estimating the size of the river and the sand bodies within the system as well as predicting the sites for further sand bodies. Knowledge of the thickness of the sequences and their silt : sand ratios can be used to estimate channel depths and hence the width of the river. In some alluvial sand bodies the curvature of the meander can be determined by careful mapping along the edge of the body and the stream width estimated. If one could somehow estimate the mean velocity from the grain size and stratification one could attempt to attempt to estimate the palaeodischarge.

The prediction of the elongation and lateral extent of a known sand body is less difficult than locating an unknown sand body. One approach is to study the orientation of other sand bodies within the same basin and use this as a guide. Generally this is a sound strategy because the palaeoslope in many basins was stable for appreciable periods of time and as a result, the orientation of sand bodies would change very little in successive cycles.

Cross-bed orientation is one of the prime tools for predicting downstream trends. It may also be possible to predict the maximum and minimum directions of its anisotropy.

Lowell (1955) found that when plotting the dip direction of cross-strata and plotting histograms and vector resultants, the palaeostream flow directions could be determined. This is the direction of maximum porosity and hence the direction along which uranium ore bodies and the alteration haloes that surround them are most likely to be found. The

plotting of the sedimentation structural features defines intersections of ancient systems and these localities appear to be favourable loci for the deposition of uranium ore.

There is no evidence to suggest that the ore solutions travelled through a single ancient stream scour in a mineralized region; rather, they percolated through a network of overlapping channels - the optimum paths of maximum permeability. Therefore, groups of cross-stratified directions each of which indicates a local direction of paleostream flow, have greater significance than individual directions in projection of palaeostream flow - the path of greatest permeability and hence uranium ore trends. A method of grouping cross-strata data dip directions is also useful in determining on the regional scale patterns of ancient stream flow. There are cases where reversed trough cross-bedding readings occur and they are explained as alternating directions of flow through channels at the confluence of streams at times of flood (Lowell 1955)(Figure 61).

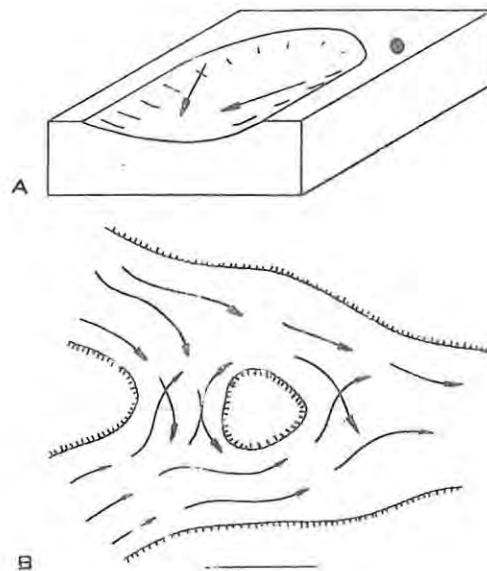


Fig. 61A Sketch showing divergent directions of dip on opposite sides of a trough cross section.

Fig. 61B Sketch showing confluence of streams and areas where current directions reverse during floods.

(after Lowell 1955)

In mapping several mineralized areas in detail, a similarity in the pattern of diverging current directions was noted around the orebodies. This

repeated pattern appears to occur always at the junction of two consistent currents (Figure 62). There appears to have been an increase in turbulence

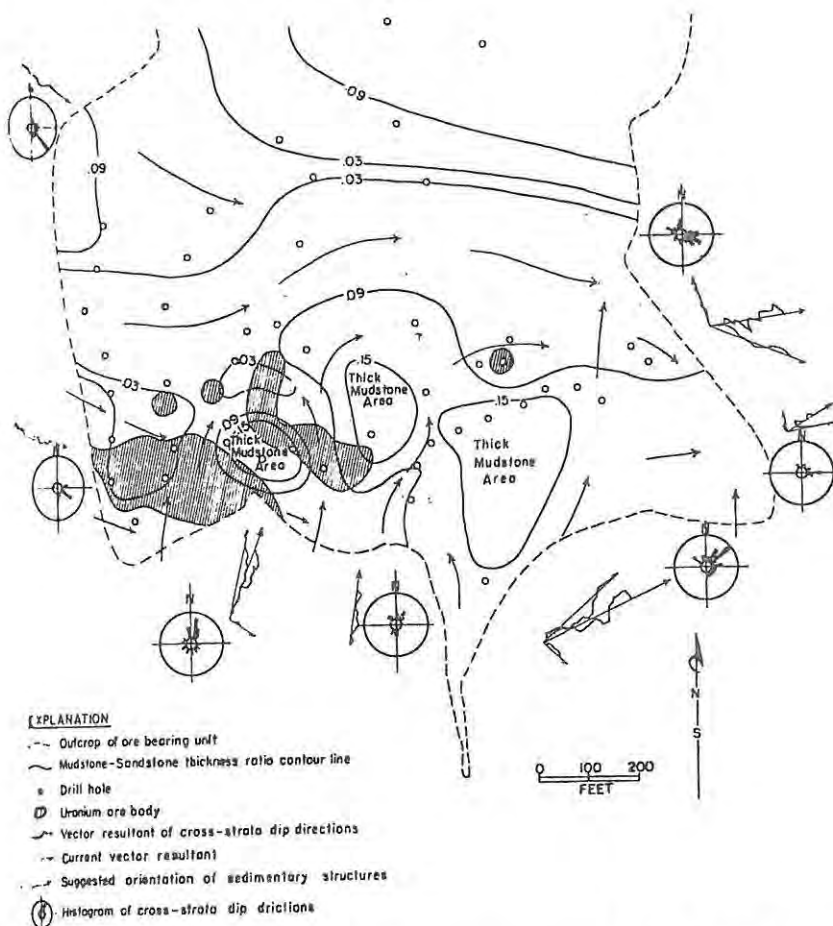


Fig. 62 Orientation of primary sedimentary structures, Three Point Mesa, Apache County, Arizona.

(after Lowell 1955)

at this site resulting in a different type of material being deposited. The type of trough cross-bed in this area is therefore modified and there is a localized increase in the percentage of sandstone over mudstone as well as the development of diagonal mud bars. (Figure 62)

Shifting channels at these intersections appear to have favoured rapid burial and preservation of logs and plant debris. These factors may also have indirectly favoured mineralization through creation of favourable permeability as well as by the accumulation of organic material which later became the precipitating agent.

Stokes (1952) describes a concentration of mineralization in the Thompson district in broad meander curves where intersections of crescentic channels were common. On the basis of earlier fieldwork he advanced the idea of sedimentary uranium controls.

A decrease in velocity of movement of the uranium-bearing solutions is assumed to have favoured uranium precipitation. The interstitial velocity of mineralizing solutions would have decreased as the permeability of the rock through which they passed, increased. The sorting of the clastics tends to improve and hence the permeability of rock tends to be greater at the locality where the depositing currents changed from lower to higher velocities (Illies 1949). Different velocities of the ancient currents are reflected by different types of cross-bedding which can be identified in the field. By identifying the types of stratification, the relative permeability of the rocks can be compared and hence the potential for uranium-bearing origins can be determined. This is based on the assumption that all other factors affecting deposition remain constant. This method has been shown to save unnecessary drilling which might have been expended in "hit-or-miss" drilling behind a mineralized outcrop.

The limiting factor of this technique is that the sedimentary structural features mapped are divergent in direction, both in any specific horizon and between horizons. As a result the projection of trough cross-bed data is only reliable for 50 - 100 metres in extent.

Stratifications of modern sands

Harms, MacKenzie & McCubbin (1963) in their studies of two modern point-bars showed the following characteristics.

The types of stratification observed included trough-shaped and tabular sets of cross-strata and horizontal lamination (Figure 63 on page 107). The most abundant type is trough-shaped cross-stratification which are present on two scales. The large sets have average thicknesses : width : length dimensions of 3 : 15.5 m and the small sets ("rib and furrow") have dimensions 2 : 10 : 20 cm. The surface expressions of the small sets appear to be cusate ripples. The axes of the large and small trough-shaped sets have a strong preferred orientation parallel to be local stream-flow

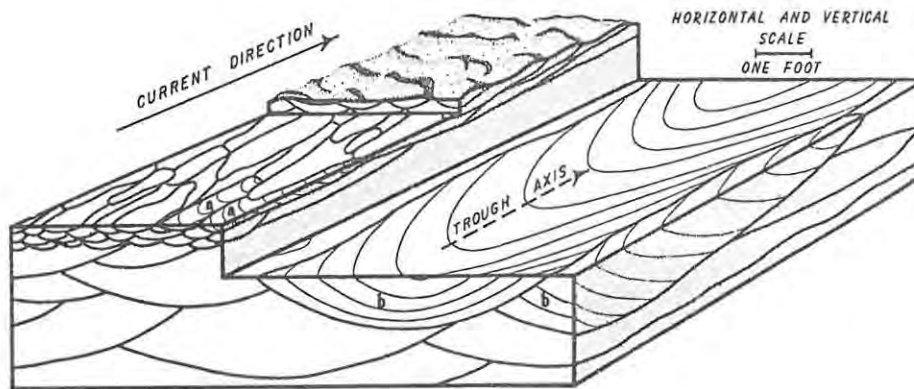


Fig. 63 Block diagram showing large and small trough-shaped sets of cross-strata. Only the two small sets marked a and the two large sets marked b show traces of stratification plans within sets. Cuspate ripples are shown on uppermost surface of block.

(after Harms, McKenzie & McCubbin 1963)

direction.

The resultant vectors obtained by summing observations on individual cross-stratification plans within large sets also point downstream, but have much weaker magnitudes because of the variability associated with the diverse orientations of cross-strata within any individual set.

Spoon-shaped depressions on the surface of the bar, oriented with the tips of the "spoons" pointing downstream may represent scours incompletely filled with large trough-shaped set of cross laminae. At the

upstream end of one of these scours, cross-laminae in the upper part of the sand that partially fills the scours are "overturned" downstream. The deformation before deposition of any overlying strata and probably during subsidence of river level.

Work by Roach & Thompson (1959) on the Peanut mine in the Salt Wash member of the Morrison formation of the Colorado Plateau has shown that the sedimentary structures, particularly the trough cross-laminations have influenced the localization of the ore and the pattern of oxidation of individual ore bodies.

The shape of the ore bodies conforms to the outlines of trough cross-beds which appear to be best developed on the flanks of the channels. The most common form is produced by the intersection of three cross-beds resulting in a "festoon solid". (Figure 64)

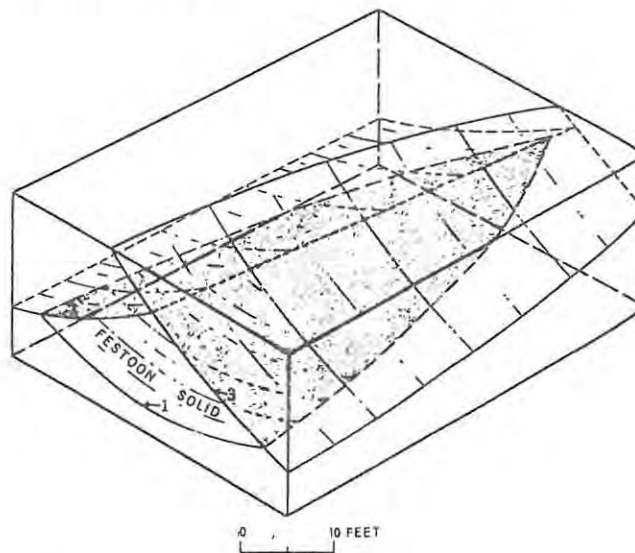


Fig. 64. Diagrammatic sketch of a festoon solid, showing festoon surfaces under which ore occurs. Numbers indicate order of formation of surfaces. Shaded areas represent roof of festoon solid under which ore occurs.

(after Roach & Thompson 1959)

The ore bodies are contained within these festoon solids and are found only in the part of the festoon solid having structural closure and large ore bodies nearly fill a festoon solid but most ore bodies are smaller and occur in the upper portion of the structure. Some "festoon solids" are

skewed rather than symmetrical. Some of the most common forms are shown in Figure 65.

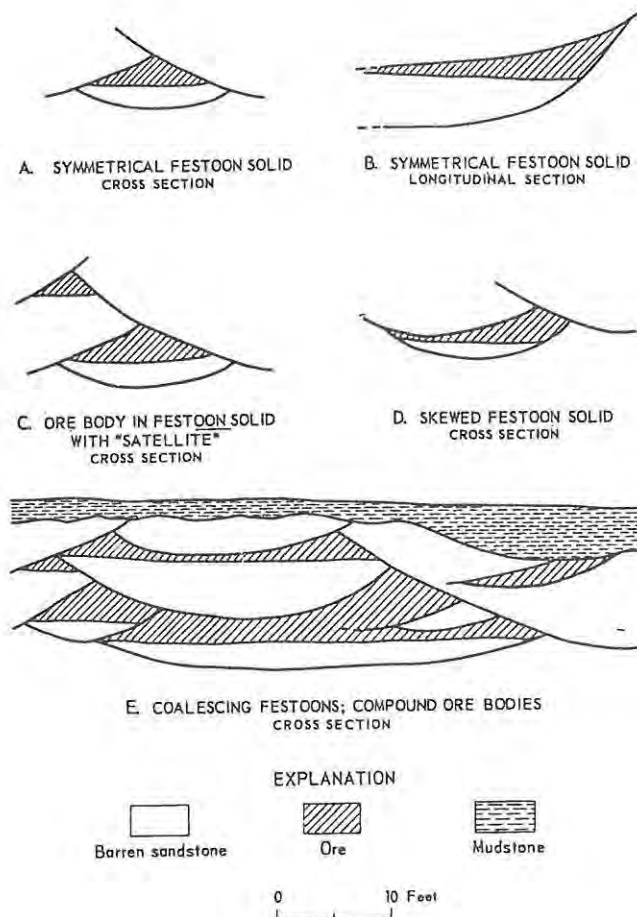


Fig. 65. Various types of festoon solids and their relation to ore bodies.

(after Roach & Thompson 1959)

It can be seen from the generalized cross-section of a cluster of closely spaced, coalescing ore bodies that the prediction of the location and extent of ore bodies is impossible without the recognition of the relation of ore bodies to the trough cross-bed surfaces. In this case, mining methods were adapted to the controlling influences of these cross-laminations and a number of ore bodies were located which otherwise might not have been discovered.

Permeability measurements were carried out from various positions within a festoon solid and the findings supported by the occurrence of

perched water tables indicate that the trough-bedding plane surfaces are relatively impermeable. A thin clay seam is commonly present along this surface which increases the impermeability normal to the bedding more than a hundred times in the direction parallel to bedding.

Most of the ore bodies of the Peanut mine are unoxidized but even though the regional water table is several hundred feet below there are cases where oxidation does occur. Figure 66.

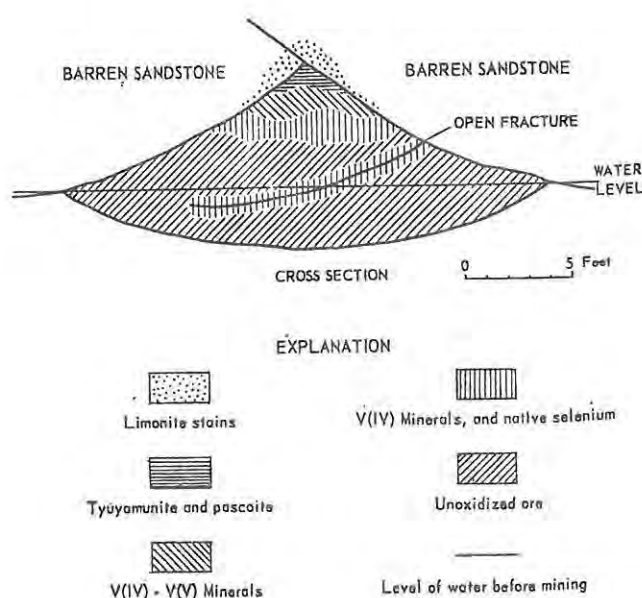


Fig. 66. Pattern of oxidation of a typical ore body in the Peanut mine, Montrose County, Colorado.

The controlling influence of the trough cross-beds on oxidation appears to be due to the relatively impermeable basal trough cross-bedding surfaces. After the regional water table was lowered, perched water tables were formed by the impermeable surfaces and the ore bodies contained in standing water thus restricting the oxidation to the upper portion of the ore bodies.

In the Homestake - Sapin deposits of the Ambrosia Lake area where redeposited stack deposits occur, the structural control of redeposition has provided a means of locating mineralization. This is done by the projection of the strike of the fractures from an area of known occurrence

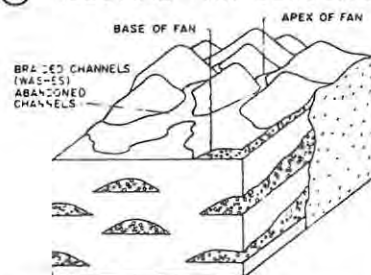
to a previously unexplored area. Exploration downdip of roll deposits and diagonal to the strike of the fractures has located large masses of ore.

A final feature which should be taken into account in delineating a uranium body is the effect of postdepositional deformation. Qidwai & Jensen (1979) suggests the following information should be ascertained before drilling.

A tilt correction should be applied to the palaeocurrent data where the dip of the beds exceeds 10° . The palaeocurrent direction should be inferred and a relationship established between the palaeocurrent direction and the postdeformational dip of the sand body. Based on the depositional environment the expected position of the fine clastics in relation to the sand body should be predicted. The borehole should then be sited to take into account the direction of movement of the ground water, the elongation direction of the sand body, the postdeformational dip, and palaeocurrent direction of sand bodies and associated lithologies. Figure 67 on page 112 summarizes the potential continental depositional environments while Figure 68 on page 113 shows the approach to locating mineralization within a sand body.

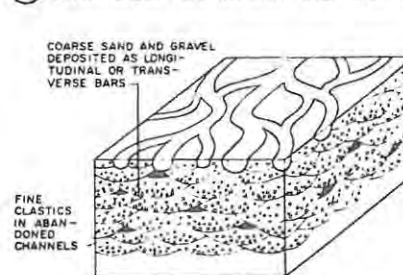
In conclusion the examples quoted in this section illustrate the importance of a good understanding of the mechanisms involved in the formation of a uranium deposit as an aid to the location of new ore bodies. The same concepts can be used in the calculation of the grade and tonnage of a uranium deposit. Drill hole information will supply data which if used in combination with the knowledge of the various interrelated factors affecting the formation of the deposit, will enable one to make a realistic determination of the ore distribution and its continuity.

(A) ALLUVIAL FAN DEPOSITS



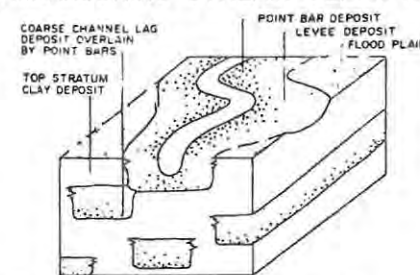
RADIAL PALEOCURRENT PATTERN FROM APEX OF THE FAN TOWARDS BASE OF THE FAN. PERMEABILITY WILL BE PARALLEL TO THE RADIAL PALEOCURRENT PATTERN. URANIUM WILL PRECIPITATE NEAR THE BASE OF THE FAN IN INDIVIDUAL CHANNELS AS A CONSEQUENCE OF THE DECREASE IN GRAIN SIZE.

(B) BRAIDED STREAM DEPOSITS



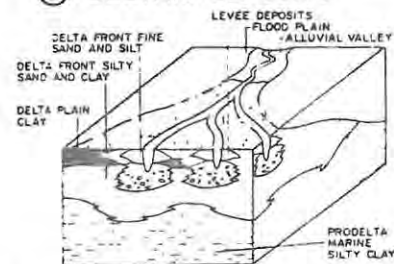
UNIMODAL PALEOCURRENT PATTERN WITH LOW SCATTER. ELONGATION OF SAND BODIES AND THEIR MAXIMUM PERMEABILITY PARALLEL TO THE PALEOCURRENT DIRECTION. URANIUM WILL PRECIPITATE IN INDIVIDUAL CHANNELS IN THE DOWN DIP AND DOWNCURRENT DIRECTION. FINE CLASTICS WILL OCCUR LATERALLY AND BELOW THE CHANNEL SAND AT THE PLACE OF PRECIPITATION.

(C) MEANDERING STREAM DEPOSITS



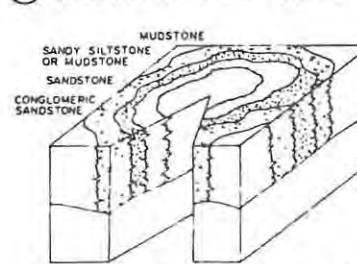
UNIMODAL PALEOCURRENT PATTERN WITH LARGE SCATTER. ELONGATION OF SAND BODIES AND THEIR MAXIMUM PERMEABILITY PARALLEL TO THE PALEOCURRENT DIRECTION. URANIUM WILL MIGRATE AND PRECIPITATE IN INDIVIDUAL POINT BAR SANDS IN THE DOWN DIP AND DOWNCURRENT DIRECTION. POINT BAR SANDS ARE ALWAYS ENVELOPED BY FINE CLASTICS.

(D) DELTAIC DEPOSITS



OVERALL FAN SHAPED PALEOCURRENT PATTERN. HOWEVER, INDIVIDUAL DELTA FRONT SAND AND SILT EXHIBIT UNIMODAL PALEOCURRENT PATTERN. ELONGATION AND MAXIMUM PERMEABILITY OF THE DELTA FRONT SAND BODIES PARALLEL TO THE PALEOCURRENT DIRECTION. MIGRATION AND PRECIPITATION OF URANIUM WILL BE IN THE DOWN DIP AND DOWN CURRENT DIRECTION IN INDIVIDUAL SAND BODIES.

(E) LACUSTRINE DEPOSITS



CENTRIPETAL PALEOCURRENT PATTERN. IRREGULAR SHAPE OF SAND BODIES. NEVERTHELESS, MOVEMENT OF GROUND WATER WILL BE FROM COARSER CONGLOMERATIC SANDSTONE TOWARDS MUDSTONE.

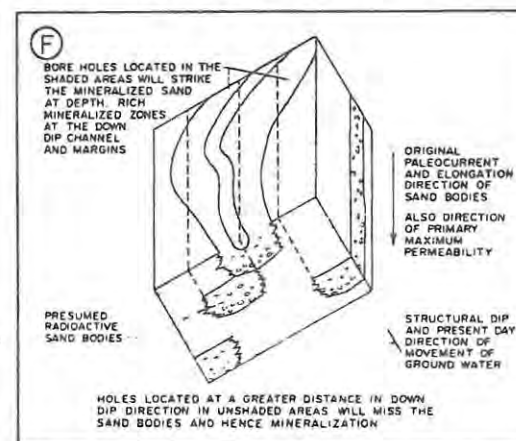


Fig. 67. Shows major physiographic components, lithologies, shapes of sand bodies, and paleocurrent pattern for continental depositional environments important for uranium (A-E tectonically undisturbed setting). F shows tectonically disturbed setting

(after Qidwai & Jensen 1979)

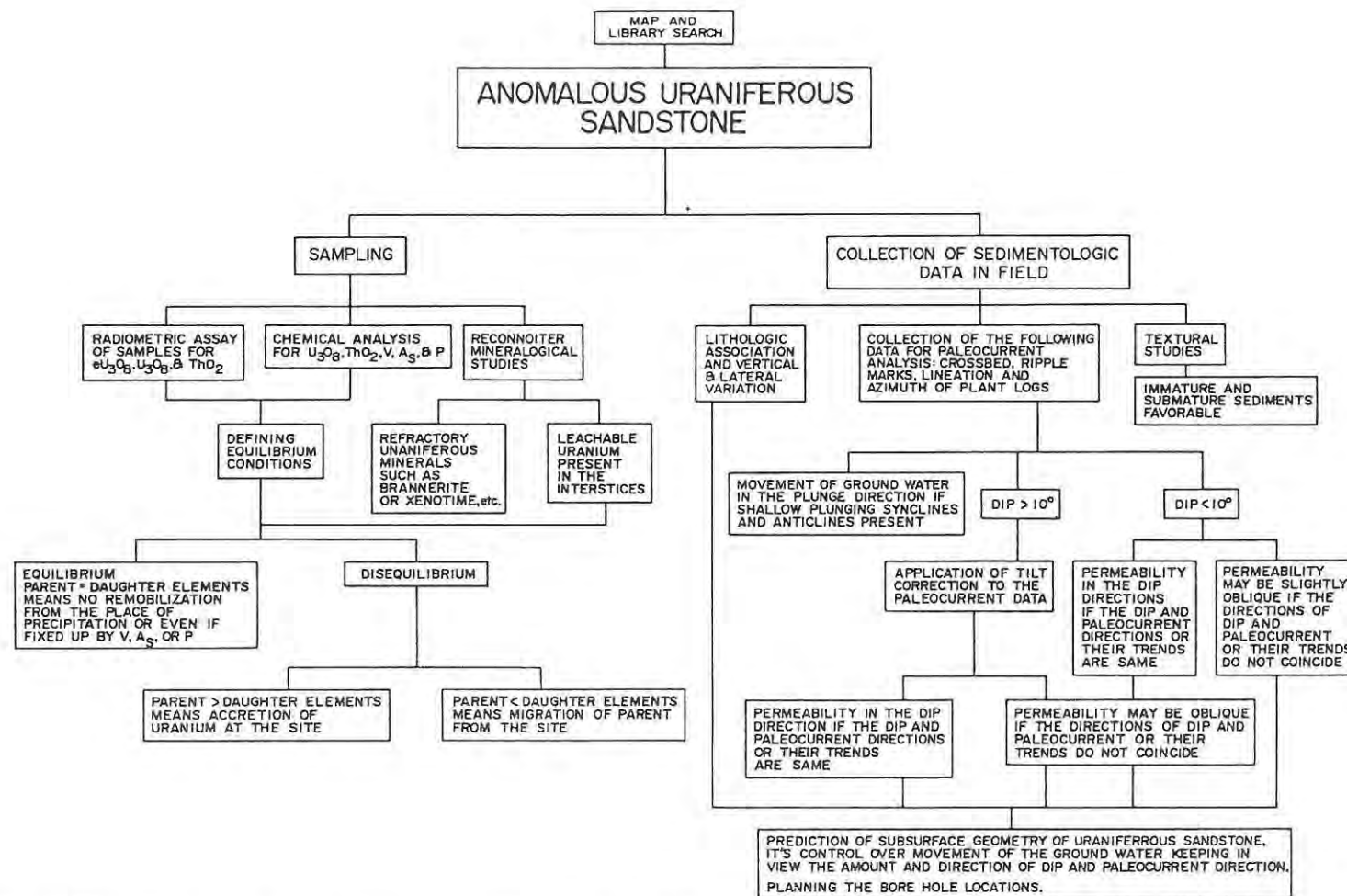


Fig. 68. Flow sheet illustrating systematic sedimentological, mineralogical, and geochemical approach for rapid appraisal of uraniferous sand bodies

(after Qidwai & Jensen 1979)

9.

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10.

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