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22/RMO-44/C.2

UNITED STATES ATOMIC ENERGY COMMISSION

RMO-44

EXPERIMENTAL SIMULATION OF PLATEAU
TYPE URANIUM DEPOSITS

By
George W. Bain

January 1953
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Amherst College
Amherst, Massachusetts

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Subject Category, GEOLOGY AND MINERALOGY.

Work performed under Contract No. AT-30-1-1172.

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Plate 1. The laboratory arrangement for sedimentation studies.

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ABSTRACT

Experimental simulation of Colorado Plateau type uranium deposits is divided into seven parts. The first three summarize the essential features of geological occurrence for the ores. Details are omitted since they are available in other reports to which reference is made. The last four parts outline the results of experimental investigation arranged according to each geological group of features influencing mode of occurrence. Both field distribution and laboratory approaches to the problem suggest that the origin for the uranium and for the vanadium are disconnected problems.

The plateau ores occur in or adjacent to fluvial sediments and generally avoid flood plain and aeolian accumulations. For this reason, a large part of the rocks of the plateau section are not potential host to economic deposits. Even the Shinarump conglomerate fluvial deposits have the principal producers distributed in a pattern which resembles that of the stream placers in seasonally dry regions. The principal deposits occur well down towards the bottom of synclines and are there distributed frequently along a near-contour line; this ore axis may transgress several strata although it stays usually on contour in a stratum. Of the several explanations suggested, only the one attributing the ore to slight redistribution by artesian groundwater fails to leave anomalous situations. The structural and physiographic history of the region indicates earliest age for artesian circulation as late Cretaceous and the youngest age as the Canyon Cutting cycle of the late Pliocene. The ores came into their present site during this time interval.

The red jasperoid pebbles of the Shinarump conglomerate carry a small amount of the primeval uranium of the Plateau deposits. The direction to the source for these pebbles was indicated by field studies. The modification of detritus during transportation was investigated experimentally to estimate how far they had come. (Part IV). Rate of change in size of grain and sphericity of grain was measured under controlled conditions and a source estimated to be along the westward extension of the Uncompahgre axis almost 30 miles northwest from the Dirty Devil claims on the San Rafael Swell. Other source regions are believed to have supplied the primeval uranium as heavy detrital minerals and as uraninite occluded in the jasperoid pebbles.

The deposition of heavy minerals in intermittent streams was investigated experimentally and the sites determined. (Part V). Principal deposition occurred in-channel just below scour pools on meanders. Heavy mineral deposition occurred during flood stage and the accumulation was covered by various deposits of the ebb stage. Aggregate downstream migration of a placer rarely depletes the upstream deposits significantly but derives its minerals from the original lode or highland source.

The patterns of the deposits indicated a groundwater flow parallel to structural axes at far below the watertable level in existence when the ores were formed. A simulated aquifer showed that this happens and that the principal groundwater discharge occurs along paths parallel to structures at far below the watertable and near the structural axis of synclines. (Part VI). The effect of rate of recharge and plunge of the

structural axis was investigated and the results are presented.

Factors influencing precipitation of uranium from uranyl solutions were investigated and it was found that the principal cause for precipitation was reduction in availability of the "vehicle" anion for the uranyl cation. (Part VII). Uranyl sulphate was the principal solution studied. Calcite and V_2O_5 abstracted SO_4 ion and caused precipitation of uranium. Precipitation in the case of calcite was proportional to the original uranyl ion concentration and to the thickness of calcite penetrated. Vanadium was very effective in removing SO_4 ion and caused precipitation of uranium up to exhaustion of the V_2O_5 . Many materials, hitherto considered important precipitants, were found to have only minor influence unless accompanied by an SO_4 ion "abstractor".

I. INTRODUCTION

Observations on the mode of occurrence for uranium minerals in the Colorado Plateau region suggest that significant aid in understanding the distribution could be derived from experimental investigation into channel and fan alluviation, rounding of grains and disintegration of detritus in transit, behavior of groundwater in folded aquifers, and conditions attending precipitation of uranium from groundwater type solutions. The observations include published descriptions, communications by Atomic Energy Commission personnel, a visit to selected localities in 1946, a season of field work during 1951, and an extensive petrographic study at intervals over a period of about seven years. The observation that a significant part of the uranium distribution pattern followed stream channel patterns, that fluvial formations were the outstanding hosts to deposits, and that the Salt Wash member was a fan redistributed continuously in a northeastward direction, combined to focus attention on formation of stream detritus and selective deposition of its minerals. Histograms for sphericity and size of Shinarump channel conglomerates indicated both high stream turbulence, and such unusual pool conditions for deposition, that study of distance moved to produce a measured sphericity and size reduction seemed essential. The tendency for all deposits to be far down the limb of a syncline and for each deposit of a series along a single stream channel to be deflected in the direction of groundwater spill for the syncline, suggested that some understanding of groundwater paths through folded structures is essential to interpret and segregate the secondary modifications of patterns from the primary distribution. A characteristic localization to occurrence of the ur-

anium and vanadium minerals, particularly in the vicinity of carbonate mineralization, indicated pertinence of some experimental study of chemical conditions attending transportation and deposition control for these elements to uranium occurrence in plateau type deposits. Accordingly experimental simulation of field conditions, with due regard for scale reduction, was undertaken in each of the four fields and considerable success has been attained.

Principal Mode of Occurrence for Uranium in uniform Sandstone.

Uranium deposits of any group in the moderately uniform Salt Wash sandstone are generally aligned in NE-SW trend along channels with many individual producers elongated across this trend on lines parallel to synclinal axes. Rich deposits are associated with dilation cracks in the sandstone only a few feet above a mudstone or shale in a relatively continuous and moderately thick bed. Conversely the anticlines and higher parts of the synclines and also formations of either aeolian or playa origin are singularly poor in uranium minerals. Individualistic fluvial sedimentation patterns, indications from sphericity of detritus, and fineness of fragmentation are attributes of the primary ore host. The groundwater paths and the conditions for movement and precipitation of the secondary uranium compounds are related to redistribution of concentrations within or near the general primary control pattern. These will receive some elaboration in later sections.

Occurrence in nonuniform Shinarump Conglomerate.

Uranium minerals in the nonuniform Shinarump conglomerate are confined to channels or to sandstone immediately adjacent to high grade channel depos-

its. The highgrade ores occur principally in the conglomerate with a persistent but low content adsorbed on the underlying mudstone. The uranium content is low up-dip from the orebodies, and may be essentially absent; also an abrupt decline in content begins below the very rich ore section, and productive occurrences rarely reappear below a low grade unweathered zone. The conglomerate and mudstone have an "in-channel" deltaic type of crossbedding and the mudstone acts as a separator between individual rich bodies. The primary "in-channel" structure, and selectivity for ore occurrence is distinctive and the disappearance of uranium up-dip and diminution of it down-dip are outstanding.

Inference on origin.

The Shinarump conglomerate seems to be principally a series of river channel fillings containing materials worn to fluvial sphericity in sizes down to ordinary sand. The "in-channel" deposition of deltaic mud suggests that the stream had flood and ebb flow and the muds appear to have been laid in disconnected pools, during the ebb stage. Association of the uranium minerals with the channels, in amount as well as in patterns, suggests a common alluvial origin for the uranium along with common detritus, but the rarity of uranium up-dip and the concentrations along strike suggest some groundwater reconcentration.

The Salt Wash fan has been denuded progressively in the west and spread eastward. Pollen grain studies show a Jurassic age for western occurrences and a Cretaceous age for eastern. However this formation, like the Shinarump,

is fluviatile and the intervening aeolian sands and playa mudstones are nonproductive. This in itself indicates that fluviatile conditions had some initial control over importation of the uranium, and the detailed study in the Dirty Devil deposits indicates derivation in detritus from leptothermal type deposits.

Experimental Investigation

The initial experimental operation was set up to investigate "in-channel" alluviation including pool deposition of both heavy, average and low gravity minerals. The experimental detritus was silt having a reasonably wide range in grain size; samarskite, crushed to equivalent fineness, served as a heavy mineral which was traced easily. Rain for erosion was provided by atomizers yielding proportionately minute drops.

Alluviation.

Alluvial fans, formed by deposition of the transported waste, had the heavy samarskite laid initially near their deployment point. Continued alluvial activity saw the upper ends of the fans denuded, the fan rim extended and the heavy minerals spread down the channel courses only. Other fans formed down the drainage system and the heavy minerals were redeposited initially at the place of stream deployment. The heavy minerals stay with the channel deposits and never reach either the playa or sheet-wash accumulation sites.

Shaping of the Detritus.

The field work showed that, at any one time, pools in the Shinarump channels accumulated a principal part of all variety of material in the stream load and yielded a proximate sample for study of both reduction in size and improve-

ment in sphericity. Experimental data on distance detritus must be moved to produce equivalent changes seemed desirable to interpret the observations. Experimentally, inconsequential difference exists between the effect of a moving water mass upon a bed of agitated detritus and the effect of a nearly stationary water mass upon a moving bed of agitated detritus because in either instance the water and the detritus mill together as they move relative to any unyielding substratum. A moving bed was devised by using a wheel 8 feet in diameter capable of holding a foot deep "stream" of water. This was designed to travel at controlled equivalent water speeds from two to fourteen miles per hour. The sphericity, reduction in size, and surviving fragments were examined, sampled and their characteristic features measured quantitatively at 10 mile intervals of travel.

Groundwater Paths

Circulation of artesian groundwater was simulated by building a syncline of plastic sheets to contain a 2 inch thick sand bed. Projected photographs of synclines showed that their curvature conformed most closely to an hyperbola and this form was adopted in the construction. Groundwater solutions colored differently for the several recharge points were introduced along the edge of the syncline and their paths and domains were traced out for different heights of structural closure and constant rate of recharge per foot along the outcrop.

Segregation of Uranium

Transportation and precipitation of uranium was investigated by allowing sulphuric acid of pH 4 to percolate through a crushed uranium mineral diluted with quartz. The acid picked up its supply of uranium and then passed through

a crushed quartz filter to bring it to stability before entering a modified zone below. This zone had various natural types of modifiers such as pyrite, V_2O_5 , and $CaCO_3$. The effect of these upon uranium content, pH, and SO_4 availability, was measured after passage through another stabilizing zone. Low pH increased the uranium content of solutions but had a lesser effect than availability of SO_4 . Both calcium and vanadium expropriate SO_4 from uranyl sulphate solutions and lower capacity of a solution to carry uranium at any specific pH.

Order of Presentation

A general account of the occurrence of uranium on the Colorado Plateau is presented first, in order to direct the experimental work along pertinent and productive lines. The experimental work which observational data indicate as being pertinent is outlined next. The experimental study of travel distance to produce a given improvement in sphericity and reduction in size follows. The simulation of heavy mineral alluviation on a reduced scale constitutes the third topic in this series. Thereafter the series of investigations turns to redistribution of the uranium by groundwater type of solutions. The paths of groundwater in synclines becomes the fourth study. The fifth phase concerns solution, movement and precipitation of uranium in a sandstone environment. Thus the entire series of investigations, complete as each is in itself, are a unit in a larger study of an extremely complex and important group of mineral deposits.

II. GEOLOGY OF THE PLATEAU URANIUM DEPOSITS

Introduction

The important productive uranium deposits of the Colorado Plateau occur in association with fluviatile sediments of Mesozoic age located on the lower part of synclines particularly in or near rocks which deplete the solutions in free sulphate ion. Geological aid to search for these mineral deposits can be resolved into several levels of benefit. The first reduction in nonproductive exploration is attainable by segregation of the productive fluviatile stratigraphic zones from the nonproductive aeolian, playa, flood plain or marine type which occur between the Permian age Kaibab limestone and the Upper Cretaceous age Dakota sandstone. Second, production from far up the flanks of the synclines has been inconsequential, even in favorable fluviatile formations which are productive elsewhere, and generally merit reconnaissance study only. Third occurrence of enriched zones along joint directions induced by folding indicate that present distribution was attained in part since the Laramide disturbance and is due to solution activity. Most of these latter enrichments occur where the rocks have been depleted in calcite or other carbonates and carry an abundance of calcium sulphate.

Any systematic elimination of improbable areas starts with investigation of the sequence of strata and rejection of the unfavorable zones. Even the favorable zones are productive only locally and distinction of uraniferous from non-uraniferous parts becomes the next most pertinent phase of study. Only a few uraniferous deposits can be operated profitably today and the structural and chemical environments favorable to precipitation of uranium, gathered from a wide area into a small compass, becomes the height of current specialized

TABLE I. STRATIGRAPHIC COLUMNS FOR AROUND THE PLATEAU URANIUM AREA.

Location		1. Globe, Ari.	2. Silver City, N.M.	3. Northeast Ari.	4. Zuni Uplift	5. Hermosa Park, Col.	6. Snowmass Mtn., Col.	7. Garmesa Well, Col.	8. Nephi, Utah	9. Marysvale, Utah.	10. Green River, Utah	11. Yampa Canyon, Ut.
Cenozoic formations		Gila congl. Volcanics	Palomas congl. 1225 Datil form. 1000 Volcanics	Volcanics Chuska ss. Volcanics	Volcanics	Telluride congl.			Volcanics	Volcanics		Browns Park ss. 1200 Bishop boulder congl. 50
Cretaceous	Mesa Verde		Chamiso form. 925	Zihhlejini form. 120 Mesa Verde ss. 700	Mesa Verde ss. 1000							Mancos sh. 5000 Frontier ss. 200
	Mancos		Miguel form. 1050	Mancos sh. 650	Mancos sh. 750	Mancos sh. 300	Mancos sh. 2000	Mancos sh. 3800				Mowry sh. 125 Dakota ss. 48 Cloverly ss. 54
	Dakota		Dakota ss. 0-40	Dakota ss. 60	Dakota ss. 185	Dakota ss. 125	Dakota ss. 205	Dakota ss. 120				
	Morrison		Comanche ls. 200	Morrison form. 550	Brushy Basin st. 60 Westwater Cr. ss. 170 Recapture Can. ss. 70	McElmo ss. 450	Morrison qtz. 400	Morrison form. 580	Ls., Sh., & Ss.			Morrison form. 756
Jurassic	San Rafael			Bluff (?) ss. 40 Summerville (?) 100 Todilto ls. 5 Entrada ss. 65 Carmel (?) ss. 80	Bluff ss. 425 Summerville ss. 95 Todilto ls. 15 Entrada ss. 200 Carmel ss. 160	La Plata ss. 325	Entrada qtz. 30	Entrada ss. 110 Carmel form. 50	Gypsiferous beds	Gypsiferous sandstone & shale	Entrada ss. 487 Carmel form. 208	Entrada ss. 165 Carmel st. 125
	Glen Canyon			Wingate ss. 750	Wingate ss. 60			Navajo ss. 350				
Triassic	Chinle			Chinle sh. 700	Chinle sh. 850			Chinle sh. 100				
	Shinarump			Shinarump congl. 80	Shinarump congl. 60							
	Moenkopi	(Border)	Lobo form. 175	Moenkopi sh. 600	Moenkopi sh. 675	Dolores form. 275						
Permian	Kaibab ls. Coconino ss. 260	Gym ls. 600	Cutler form. ? Rico form. ?	San Andreas ls. 500 Yeso ss. 420 Abo ss. 600	Cutler form. 1500	Maroon form. 2350				Limestone 500	Kaibab ls. -5	Moenkopi sh. 800 Park City - Phos- phoria form. 50
Pennsylvanian	Supai form. 600	Fierro ls. 400	Hermosa form. 1100 Molas form. 40		Hermosa form. 2100 Molas form. 40				Limestone 550	Ls., dol. & qtz. 650		Webber ss. 1000 Morgan ls. 1281
Mississippian	Redwall ls. 250	Lake Valley ls. 300	Redwall ls. ?			Leadville ls. 220						Madison ls. 600
Devonian	Martin ls. 200	Percha sh. 250	Ouray ls. 70 Elbert form. 50			Ouray ls. 200 Elbert form. 80						
Silurian		Fusselman ls. 150										
Ordovician		Montoya ls. 250 El Paso ls. 500										
Cambrian	Abrigo ls. Troy qtz. 700	Bliss ss.	Tapeats ss. 40	(?) congl. 15	Ignacio qtz. 40	Sawatch qtz. 250			Quartzite 900	Ophir qtz. 900		Ladore form. 375
Precambrian	Apache group Granite Pinal schist	Metamorphic complex		Metamorphic complex.		Metamorphic complex.		Granite & Gneiss				Uinta Mtn. group 12000

Condensations adopted: Congl. - conglomerate Ls. - Limestone Qtz. - Quartzite
 Ss. - Sandstone Dol. - Dolomite
 St - Siltstone Form. - Formation

Thickness of strata given as a range are quoted here as the numerical average of the range

Fig. 1. Stratigraphic column for the Colorado Plateau area.

study at the existing state of knowledge.

The Stratigraphic Column

The succession of strata from the Kaibab limestone to the Dakota sandstone, at areas spaced to represent the entire Colorado Plateau, are presented in Table I and Figure 1. Marine strata have limited areal extent and almost inconsequential thickness; over half the section is aeolian and only two thin formations have significant fluviatile deposits; the remainder is built up essentially from playa and sheet flood accumulations. Only the Shinarump conglomerate and the Morrison group have uranium deposits of consequence. Descriptions of the formations are given by Baker et al ⁽¹⁾, Gilluly ⁽¹⁾, and Gregory et al ^(1, 2, 3). The essential data is extracted from these reports and field studies and is synthesized as accurately as possible in the space here available.

The Moenkopi Formation

The Moenkopi formation is predominantly laminated, red or maroon colored silts, with local sandstones and shales. The sandy phases increase in amount in the vicinity of the late Paleozoic swells to north, east and south. Giant mud-cracks are a distinctive feature of the finer textured phases nearly everywhere. Rarely are beds traceable for ten miles; this lack of continuity suggests that deposition was in playa basins and on flood plains. Sheet wash appears to have been the principal mode of alluviation. The record shows no deposits, such as might be left by streams with high transporting power, at any place far removed from the swells.

The Shinarump conglomerate.

The Shinarump conglomerate is absent in at least half of the Plateau but few areas of five miles width lack it. It can appear on a cliff and increase to over 100 feet thickness within 400 feet horizontal distance and thin with equal abruptness farther along. These thick lenses rest disconformably upon the underlying Moenkopi shales or older beds and are in sinuous shoe-string strips of sediments having a N.W. -S.E. trend for most of the area. Texturally and structurally they have all the characteristics of alluviated stream channels incised both into sheet wash plains of the Moenkopi and also into the structural swells from which the Moenkopi detritus was derived.

The channels have an undulating bottom with numerous reverse grades to make pools. Many pools have "in-channel" deltaic structure with mudstone, conglomerate and sandstone succeeding each other in that order. The sequence represents a flood and ebb flow condition; the mudstone is the deposit of the ebb season when the pools were water bodies disconnected at the surface and having only seepage flow if any. The conglomerate is the flood record and the sandstone is the intermediate phase. The conglomerate and, even the incised channels that lack conglomerate, have heavy mineral detritus and minor uranium content. The heavy minerals present vary with the source area.

The channels north of the San Juan Basin have a general southeasterly course, are characterized by smoky quartz and jasperoid pebbles where they are in a uraniferous zone and were filled from the north. (Bain⁽¹⁾). The jasperoid carries leptothermal mineralization and the microveins have primary uranium in recoverable amount. Hydrocarbon is an important component of all deposits.

The channels south of the San Juan Basin were filled from the southeast; red jasperoid pebbles from a southerly source have been identified there also and appear in all uraniferous conglomerates.

The Chinle Formation

The Chinle formation is a mudstone with occasional thin channel sands in it. The coniferous logs of the Petrified Forest in Arizona to southward were rafted from a highland through channels fringed by cycads and ferns and were left stranded by the overflow of the sheet floods. Another highland occurred north of the San Rafael River where this formation becomes almost entirely sandstone as it thins to less than 100 feet in its last exposure and disappears against the western prolongation of the Uncompahgre Uplift. No upper Triassic age strata have been identified in the Wasatch Range although the thin argillaceous and conglomeratic Ankareh formation of uncertain age appears below the Jurassic strata of the Park City area and has been correlated tentatively with Chinle. (Boutwell⁽¹⁾) The Chinle disappears east of Durango where it passes into the sandy and conglomeratic Dolores formation.

The Chinle formation was derived from the same area as the Shinarump conglomerate but, under diminished water supply, fluvial deposits were confined to the margins of the basin and only sheet wash reached the central playas with mud and dissolved solids.

The Glen Canyon Group

The Glen Canyon Group, probably of Jurassic age, has at least three members. (Baker et al⁽¹⁾) The middle member known as the Kayenta formation has thinly bedded sandstone and shale with numerous salt lake limestone beds in-

cluding the Todilto limestone. Its environment and limits resemble closely the corresponding features for the Triassic strata. The Wingate sandstone below and the Navajo sandstone above are thick aeolian deposits almost coextensive with this Mesozoic basin.

The San Rafael Group

The San Rafael group is conformable with the Glen Canyon group in the center of the basin but lies disconformably over all formations in the rim region, including the western side which began to rise at this time. The lowest member known as the Carmel formation, has marine fossils locally and its distribution is essentially that for the Glen Canyon Group.

The wind blown Entrada sandstone overlies the Carmel formation. This member is well-bedded only in the extreme eastern part of the plateau north of Durango.

A mixed brackish water and marine group of sediments were deposited on a N.E. - S.W. front that was advanced into the reinundated basin from the vicinity of Great Salt Lake; this is the Curtis formation. These beds were overlaid by the Summerville sandstones which have a N.W. - S.E. front with greatest thickness in north central Arizona. This alluviation, and the swell from which it came, excluded the western seas from the Plateau Area basin from that time onward.

The Morrison "Group"

Recent usage elevates the Morrison formation to group status and raises its various members to the rank of formations. The two principal parts are the Salt Wash member below and the Brushy Basin beds above. The Salt Wash is

prevailing sandstone and the Brushy Basin is almost entirely bentonitic mudstone. However many variations appear in the Salt Wash part. Brushy Basin mudstone is usually green. Salt Wash mudstone is usually red except below uranium deposits or deposits depleted by leaching where the rock becomes gray. Gradation of red shale to gray is accompanied by depletion of ferric iron in all cases and by an increase of ferrous iron in a few instances. (Weeks⁽¹⁾)

The Salt Wash member in the Henry Mountains has negligible interbedded mudstone; the mudstone increases eastward to constitute up to 65% of the section east of Uravan. Pollen studies of the shales show a distinct Jurassic flora in the Henry Mountains and a Cretaceous flora for the area near Uravan. (Wilson⁽¹⁾) This suggests reworking of the detritus to spread the finer fraction eastward and leave a gravel armor residue in channels across the degraded fan within the western area. An arcuate arrangement of heavy mineral suites marks off stages in this redistribution of detritus.

The center of this main arc is near Lee's Ferry and the river channels in the Salt Wash member radiate from this center. (Craig et al⁽¹⁾), p. 21) The channels rarely attain 15 feet depth; most are reasonably wide and are filled with coarse sand in the east and grit in the west. Logs and trash pockets are numerous. One mine at Slick Rock displays up to five small channel fillings superimposed upon one another. Principal uranium in the Salt Wash occurs as carnotite in and along dilation cracks bordering the massive channel sandstones.

A second and minor alluviation center occurs at the southeast edge of the basin in the vicinity of the Zuni uplift. The beds below the Brushy Basin member are divided into the Bluff sandstone at the bottom, the Recapture shale and

the Westwater Canyon sandstone at the top. Principal uranium occurs near the bottom of the Brushy Basin member. Extent of this source has not been determined yet but its uranium occurs along channels at least as far north as the Carrizo Mountains on the Arizona - Utah line.

The Upper Cretaceous Age Strata

A thick series of brackish water, swamp and piedmont plain accumulations of Upper Cretaceous age overlie the Brushy Basin mudstones. Usually a massive sandstone called the Dakota but of variable age, forms the base of the series. It is separated from the thick coal bearing Mesa Verde sandstones by the Mancos shales. These strata carry only inconsequential amounts of introduced uranium, have no stratigraphic influence on distribution and exert only structural guidance on groundwater movement.

The Upper Cretaceous formations are stripped from most of the area but remain essentially intact in the eastern part of the San Juan Basin, and west of the San Rafael Swell where they bury the uranium horizons under their thousands of feet of beds. Elsewhere these strata conceal locally the productive beds with varied thickness and over small areas.

The Structural Pattern

The structural pattern in the Plateau originated during the Laramide disturbance which raised the region above river grade and ended deposition of the Mesa Verde beds. The Colorado Plateau uranium province is caught between the Bannock - Wasatch - Muddy Mountain deformation on the west and the Colorado Rocky Mountain arch in the east. (Figure 2) . A series of swells diverge

FIG 2 STRUCTURAL POSITION OF THE COLORADO PLATEAU URANIUM PROVINCE

westward from the Rocky Mountain axis after the fashion of the ends to the island arcs of the western Pacific and successive swells from north to south show decreasing magnitude and intensity. The Medicine Bow - Rawlins uplift-Wind River Range system forms a northeast border to the Plateau province and is the least curved of any cross structure between the boundary mountain masses. The Sawatch - White River uplift - Uinta Mountain arc splits the Washakie Basin off from the Plateau proper and is arced through almost 90° of curvature. It exerted a major influence on the artesian water flow during the Cenozoic but had only minor control on the later drainage and topographic development. The San Juan - Uncompahgre Swell is even less conspicuous in the Mesozoic strata than the Uinta arc which it parallels closely. A series of N. W. trending folds occur in the Plateau south of the Uncompahgre uplift and, continuing the Pacific analogy, correspond in pattern to the swells carrying the basaltic volcanoes on the massive Pacific floor.

The north margin of the Sonoran crystalline oldland crosses central Arizona and New Mexico. Extensive areas of these crystallines have been exposed since the middle Lower Cretaceous time. This constitutes the southern limit to the Colorado Plateau block.

The Wind River and the Uinta arcs and the Colorado Rockies, from which they diverge, were stripped to the crystalline floor by early Eocene time and all aquifers were exposed for recharge. The Uncompahgre Swell and N. W. trending folds were not stripped until establishment of the Rocky Mountain peneplain in the Colorado River drainage by late Miocene time. These Plateau area structures constituted artesian flow guides throughout all early Cenozoic time.

The Topographic Development of the Plateau.

The Colorado River drainage basin was reduced to grade everywhere except at the headwaters by the end of the Miocene period. (Gilluly⁽¹⁾, Bain⁽²⁾). The rolling uplands at the headwaters had a series of great alcoves and each was the catchment area for a major tributary. A broad warping of the continent occurred at the end of the Miocene and was accompanied by some volcanic activity. The well established drainage systems of the Miocene were rejuvenated and the stream courses, superimposed upon the soils of the peneplain, became entrenched without regard for rock type. Eventually some approach to stability was attained and the main rivers of the system wore their beds down to approximate grade; however the less competent secondary streams eroded the incoherent rock more effectively than the coherent types and the rock pattern appeared in the topography. Some canyons have a systematic pattern, totally discordant with the structure and present topography; these are the superimposed streams whose pattern was established on the peneplain. Most small canyons are without pattern or system and represent results of normal headward erosion.

In addition to the principal Rocky Mountain peneplain, a younger base-levelled surface is recognized around the Carrizo Mts. and Henry Mts.; its surface is covered by a layer of very coarse cobbles. This surface seems to correspond to the level of many large mesas like Mesa Verde in the east and others between the Green River and Hanksville in the west, but it is well below the summit level of large features like the San Rafael Swell. The canyon pattern cut out of this surface is very intricate whereas the superimposed drainage across the Swell,

the Uinta Mts. , and the Uncompahgre is cut in bold lines.

The Rocky Mountain peneplain slopes towards the site of the Colorado River from the Wasatch Mts. , the Sevier Plateau and Aquarius Plateau in the west, from the Wyoming Basin in the north, and from the Park, Sawatch and San Juan Mountains in the east. Low knobs and ridges project above an uniform skyline in each of these areas and represent monadnocks. The high point of the Wind River Mts. and the Gros Ventre Range are monadnocks that hemmed in the system on the north. The Aquarius Plateau, southeast of Marysvale , is the south end of the western group of monadnock divides. The top of North America, from Longs Peak in the Front Range to Chama Peak in the San Juan Mts. , limits the drainage to eastward. The Colorado and the Green Rivers occupied essentially their present courses. The principal tributaries from the west were - from north to south - the San Rafael River, and possibly the Dirty Devil and Escalante Rivers, although the major eastern tributaries were the Yampa, Gunnison, Dolores in part, and the San Juan. The inclination towards these drainages furnished the slight hydraulic head for any artesian system which persisted up to the Miocene; it is my opinion that the artesian systems had stagnated by this time and that they operated only during the periods of higher topographic relief and with spillage directions about as the ultimate drainage would suggest.

Uplift at the end of the Miocene rejuvenated the Colorado and Green Rivers; they entrenched their courses, followed in order by incision of their major tributaries as new and lower base levels were set for them. This development can be illustrated for one river on each side of the Colorado. The San

Rafael River was flowing on a plain graded from the eastern margin of the Wasatch Plateau across the top of the San Rafael Swell structure; it was entrenched in one stage down to the level of Castle Valley, whereupon the less competent tributaries excavated the weak rocks and fed them to the river load to be discharged through the entrenched channel across the resistant rocks of the Swell. The course was entrenched again during a late Pliocene to early Pleistocene uplift and the stream is still struggling to attain grade across the more coherent rocks of the Swell situated upstream from where it had reached maturity in the course over incoherent strata in the San Rafael Valley. The Dolores River has a general northwest course, with only minor deviations, from its source in the northwest alcove of the La Plata Mts. to Dewey on the Colorado. This is the usual pattern for a tributary stream. Its channel is cut through several deep gorges and across a number of broad open valleys; the top of the gorges is not higher than the Rocky Mountain peneplain and all of the lowlands have been excavated since Miocene time; thus for this area, topographic development has post-Miocene age.

The late Pliocene-Pleistocene uplift is responsible for cutting the many narrow inner canyons. The base-level established just previous to it corresponds in time to excavation of the Wyoming Basin and Colorado's North Park, the Toroweap in the Colorado Plateau and perhaps the Unaweap across the Uncompahgre. These canyons disrupt continuity of the older artesian flow systems.

III. EXPERIMENTAL WORK SUGGESTED BY OBSERVATIONAL STUDY.

General Statement.

The geology of the Plateau uranium deposits suggests experimental work on sedimentation in river channels, wear of detritus during transit, lines of flow to ground-water flowing through folded structures and selective precipitation of uranium by other minerals. The background for belief in the need for this experimental study is outlined in each of the following sections, and discussed in the order mentioned.

The Pattern of Uranium Distribution and River Channel Sedimentation.

The pattern of uranium distribution conforms in stratigraphic position within the geologic column and in areal extent to sedimentary formations laid down by turbulent stream flow and profitable ore production is essentially absent away from such areas or such formations. It is possible that the rule may be extended in principle to other strata where formations were laid at steep stream channel grades near the edge of the basin.

The Shinarump channels lie in a zone essentially parallel to, but west of, the line along the Green River from the town of Green River to the Junction of the Green and the Colorado below Moab, Utah. Furthermore a 50 mile wide zone would encompass practically all occurrences except the small one at Moab itself. Channels north of the San Juan River were filled in by streams flowing southward whereas those in Arizona flowed northward. Rich sites in the channel zone are associated with the conglomerates interstratified with deltaic mudstones which have a thickness variation consonant with pool deposition.

Channel sandstones control the pattern of the Salt Wash deposits. The

channel system south of the San Juan River trends northerly with long stretches running northeasterly but the general axis is down the Westwater Canyon fan and almost parallel to the Shinarump trend. The channel system north of the San Juan River trends northeasterly and is almost at right angles to the Shinarump system to make the vertical part of a T with it. (Craig et al⁽¹⁾, p.59).

Secondary redistribution of uranium in carbonates and sulphates and in tyuyamunite and carnotite occurs in many areas and confuses the general pattern slightly. The Grant's, N.M. occurrence is one; here the geological occurrence and physical qualities of the Todilto limestone deposits have been accounted for satisfactorily only on the basis of secondary redistribution from Westwater Canyon and Brushy Basin channels and the uranium should be considered to have been derived from these sources by groundwater. The Chilchinbeto occurrence is another deposit of strictly groundwater derivation.

Inferences Regarding the Origin of the Pattern

Association of uranium with conspicuous channel sediments, accumulated under conditions of turbulent flow, and absence of uranium in productive amounts where deposition is either aeolian or occurred as sheet flow, suggests of itself an original importation of the uranium with a detrital mineral of high specific gravity or pieces of high mass. Actually primary components of the coarse pebbles in the Shinarump conglomerate at the Dirty Devil claims carry enough uranium to account for a large part of the total amount in this deposit. The simplicity of pattern is masked in finer textured sediments, like the Salt Wash beds of the Uruan area, where greater exposure of the uranium minerals to groundwater permitted solution and later dispersion before local precipitation.

Shinarump Conglomerate Detritus and Source for Original Uranium

A detailed study of the Shinarump conglomerate in the Dirty Devil claims (1) (Bain) showed first, that jasperoid pebbles and sand grains carried one third of the uranium in the deposit, second that, exclusive of aeolian sand, 35% of the river load had been reduced to silt size, and third that sphericity had reached fluvial equilibrium at 0.80 for all sizes coarser than 208 microns (+ 65 mesh). Low sphericity of material which passed through a 65 mesh screen indicated either recent fragmentation off larger pebbles or suspension transport of this size group. The equivalent distance of travel to produce both the observed sphericity and degree of fragmentation of detritus was important first to understanding the variation in texture and uranium content of the Shinarump channel deposits, and second to interpret the fluvial deposits. (See Part V).

Sphericity and Distance of Travel.

Observations on stream alluvials and on the charge in ball mills of crushing plants shows that a considerable part of the fines produced are derived from the edges of large fragments. These chips are removed in the process of increasing sphericity of large pieces and the size is reduced proportionately. It has been recognized that the coarse fraction of the fragment load acquires rounding but that the fines moved principally in the suspension load have nearly the same angularity at all distances of travel. Rounding of sand occurs only after most pebbles have been removed from the charge.

The Shinarump channels had detritus with sphericity values ranging from .802 to .816 in the size range 208 microns to 10000 microns. This sphericity dropped to crushed fragment sphericity of 0.76 in the 150 mesh silt. Quartz

crystals and argillite fragments were worn little; jasperoid was ellipsoidal.

Information on distance of movement to produce this rounding is not available and all statistics are in the general terms of short, intermediate or long distance without any scale for terms. The pebble size at Dirty Devil indicated a stream velocity of about 6 to 8 m.p.h. and so the number of miles of travel became important in order to know the length of time the uranium bearing pebbles were in contact with continuously replenished forest soil water. Stream cross section size and velocity suggest 50 miles as a reasonable estimate to distance of travel to produce the observed sphericity.

Size Reduction and Distance of Travel

Ball mill grinding of fragmented rock produces an amount of fines proportional to the increase in sphericity and to reduction in amount of the coarse material. The pool deposition in the Shinarump channels retained the fines, which perennial streams normally would have carried away to distant settling basins, and makes measurement of size reduction possible. Again no quantitative estimates of distance moved to produce a given reduction in size (increase in area of all grains) is available and all statements are couched in generalities. However comparison with ball mill crushing suggests that the number of impacts at 6 m.p.h. to reduce one third of the fragments to -65 mesh would require 5 to 8 hours of time or 30 to 50 miles of travel.

The Shinarump Conglomerate and Source for its Detritus

The Shinarump conglomerate carries fragments of Moenkopi silicified wood, jasperoid with remnants of Permian age bryozoans and foraminifera and smoky quartz both from veins and in euhedral crystals. The occurrence

of Moenkopi silicified wood is not pertinent to identification of source because the channels are cut into Moenkopi formation at too many places. No occurrence of smoky quartz veins has been reported in either this area or the Wasatch Range so they afford little aid. The jasperoid could be a mineralized part of the Kaibab limestone or the Webber limestone. The Moenkopi intervening between the Kaibab limestone and the Shinarump conglomerate is more than 100 feet thinner at the Mexican Bend of the San Rafael River than elsewhere in this area. This is along the prolongation of the Uncompahgre axis to westward and any accentuation of the axial upwarp west of the Black Box on the San Rafael River could be expected to expose the Kaibab to erosion during Upper Triassic time. This arch is the most probable source for the jasperoid pebbles. The axis is 30 miles north of the Dirty Devil claims measured in the direction of average channel courses in the San Rafael Swell.

The nearest major mineral deposits are at Park City, Utah where age of mineralization, other than being post Lower Triassic has not been determined. The intervening area is concealed by a deep syncline of Mesozoic and Cenozoic sediments. The only data which is likely to become available concerning source for this conglomerate is from pebbles themselves or from exposures in the Black Box of the San Rafael River.

Experimental Study Suggested

The observational data on sphericity and size reduction of detritus to make the Dirty Devil conglomerate suggest that some indication of distance to the source might be obtained by quantitative laboratory measurement of relationships between distance moved, sphericity improvement, and size reduction.

The eight foot wheel mentioned earlier was set up to do this work and Hal P. Eastman carried out the study with very informative results. These are given in Part IV of this report.

The Synclinal Occurrence of most Carnotite

The Salt Wash formation of the Morrison Group has about half mudstone and half sandstone where it is most productive in the Uravan mineral belt (Craig et al⁽¹⁾, p. 59) and appears to have been deposited along large river courses through an area with numerous dunes. The region was deformed during the Laramide disturbance and raised along several N.W. trending major anticlines. The uranium occurs on the lower flanks of the synclines. (Bain⁽²⁾)

Relation of Uranium to Specific Deposition Structures in the Salt Wash

The alternation of white sandstones with gray and red colored mudstones or shales is a prominent characteristic of the Salt Wash formation and profitable uranium deposits occur where an almost equal amount of each rock type are present in the section. The mudstone lenses extend for only short distances and few attain 15 feet thickness. The bedded sandstones above them usually have nearly massive shoe-string bodies of distinctive sand which have a lenticular cross section with a flat upper surface and convex downward lower surface. The bedded sandstone usually has intercalated mudstones at one quarter to one mile away from the massive shoe string sand and stratigraphically above the mudstone below the channel. Most channel sands are massive but others have deltaic structure simulating aeolian crossbedding; the deltaic structure may be dune crossbedding in some instances but much of it resembles struct-

ure in the slip-off slope of deposits on meanders. Most channels both in the Uravan mineral belt and in the Lukachukai area meander considerably. Plant trash pockets occur along nearly every channel fill and are a part of it.

The sandstones resemble channel fill of desert rivers bordered by natural levees of sand. Back stream deposits from numerous overflows into the dry interstream lowlands during flash flood periods and occasional stoppage by dune fillings account for other types of accumulations. Too high aggradation of the natural levees was followed by abandonment of the course for an inter-stream area.

The eastward redistribution of Jurassic age high slope alluvial fans to make younger low slope plains type deposits to eastward has been emphasized already. The sheet wash deposition and levee raising along the stream courses continued well into the Cretaceous period. This sort of process occurs now in the dry savannahs and desert margins of Africa and has heavy cycad growth in the sandy deposits for only a few feet back from the stream courses. The back area lowlands are inundated only during the occasional floods and have a thick deposit of mudstone.

The uranium deposits are distributed along these shoe string sands. Principal high content rock is outside the channel but increased prices have made many of the channels workable in recent years. The plastic clay under the "shoe strings" has suffered solifluction and the superjacent sands between the competent shoe string and the clay have developed dilation cracks. These dilation cracks are the guiding surfaces for many rolls and rich carnotite deposits, and usually, but not always, are parallel to the channel length. (Fischer, 386).⁽¹⁾

Relation to Tectonic Structures.

The great deposits of Long Park and the Uravan area are near the bottom of the syncline followed by the San Miguel River. Generally the richest mineralization is on the gentler limb. The northeast limb is the steep limb at Naturita and has negligible production whereas it is the gentle one at Calamity Mesa and has been a great producer. The southwest limb is gentle at Naturita and Uravan and is the greatest of all producers but becomes the steeper one farther west and there productive deposits on it are rare.

Clustering of deposits towards the bottom of a syncline recurs at Egnar and Slick Rock and Gypsum Valley on either side of the Disappointment Valley syncline. Known deposits near Cove School in the Lukachukai Mountains of Arizona are all on the gentle limb of the syncline and very close to the bottom of it.

The pattern is repeated so often that it becomes very impressive. It is carried over even into the Shinarump deposits even where almost all of the uranium is in the shoe-string rather than in the dilated sandstones adjacent thereto.

Grouping of Deposits

The Salt Wash uranium deposits of the several areas on the plateau are clustered along lines which were obvious to prospectors even before the affinity with stream channels was recognized. Whole series as at Egnar, or Slick Rock or Long Park or Uravan are in a linear series independent of the tectonic structure and the group is aligned usually in a general S.W. - N. E. direction. These groups are in the general stream pattern alignment on the main Salt

Wash fan and their long axes are parallel to the length of fossil logs in them. This control supercedes all others and is the basic one for the area.

Elongation of Individual Deposits

The individual deposits of a group strung out on a channel are elongated or at least have a modified extension nearly parallel with the regional structure. Many deposits are reported to be at mere terraces on the flank of the syncline and the boundaries of the area with the uranium in more than average abundance is usually extended beyond the shoe string along the terraces.

Oftimes at Slick Rock, the elongation of a deposit is the dilation crack trend but at Lukachukai #12 the productive orebody, while remaining close to the channel sand, has its elongation independant of the dilation features or channel trend.

The arrangement suggests structural control over groundwater movement and this was confirmed in part by equilibrium studies of the uranium ores at different distances up the limbs of synclines ⁽¹⁾ (Roth). These showed that the higher deposits had excess radioactivity (residual radium) for the uranium content. The deposits far down the limb of a structure had in the very rich sections slight excess uranium (imported uranium) for their radioactivity. This was checked at Slick Rock, Monument Valley and Lukachukai. However the elongated deposits occurred at successively lower levels down the flank of the syncline and could not be attributed to any simple watertable or spill-level of groundwater flow.

Experimental Study Suggested

The occasional angular deviation of the elongation to the deposits from the

general linear trend of the deposits in a group, suggested study of groundwater flow along pitching synclines to a spill point. An experimental syncline was built with one steep and one gentler limb. Colored solutions were introduced at different points and at different rates and the paths traced out. This problem was studied by Mr. C. R. Maise. He found that principal flow was directed to near the bottom of the syncline and at far below the water table and thence nearly parallel with the tectonic axis to the spill point. Several modifications to groundwater movement were recognized and are described in Part VI of this report.

Local Precipitation of Uranium

The formation of concentrations of uranium vanadate minerals under a great variety of conditions, accumulations of black uranium oxide at or just below the watertable, the association of many Plateau uranium mineral deposits with carbonates or leached carbonate areas, and depletion of uranium content of groundwater with depletion in available SO_4 ions and hydrogen ions suggested chemical influences upon solution and local precipitation of uranium. Petrographic study of the deposits showed that most uranium vanadates were a replacement of the quartz and jasperoid particles in the sandstone. All these observations showed that chemical environment for uranium precipitation was a potential fertile field for experimental study.

Uranium and Associated Minerals Above the Watertable

The Shinarump channels north of the San Juan River have few vanadate minerals whereas those to southward and all in Salt Wash beds have excess vanadium over uranium to make carnotite. Even in the area north of the San

Juan, most reports of uranyl vanadate minerals from the Shinarump beds are limited and from localities at Temple Mountain and Moab. Principal minerals elsewhere are sulphates, phosphates and thucholite complexes.

Vanadium becomes more abundant around the southern source area in association with the siltstones in the basin aggraded by intermingled components from southern deposits and other sources. In any case, vanadium content increases with the shale content of the host formation and is essentially independent of shale content of the entire stratigraphic column. It becomes evident at the outset that the chemistry of deposition concerns all uranium minerals and not merely carnotite.

The Happy Jack Mine in White Canyon and some of the deep mines at Urvan are the only workings to reach the present watertable and these show unique features in mineralogy. Doubtless the rocks of other mines were below the watertable of past times but the equilibrium characteristics of the minerals indicate recent origin and the mineralogy of the deposits at remote time is unknown.

The vanadate, carnotite, is abundant in the San Rafael Swell area only at Temple Mountain and the other locality at Dirty Devil has only a small amount. Other vanadates are reported from only Temple Mountain in the swell area. Thucholite, torbernite, johannite, zippeite, and a series of yellow uranium oxides are characteristic uranium minerals. (Gruner⁽¹⁾). In the Dirty Devil area, a considerable part of the uranium which is not held inside the jasperoid or the thucholite, is water soluble. (Bain⁽¹⁾).

The Moab and Poison Spring areas have a progressively larger part of the

uranium in the vanadates tyuyamunite and carnotite and even have excess vanadium to make calciovolborthite.

The White Canyon area yields uranyl silicates, sulphates, phosphates, and hydrates and even uranium oxide but not even specimen amounts of vanadate have been recovered.

The Monument Valley deposits have excess vanadium to form rauvite and metaheuwettite. Autunite and torbernite are present also but sulphates are generally absent. Apparently vanadium can expropriate SO_4 from uranyl compounds, and uranyl sulphates exist only in the absence of vanadium to take up the sulphate.

The Salt Wash deposits have carnotite and tyuyamunite as the principal uranium minerals. Vanadium occurs in excess to form the hydrated minerals, metaheuwettite, corvusite, vanoxite, rossite, and others.

Uranium Minerals at the Watertable

The Happy Jack Mine has passed below the watertable and recent operations at one mine in the Uravan - Long Park area was reported to have done likewise. Black uranium oxide giving the X-ray pattern for uraninite has been found at both places. The Happy Jack occurrence has a highly enriched zone of sooty black uranium oxide and associated firm uraninite in botryoidal, and irregular masses, and replacements of wood and sandstone at the watertable zone. New workings below this level have no uranyl minerals but all the headings opened more than two weeks previous to the writer's visit had soluble yellow uranium minerals in fissures and locally on the clay surface. However the uraninite had similar coatings. The sooty black oxide and the

firm uraninite do not go more than inches below the undisturbed watertable at the Happy Jack Mine and uranium minerals at greater depth are very rare indeed .

Hydrogen Ion and SO_4 Ion Concentration in Mine Water

The hydrogen ion concentration of mine water from below the watertable at the Happy Jack Mine was 6.7 and at Lukachukai #23 was 7.4. Water from above the watertable was very acid and had ferric sulphate suggesting a pH of 3.5 to 4. Amount of salts in mine water depends upon the carrying capacity and partly upon the length of time the water is in contact with a source of salts. The water sampled has less than 0.05 parts of U per million of solution. The uranium decreased with increasing pH from 10.9 parts per million at pH 6.7 to 0.12 parts per million at pH 7.4.

The SO_4 ion dropped from 3130 parts per million where U was highest to 32 parts per million where it was low. Ratio of U to SO_4 was reasonably steady at 0.0010 to 0.0037 showing much closer agreement than when compared with the hydrogen ion.

Observed Microstructures in Deposits

Corrosion of the sand grains in the uranium - vanadium deposits of the plateau has been recognized and this was noted in the thucholite ores of the San Rafael Swell and Placerville. Usually a clay mineral is left in the dissolved space and the thucholite, vanoxite (?) or carnotite is deposited on or around it.

A petrographic study of some "pocket edition" rolls showed zoning. The barren sandstone passed into a non-ore zone wherein carbonate (calcite or

dolomite) filled cusped embayments in the quartz and jasperoid sand grains. Measurement showed that quartz residues in this rock have a sphericity ratio of 0.60 in contrast to 0.76 for crushed rock, 0.81 for stream sand and 0.86⁽¹⁾ for aeolian sand. (Sage⁽¹⁾). The carbonate zone is succeeded by a carnotite zone wherein the carnotite occupied the space of the carbonate and the quartz was indistinguishable in size or sphericity from the adjacent bands. A vanoxite band occurred between the carnotite and a dilation shear joint; its quartz was like that in either of the other mineralized bands and the vanoxite took up the space occupied by the carbonate or carnotite of the outer zones.

The carbonate appears to represent the preparatory mineralization which preceded the introduction of uranium and vanadium ores and its introduction was accompanied by solution of quartz.

The groundwater of the Happy Jack Mine has 89 parts per million of bicarbonate just below the black oxide enrichment zone and this increases to 372 parts per million in the deeper workings. The water from the bottom of the syncline at Lukachukai Mine #23 contains 329 parts per million of bicarbonate. These meagre figures suggest that bicarbonate is a more abundant component of the deeper circulation than of the shallow one and could introduce the carbonates of the preparatory mineralization phase. It is at least possible that the preparatory carbonate replacement of the sand may be only one phase of a single continuous mineralization sequence rather than an entirely independent sequence but this is unimportant and seemingly irrelevant.

The introduction of uranium and vanadium was accompanied by displacement of the carbonate with carnotite which seems to require more of a car-

bonate environment than the vanoxite. The abundance of calcium sulphate in the vicinity of most deposits at least suggests removal of the calcium as the sulphate and extraction of SO_4 from solutions bringing the uranium and vanadium. The general picture suggests that an early or preparatory carbonate mineralization determined where favorable ground was to be and migrant sulphate solutions used this place to drop their uranium and vanadium when the carbonate reduced the hydrogen and available SO_4 ion content.

Experimental Study Suggested

The role of carbonate in the sand replacement and its known capacity to reduce both hydrogen and available SO_4 ions suggested that percolation experiments under controlled conditions might yield pertinent data on local precipitation of uranium and vanadium minerals in sandstone. A uranium source used 1.4 grams of uranium; uraninite and carnotite were tried in a variety of tests. Sulphuric acid diluted to pH 4 or about one drop in four liters was used as a simplified groundwater. Various possible ore host sands were made up of quartz, quartz and carbonate, quartz and pyrite, or quartz, carbonate and pyrite. Both pH and uranium content of the solutions were measured at three places as they travelled through these mixtures simulating Salt Wash materials at the rate of about a liter per day. Beds of hydrocarbon, pyrite, and V_2O_5 were introduced between two solution sampling points of several tests to determine their effect, as well as that of calcite, upon uranium solubility in the resulting solution.

The work was done by Mr. P. M. Bethke and the results are presented in Part VII of this report.

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IV. MODIFICATION OF DETRITUS DURING TRANSPORTATION

Introduction

The modification of detritus during transportation was investigated experimentally in an attempt to derive a correlation factor between distance of travel and attendant size reduction, sphericity increase, and the characteristics of mineral dissolution incurred during movement of a particular rock type. The detritus used was crushed pegmatitic Pelham gneiss from North Amherst, Massachusetts, having bands of fine textured micaceous gneiss alternating with coarse textured granite streaks. The size of particles was determined by sizing with Tyler screens. Sphericity was measured according to the method devised by Waddell⁽¹⁾. Extent of mineral and rock dissolution was estimated qualitatively by megascopic and microscopic inspection of specimens of the sediment.

Experimental apparatus included an eight foot diameter annular trough for the simulated stream bed, and instruments for mechanical analysis of the sediment, such as standard Tyler screens, microscope projection apparatus and a polar planimeter. The equivalent travel of the sediment was 80 miles, and mechanical analysis was made of the entire charge at intervals throughout this distance.

The results of the work, subject to experimental limitations show excellent correlation between distance travelled on the one hand and size reduction and sphericity increase on the other. This furnishes a semi-quantitative correlation factor between distance of travel and either form modification or average size reduction of detritus of the type investigated.

Computation of correlation factors for other rock types could afford a method of estimating distance back to source for detritus, with measured characteristics, for a large number of conglomerates.

Objective of Study

The study was suggested by the mode of occurrence of uranium minerals in pebbles of the Shinarump conglomerate in the Colorado Plateau region. It was the expectation that the experimental production of detritus and measurement of reduction in size and increase in sphericity of fragments during transit could be applied through comparison of histograms to estimate distance from present conglomerate site back to original source, thereby narrowing the zone of search.

Field study of uranium occurrence in the Shinarump conglomerate of the Dirty Devil claims in the San Rafael Swell shows that concentrations of uranium in productive amounts are associated with detritus of high specific gravity or pieces of high mass and, that accumulation into deposits formed under conditions of sheet flow deposition is negligible. Silt size particles composed 35% of the total river deposit in the conglomerates of high uranium content and the sphericity value for particles in all screen sizes coarser than 65 mesh had reached an equilibrium at 0.80. The frequency to occurrence of uranium deposits seems to fall off rather sharply in Shinarump conglomerate where sphericity of detritus increases further and average size of particles is reduced greatly. Presumably the grain form, revealed by mechanical analysis, indicates distance of travel in a relative way but distance in miles is essential to practical explora-

tion and estimation of this distance requires measurement of some experimental constants.

The streams which deposited the Shinarump conglomerate were unusual in that they left fine silt along with coarse gravel. Normal graded streams have their detritus dropped differentially in graded sizes throughout the stream course; the very coarse sizes are near the headwaters and successively finer sizes appear downstream. Mechanical analysis of the Shinarump conglomerate indicates an ebb and flood type of flow, with deposition occurring in successive pools, (Bain and Ruckmick⁽¹⁾), and all sizes of detritus were left together providing a relatively complete sample of all material in the river load.

The Problem

The experimental problem was to determine the distance of travel for detritus to acquire the sphericity and size combination (size reduction) found by mechanical analysis of the Shinarump conglomerate. To this end, a mechanical analysis of the experimental detritus was made after preparation and also after 10, 20, 40, and 80 miles of travel in the simulated stream channel; this analysis could be expected to be analogous to that of talus and of talus carried downstream for distances of 10, 20, 40, and 80 miles.

The Laboratory Apparatus

Simulation of field conditions requires reduction of scale, reduction in extensiveness of area duplicated or some compromise that is appreciated fully. It was considered that the effect on detritus would be the

same whether turbulent water moved over a stationary bed or a bed moved under almost stationary turbulent water. The latter was easiest to maintain within laboratory confines and was adopted in the experiment. An annular trough of 25 circumference, and slightly over one foot square cross section simulated the stream channel. (Plate I). The motion of the trough to simulate velocity was adjustable from 2 to 14 m.p.h.. The pebbles bounced along on each other as the water moved into the bottom of the rotating annulus and the relative motions were similar to those in a natural stream. The equivalent distance travelled in feet was 25 times the number of revolutions of the wheel.

Limit on Use for Data from Simulated Channel

Exact similitude between field and laboratory conditions would be practically unattainable due to the large number of variables involved, such as initial size proportions of unworn detritus, original angularity of the fragments, type of detritus, exact rate of flow of the current, role of tributaries, fluctuating as contrasted with uniform velocity, and almost too many others to mention. The objective and the results of this experiment need to be circumscribed with qualifications imposed on any mathematical constants given; nevertheless the results improve the interpretive use of mechanical analysis of sediments by at least an order of magnitude.

The Experimental Work Completed

Runs were made for distances of 10, 10, 20, and 40 miles respectively, to give the sample detritus a total equivalent distance of travel of 80 miles.

One additional run of 20 miles was added to the principal sample when it had run 20 miles. The secondary run was added in an attempt to simulate tributary conditions and provide an additional bed load fraction which normally is augmented by the entrance of side streams.

Measurements show that the greatest increase in sphericity occurs in the first ten miles of travel. Graphs showing sphericity of selected mesh sizes, relative to miles travelled, have continuously diminishing slope. Sphericity does show an increase for all mesh sizes down to 200, throughout the entire 80 miles. The coarser sizes reach an equilibrium plateau in the first ten miles of travel. The progressively finer sizes reach their respective plateaux at successively greater distance of travel.

The increase in amount of the silt size components through successive miles of transport seems to remain fairly uniform with a slight diminishing return characteristic. This merely indicates that as wear of a fragment progresses it loses its angularity and presents fewer corners to be knocked off and added to the silt size.

Application to Major Problem

The Shinarump conglomerate had 0.80 sphericity for sizes coarser than 65 mesh and 35% of the fluvial fraction was in silt size or finer. The experimental sediment attained a sphericity of 0.80 for sizes above 65 mesh at about 36 to 40 miles equivalent distance of travel. About 35% of the total charge was reduced to silt size after 28 to 30 miles of travel. The suggestion is very strong that the Shinarump conglomerate at Dirty Devil has been moved about 30 to 50 miles.

Acknowledgements

The problem was undertaken as one unit of a broader project investigating the formation of uranyl salt minerals which was carried on under U.S.A.E.C. Contract AT (30-1)-1172. The work was performed under supervision of Dr. George W. Bain as project director, and Mr. R.E. Schortmann built the apparatus to serve as the simulated stream.

Preparation for Experimental Work

Preparation for the experimental work involved building the apparatus to simulate a river channel, preparation of a source of detritus, devising a scheme for measuring amount of wear relative to distance, and planning a procedure for carrying out the work systematically.

Construction of a Simulated River Channel

A large diameter annular trough was planned to simulate a stream bed, yet compact enough to be housed in a laboratory. The trough was built up out of sections of heavy gauge sheet metal attached by soldered lap joints. The annulus has to be circular within 1/16th inch in order to run smoothly. The sides of the trough were spread one inch per foot and drip flaps were soldered to the inside edges at the small diameter of the trough to reduce drip loss in the inverted position. Twelve cross bars, were added to increase lateral rigidity of the trough, and the six spokes on each side radiating from the axle were bolted into place to put the axle at the exact center of the annulus. This part of the apparatus was held in pillow blocks on rigid supports extending down from above. The entire

surface of rubber and exposed metal was painted with several coats of latex to insure water-tight conditions and metal protection.

The annulus was belt driven on its periphery by a power source consisting of a one horsepower electric motor and a cone pulley system to give controlled variable speeds. The cone pulley system was selected to give six speeds ranging from 2 to 14 miles per hour.

The Detritus Source

Pelham gneiss was chosen because its wearing qualities seemed to approximate the limestone and jasperoid content of the Shinarump conglomerate more closely than any other local rock. This gneiss has bands of foliated schistose rock which, like argillaceous limestone, is somewhat friable just as the granite streaks, like the jasperoid, are very coherent. Micaceous bands predominated over the quartz and granitic rocks.

The gneiss was crushed until no individual fragment was over an inch and a half in diameter, and the size histogram showed a narrow range in amount of material for each standard size group down to the 200 mesh grade (Fig. 3 and Table II). The 4 mesh material includes all the standard sizes from 4 mesh upward; subclassification of that grade showed continuation of uniformity in size distribution.

Measurement Methods

A procedure was established for mechanical analysis of the detritus to estimate amount of wear in terms of distance travelled by measure of size reduction and sphericity increase. This procedure was standardized and followed in the analysis of the original detritus and after every run. The

A-1. Size histogram of original charge

B. Size histogram after 10 miles of travel.

C. Size histogram after 20 miles of travel. (Original charge)

A-2. Size histogram of secondary charge.

D. Size histogram after 20 miles of travel. (Secondary charge)

E. Size histogram after 20 miles of travel. (Combined charges)

F. Size histogram after 40 miles of travel.

G. Size histogram after 80 miles of travel.

Fig. 3. Size histograms of experimental detritus.

detritus was weighed dry before being charged to the trough. After a run it was collected from the trough, dried and weighed and the per cent loss estimated.

SIZE MEASUREMENT. The entire detritus was separated into two fractions; one was over 4 mesh size and the other passed through 4 mesh. Both fractions were weighed to determine their respective percentage of the total weight. The 4 mesh fraction was sized through openings of 19, 14, and 11 mm., each cut was weighed and the percentage of the entire charge calculated. The minus four material was thoroughly mixed, split in a sampler until the volume contained four to six hundred grams. This sample was sized through standard Tyler screens and the fraction caught on each screen was weighed. The ratio of each fraction was used to determine its percentage of the entire charge in the trough, which value was recorded. The average size of the material in a run was estimated by summation of the product of each size and the fraction of the charge having that size. This average value was measured for each test and, except for a discrepancy due to an operational error in one run, shows continuous decrease with elapsed time.

SPHERICITY MEASUREMENT. Sphericity was measured on a sample of 50 grains. Samples were taken from each run from 4, 20, 65, 100 and 200 mesh sizes and the average sphericity for that size at the miles travelled was calculated. Sphericity of each grain of the 50 included in the sample was determined by tracing the projected outlines of the grains on paper, and measuring the area of the projection with a polar planimeter. The

TABLE II. CONSTITUTION OF CHARGE OF CRUSHED GNEISS.

Total weight	8270	gms.	Adjusted weight	8270	gms.	
Weight - 4	3290	"		3290	"	39.8 %
Weight - 4	4980	"		4980	"	60.2 %
Average sphericity for entire charge				0.761		
Average diameter for entire charge				11.37	mms.	
Weight of - 150 size	504	gms.		504	gms.	6.09 %
Sphericity of - 4 material				.778		
Analysis of - 4 material						
Screen size	Grams		% of total weight	Sphericity		
6	643		7.77			
8	635		7.69			
10	573		6.94			
14	502		6.07			
20	388		4.69	.754		
28	380		4.6			
35	322		3.9			
48	309		3.74			
65	276		3.34	.749		
100	254		3.07			
150	177		2.14			
200	124		1.5	.756		
-200	380		4.59			

REMARKS: The histogram shows fairly uniform distribution of sizes with some decreasing abundance of the smaller mesh sizes.

radius of the circle of area equivalent to the area of the grain divided by the radius of the circumscribed circle is the coefficient of sphericity.

The average sphericity of a charge was calculated from summation of the products of the sphericity coefficient and that fraction of the mass of the total charge which it represents. For purposes of calculation, the sphericity value determined for a size was considered to extend to all sizes up to the next determined value. Also the value for the 200 mesh was applied also to the - 200 mesh portion.

Operational Procedure

The operational procedure consists simply of placing the sediment in the annulus of the wheel, covering it with a foot of water, and then letting the wheel run for the number of revolutions, recorded on a comptometer, to give the prescribed distance in miles. The detritus is collected from the wheel, and dried. The wheel itself is allowed to dry and the adhering silt is brushed out for the addition to the remainder of the dried load.

The most difficult mechanical aspect of the operations were precautions for recovery of not less than 96% of the detritus. During the 10 miles per hour runs an appreciable amount of the coarse material bounced out of the trough; except during the first run, almost all of this material was caught in a large catch basin set underneath the trough, recovered and returned to the trough before any significant mileage loss was incurred.

The coarse material was merely scooped out of the annulus by hand at the end of a run and set aside in porcelain pans to dry before analysis. The finer sizes were settled in a thick mud, after the wheel stopped, and this

was scooped out and set aside to dry. Much silt was left in suspension in the water and this was siphoned into the catch basin where it was allowed to settle, and the clear water was siphoned off; the material was left to dry. The loss of nearly 2000 grams by the end of the first twenty miles of travel is explained partly by negligence on the part of the experimenter in not allowing the fine material sufficient time to settle out of its suspended state, and partly by loss of material before the catchment basin was installed as a check to material thrown by the wheel.

The tendency of even coarse material to leave the trough at high speeds of travel, caused reduction of equivalent rate of speed used to 4.9 miles per hour after the first two runs. This speed was maintained over the next 20 miles of movement. During the second 40 miles of wear the speed was reduced, and held constant at 2.5 miles per hour.

The type of flow in this simulated stream-bed is quite similar to that present in turbulent streams. The greatest speed of current by back flow of water occurs in the middle of the trough, and here also is the greatest movement of detritus.

Certain limitations on the results of this experiment have been imposed by the operational procedures, or by error therein. The loss of fines and other sizes incurred while collecting the detritus from the trough after the first ten miles of travel, had a definite effect on the calculated size ratios and this effect carries on in diminishing degree throughout the 80 miles of travel, to reduce the figure representing the proportion of fines present. Sphericity values, determined on 50 grains from each selected

mesh size gives only a close approximation to true average sphericity for that size. Plotting of sphericity for the different mesh sizes against the distance travelled, produces anomalous minima on graphs whereas sphericity was expected to increase progressively with distance travelled; the anomalies are very minute but they appear to be errors in sampling rather than true anomalies.

Experimental Operation - Data Gained

Mechanical analyses of the detritus were made for sphericity, size ratios, and selective disintegration of different types of rock after equivalent travel distances of 0, 10, 20, 40, and 80 miles. The calculations for sphericity and size ratios were summarized in tables and then plotted on graphs in order to compare them.

General Features

The size features treated in this presentation are size distribution compared with initial average diameter of the entire charge, average diameter after successive runs, average diameter and change in size distribution as a function of distance travelled and average size reduction as a function of distance travelled. Sphericity is analysed from the viewpoint of sphericity increase with respect to initial average sphericity of the entire charge, average sphericity for the entire charge after successive runs, average sphericity increase as a function of distance travelled and extension of the sphericity plateaux in finer sizes as a function of distance travelled.

The features of size distribution and sphericity distribution, as a func-

TABLE III. CONSTITUTION OF FIRST CHARGE AFTER 10 MILES RUN.

Total weight	6401.2 gms.	Adjusted weight	8270 gms.	
Weight - 4	2991.2 "		2991.2 "	
Weight - 4	3410 "		5279 "	36.2 %
Average sphericity for entire charge			0.802	
Average diameter for entire charge			-	
Weight of - 150 size		Adjusted weight	2662	
Sphericity of - 4 material			.812	
Analysis of - 4 material				
Screen size	Grams	% of total weight	Sphericity	
6	526	8.21		
8	403	6.30		
10	320	5.00		
14	260	4.06		
20	206	3.25	.809	
28	148	2.30		
35	125	1.96		
48	128	2.00		
65	143	2.23	.795	
100	178	2.78	.793	
150	180	2.81		
200	183	2.86	.765	
- 200	610	9.52		

REMARKS: Loss in recovery, of 1869 grams, largely in the fines, explains percentage increase of coarse - 4 material before adjustment. The histogram shows greatest proportional wear incurred by the middle range, around 35 mesh size. Reduction of sizes smaller than this show increase in weight. Most of the loss is believed to have been in - 150 mesh size.

TABLE IV. CONSTITUTION OF FIRST CHARGE AFTER 20 MILES RUN.

Total weight	6385	gms.		Adjusted weight	8270	gms.	
Weight - 4	2425	"	38 %		2425	"	29.4 %
Weight - 4	3960	"	62 %		5845	"	70.6 %
Average sphericity for entire charge					0.790		
Average diameter for entire charge					6.52	mms.	
Weight of - 150 size	1366	gms.		Adjusted weight	3235	gms.	
Analysis of - 4 material							
Screen size mms.	Grams		% of total weight		sphericity		
19	1529		23.9		.816		
14	319		5		.816		
11	188		2.95		.816		
4.7	389		6.1		.816		
Analysis of - 4 material							
6	576		9.02				
8	459		7.19				
10	356		5.58				
14	218		3.42				
20	108		1.69		.789		
28	84.3		1.32				
35	62.2		.97				
40	80.5		1.26				
65	118		1.85		.803		
100	235		3.68		.797		
150	296		4.63				
200	356		5.58		.770		
-200	1010		15.8				

REMARKS: Loss of detritus is negligible in this run and hereafter and only adjustment is for loss in previous run. Mesh sizes 6 through 10, and 150 through -200 had weight added to them, while in other sizes loss exceeds transfer to them. Again the greatest proportional wear appears in the middle size around the 35 mesh grade.

TABLE V. CONSTITUTION OF SECOND CHARGE OF CRUSHED GNEISS.

Total Weight	10700	gms.	
Weight - 4	8060	"	75.3 %
Weight - 4	2640	"	24.7 %
Average sphericity for entire charge			.761
Average diameter for entire charge			11.37
Weight of - 150 size	247	gms.	2.3 %

Analysis of - 4 material

Size in mms.	Grams	% of total weight	Sphericity
19	4527	42.35	
14	1322	12.35	
11	548	5.12	
4.7	1659	15.49	

Analysis of - 4 material

6	340	3.18	
8	337	3.15	
10	304	2.84	
14	266	2.49	
20	205	1.92	.754
28	202	1.89	
35	171	1.60	
48	164	1.53	
65	147	1.37	.749
100	135	1.26	
150	94	0.88	.756
200	66	0.62	
-200	201	1.88	

TABLE VI. CONSTITUTION OF SECOND CHARGE AFTER 20 MILES RUN.

Total weight	10700		
Weight - 4	5971.7 gms.	55.8 %	
Weight - 4	4728.5 "	44.2 %	
Average sphericity for entire charge		-	
Average diameter for entire charge		7.31 mms.	
Weight - 150 size	3320 gms.		

Analysis of - 4 material

Size in mms.	Grams	% of total weight	Sphericity
19	1861	17.4	
14	1772	16.55	
11	726	6.78	
4.7	1618	15.1	

Analysis of - 4 material

6	369	3.44	
8	199.5	1.86	
10	108.5	1.16	
14	63.4	.59	
20	36.4	.34	
28	22.9	.21	
35	15.6	.15	
48	26	.24	
65	48.7	.45	
100	180	1.68	
150	325	3.02	
200	330	3.18	
-200	2990	27.9	

TABLE VII. CONSTITUTION OF COMBINED CHARGES AFTER 20 MILES RUN.

Total weight	17070 gms.	Adjusted weight	18945 gms.	
Weight - 4	8396.7 "		8402 "	44.5 %
Weight - 4	8673 "		10543 "	55.5 %
Average sphericity for entire charge			.801	
Average diameter for entire charge			7.02 mms.	
Weight - 150 size	-	Adjusted weight	6565 gms.	34.6%
Analysis of - 4 material				
Size in mms.	Grams	% of total weight	Sphericity	
19	2585	15.15 %	.816	
14	2459.7	14.39	.816	
11	1118	6.05	.816	
4.7	2239.3	13.10	.816	
Analysis of - 4 material				
6	945	5.54		
8	658.5	3.86		
10	464.5	2.72		
14	281.4	1.65		
20	144.4	.85	.789	
28	107.2	.65		
35	77.8	.46		
48	106.5	.62		
65	166.7	.98	.803	
100	415	2.43	.797	
150	621	3.64		
200	686	4.02	.770	
-200	4000	23.45		

REMARKS: In this combination of secondary and original charges, all sizes had their weight increased, except the 19 mms.; greatest proportional increase was in 4 to 10 mesh and 65 to - 200 mesh.

TABLE VIII. CONSTITUTION OF COMBINED CHARGES AFTER 40 MILES RUN.

Total weight	17063.8 gms.	Adjusted weight	18945 gms.	
Weight - 4	6162.4 "	6162 "	32.5 %	
Weight - 4	10901.4 "	12783 "	67.5 %	
Average sphericity for entire charge		.802		
Average diameter for entire charge		4.62 mms.		
Weight - 150 size	8153 gms.	10022 gms.	52.9 %	

Analysis of - 4 material

Size in mms.	Grams	% of total weight	Sphericity
19	1747.1	10.23	.812
14	1596.7	9.35	
11	654.3	3.83	
4.7	2164.3	12.7	

Analysis of - 4 material

6	954	5.69	
8	552	3.24	
10	337	1.98	
14	187	1.10	
20	117.7	.69	.812
28	53	.31	
35	35.3	.21	
48	41.2	.24	
65	48.3	.28	.794
100	174.6	1.02	.798
150	246.7	1.44	
200	972.8	5.70	.788
-200	7180	42.1	

REMARKS: Mesh sizes 6, 200 and -200 have had weight added to them, and in all other sizes loss exceeds additions. Extensive wear occurring in the 19 and 14 mm. sizes of - 4 mesh, and in the 35 mesh size of the sands, has practically eliminated them.

TABLE IX. CONSTITUTION OF COMBINED CHARGES AFTER 80 MILES RUN.

Total weight	17021.8 gms.	Adjusted weight	18891 gms.	
Weight - 4	5118.7 "	5119 "	27.1 %	
Weight - 4	8152.8 "	13772 "	72.9 %	
Average sphericity for entire charge		.807		
Average diameter for entire charge		3.57 mms.		
Weight - 150 size	10258 gms.	12127 gms.	64.3 %	

Analysis of - 4 material

Size in mms.	Grams	% of total weight	Sphericity
19	1212.6	7.12	.816
14	1255.6	7.37	.815
11	549.3	3.22	.815
4.7	2101.2	12.34	.815

Analysis of - 4 material

6	680	3.99	
8	395	2.32	
10	221	1.30	
14	109.7	.64	
20	60.3	.35	.820
28	30.5	.18	
35	15.4	.09	
48	14.0	.08	
65	31.5	.18	.821
100	32.9	.19	.806
150	61.3	.36	
200	1054	6.19	.798
-200	9204	54.1	

REMARKS: Only 200 and - 200 mesh sizes have increased in weight. The minimal point on the histogram has shifted from the 35 mesh size to the 48. Average sphericity and the sphericity of all sizes continues to increase gradually with highest sphericity values falling in the 20 to 65 mesh range.

tion of miles travelled are found in Tables II through IX while the other features mentioned are treated under remarks given below the tables.

Eighty miles of travel caused almost full elimination of the original sand size detritus and a transfer of a significant part of the coarse gravel size to the silt size as is evident from examination of the histograms (Figure 3). The average size diminished to 31.4% from 11.37 mms to 3.57 mms. Between 0 and 80 miles the 4 mesh fraction declined to 45% from 60.0% to 27.1 and the -150 mesh fraction rose 16 1/4 fold from 3.96 to 64.3%; values of size reduction at less than 20 miles are approximated from the tributary fraction because of inadvertant loss as mentioned previously.

The sphericity improved as size was reduced. No size class of fragments had attained maximum sphericity after 10 miles of travel. The 4 mesh size was rounded after 20 miles of travel and even the 20 mesh sand had come to the roundness plateau after 40 miles. The plateau grade of sphericity included the 65 mesh but not the 100 mesh after 80 miles of travel. Ten miles of travel raised the average sphericity from .761 to .802 but improvement per mile was little thereafter due to the increase in low sphericity fines. It appears now as though average sphericity does not increase appreciably after 10 to 20 miles of travel and that improvement essentially ceases below a selected size; below this size the angular fines in stream load are removed in suspension. If the -200 mesh fraction of the detritus which travels in suspension is excluded, sphericity shows a continuous but slow improvement (Table XI). The sphericity for the +200 mesh size was compared at different distances of travel by plotting on both regular and log-

coordinate paper; it was found that the relationship was not simple. A number of trial combinations revealed finally that $\phi - \frac{\sqrt{\text{miles}}}{10}$ plotted against the square root of the distance in miles gave a straight line graph. (Figure 7). Mathematically this graph can be expressed as:

$$\frac{\phi^2 - \frac{\sqrt{\text{miles}}}{10}}{\sqrt{\text{miles}}} = K$$

ϕ - Sphericity

K - Slope of the graph.

Initially sphericity improves greatly in proportion to distance travelled but continued improvement becomes increasingly slow and difficult. The constant "K" can be expected to decrease as the coherence of the rock increases.

Analysis and Interpretation of Data

The data show that milling in transit is highly selective for rock type and that coherence varies greatly. The size reduction is a conspicuous feature, but due to heavy loss in the initial runs, quantitative evaluation of the data on selective effect on rock type is not feasible and the results generally are discussed on a purely qualitative basis. Sphericity is affected only slightly by losses; this source of information has been emphasized previously and will be considered again at length in this section.

Selectivity for Rock Type

Two types of rock constituted the gneiss in this experiment; one was essentially coarse granite, and the other was a slightly foliated micaceous gneiss. Each type of rock reacted in its own characteristic fashion to

stream wear.

The non-cleavable massive granite bands, having essentially the same strength in all directions, approached a high degree of isometric sphericity. The micaceous sort formed ellipsoidal pebbles flattened parallel to the foliation plane and had a fair degree of sphericity only along the plane of its "a" and "b" axes; even in this plane the pebbles are ellipsoidal, rather than spherical. The abundance of this foliated type of rock exerts a strong influence in lowering the sphericity of the total charge.

The granite is the more refractory of the two rocks. Granite and the gneiss were approximately equally abundant in the original material in the 4 mesh sizes but granite comprised 70% of these sizes at the end of the 80 mile run. The -4 mesh sizes show the gneiss dominant. Evidently the coarse gneiss has been broken up, and reduced in size, with the resultant fragments increasing the gneiss fragment proportion in the smaller grades.

A breakdown of the -4 material shows schistose rock fragments dominant over the quartz and granite fragments down to the 35 mesh size. Quartz and alkali feldspar grains constituted most of the detritus from the 35 mesh size to the 65 mesh size. Mica fragments begin to appear in abundance through the smaller sizes and represent over half of the minerals present in the -200 mesh size; muscovite is about twice as abundant as the biotite.

The differential rates of wear and sphericity increase measured for these two rock types indicate that the experimental data represents a

mean value. All of this points to the fact that type of detritus used exerts a strong influence on size reduction and sphericity increase during stream transport and that mathematical constants need to be determined for a wide range of rock types before a definite value for distance to source can be offered on the basis of mechanical analysis of the detritus.

Size Reduction - Mileage Scale

The high proportion of the -150 mesh size to the large sizes, in the Shinarump conglomerate, draw special attention to the buildup of the -150 size during the course of this experiment. Data for this particular feature of the experiment are found in the preceding tables and figure 4 shows the percentage of the total weight of the -150 size plotted against the miles travelled. All values are adjusted for the loss of fines in the first 20 miles of run.

The amount of fines produced seems to progress at only a slightly diminishing rate up to the 40 mile distance, where it composes 52.9 percent of the detrital mass. Beyond this point the amount of -150 mesh material produced begins to show a drop, but at 80 miles its mass had increased to 64.4% of the total. This is to be expected as the rocks continue to be worn through successive miles of travel, and the corners and small projections are knocked off. Antilog. of % -150 increases approximately proportional to the logarithm of the distance travelled. (Fig. 4).

The greatest proportional wear appears to take place in the middle sizes around the 35 mesh. This middle size rock is apparently too large to be carried in suspension, heavy enough to have considerable force of

Fig. 4. Production of -150 mesh size relative to distance of travel.

TABLE X. SIZE CHANGE RELATIVE TO DISTANCE TRAVELLED.

Miles of travel	0	10	20	0	20	20	40	80
Charge	Primary	Primary	Primary	Secondary	Secondary	Combined	Combined	Combined
Total Wt. grams	8270	6410	6385	10700	10700	17076	17064	17022
Adjusted weight*	8270	8270	8270			18945	18933	18891
Grams - 4	3290	2991	2425	8070	5972	8402	6162	5119
Grams - 150	504	793	1366	247	3320	4686	8153	10258
Av. diameter			6.52	11.37	7.31	7.02	4.62	3.57
% total in - 4	39.8	36.2	29.4	75.2	55.8	44.5	32.5	27.1
% total - 150*	6.1	32.2	39.2	2.3	31.0	34.6	52.9	64.3
Av. diam. - 4				14.7		13.48	11.81	11.0
Av. diam. - 4			0.771			0.735	0.553	0.37

* Adjusted for loss during first ten miles of travel of primary charge.

TABLE XI. SPHERICITY CHANGE RELATIVE TO DISTANCE TRAVELLED.

Miles of travel	0	10 *	20	0	20	20	40	80
Charge	Primary	Primary	Primary	Secondary	Secondary	Combined	Combined	Combined
Av. sphericity.	.761	.802	.790			.801	.802	.807
Sphericity - 200	.761	.803			.807		.809	.813
ϕ^2	.579	.645			.651		.654	.661
$\phi^2 - \frac{\sqrt{\text{miles}}}{10}$	.591	.329			.204		.022	-.233

* Heavy loss of low sphericity fines affects average sphericity and raises value considerably.

impact and yet small enough to be caught between rocks of greater size and mass where it is nipped and crushed. The histogram minimum at the 35 mesh size (Fig. 3) is due partly to turbulence controlled by current velocity; slowing the current to 2.5 miles an hour, shifted the minimum point to the 48 mesh size as the size of particles capable of remaining in the suspension load diminished. Identification of the minimum point on the histogram as a function of current rate, may be useful in calculating rates of flow of a stream at varying distances from the stream source but its use will be handicapped by selective removal of the fines fraction and the minimum point may have to be identified indirectly by other characteristics. The addition of the tributary supply after 20 miles might be expected to have some significant effect upon the wear of the detrital material, but analysis shows no outstanding change in size proportions or sphericity increase. However the average diameter takes a pronounced drop from 7.02 mms. to 4.62 mms. during the travel from 20 to 40 miles, and the -150 mesh material increased abnormally after this new supply was added. Average diameter values for the first 20 miles of travel of the original detritus cannot be used due to loss of 2000 grams between the first and second ten miles of travel and to lack of subclassification of the -4 mesh fraction. Addition of detritus results in an increase in wear and production of fines somewhat in proportion to the mass of the added material.

The average diameter of the tested sediment drops from 7.02 mms. at 20 miles, to 3.57 mms. at 80 miles, a total decrease of 3.45 mms. over

Fig. 5. Variation in average diameter relative to distance of travel.

Fig. 6. Variation in sphericity relative to miles travelled and for selected sizes.

60 miles distance, and an average decrease of 0.06 mms. per mile of travel; however the rate between 20 and 40 miles is almost five times that between 40 and 80 miles. Generally the square root of the diameter diminishes almost uniformly relative to the logarithm of miles of travel. (Figure 5).

The Sphericity of Selected Sizes

In interpreting the values of sphericity, uncertainty exists whether an average sphericity of 50 grains for each selected size will give a true representative sphericity for that size. This number appears to be insufficient, for when sphericity is plotted against miles travelled for each of the five selected sizes (fig. 6), the graphs show irregularities which seem anomalous. A graph for the average sphericity of all sizes, drawn between the plotted points, appears to give a fairly true representative picture of what is happening to the sphericity of these rocks as they progress through successive miles of wear. It conforms to an exponential equation. (Fig. 7).

The graph for sphericity plotted against miles of travel shows diminishing rate of change per mile of travel in the + 200 mesh sizes. The + 4 mesh material improves its sphericity quite rapidly from .778 at 0 miles to .812 in the first ten miles at an average increase of .0034 units per mile. The rate diminishes thereafter and for the next 70 miles the average increase is too low to be critical. The 20 and 65 sizes show somewhat similar variation, though the sphericity shows reduced rate of improvement per mile as finer sizes are studied. At decreased velocity of travel, higher sphericity values appear in material of size around the mini-

Fig. 7 . Variation in sphericity relative to miles of travel, plus 74 micron sizes.

imum of the size histogram at 80 miles rather than in the + 4 size group; there is a suggestion that velocity of travel, size and sphericity are interrelated. The + 200 mesh size graph for sphericity plotted against miles traveled shows sphericity improvement at much slower rate in the first ten miles than for the remaining distance of travel. Very little improvement in sphericity of the - 200 mesh size above the .765 value was expected when this experiment was undertaken; this is not valid but sphericity improves slowly when velocity is diminished to allow this material to enter the bed load.

Average sphericity

The average sphericity seems to behave much like the sphericity for individual selected sizes, in that it improves with distance travelled but at a diminishing rate. The square of the sphericity improves approximately proportional to the square root of the miles travelled (fig. 7). The average rate of improvement is a not too complex mathematical exponential function. (See p.71) Experimental constants can be measured for rock types, for water velocity, and for either average size or any specific size range of detritus.

The experimental data indicate that sphericity induced by stream transportation seems to approach 0.82 irrespective of the original sphericity or the rock size selected for study. The value appears at shortest distance of travel in the coarser sizes and is attainable only by pieces in the bed or saltation load.

Summary and Conclusions

This summary includes a summation of the facts learned, a list of obvious additional work essential to develop this exploratory research to a practical technique of investigation, and refers to manipulation techniques which should be avoided.

Facts learned

1. Rate of improvement in sphericity and reduction in size differs so much for granite fragments in comparison with those of gneiss that numerical values must be assigned to only the particular type of detritus tested. (P. 72). The relative rates of change would seem to apply to all materials and could be applied generally after the essential constants were determined experimentally for each rock type.

2. Comparison of the histograms, and sphericity measurements with those of the Shinarump conglomerate suggests that the Dirty Devil deposit was moved about 30 to 50 miles from its source. The difference between the rock studied experimentally and the Shinarump detritus leaves this estimate subject to revision, probably to a slightly greater distance.

3. The improvement of the average sphericity of the total + 200 size (p. 71 and 81) is given by the following equation:

$$\phi^2 - \frac{\sqrt{\text{miles}}}{10} = K$$

ϕ - sphericity

K - constant

4. No improvement in sphericity could be identified unless the frag-

ments had formed a part of the bed load. Transfer from suspension to bed load is attained experimentally and in nature by variation in stream velocity across the width of the channel. All sizes have a threshold velocity above which sphericity does not increase (p.79).

5. The sphericity limit in stream transport seems to be about 0.82.

6. The distance of transport to attain maximum sphericity bears a reciprocal relation to size. Tentatively the product of cube root of the diameter and square root of the distance travelled have a constant value where sphericity attains plateau level. (Fig. 6)

7. Size reduction eliminates the finest material which will stay in the bed load (p. 75), and the histograms show that it disappears from the load. This feature of the histogram affords a method of estimating bed velocity of a stream which formed a particular sediment.

8. Production of suspension size particles occurs partly by removal of projections on large pieces and partly by nipping of the near suspension sizes between large fragments. The first method causes normal size transfer downward. The second eliminates a size grade. (P. 76).

9. The 28 mesh size was the threshold size for 4.5 miles per hour stream velocity and the 35 mesh size became the threshold at 2.5 miles per hour bed velocity.

10. Increase in the -150 mesh or the suspension fraction diminished slightly with each mile of travel. The antilog. of per cent of the load in the -150 mesh size, plotted against the logarithm of miles travelled is approximately a straight line (p. 74). This indicates an exponential rate

to decrease in production fines per mile of travel.

11. The square root of average diameter diminishes approximately uniformly with the logarithm of distance of travel (P 77).

Additional study.

1. A wide variety of rocks needs study and it is suggested that massive sorts will lend themselves to analysis better than the banded ones used in this investigation.

2. The effect of velocity upon size at which grinding is relatively complete needs investigation by running a full mileage series at one speed of travel.

3. The mathematical constants to be substituted in the equations for average sphericity in terms of miles travelled, for production of fines in terms of miles travelled, and for reduction of average diameter in terms of miles travelled, would be very valuable to interpretation of remoteness of the derivation site for detritus in sedimentary formations.

Manipulation.

1. Provision should be made both to recover all material spilled from or formed in the experimental apparatus after each mile of travel and also to return it to the trough.

2. The speed of the current should be adjustable to one mile increments from $1\frac{1}{2}$ to $12\frac{1}{2}$ miles per hour.

3. The initial charge should have an almost completely random distribution of sizes to provide at least ten particles of each size from pebbles to clay.

4. A double run should be made of all early mileage tests in order to have an adequate supply of prepared material to replace the amount passed into the fines. A minimum bed load in the apparatus is essential.

5. Use of 50 grains for a sphericity measurement may be inadequate. It is suggested that 100 be used in future measurements and that these be studied in two lots of 50 to determine the minimum necessary to give reproducible results.

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SITES FOR HEAVY MINERAL ACCUMULATION IN FLUVIAL DEPOSITS

Introduction

This experimental study undertakes a detailed laboratory investigation and analysis of the features, characteristics, and patterns of development of an intermittently flowing stream, and the sites of deposition of heavy mineral therein. The results are based almost exclusively upon work done in the laboratory under controlled conditions and are correlated with field occurrences only through available descriptions. The laboratory patterns of form at reduced size of grain, and frequency distribution, are so similar to those of nature that approximate simulation may be assumed to have been attained. The shift of channels was mapped in detail after each flood stage and the redistribution of heavy minerals from the original source and from secondary sources in the channels was surveyed. Careful record was kept of the conditions producing any shift. Finally the size redistribution of detritus was measured by screen analysis at the end of the experiment. Some local concentrations of heavy minerals were so significantly different from the average as to constitute a simulated mineral deposit.

Definition of Terms

The terms used in the description of this simulated occurrence are essentially those in current use if reduced scale is considered in the real prospective. Some are used in a more liberal sense, others in a more restricted one and many are circumscribed by limitations.

Fig. 8. Arrangement of equipment for study of fluvial deposits of heavy minerals.

A mineral deposit is a local occurrence of useful or desirable minerals in recoverable form and in a quantity significantly more than the average per unit area of the earth's surface. A placer deposit is a mineral deposit formed through the selective deposition and concentration of minerals of high specific gravity by moving water. The term - heavy mineral - implies a high specific gravity; minerals having a specific gravity of four or greater are generally described as heavy minerals. A significant concentration of heavy minerals, samarskite in this experiment, can be defined as a concentration representing a departure from the average which is at least twice the amount detectable as above average.

The term intermittent stream as employed in the context of this project can be defined as a stream that has negligible surface flow at one time alternating with high water or flood conditions at irregular intervals.

Inhomogeneous Distribution of Heavy Minerals.

All known placer deposits such as the high level gravels of the Klondike (McConnell) and the Tertiary gravels of the Sierra Nevada (Lindgren) show an inhomogeneous distribution of heavy minerals along channels and resultant concentrations at certain sites of deposition. This inhomogeneous distribution of heavy minerals suggested this experiment in the hope that a detailed analytical study of placer formation under observable and controlled conditions might increase understanding of this type of deposit.

Equipment and Materials Assembled for Investigation

This experiment was carried out on the floor of a former indoor swimming pool. A 10 1/2 by 60 foot area of the tile floor was enclosed by 2 by

12 inch wooden planks to form a large "box" with sides 12 inches high. (Fig. 8). This area was filled with a base material of glacial lake silt to constitute the bed of the stream and the highlands source of water and silt. The texture of this base material is represented by the size histogram F. (Fig. 9)

The uranium bearing mineral samarskite was selected as the heavy mineral to be employed in this experiment on the basis of its suitable physical properties. Samarskite is radioactive, is very coherent, has a specific gravity ranging from five to six, and does not decompose easily. The mineral was crushed to 150 microns diameter.

A Victoreen geiger-counter survey meter, model 263A, with modified probe was used to measure the relative density of the samarskite in the experimental area.

Acknowledgements

This work was done as part of a project to study formation of uranyl salt minerals, carried out under U.S.A.E.C. Contract AT(30-1)-1172, and involved one phase of investigation into deposition of the environmental sediments. I would like to express appreciation and gratitude to Dr. George Bain whose advice, organization of equipment and materials, and supervision made this experiment possible. Gratitude is also extended to Mr. Sanborn Partridge for contributing scientific equipment and advice in photographing the features of the experiment.

Scale Reduction for Laboratory Study

Experimental simulation of a natural process requires proportional

scale reduction with due consideration for each factor affecting the ultimate structure. In this investigation of alluvial deposits, stream size and slope must be so reduced as to give proper scale reduction to transporting power at both ebb and flood, and the particle size must be scaled down to correspond with this competency to move fragments. Furthermore a range in size within the silts must exist to provide variable load characteristics.

Laboratory Limits on Dimensions

Working space available for this particular experiment measured 10 1/2 feet by 60 feet. Therefore it was necessary to scale down distance extensively to include in this area a simulated mountain range and a complete river system. The reduction was made on the basis outlined by (1) Hubbert

Relations of Particle Mass to Water Velocity

The relationship between the diameter of a particle of quartz and the velocity of a stream that will move it is expressed as follows:

$$D = CV^2$$

D = Diameter of the particle.

C = Constant.

V = Velocity of the water.

The average velocity of the stream in this experiment was calculated to be 156 mms. per second. The size of a particle of quartz that this velocity would move was found to be 0.10 mms. in diameter. Since samarskite is more than twice as heavy as quartz, velocity change from flood to ebb or from place to place in the channel would have to fluctuate widely

for samarskite particles to be carried by the stream.

Relation of Water Velocity to Slope and Stream Size

Bazin's formula gives a relationship between water velocity, slope, and size of a stream:

$$\text{Velocity} = \frac{87\sqrt{rs}}{0.552 + \frac{c}{\sqrt{r}}}$$

s = Slope.

r = Hydraulic mean depth.

c = Roughness of the stream bed

It can be seen that velocity varies in proportion to both slope and size of the stream. The slope remains reasonably constant but the hydraulic mean depth having a greater proportional influence changes from place to place and with ebb or flood stage.

Items Subject to Scale Modification

The following aspects can be considered subject to scale modification:

1. stream dimensions.
2. size of detritus.
3. grade.
4. raindrop size.

All of these items are integrally related. The size of detritus carried by the stream has been shown above to be dependant upon velocity which in turn is dependant upon grade and stream size. The size of detritus carried is also directly proportional to the amount of water delivered to the system, or the raindrop size. Therefore a compromise among these variables was of importance in setting up the scale model used in this experiment.

The Final Compromise.

SIZE OF DETRITUS. A silt was selected as the principal base material. A size histogram shows that more than 50% of this silt was smaller than 0.150 mms. in diameter. (Fig. 9). The maximum particle diameter of the heavy mineral component employed was 0.1 mms. in diameter and most of the samarskite was reduced to less than 0.074 mms. in diameter. This data is the same for the quartz which was mixed with the samarskite to form the mineral vein.

SLOPE TO THE SYSTEM. The slope of the surface of the project was about 5 per cent. Locally this was about 10 times as great in the highland region.

RAINDROP SIZE. The volume of the average raindrop produced by the fog nozzles was estimated to be 1.762×10^{-5} cubic centimeters in contrast with a normal raindrop size of about 10^{-3} cubic centimeters. The two fog nozzles used in the experiment delivered jointly 7260 drops per minute per square centimeter on the surface of the project.

THE NATURAL RIVER CROSS SECTION. The experimental stream was measured at several different places down the course of the channel. The average cross section of the valley where the stream was not aggrading was found to be 50 mms. wide and 2 mms. deep. The stream channel itself was only 25 mms. wide and about 2.0 mms. deep. Variations in river cross section will be discussed under Experimental Results.

Comparison of Simulated and Actual Rivers

The mountain range built up from the base material in this experi-

ment was terminated abruptly at a lowland plain in the manner of block faulted mountains. The area exposed to the fog nozzles was equivalent to the rainforest slope. After each period of rain, the exhaust fan was switched on and warm air passed over the project to allow the stream channels to desiccate in varying degrees in order to simulate wet and dry seasons. A naturally occurring river with characteristics comparable to the experimental stream would be in a dry or seasonally dry climate. Its water originates in mountainous country, would be subject to high and low water conditions or no flow at all dependant upon rainfall in the mountains and would be classed as an intermittent stream. These conditions and this type of stream are common to the principal area of the world which lies between the tropical rainforest and the northern forest regions

Procedures Adopted in the Experiment

Planning and execution of the experiment required preparation of a suitable base of detritus, inlay of a heavy mineral band simulating a vein, laying out a reference coordinate system for the area, devising methods for measurement of the heavy mineral content of the stream deposits and setting up a systematic arrangement of the records. The details of the scheme follow.

Preparing the Base.

The material used for the base in this experiment was glacial silt with a rather uniform distribution of sizes from 1.65 mms. down to

0.04 mms. The size distribution in this material is shown on the histograms. (Fig. 9). The silt was spread out in the area used for the experiment and dried. A heavy lawn roller and rake were used to break up clods and reduce the base to individual particles. A portion of the silt was then arranged at the upper end of the project to simulate a scaled-down mountain range. The height of the base here averaged about 30 cms. The remaining portion of the material was spread out from the mountain range to the lower end of the project in a blanket varying uniformly from an 8 cm. thickness immediately adjacent to the mountains to a 3 cm. thickness at the lower end of the project. (Fig. 8).

Inlay of the Heavy Mineral Source

The mineral vein was introduced into the system after the two fog nozzles had been turned on long enough for the water runoff to confine itself to several main channels. The mineral vein was placed transverse to these main channels.

The durable, radioactive, and heavy mineral samarskite used in this experiment was first reduced to particles 0.074 mm. in diameter and smaller by means of a ball mill and screens. The samarskite was diluted to 20 per cent with pure quartz sand of the same size to make the simulated vein fill. Two metal sheets one meter in length were forced down into the base material of the mountain range to a depth of about 25 cms. and then spread 2 cms. apart in the center. The mixture of quartz and samarskite was poured between them. Removal of the metal sheets then left a "vein" of samarskite and quartz subject to interception by headward erosion from

Fig. 9. Size histograms of alluvium in the experimental channel.

the main stream channels.

The Coordinate System

An accurate and efficient coordinate system was devised for measurement of the patterns of stream development and heavy mineral migration. The wooden planks bordering the area on both sides were marked at 30 cm. intervals. (Fig. 8). Several 2 by 12 inch planks were placed across the project and rested loosely upon the side-boards for easy movement; these served for access to the various parts of the project, and were marked at 30 cm. intervals. The side-boards and cross planks provided a convenient 30 cm. coordinate system for easy transfer of the features of the system to coordinate paper.

Measurement of Heavy Mineral Content

The distribution of samarskite or heavy mineral was estimated by use of a Geiger counter with the probe tube shielded by 2.5 cms. of lead except along a narrow slot at one side of the lead cylinder. This eliminated 90 per cent of stray radiation and made the instrument highly directional and almost quantitative in estimation of content. The portable counter tube was attached to the survey meter by a four foot cord to permit facile traversing over the surface of the project. The first three sets of readings were taken by holding the counter at the height of the cross plank, 20 cms. above the surface of the project, moving it along the plank, and recording readings every 15 cms. Later this system was abandoned in favor of holding the counter as close to the surface as possible.

Keeping Records

Records included fog nozzle discharge time, intermittent or periodic nature of the discharge, charting a redistribution to radioactivity and mapping of the shifting stream channels.

The fog nozzles were allowed to run for periods ranging from a few minutes to one hour and the running time was recorded. After 3 hours discharge, the water was shut off and the stream channels and alluvial fans were mapped carefully by means of the coordinate system mentioned above.

The Geiger counter was then used to estimate the radioactivity at points 15 cms. apart both laterally and down the length of the stream channel. Areas between these points were scanned for radioactivity but were mapped only if a significant deviation was detected. The radioactivity map was superimposed upon the map of the stream. The maps were combined and transferred to transparent sheets for facile comparison and correlation with results of other 3 hour runs. (Figures 10 to 20).

In addition to the systematic mapping at 3 hour intervals, notes, sketches, and radioactivity readings were made frequently throughout the duration of each 3 hour period to assist recording and understanding specific features of both stream pattern development and heavy mineral movement. Graphs were prepared from these charts to show the downstream redistribution of heavy minerals in relation to elapsed time.

Photographs were taken of specific features at intervals. After 30 hours of rain, photographs were also taken in sequence to show the pattern of the stream in panorama.

Ten gram samples of detritus were collected from six areas along the stream channels after 30 hours of rainfall and size histograms were prepared. (Fig. 9).

Preparation of Summaries

The maps of each 3 hour period were studied individually and comparatively with regard to stream patterns, heavy mineral distribution, and concentration sites. These were correlated with the notes and sketches made between periods of mapping, with the charts indicating the movement of heavy minerals downstream, and with photographs. The information derived from these experimental results was then applied, with due regard for scale, to a study of natural occurrences.

Experimental Results

The experimental results relate partly to development of stream patterns under controlled conditions but mainly to distribution relationships of heavy minerals to source and the stream pattern features. Some general features of the distributional associations are outlined first in order to give coherence to the data on modifications attended by outstanding concentrations which are described later in the text.

General Distribution of Heavy Minerals

The heavy mineral migration with elapse of time is recorded in the tables and shown on graphs of figures 21 and 22. The radioactivity units on these charts are in milliamperes taken directly from the survey meter; conversion to per cent samarskite seemed unnecessary since the survey

A

B

Fig. 10 A. Channel pattern at the start of the experiment.
Fig. 10 B. Area alluviated after 30 hours of flow.

Fig. 11

Fig. 12

Fig. 11. Channel pattern and samarskite distribution after 3 hours.
Fig. 12. Channel pattern and samarskite distribution after 6 hours.

Fig. 13

Fig. 14

Fig. 13. Channel pattern and samarskite distribution after 9 hours.
 Fig. 14. Channel pattern and samarskite distribution after 12 hours.

Fig. 15.

Fig. 16.

Fig. 15. Channel pattern and samarskite distribution after 15 hours.
Fig. 16. Channel pattern and samarskite distribution after 18 hours.

Fig. 17.

Fig. 18.

Fig. 17. Channel pattern and samarskite distribution after 21 hours.

Fig. 18. Channel pattern and samarskite distribution after 24 hours.

Fig. 19.

Fig. 20.

Fig. 19. Channel pattern and samarskite distribution after 27 hours.
 Fig. 20. Channel pattern and samarskite distribution after 30 hours.

Fig. 21. Downstream redistribution of samarskite.

TABLE XII. MOVEMENT OF HEAVY MINERALS DOWNSTREAM RELATIVE TO ELAPSED TIME.

Hours of rainfall .	Zone A	Zone B	Zone C	Zone D	Total heavies.
0	-	-	-	-	-
3	3.2	-	-	-	3.2
6	6.1	3.1	0.5	-	9.7
9	11.3	5.2	2.8	-	19.3
12	9.2	5.3	2.5	-	17.0
15	8.8	4.1	2.9	1.1	16.9
18	10.9	3.3	1.3	0.8	16.3
21	10.3	4.5	3.7	1.7	20.2
24	12.2	5.9	3.5	2.1	23.7
27	8.7	6.2	3.1	1.2	19.2
30	10.5	6.3	2.9	1.7	21.4

Fig. 22 Downstream migration by areal groups in Table I.

was intended to show only relative redistribution referred to an arbitrary standard. The graphs showing downstream redistribution of samarskite (fig. 21) are derived from the transparent tracings (figs. 10 to 20); each graph represents the radioactivity along the stream channel after each 3 hour period of "rain". The shifting channels leave deposits stranded off to one side and the downstream migration is consistent and shows only in a general way when an average of two to three profiles are considered together. The left hand recording on the profiles is 15 cms. downstream from the mineral vein and each consecutive reading was taken in the main channel 15 cms. downstream from the previous reading.

A quantitative estimate to amount of heavy mineral transfer movement was desirable and was attained by measure of the area under each graph in figure 21. Irregularities were reduced slightly by averaging the readings over 150 cm. intervals of channel and these appear in the Table XII. A graphic representation of the table appears in figure 22.

It can be observed in a general sense that the concentration of heavy minerals in the stream channel maintained an inverse proportion to the distance from the vein. No radioactivity was detected at any time at more than 6 meters downstream from the vein. Since the stream was continuously aggrading or building its alluvial fan system above this point it can be concluded that no heavy minerals were carried past the last alluvial fan. An initial rapid increase of heavy mineral content can be observed in the "A" zone, or upstream section of the channel. The average content for this section at the end of nine hours of rain was 11.3 units which this section

continued to maintain as an equilibrium figure while additional material was transferred downstream. The heavy minerals were continuously transferred downstream and concentrated there. An example of this behavior is represented by the data in section "B" which shows a steady increase in heavy mineral content with elapsed time. This is true to a lesser degree in section "C". Section "D" exhibits no steady increase after the heavy minerals reached that part of the stream system after 15 hours of rainfall. This data can be explained by the fact that the stream occupied a much more confined channel in section A, B, and the upstream portion of section C while the downstream portions of the stream were fanned out and braided in the area of aggradation. Consequently lower channels changed position rapidly, spreading the heavy mineral content laterally over a large area. A comparison of the transparent tracings exhibits this fact. This spreading and increase in area suggests that an exponential increase in time is required to bring heavy mineral alluviation in C and D zones to equilibrium.

Development of Stream and Heavy Mineral Patterns

The heavy mineral distribution is related first to diffuse deposition on alluvial fans, second to reconcentration near curves on the streams as they become incised into the alluvial deposits, and third to scour pools along courses subject to ebb and flood flow conditions. Only the first mode of occurrence appears below the degradation - aggradation boundary and the latter two are exclusively above this limit.

Heavy Mineral Deposition on Alluvial Fans

The first hours of rainfall witnessed great decrease in stream velocity, and therefore carrying power, as the stream grade declined abruptly where it passed from the mountain slopes to the flat lowlands. An alluvial fan built up immediately adjacent to the mountain front and is the principal form to the stream patterns shown on figures 10 and 11. The stream degraded its bed in the mountains, became entrenched, and simultaneously aggraded the alluvial fan to grade. Later, after equilibrium grade was reached, the stream continued to entrench its course, cut into the previous deposit adjacent to the mountain front, and transferred the alluvium progressively farther downstream. Figure 12 shows that the degradation - aggradation boundary has moved 60 cms. downstream from the mountain front, to 120 cms. from the vein and the alluvial fan is being deposited below that line. Figure 14 shows the degradation - aggradation boundary moved 1.8 meters from the mountain front and the alluvial fan is being built up below that point. Figure 18 shows 60 cms. additional progression and figure 19 has the degradation - aggradation boundary situated 2.75 meters from the mountain front, and another extensive alluvial fan is being built below this point.

The slope of the alluvial fan was observed to be less than that of the stream channel above the degradation - aggradation boundary and the velocity of the water decreased rapidly as it passed onto the fan. The width of the stream channel also increased as it passed the degradation - aggradation line. The depth of the stream simultaneously decreased at this

point. Average width of the stream valley above the fan was 5 cms. and average depth 7 mms. At the degradation - aggradation boundary, width of the channel was 9 cms. and the depth 2 mms. The wetted channel was about 5 cms. wide and 2 mms. deep at flood stage. Immediately below the degradation - aggradation boundary the stream deployed and moved in a braided system of channels over the fan. Average width of each of these channels was near 4 cms. In most cases sheet flow extended between these channels on the fan and, towards the downstream portion of the fan, water moved slowly in a laterally extensive sheet.

The maps of the stream patterns show them passing from a degrading channel onto an alluvial fan to form a significant concentration of heavy minerals as an apron at the apex or upstream edge of the alluvium with highest concentrations in the channel at the point of deployment. This is illustrated on Fig. 13. Fig. 14 shows the degradation - aggradation boundary moved 1.1 meters downstream, but the concentration of heavy minerals at the apex of the old fan in figure 13 is still in situ. This concentration remains throughout the experiment and is supplemented by additions during the later stages. Figure 19 shows a beginning of a concentration at the point of deployment of the stream on the apex of the alluvial fan 2 meters downstream from the mountain front. This concentration also remained in situ after the point of aggradation had moved 0.9 meters downstream during the next 3 hours of rainfall. (Fig. 20). This repetition of pattern indicates that a concentration of heavy minerals at the point of deployment of the stream on an alluvial fan remains in situ in the stream chan-

nel after the aggradation - degradation boundary has moved downstream.

Excavation of detritus and investigation of the depth to radioactivity in several of these deposits showed the heavy mineral concentration to be associated with the coarser detritus at the bottom of the channel scour. Apparently the stream, in reworking an alluvial deposit, distributes new material downstream and leaves in situ, at the depth of scour of the channel, most of the original concentration of heavy minerals or their equivalent.

RECONCENTRATION. No significant meandering or deviation in course of a stream occurred until a near grade condition of stream bed was attained. This is illustrated by the behavior of the stream channel on the maps. Small curves were formed in the channel eroded into the mountains due to lateral variations in grade which determined the swing of the current as it passed onto the alluvial fan at the base of the mountain front. Meanders appeared as soon as this fan was built to grade (fig. 11). Early meanders were confined to the area near the mountain front and channels were generally straight for the downstream portion.

The forms described here as meanders are not true meanders but reflections of the incident current at normal flow; they are wiped out by the flood stage in many instances.

Meanders were observed to occur at points where swing of the current was directed against the bank of the channel. An undercut bank was formed first, later a curve developed and progressed rapidly into the pattern of a pseudo-meander. The upstream, outside bank of the meander appeared as a gentle deviation while the downstream bank always appeared as a

curve of short radius. Water follows the curve of the meander and exerts the greatest turbulence and erosive force against the outside bank on the downstream portion of the meander. This causes the meander to migrate laterally and downstream. A slip-off slope is filled in on the inside of the meander. The development of meanders can be observed by comparison of figures 18 to 20.

The meander extends itself laterally and water begins to cut into the upstream edge of the slip-off slope and actually to flow over it at flood stage. The meander is then by-passed by the new channel across the slip-off slope. During meander formation, principal erosive force is directed against the outside downstream bank of the meander to cause maximum scour; local aggradation appears immediately downstream from the scour site. (Figs. 23 and 24).

Some concentration of heavy minerals was observed in areas of local aggradation immediately downstream from meander scour. With very few exceptions, these concentrations were of relatively high content. This is illustrated by the data on the maps which indicate however that this is the most persistent feature of heavy mineral concentration observed in this experiment. A detailed study of concentration showed that the channel immediately upstream from a meander consistently had less samarskite than immediately below the meander. Lowest radioactivity was in the area of scour in the meander. Highest concentration was at the upstream termination of the area of aggradation immediately below the meander scour. The air photographs of Rio Soto la Marena show this alluviation feature

Fig. 23. Meander formation and scour.

Fig.24. Local aggradation below sites of meander scour

duplicated in a field occurrence. (Fig. 25). The degree of concentration in the experimental stream waned in most cases as the area of aggradation was followed downstream. These features of scour and fill are shown in figure 26. Degree of significant concentration usually extended for 10 to 15 cms. downstream from the lower termination of the meander. Larger areas of local aggradation were observed to form over a longer period of time and high heavy mineral concentration was maintained over a somewhat greater length of the stream channel. For purpose of study, samples of detritus were removed in layers at these sites of high concentration and the heavy mineral content was found to be associated always with the coarsest detritus at the bottom of the channel scour. The overlying detritus was graded to much finer material at the surface indicating, as in previous investigations, a horizontal sorting along the stream bed as well as a vertical size assortment.

The depositional slip-off slopes of the meanders had very high concentrations of heavy minerals in some places. Radioactivity in this type indicated principal concentration of heavy minerals towards the upstream border of the slope and degree of concentration decreased towards the downstream portions. Investigation showed also that the concentration increased with depth but appeared to be more diffuse vertically than in channel concentrations previously investigated.

Natural levees formed on the outside bank of a stream curve where the bank was not excessively high. These levees were deposited at high water conditions by a portion of the stream overflowing its bank and depositing

Fig. 25. Air photograph of pools in drainage of Rio Soto la Mareno.

Fig. 26. Photograph of scour and fill in meanders in experimental stream.

detritus as it becomes incompetent through loss of velocity. This detritus was predominantly coarse and locally heavy minerals were concentrated at these sites.

SCOUR POOLS. Scour pools formed at many places along the course of the stream system where scour points developed in the main stream channel. They varied considerably in size; the largest pools were between meanders in the straighter portions of the stream channel. The average pool was 20 to 25 cms. long, 2 to 3 cms. wide, and 0.75 cms. deep. They were scoured continuously at high water and developed no significant heavy mineral concentrations during the high water stage.

Some small scour pools also formed in the straighter portions of the stream channel but usually in conjunction with the scour conditions near stream meanders. These pools averaged 6 cms. long, 2 cms. wide, and 0.75 cms. deep. They were immediately downstream from a meander and either in or just upstream from the area of local aggradation due to the meander. (Figure 25). During high water conditions these pools were floored over slowly with very coarse detritus during approximately one hour of rainfall.

After the fog nozzles were turned off, the volumes and velocity of flow of water in the channels gradually subsided over a period of two minutes, fine detritus filled the smaller scour pools rapidly and small deltas were built into the larger scour pools from the upstream end. Coarse material was deposited early followed by fine material in later stages of ebb flow. Very fine silt was deposited during the last stage of ebb flow.

Renewal of rain conditions, caused the stream to scour the deposits of ebb flow. It was observed, however, that if the fine fill resulting from ebb flow was allowed to desiccate for a period of 24 hours it was not removed by subsequent stream scour.

All filled in small scour pools have high radioactivity indicating a concentration of heavy minerals. Investigation of the deposits showed that heavy minerals were associated with coarse detritus in the lower portion of the pool. It can be concluded that these heavies were deposited with the coarse material during high water conditions.

Desiccation preserved the in-channel deltas built into the larger scour pools. The radioactivity exceeds readings taken previously in that portion of the pool. Heavy mineral content was augmented in the pool during the formation of the delta but content generally was too small to be considered a significant part of the concentration. The data suggests that if this cycle of desiccation and intermittent stream flow was repeated over an extended period of time, deltaic pool filling might form a significant concentration of heavy minerals. This was not feasible in this experiment because of the time factor, the unconsolidated base material and the consequent rapid change in nature and location of stream channels.

Filling of larger scour pools was due to local shift from degradation to aggradation. The aggrading conditions caused by the increase in radius of curvature of the meander filled the scour pool from upstream and over approximately six hours of rainfall, as the meander located upstream from the area of scour migrated laterally and downstream. (Figs. 24

-26). Reference is made also to comparison of the main channel between downstream coordinates 6 and 7 which illustrates this type of pool deposit. This type of pool, when filled, has very high concentration of heavy minerals along the entire length, whereas the usual concentration below a meander characteristically decreased in very little distance downstream.

Correlation with Natural Occurrences

The heavy mineral concentrations and patterns in the stream of the experiment simulate the channels and deposits of seasonally dry and almost continuously dry regions. Today these appear in North Australia, parts of Africa, the eastern coastal plain of northern Mexico and in the American Southwest. The Tertiary age auriferous gravels of the Sierra Nevada and of the Yukon Basin have remains of such grassland animals as the horse and bison and appear to have formed near a savannah or steppe climatic zone. The red-bed formations of other geologic ages show partial sections with similar structure and presumably comparable origin, and, in this category, the Shinarump conglomerate of the San Rafael Swell and Monument Valley is outstanding.

Pool Filling in a Dry Climate

The Rio Soto la Marena north of Victoria in Mexico affords an interesting comparison with the experimental stream. This river and its tributaries traverse a generally dry climatic area which is intermittently subject to high water conditions during seasons of high sun. Dry season flow is either by percolation or is confined to scour channels and many scour

pools are evident. (Fig. 25). These pools are between deviations from the average course and are identical in location with pools formed experimentally. The coarse and heavy material removed from upstream pools is deposited immediately downstream from meander reflections to make gravel bars about midway in a pool section between two meanders. Sand and silt deltas are built into the upstream end of pools during low water.

Another example of this type of stream is the Winnecke Creek in North Australia, (David, p.48). The Winnecke Creek traverses a very dry savannah area and is subject to flooding once, twice, or three times a year. The characteristics of the pattern of the stream are very similar to the Rio Soto la Marena and the experimental stream.

Alternating cross-beds of clay and conglomerate fill Shinarump channels of the San Rafael Swell area and appear also in Monument Valley. Pitch of the cross-beds suggests an in channel deltaic fill structure. Using information derived from experimental laboratory study, it could be inferred that these beds represent the scour of Shinarump channels during high water conditions and fill during ebb flow. Conglomerates, in this case, would represent the scour of stream channels during periods of high water. The clays would then represent ebb flow conditions attended by deposition of finer material above the conglomerate.

Heavy Minerals in Alluvial Gold Channels

Experimental study of placer formations shows heavy particle deposition simulating such natural occurrences as placers in Tertiary gravels of the Sierra Nevada and Klondike channels. The horizontal distribution of

**Fig. 27. Distribution of heavy minerals in the Mayflower channel.
(Modified from Lindgren).**

the gold in the Mayflower channel shows location of all pay streaks valued at more than ten dollars per ton just downstream from meanders. (Fig. 27). (Lindgren, p.151). Gold content is high at the very bottom of channel scour. The White Channel of the Klondike has \$4.10 of gold per cubic yard for the lower four per cent of the alluvium. At six per cent of depth from bedrock values are below five cents per cubic yard. The Klondike channels (McConnell, p.10) exhibit features of vertical and horizontal distribution of heavy minerals similar to the Sierra Nevada placers.

The placers described above exhibit characteristics of vertical and horizontal distribution of heavy minerals that coincide with the data derived from the experimental study of this project. It can be inferred that concentration of the gold at bedrock in the placer channels can be attributed to repeated scour of the channel during periods of high water. It can also be inferred that the horizontal concentration immediately downstream from meanders is explained by the local scour and fill conditions created by the meanders during high water periods.

Carnotite at Heavy Mineral Sites in Shinarump Channels

It has been noted in field observations concerning Shinarump channels of Monument Valley and the San Rafael Swell area that the carnotite ore in these areas exists in recoverable form and in significant concentration at sites similar to heavy mineral deposition in the gravel of stream channels elsewhere. Furthermore these are sites of deposition of heavy minerals including rutile, brookite, zircon, garnet, and others. Definiteness of the alluvial pattern to these carnotite deposits and the occur-

rence in them of refractory high specific gravity minerals in unmodified form, at least suggests that uranium was introduced as a placer and has been redistributed by groundwater as the secondary carnotite in more recent time. On this basis the uranium ore at these sites is visualized as a syngenetic placer deposit in heavy mineral form. The carnotite is considered a secondary of "weathering" product and due to subsequent reorganization of the mobile uranium by groundwater movement.

Summary and Conclusions

Intermittent stream flow develops an in-channel deltaic structure with definite patterns associated with high and low water deposition. Detritus has vertical and horizontal distribution according to size and specific gravity assortment in accord with stream carrying power.

During high water stages, degrading upstream portions of the channel show a progressive and rapid loss of finer detritus which is consequently accumulated downstream where the stream is aggrading on an alluvial fan. (Fig. 8 and 9E). Detritus of greater size or of relatively higher specific gravity is not as subject to movement and is therefore lowered to the depth of scour in the degrading portion of the channel. (Fig. 9E and 9D). During low water stages the movement of detritus is necessarily greatly reduced and the finer material is deposited in the channel particularly in the pools upon a base of the coarser and heavier detritus.

Repeated scour during high water and fill during low water stages results in a vertical sorting of the stream channel with the coarser material located at the depth of scour and the gradation to finer material immedi-

ately above. Intermittent stream flow introduces a high degree of vertical sorting but is responsible for little improved horizontal sorting along the length of the channel.

The pattern of vertical distribution of heavy minerals exists jointly with this vertical size sorting due to repeated scour and fill of stream channels. In all cases of significant heavy mineral concentration it has been observed that it is located with the coarser detritus at the depth of scour.

No significant concentration of heavy minerals occurs below stream deployment at the apex of alluvial fans. Heavy minerals were not observed to move downstream across an alluvial fan until grade had been attained across the fan and the degradation - aggradation boundary had moved downstream.

Sites of heavy mineral concentration are located:

1. Immediately downstream from meander scour.
2. In the stream channel at the point of deployment on the apex of the alluvial fan.
3. In scour pools in the stream channel.
4. In slip off slopes of meanders.
5. To a lesser degree in natural levees formed on the stream bank.

Reworking of an alluvial fan or of alluvial channels leaves most of the former concentration of heavy minerals at one of their original sites at the depth of scour and they are not effectively redistributed downstream in a short period of time.

Comparison of simulated deposits with such natural occurrences of placer deposits as occur in the Klondike and Sierra Nevada gravels has shown that a definite correlation exists between experimental deposits and

those in nature. Other extensive geological studies failed to show that these alluvial patterns originate in other ways and therefore secondary or weathered minerals with alluvial patterns of distribution, are presumed to have formed by action of groundwater on concentrations originally of alluvial origin.

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VI. GROUNDWATER CIRCULATION IN A SYNCLINAL AQUIFER

Introduction

Experimental investigation of groundwater circulation in a synclinal aquifer involved, determination of form to a syncline to simulate natural conditons closely, selecting a sand for the aquifer, development of tracers to mark the water channels between recharge and discharge points, and devising methods of varying the rate of flow. The apparatus was constructed as a plunging syncline so that conditons of flow and amount of closure during any test could be varied systematically. The flow was through a syncline having the cross section form of an hyperbola. The aquifer was two inches vertically from hangingwall to footwall and was a pure quartz sand of essentially 40 to 90 mesh size. Water soluble dyes were used to trace the input away from each recharge point; intermingling of the solutions was moderate and color identity was maintained so that circulation patterns could be followed throughout the system. The recharge was by stopcock controlled tubes from reservoirs; the reservoirs measured the amount of flow per unit of time and the stopcocks provided the essential control to rate of flow.

Objective

The fundamental aim was to investigate experimentally a field-observed pattern of uranium mineral deposition in the Salt Wash sandstone of the Colorado Plateau. Here uranium minerals were observed to be concentrated within the gentler dipping limb of synclines, sometimes be-

low the watertable and parallel to the strike of the synclinal axes. Such conditions suggested the possibility that these depositional sites might have a groundwater type of control. The present experiment was designed, therefore, to simulate obvious structural conditions found in the Salt Wash sandstone, and to make possible observation of a groundwater circulation similar to that therein.

Synclinal guidance to oxidizing type groundwater solutions appears in many mineral deposits throughout the world, notably the Roan Antelope mine in Northern Rhodesia, the Marquette Iron Ranges of northern Michigan, and others. The oxidation along the synclinal trough at the Roan Antelope occurs to below 1140 feet depth or more than 700 feet below the top of the surface oxidation extending down the limbs from the outcrop. The residual hematite ores in the deep mines of the Iron Ranges are in trough structures from which the soluble minerals have been leached to leave residues identical with those in the surface enriched deposits. It has been current opinion that these ores were due to intensified flow of groundwater under structural guidance but the mechanism of this deep underflow has never been explained adequately.

Arrangement of Report

The report on this experimental investigation outlines the construction of the apparatus, the plan of operations and procedure for the study, a summary of the observations essential to evaluate the different anticipated variables, a listing of the observations, and the essential features learned from the study. Flow paths, as distinct from amount of flow,

are controlled by the structure rather than by the height of the water-table as had been believed; this item is enough in itself to repay the effort expended on the work. Many other minor facts were learned during the course of study.

Acknowledgements

The project was carried out as one part of a broad planned investigation into origin of uranyl salt mineral deposits under U. S. A. E. C. Contract AT(30-1)-1172. Mr. R. L. Schortmann built the apparatus and Mr. Sanborn Partridge supervised the laboratory procedure and rendered many helpful suggestions on construction and measurement.

Construction of Apparatus

The construction of the apparatus involves the design of a structure simulating a syncline in cross sectional form, an assembly of materials that insures rigid maintenance of this form throughout any specific experimental runs, potential modification in order to test factors under varied conditions, and provision for accurate measurement of charged solutions and effluent product. The assembly was on a reduced scale with accentuation of some features that reduce the time element to obtain preliminary data. Better grade quartz sand than is in most sandstones was used for the aquifer in order to avoid color obscurity in the tracers. The containing walls were impermeable plastic sealed to contain all solutions and transparent to afford a clear view of their movement.

Design

Determination of curvature of natural synclines constituted the first problem. Photographs of synclines were projected, traced, and analysed mathematically. The results showed synclines to be almost hyperbolic in form.

Several hyperbolae were then drawn to the scale of the proposed model and considered with respect to steepness, model construction problems, and similarity to folds found in the Salt Wash formation. The curve chosen as being most suited to experimental use was somewhat steeper than is characteristic of Salt Wash structures and was an hyperbola with the formula.

$$\frac{x^2}{900} - \frac{y^2}{257.14} = 1$$

Asymmetry of structure was attained by turning its axial plane from vertical and to 75° inclination; relative to the earth, such a structure has one steep and one more gently dipping limb. This cross section was applied without variation along the entire length of the model, and set the pattern for both the top and bottom of the aquifer.

The model itself consisted of two parts; a top section fitted exactly into and conformed to a bottom one. The adjacent surfaces of each section were covered with a continuous layer of impermeable plastic. In use, the top and bottom sections were separated by the distance chosen for thickness of the aquifer.

Assembly

The construction assembly plan was to use 19 plywood sheets cut to the planned curve, spaced 8" apart, and nailed to longitudinal struts. These sheets served as septa set at right angles to the axis of the syncline and held the hyperbolic form rigidly. The sizes varied progressively so that the synclinal form was 30" deep at one end, and 3" at the other. Light longitudinal strips were recessed into the septa at 6" centers and parallel to the axis of the structure in order to preserve the smooth surface and provide in the intervening space that support essential for the plastic sheeting.

The plastic sheeting, used to simulate impermeable walls of the aquifer, was .01" thick and came in rolls 40" wide. Width necessary to cover the form was obtained by brushing acetone along a one inch wide strip at the edges of two sheets and then pressing them together. This formed a firm bond which was mechanically strong, waterproof, and smooth. The large sheets thus made were put in place on the top and bottom sections and held in position temporarily by thumb tacks along the edges until later when the sand was poured into the aquifer space. The deep open end of the syncline was closed and sealed off. An extra piece of plastic was bonded to the lower sheet at the smaller or discharge end for a spillway. The top section was lowered into place and supported so as to rest 2" vertically above the lower section, and was firmly clamped in place to prevent it from floating upward or sidewise as the water was added to the aquifer.

The sand selected was a commercial grade of quartz foundry moulding sand. The crude material contained a considerable amount of "rock flour"

Fig. 28. Photograph of the experimental syncline from the side.

which was removed to prevent blocking pore spaces in the projected aquifer. The fines were washed out of the sand and the residue had a size of about 40 to 90 mesh. The sand was then dried, so as to flow into all parts of the syncline without puddling out at the effluent end, and 750 pounds of it was poured into place between the plastic sheets. The aquifer was saturated with water and more sand added as the mass settled into place.

Operational Hazards

Several wrinkles appeared in the lower sheet of plastic as the form was filled, and these defied all attempts to remove them. One large one occurred down the center of the trough for 40 inches near the spill point and had some effect in limiting the diffusion of the liquids on the lower surface of the aquifer. However, no effect due to it was observed later on the upper surface of the aquifer.

The hydrostatic pressure due to the weight of the sand and water, was enough to make the plastic sheets bulge outward between the supporting strips and septa. This gave a "waffle effect" in which the septa and the supporting strips acted as constricting influences on the sand layer and introduced an unintended and also unmeasured element of local guidance to movement of the liquids along the upper and lower bounding surfaces of the aquifer.

Orientation

The model was oriented with the axis plunging to the west, and with the north limb as the steep one. Any subsequent compass directions in this discussion will relate to this orientation.

The overall picture (Fig. 28) was of a westward plunging syncline, with the spill point uphill to the east or right from the lowest point. The approximate dip of the north limb was 72° , and that of the south limb was 45° . The tapering of the framework was for convenience in construction and to facilitate observation.

The Flow Tracers

Four colored solutions were used to trace the circulation of the water through the aquifer. Primary considerations for coloring agents were intensity, lack of a precipitate on mixing, the ease with which they could be flushed out of the sand, and the expense. A liquid coal tar dye, available in a 2% solution of water and propylene glycol, commonly used in food coloring was adopted. Yellow, green, red, and violet were used; 1/4 ounce per gallon was sufficient to give easily traceable color intensities for the green and violet, while 1/2 ounce per gallon was necessary for the red and yellow.

The solutions were introduced along marginal outcrops by siphon tubes from reservoirs set above the center of the model. The rate of flow of the solutions was controlled by screw clamps placed near the lower ends of the tubes.

Experimental Procedure

General experimental procedure began with listing variables to be investigated, proceeded to methods of recording the data, and investigated difficulties in carrying out the essential measurements by a trial run.

Variables Investigated

Rate of recharge of the aquifer, place of recharge relative to structure, and change in plunge to structure were investigated and a number of lesser variables were left for future study. The first variable, or rate of recharge, was studied at three volumes of flow; these were, slow at one drop in five seconds, moderate at one to two drops per second, and rapid at between three and four drops per second.

The second variable related to method of recharge. Four drip points were spaced 60 cms. apart along each outcrop of the aquifer, and the tracer solutions were delivered symmetrically on both sides of the syncline. The solutions dripped into the sand at a uniform rate according to one of the following plans for each run and in the order listed.

1. All eight points at a time.
2. At four points on the gentle limb only.
3. At four points on the steep limb only.

Third, the plunge of the synclinal axis was changed by raising the east or "spill point" end of the model. The first series of runs had the axis plunging 2.5° west. This was increased to 5.5° west for the second series.

Other variables which were considered but reserved for subsequent work included:

1. Varied spacing of the recharge points.
2. Additional combinations of points operating at any given time.
3. Raising the northern side of the model to modify the symmetry.

Method of Recording Data

First, volume of solution used and second, its spatial disposition at any given time needed to be recorded. The second item was most important

Fig. 29. Pattern of flow at upper surface of aquifer; Run 1, Series 1A.

and gave the most difficulty.

VOLUME MEASUREMENT. Both volume of liquid charged into the aquifer and amount of effluent at the spill point were measured and recorded throughout the experiment. This gave amount of liquid in the aquifer at any given time and the rate of percolation for a given watertable height.

GROUNDWATER PATHS. The groundwater paths were observed in the color patterns which developed within the aquifer due to the circulation of the colored tracers. These patterns were "mapped" color for color on a one tenth scale grid sheet which corresponded to the area of the synclinal surface of the aquifer.

THE MAP PLAN. The surface of the syncline was treated as if rolled out flat for convenient representation of its curved surface on a flat piece of paper. (Fig. 29). The method of representation selected allows direct sketching of the patterns simply by orienting the grid sheet with the model; it can be utilized without change for any plunge of the synclinal axis, and permits easy drawing of structure contour lines. In practice the map was made by means of a surveyors' level with a meter stick for a rod and the ribs and recessed longitudinal strips of the model for coordinates. The contour lines gave a basis for easy comparison of the relative elevations of the color patterns and watertable. The contour interval adopted was ten centimeters. In addition, the plot for each run showed the level to which the sand filled the syncline, the position of the recharge points, and the position of the watertable. It was thus possible to observe shifts in the watertable from one run to another, and to indic-

TABLE XIII. OPERATIONAL DATA FOR ARTESIAN FLOW EXPERIMENTS.

Run no.	Volume in gallons					Running time in hours	Rate	Limb charging
	Yellow	Green	Red	Blue	Overflow			
<u>Series I</u>								
1	3	4	3	3	-	4.5	fast	both
2	3	4	3	3	9	70	slow	both
3	1.5	1.2	1.2	2	2.7	5	medium	both
4	3.1	4.5	2.2	2	10	48	medium	gentle
5	3	1	1.5	1.2	2.5	27	medium	steep
6	2	1.2	1.2	1.5	4.2	30.5	medium	steep
<u>Series II</u> *								
7	4.8	3.4	3.4	4	13	26	medium	both
8	2	2.1	2.4	2.1	7.1	30	medium	gentle
9	1.9	1.8	1.6	1.7	6	48	medium	steep

* Aquifer flushed out with approximately 50 gallons of water.

ate the relative position of the circulation pattern with respect to it and to a horizontal or contour surface.

THE WATERTABLE. The watertable was taken as the level to which water was observed to be in contact with the plastic sheet on either the upper or lower surface of the aquifer, without allowing for capillary effects. In practice, the wetting boundary was often indistinct and some difficulty was encountered in determining its position; also capillarity gave a wetting boundary slightly higher than the true watertable. Mapped watertables are therefore consistently higher than the true watertable.

General Performance

Both top and bottom surfaces of the aquifer were visible through the plastic sheets and paths of flow were visible and well defined. The circulation patterns lay well below the point of discharge level and were far down in the zone of saturation so that indefiniteness of the watertable position is largely irrelevant. During the first series of runs, attention was concentrated on working out the details of experimentation, and in detailed mapping of the circulation patterns which developed on the upper surface of the aquifer. Observation at the lower surface showed patterns due to a slower diffusion of liquids through the sand but were not mapped during the initial series of runs. The colors fanned out slowly from the recharge points to make contact. Then a gradational zone of mingling developed over about one centimeter or less wide where the boundary did not appear sharp. Generally intermingling of the colors was confined to a small volume.

FIG. 30.

Fig. 30. Pattern of flow at upper surface of aquifer; Run 2, Series 1A.

Record of Observations

Observations were carried on for two different positions of the experimental syncline. The first series had the plunge of the synclinal axis 2.5° to the west, or away from the spill point and consisted of six runs. The second series had the plunge of the axis increased to 5.5° west and consisted of three runs. The first series investigated effects of both rate of recharge and place of recharge. The second series investigated only effects of place of recharge. The aquifer was saturated with water and allowed to stabilize before either series of runs began. Its capacity is about 25 gallons. No definite running time was selected. In general, the aquifer was recharged until observation at intervals indicated that a stable pattern had been achieved, at which time the patterns were mapped. Running time varied from a maximum of 70 hours to a minimum of 4.5 hours; the usual elapsed time was about 30 hours.

Series I - Plunge 2.5° Away from Spill Point

The runs in Series I consisted of two groups of three each. The first group investigated effect of rate of recharge and had three in which the liquids were charged into both limbs of the aquifer, one at a fast rate, one at a slow rate, and one at a moderate rate, in that order. A second group of three runs investigated effect of place of recharge and had one with recharge on the gentle limb only, and two with recharge on the steep limb only (one at a moderate and one at a slow rate).

GROUP A RUNS. The map on the first run (Fig. 29) was made after both

Fig. 31. Pattern of flow at upper surface of aquifer; Run 3, Series 1A.

sides of the syncline had been recharging for 4 1/2 hours at the fast rate of about three to four drops per second from each of the eight points. The pattern had blocks of color spread downward and laterally from the points of recharge. At an elevation below the level of the spill point, the liquids approached the trough of the syncline, then turned and moved towards the spill point in bands generally parallel with the trough axis. The bands meandered somewhat, but were confined to about 25 centimeters on either side of the trough axis. The maximum shift of any single band was about 10-15 cms. from its average position. More deviation from the parallel trend was observed on the steep limb than on the gentle limb and there too the color bands frequently broadened out. The watertable level ranged between one and five centimeters higher on the steep limb than on the gentle one.

The second map (fig. 30) was drawn after both limbs had been recharging at the slow rate for 70 hours. Colors were less intense and more intermingled than in the previous run, particularly within about 25 cms. of the trough axis. The watertable fell five to ten centimeters along its whole length from its former position; on the steep limb, it still stood from three to eight, and occasionally almost ten centimeters above that on the gentle limb. The observed color bands were well below both watertable, and also the spill point. Green or the second color from the west end of the steep limb of the syncline had put out a thin stringer to westward whereas most of the color turned and moved eastward. This stringer was about three centimeters above the trough axis, well below the level of

Fig. 32. Pattern of flow at upper surface of aquifer; Run 4, Series 1B.

the spill point, and extended westward about 60 cms. from the main block of green. This was the only such occurrence observed in the first series.

The third run had liquids recharging into both limbs of the syncline at the moderate rate of two drops per second. The color blocks, patterns and relative positions were similar to those established in the first run (fig. 31); even a dividing and recombining of the lowest color band was repeated in the same position. Individual color bands were somewhat narrower than in the first and boundaries between the colors were less distinct because of intermingling. The thin westward streamer of green remained during this run. Intensity of its color was reduced and it was disconnected from any other green, suggesting a relic origin from the preceding run. The watertable rose considerably to about ten centimeters higher on the steep limb and nearly 15 cms. on the gentle limb. As before the watertable on the steep limb stood above that on the gentle, and measured two to eight centimeters higher.

GROUP B RUNS. The fourth run in this series recharged only the gentle limb and at a moderate rate. The pattern developed in this case (fig. 32) showed color from the gentle limb widened out, passing across the trough axis and moving up the steep limb to 3 cms. greater elevation. The steep limb bands were compressed as they were displaced up-dip. Bands were more irregular than in any of the previous runs but this could be expected with input reduced to half. The watertable was higher on the steep limb than on the gentle one by about five to eight centimeters.

The fifth run had recharge at moderate rate and on the steep limb

Fig. 33. Pattern of flow at upper surface of aquifer; Run 5, Series 1B.

only. Approximately the reverse of the previous run took place; the color bands moved across the trough axis (fig. 33) and part way up the gentle limb. The two colors originating farthest to the west intermingled gradually as they moved up along the trough axis and climbed farther up the gentle limb as they approached the spill point to become one band 15 cms. wide at about 15 cms. up the gentle limb. The watertable on the steep limb rose two or three centimeters and dropped by a similar amount on the gentle limb over levels of the previous run.

The sixth and final run in this series was made with only the steep side being recharged but rate was reduced to less than one drop per second. Color bands broadened out somewhat, (fig. 34), became more intermingled, and retreated down the gentle limb to the trough axis to become stabilized in the position obtaining when both sides operated at moderate flow. Two sites of no color occurred along the trough axis. The watertable on the steep limb dropped about three to four centimeters, but remained essentially the same on the gentle limb as it had been in the previous run.

THE SERIES I RUNS CHARACTERISTICS. The recharge liquids moved down dip to well below the watertable and the spill point level before turning and moving toward the spill point. A slight and purely local tendency existed for solutions to move down the plunge of the synclinal axis. Most discharge circulation came within a 25 cm. wide band on either side of the trough axis. Patterns resulting from different rates and places of recharge were similar; slower rates permitted more intermingling. The watertable gradients were slight; the levels were higher and the gradi-

Fig. 34. Pattern of flow at upper surface of aquifer; Run 6, Series 1B.

ents steeper on the steep limb than on the gentle one. Rapid recharge raised the watertable, but recharge on one side only did not effect the level appreciably.

Recharge of only one limb shifted the pattern and moved the lower section towards the opposite limb from the recharge; the distance moved is a direct function of the rate of recharge. The patterns shifted to a higher elevation on the gentle limb than on the steep limb when only the respective opposite limb was being recharged.

Series II - Plunge 5.5° Away from Spill Point

The spill point of the syncline was elevated 20 cms. above its position in the former series to increase the angle of plunge to 5.5° , and the closure from 17.6 cms. to 37.5 cms. The three different rates of recharge used in the first series had produced little observable variation in the color patterns, and so the Series II tests were made at the moderate rate of two to three drops per second. The recharge points remained in the same relative positions as in the first series, but the yellow and blue colors were interchanged to insure complete flushing of old tracers.

THE TEST RUNS. The first run of this series had both limbs of the syncline recharged at the moderate rate. The color moved normally down dip from the recharge points and spread out laterally only well below both the watertable and the level of the spill point. (Fig. 35). The western boundaries of the large color blocks lay farther towards the low point, or west end, of the syncline than in the previous series. Small protruberances, jutting 5 cms. to the west, appeared at the lower corners of color blocks.

Fig. 35. Pattern of flow at upper surface of aquifer; Run 7, Series 2.

As the solutions neared the trough axis, they turned and moved in bands toward the spill point. The bands were wider on the gentle limb than on the steep limb, and were sharply defined with very little intermingling on either side. Flow along the trough axis was concentrated within about 15 cms. of it on the steep side and up to 20 or 22 cms. on the gentler one. The watertable on the steep limb was very close to the outcrop toward the west end of the syncline, and emerged about halfway toward the spill point. Generally it stood from three to eight centimeters above the level on the gentle limb. Two bands of a single color separated by a thin band of another color occurred on the steep limb. The first solution in part passed over the second as it moved down-dip, and thus moved toward the spill point as two distinct bands separated by the band of the overridden color. This recurred with some modification in subsequent tests at 12 cms. from the trough axis.

The second run of this series was made with recharge on the gentle limb only. A color "front" moved down the gentle limb, across the trough axis, and up the steep limb to the first longitudinal strip, where it became stabilized. (Fig. 36). This strip marked out a barrier for a distance of about 120 cms., and the color band followed along it as it streamed toward the spill point. However, the color passed below the strip and appeared on its uphill side as diffuse patches elongated toward the spill point. Near the spill point the color occupied a broad band uncontrolled by the strip. The watertable on the steep limb dropped about three to four centimeters only, remaining very close to the top of the sand layer, and stood about five

Fig. 36. Pattern of flow at upper surface of aquifer; Run 8, Series 2.

centimeters above the watertable on the gentle limb.

The third run of this series had only the steep limb recharged. The patterns were shifted as much as 25 cms. up the gentle limb. (Fig. 37). Flow bands on the steep limb broadened out over the previous run, while the relic ones on the gentle limb became less distinct and narrower than before. Intermingling of the colors increased, particularly in the bottom of the gentle limb, and the color bands were more difficult to map. The watertable on the steep limb rose only one or two centimeters above what it had been in the previous run, and that of the gentle limb remained essentially unchanged.

THE SERIES II RUNS CHARACTERISTICS. This series shows movement of the solutions from points of recharge down dip to well below both the watertable, and the level of the spill point, before turning to stream as bands toward the spill point. The flow bands were generally wider on the gentle limb than on the steep limb. Protruding irregularities at the low western corners of the "down-dip" color blocks, and displacement of their boundaries westward from the previous series indicated some tendency for the liquids to move westward, or in the opposite direction from the spill point. This suggests temporary back-flow caused by increasing the angle of plunge to the trough axis.

The shift in pattern due to recharging only one limb was accentuated particularly for the steep limb.

The watertables in general stood close to the outcrop of the sand with the level on the steep limb consistently higher than on the gentle limb. In

Fig. 37. Pattern of flow at upper surface of aquifer; Run 9, Series 2.

all cases, the watertable was nearly horizontal. Some structural interference with the liquids due to the bulging of the plastic around the supporting strips was observed.

MOVEMENT IN THE BOTTOM OF THE AQUIFER. During the second series of runs, patterns of color on the lower surface were drawn each time the upper surface of the aquifer was mapped. (Fig. 38). This was done to observe the behavior of the slow moving color blocks, and to allow correlation between the two surfaces in order to gain a three dimensional perspective.

Recharge of both limbs moved the solution down dip on the lower surface of the aquifer at nearly equal rates on both limbs, distance travelled by the color front on the steep limb being only slightly more than the distance moved by the color front on the gentle limb in the same time. Recharge on the shallow limb moved the colors down dip on the lower surface of that limb only; normal colors and an abnormal green band on the lower surface of the steep limb remained in place. Recharge of the steep limb only, moved the colors on that limb down the dip and left the two anomalous green bands and the colors on the gentle limb static. These green bands are not visibly connected with any green color laterally or above and probably are remnants of color left from the previous series at a dead spot in the circulation. The general sluggishness with which color moved on the bottom surface may explain why these bands withstood flushing and persisted.

Selected cross sections of the aquifer were drawn in order to correlate

Fig. 38. Map of the features of the under surface of the aquifer for Runs # 7, # 8, # 9.

Fig. 39. Cross sections of aquifer showing fronts of descending solutions.

the patterns found on the top surface of the aquifer with those found on the lower surface. On each cross section, colors for a given run were noted for both the upper and lower surfaces. Corresponding color boundaries on opposite surfaces of the aquifer were then connected by a straight line. (Fig. 39). This was done separately for color boundaries on each of the three runs in the second series. The cross sections showed that the solutions advanced closer to the trough at the upper surface than at the lower surface of the aquifer. Usually boundary surfaces on the gentle limb dipped toward the trough and the steep limb dipped outward, away from the trough axis. Generally such a boundary for the gentle limb was nearer to being horizontal than the corresponding line on the steep limb, but in one case the steep limb boundary was exactly horizontal. The lower limits of these color areas were consistently below the level of the spill point.

Cross sections taken successively nearer the spill point showed a tendency for the connecting lines to approach the horizontal, particularly on the gentle limb. The boundary dipped inward on the steep limb when both limbs were being recharged, and dipped outward when only the steep limb was being recharged.

Ratio of volume of steep limb to gentle limb is 1:2 at the western limit of the syncline increasing to 7:9 at the spill point end. The absolute capacity of the gentle limb is throughout greater than that of the steep limb. This suggests that initially at least equal rates of recharge on the limbs may be unequally accommodated. This is related to the watertable consistently standing higher on the steep limb and may be responsible for the

boundary dip features mentioned above.

Watertable Modifications

Increasing the pitch of the structure changes the position of the watertable relative to reference lines but leaves the surface in essentially the same position relative to the earth's surface. Downdraw is accentuated at the end distant from the spill point. Amount of downdraw at the western end and also at the spill point end is increased when amount of recharge is reduced. Both moderate and fast rates of recharge gave essentially the same watertable levels.

Downdraw at the Western End of the Structure.

The watertable at moderate recharge rate (fig. 30) rises about 7 cms. above the 40 cm. contour at mid-length of the gentle limb; it stays very close to the 50 cm. contour on the steep limb but rises above that contour near the west end. Increase in rate of recharge causes the watertable of the steep limb to assume an almost continuous eastward slope towards the spill point (fig. 29) and moves the high point on the gentle limb closer to the western end. Downdraw by the artesian system at the western end is increased by reduced recharge (fig. 30).

Recharge on one limb only holds the downdraw on that limb reasonably uniform (figs. 32 & 33) but causes increased downdraw at the western end of the limb not being recharged. Total change is much less than when the entire amount of recharge is reduced to a low level and the effect seems to be due principally to volume available to the artesian system.

Run #6 had a low rate of recharge on the steep limb only but a faster rate was used than in run #2. In this instance some downdraw appears at the western end of even the recharging steep limb (fig. 34) but downdraw on the gentle limb extends eastward to the midstructure. This examines behavior of runs #1 through #5 under a new set of circumstances and shows that the volume-site relationships attending recharge are as expected.

Effects of Increased Plunge of Structure

The increase in plunge of the syncline from $2\frac{1}{2}^{\circ}$ to $5\frac{1}{2}^{\circ}$ brought the watertable at the western end much closer to the surface at all times. The slight fluctuation possible makes analysis of any change difficult. Moderate rate of recharge on both limbs gave a slight downdraw at the western end for both limbs (fig. 35). Downdraw extended farther eastward on the gentle limb when only the steep limb was being recharged and even the watertable level on the steep limb was lowered somewhat uniformly (fig. 37). Downdraw on the gentle limb was essentially eliminated while it was being recharged; simultaneously downdraw on the steep limb extended eastward to remove all of the high point in the midsection of the structure.

Generalization

The downdraw at the western end of the structure indicates capacity of the trough flow to withdraw a larger volume of water than the flank flow. Within limits of the experiment, The section distant from the spill point could handle greater volume than the sections near the spill point.

Conclusions

On the basis of the experimental work reported above, five main conclusions can be drawn.

1. Circulation is of two general types.

- a. Initially movement is mainly downward toward the trough axis but is accompanied by a lateral spreading to make contact with solutions from adjacent recharge points.
- b. Deep circulation toward the spill point follows; in all cases this was well below both the watertable, and the spill point level, and was confined to within about 30 cms. of the trough axis.

2. The rate of recharge has little effect on color patterns observed on the upper surface of the aquifer. This was shown by the first series of runs where three different rates of recharge were used without observing much variation in the color patterns; their relative intensities only were affected. The faster the rate of recharge, the more intense were colors and the more distinct were boundaries of the individual bands. Reduction in rate of recharge diminished the color intensity and permitted more intermingling at the boundaries of the bands.

3. Raising the spill point and increasing the plunge angle of the trough axis had little influence on the form and distribution of patterns. Some slight motion of solution in the opposite direction from the spill point was observed. This may have been due to some backflow caused by elevating the spill point.

4. Circulation on the upper surface of the aquifer is apparently more rapid than that on the lower surface. This was shown by observations in

both series, particularly in the second series, when correlation between the two surfaces was undertaken. Flow bands were less sharply defined on the lower than on the upper surface which was a characteristic identified with low volume of flow. Also as the color areas on the two surfaces approached the trough, the color boundary between any two solutions approached the horizontal. This was particularly evident on the gentle limb of the syncline.

5. The trough artesian flow causes downdraw of the watertable at the source area and has systematically depressed the watertable below the level of a continuous slope to the discharge point. This behavior is repeated in so many instances that it is obviously a regular feature of artesian patterns.

Suggestions for Further Study

The suggestions fall into two groups. The first concerns new problems or variations which should be investigated. The second lists improvements in design, recording, and study which would be advantageous.

Additional study of groundwater flow patterns might include further variation in plunge of the trough axis, operating various combinations of recharge points, and closer observation of the time necessary for stabilization to take place under various rates of recharge. No attempt was made in this experiment to determine effect of the minor folds or terraces or change in curvature of the synclinal dip of the limbs on flow pattern; these influences deserve study.

A more certain method of determining the level of watertable might also be devised, perhaps by "observation wells" spaced along the outcrop of the aquifer. The movement of liquids on the lower surface of the aquifer needs study in order to determine form of contact surfaces of solutions from different recharge points or paths.

VII. INFLUENCES ON PRECIPITATION OF URANIUM MINERALS FROM URANYL SOLUTIONS

Introduction

Conditions influencing the precipitation of uranium from solutions bearing the uranyl ion were investigated experimentally in the laboratory to determine what types of environment affect the precipitation of uranium from solutions, the manner of action of the influences, and particularly the chemical processes involved. The study was confined to the uranyl salts and was not extended to include any uranate compounds although uranates may form in some reactions at very low hydrogen ion concentrations. The components of the environment were kept to those identified by field studies as associated with almost all ore. All variations in hydrogen ion and available sulphate ion were kept under observation to identify location of mineral precipitation with deviations from the average condition of the solutions.

This investigation attempted to simulate actual field conditions associated with uranyl mineral concentrations in the Colorado Plateau area. Quartz sand with various measured diluents simulates the Plateau rocks and very dilute sulphuric acid solution duplicates natural groundwater materials for laboratory study. The final results accorded closely with field observations on the occurrence of carnotite type uranium ores. The hydrogen ion concentration of the leach solution was held at pH 4.0 and was measured daily at three points in the percoiation apparatus.

Simulation of Environment

Twelve glass tubes, 1.25 meters long and 51 millimeters in diameter, were mounted on a vertical frame and filled with acid washed quartz sand between 20 and 60 mesh screen size. (Fig. 40). The tube charge was planned to simulate observed mineral components of the plateau sandstones in the vicinity of deposits. Four tubes, uniform throughout, were run as controls. A uranium source, carnotite in some cases and uraninite in others, was set at the top of the tubes. Eight tubes had a modifying influence placed between two sampling points in the mid-section of the tube. Distance between uranium source and the discharge level of the effluent was 1 meter. (Fig. 41). The modifying influences introduced into the tubes were of four types:

1. A quartz calcite bed alone.
2. A bed of some material such as pyrite, V_2O_5 , or hydrocarbon, set alone.
3. A bed as above set in a quartz and calcite zone.
4. A bed as above set directly under a quartz and calcite zone.

Simulation of Groundwater

A simple solution approximating the active components in the groundwater solutions of the plateau areas was then allowed to percolate through the tubes at the rate of about 0.75 liters per day. The effluent was collected and kept at 1 liter volume by evaporation.

Experimental Operation

The solutions were contained in a reservoir and were fed by a siphon system to a subreservoir for each tube. The amount of solution dropping from the subreservoir into the percolation tubes was controlled by

Fig. 40. Apparatus arrangement for percolation experiments.

Fig. 41. Construction of the percolation tubes.

Fig. 42. Construction and filling in the percolation tubes.

means of a stopcock and any overflow was drawn off a few inches above the top of the sand in order to maintain constant hydrostatic pressure throughout the experiment. The rate of flow through the tubes was adjusted to about 0.75 liters per day by a stopcock at the bottom of the tube. The arrangement of these tubes is shown in figure 42.

Measurement of the pH and uranium content of samples was made at three points:

1. Just above the modifying influence.
2. Just under the modifying influence.
3. In the beaker catching the effluent.

The volume of solution passing each day was recorded and all effluent was evaporated in beaker D, on a steam bath. Cumulative uranium content of the effluent in beaker D was determined three times per week. The measurements, and estimation of total uranium passing each point are presented in graphical form in figures 43 to 55 and totals are summarized in Tables XV and XVI.

Application

This study is believed to add to knowledge of formation of uranyl minerals and sites of expectable unusual abundance. Such uranyl minerals in the Colorado Plateau area are currently the prime source of domestic uranium. Field studies show broad patterns of uranium distribution compatible only with alluvial accumulations and suggest that present deposits formed through reorganization and redistribution of alluvial uranium minerals by groundwater solutions. It is hoped that further coordination of these investigations with field studies may improve the understanding to

be gained from the great amount of research being done and directed towards improvement in methods of discovery of uranium ores.

Acknowledgements

The project was carried out as one part of a broad planned investigation into origin of uranyl salt mineral deposits under U.S.A.E.C. Contract AT(30-1)-1172 directed by Dr. George W. Bain. Mr. R.L. Schortmann built the apparatus and made the many replacements required due to breakage. Miss Marilyn Roth made all the assays and pH determinations and deserves special thanks for her effort. This project represents 144 uranium determinations and 288 pH determinations per week for a period of 9 weeks; it is difficult to appreciate the concerted effort to maintain this schedule unbroken from beginning to completion.

Observational Background

Source for uranium occurs in two principal stratigraphic horizons in the Colorado Plateau area; these are the Shinarump conglomerate and the Salt Wash formation. Both are fluvial deposits wherever they are uraniferous. (Bain 1).

The Detrital Formations

The Shinarump conglomerate has the uranium content localized in "in-channel" deltas, apparently built into pools; the entire deposit represents an alternation of flood and ebb conditions, the pools being cut during time of flood and filled at both ends during ebb conditions. This formation outcrops in the Plateau area as cliffs around buttes and mesas

and thins and thickens abruptly. It overlies the Moenkopi shales unconformably and is in turn overlain by the Chinle formation.

The Salt Wash formation is a sandstone of fluvial and aeolian origin interrupted frequently by mudstone. A calcareous phase of the sandstone appears to be the result of replacement of the borders of the quartz and jasperoid sand grains by calcite.

The Groundwater Redistribution

The source for the uranium in the Salt Wash and Shinarump beds is traceable to an alluvial pattern in the formation and the ore materials appear to have been derived from heavy alluvial uranium minerals; these are almost absent now and they seem to have been reorganized and redistributed by groundwater solutions. The Shinarump conglomerate has the uranium associated with hydrocarbon, both in and around quartz and jasperoid grains. In the Salt Wash formation, the pure quartz sandstone is generally free of uranium, and mineralization occurs only in the vicinity of quartz which is partially replaced by carbonates and vanadates. Uranium and vanadium minerals are more abundant in the southern and eastern occurrences of the formation than elsewhere; here too mudstones are abundant and probably provided the vanadium.

The Groundwater Components

Groundwater analyses from below the watertable in the Happy Jack Mine and Lukachukai Mine #23 gave pH of approximately 7 and showed an abundance of sulphates. Presence of ferric sulphate above the watertable indicated a pH 3.5 to 4. The uranium content of these solutions de-

creased from 10.9 parts per million at pH 6.7 to 0.12 parts per million at pH 7.4. The SO_4 ion concentration dropped about one hundredfold between the highest uranium value and the lowest. Structurally the quartz sand grains were found to be corroded, with carbonates or clay minerals filling the solution cavities. Uranium minerals seem to be substituted for this original replacement material. Petrographic study of ore from near some mineralized rolls showed a sequence of unmineralized sandstone passing laterally into a zone of corroded and carbonate-replaced sand grains, which in turn graded into a carnotite bearing zone with the carnotite substituting for the carbonate. (Bain and Sage). Near dilation shear joints the sequence passed into vanoxite having the same mode of occurrence as the carnotite. Calcium sulfate is abundant in most mineralized areas or nearby.

The preceding associations influenced selection of combinations for the laboratory study herein presented.

Laboratory Study

The laboratory experiment was set up to simulate as closely as possible the field conditions attending occurrence of the supergene uranyl minerals. Sulphuric acid at pH 4, simulated groundwater and percolated through the columns, picking up uranium from a charge of either carnotite or uraninite set at the top of the sand. The contaminated acid traveled through a pure quartz sand, analagous to the uniform quartz sandstone of the Salt Wash, in order to filter out mechanical particles and

TABLE XIV. TUBE CHARGE IN PERCOLATION EXPERIMENTS.

Uniform throughout.	Single charge - Homogeneous throughout - Control tubes.	
	1. SiO ₂ 100% 2. SiO ₂ 90% - CaCO ₃ 10% 3. SiO ₂ 98% - FeS ₂ 2% 4. SiO ₂ 88% - CaCO ₃ 10% - FeS ₂ 2% <u>Suggest.</u> 14. SiO ₂ 90% - Charcoal 10% 19. SiO ₂ 98% - Chalcopyrite 2% 20. SiO ₂ 90% - Chalcopyrite 10% 21. SiO ₂ 90% - Hydrocarbon 10%	
Uniform throughout with bed.	Main charge.	Bed contains.
	7. SiO ₂ 100% 8. SiO ₂ 90% 12. SiO ₂ 100% <u>Suggest.</u> 13. SiO ₂ 100% 15. SiO ₂ 100% 16. SiO ₂ 100%	FeS ₂ 10% - SiO ₂ 90% FeS ₂ 100% SiO ₂ 80% - Hydrocarbon 20% V ₂ O ₅ 100% Charcoal 100% Chalcopyrite 100%
Only A to B is modified.	No bed insert	Bed insert
	A to B* - 90% SiO ₂ 10% CaCO ₃ 5. Carnotite source 6. Uraninite source	A to B* - 90% SiO ₂ 10% CaCO ₃ 9. V ₂ O ₅ - Uraninite source 10. SiO ₂ 80% - C 20% Carnotite 11. SiO ₂ 80% - Hydrocarbon 20% Carnotite source <u>Suggest.</u> 17. Apatite - uraninite source. 18. FeS ₂ - uraninite source. 20. CuFeS ₂ - uraninite source.

Fig. 43. Graphic record of changes in solution throughout tube # 1.

allow it to stabilize. The uniform sand column was interrupted between draw off points A and B (fig. 42) by a modifying environment, analagous to the calcite or vanadium zones of the Salt Wash formation. The solutions changed content as they passed through the modifying environment and many gave up their uranyl ion. Just before passing draw off point B, the solutions reentered the uniform quartz sandstone and travelled through it to the terminal point, C, through which they dropped into a beaker at the bottom of the tube. The course of these groundwater solutions approximated the routes followed by solutions through the Salt Wash, interrupted by various modifying environments, and so simulated corresponding beds in the field.

The various combinations of modifiers and control tubes are listed in Table XIV. The uranium source at the top of each tube contained 1.4 grams of uranium and was essentially the same amount whether it was in carnotite or uraninite.

Control Tubes - Uniform Sand Throughout

Four control tubes were run to determine the effect of various environments on uranyl bearing solutions. Tube #1 with uniform quartz sand served to measure the effect, if any, of a chemically inert environment on the uranyl sulphate solutions. Tube #2 containing 90% quartz and 2% pyrite was run to determine the effect of pyritic sandstone alone. Tube #4 contained 88% quartz, 10% calcite and 2% pyrite, and was run to study the effect of pyrite acting in a CaCO_3 environment. All four tubes had a carnotite source for the uranium. Generally calcite held the pH

of solutions between 6.7 and 7.0 even in the presence of pyrite. Pyrite in an inert environment oxidized slowly to ferric sulphate and the pH dropped from 4 to 3.3. However pyrite is transformed slowly to FeSO_4 without oxidation to the ferric state in the presence of calcite and the pH stays near 7.

TUBE #1 - QUARTZ. Tube #1 was run as a control to measure any effect of pure quartz on uranyl bearing solutions. The daily pH and uranium content readings at draw off points A and B coincide closely. (Fig. 43A). Negligible uranium is precipitated by a pure quartz environment even over a long period; cumulative uranium content passing points A, B, and C, and stored in D are plotted against time in days, and the graph exhibits a very close coincidence of uranium content at all four points. (Fig. 43B). During the 50 days of operation, 13923.6 micrograms of uranium passed point A and 13032.9 micrograms passed point B. (Table XV and XVI). A negligible amount of uranium remains unaccounted for; therefore a quartz sand environment seems to have no measureable effect on pH or uranium content. This fact may be applied not only to this tube but to the effect of the quartz content of the succeeding ones as well. Dividing the cumulative uranium content at point A by the number of days the tube was run gives the rate of leach from carnotite as 278.5 micrograms of uranium per day. Dividing the cumulative uranium content at point A by the cumulative volume of solution passing through the tube gives a rate of leach for carnotite of 384 micrograms of uranium per liter. This rate of leach varies considerably for the various tubes ,

TABLE XV. SOLUTION CONTENT IN PERCOLATION EXPERIMENTS: UNCORRECTED FOR SUSPENSION.

Tube number	1	2	3	4	5	6	7	8	9	13	11	12
Days of run	50	52	50	52	52	52	50	52	52	14	52	52
Total at A	13923.6	4749.6	31152.9	16691.1	9105.5	319428.6	63866.1	20179.8	253387.8	76643.6	41084.2	32227.3
Total at B	13032.9	2582.5	15412.6	2061.1	2851.7	189847.3	18841.9	5311.7	9380.6	1162.5	7325.2	25487.1
Total at C	13087.8	2582.5	17626.5	1550.0	1614.9	157498.0	13951.7	2014.3	1656.5	1240.9	4598.3	12577.5
Liters solution	36.27	32.81	36.71	36.81	27.76	41.76	43.37	41.34	41.97	10.96	43.55	33.48
Per liter at A	384	144.5	848	453	328	7650	1472	488	6050	7000	944	963
Per liter at B	359	78.9	421	56	102.7	4550	435	128.5	223.6	106.2	168	761
Per liter at C	360	39.7	480	42.1	58.2	3770	322	48.7	39.5	113.3	105.5	376
A - B	25	65.6	427	397	225.3	3100	1037	395.5	5826.4	6893.8	776	202
A - B corrected	25	0	32	40.7	191.3	3100	607	86.4	5826.4	6893.8	213.7	12
Suspension	0	65.6	395	356.3	34	0	430	273.1	0	0	562.3	190
Per liter at B - C	0	39.2	-59	13.9	44.5	780	113	79.8	184.1	-7.1	62.5	285
(1)												
Total micrograms D	12900	1700	17200	3510 *	1930	151000	15000	2930	2280	1490	5170	13500
% discrepancy	-1.2	-23.5	2.5	-55.8	-16.4	4.2	-6.9	-31.5	-27.3	-16.6	-11.1	-6.8

TABLE XVI. SOLUTION CONTENT IN PERCOLATION EXPERIMENTS: CORRECTED FOR SUSPENSION.

Tube number	1	2	3	4	5	6	7	8	9	13	11	12
Days of run	50	43	34	46	47	52	37	43	52	14	31	36
Total at A	13923.6	1478	11902.4	3375.5	7319.5	319428.6	30648.1	5077.7	253387.8	76643.6	10821.2	12750.2
Total at B	13032.9	1483.5	11010.0	2017.5	2705.9	189847.3	10647.3	1960.2	9380.6	1162.5	5060.0	12465.7
Total at C	13087.8	731.3	13309.3	1409.1	1515.7	157498.0	9542.7	1752.9	1656.5	1240.9	3758.0	9476.8
Liters solution	36.27	24.36	27.92	33.45	24.07	41.76	32.92	35.97	41.97	10.96	26.98	25.10
Per liter at A	384	60.6	426	101	304	7650	931	141	6050	7000	401.2	508
Per liter at B	359	60.9	394	60.3	112.7	4550	324	54.6	223.6	106.2	187.5	496
Per liter at C	360	30.0	476	42	63	3770	289.5	48.7	39.5	113.3	139.1	390
A - B	25	0	32	40.7	191.3	3100	607	86.4	5826.4	6893.8	262.1	12
B - C	0	30.9	-82	18.3	49.7	780	34.5	6.9	184.1	-7.1	48.4	106

* This beaker probably was contaminated by substitution on the 23rd day. The small amount of uranium adhering to the walls of the beaker # 6 or even # 1, # 3 or # 12, if substituted without cleansing, would cause this error.

(1) The assay method used determines only three significant figures. The total at D should be the same as at C except as sampling at C was inaccurate. Except for # 4, D and C are in agreement of 9% or 825 micrograms, whichever is the greater discrepancy.

Fig. 44. Graphic record of changes in solution throughout tube # 2.

dropping to 328 micrograms per liter in tube #5 and rising to 1472 micrograms per liter in tube #7 and averaging 781 micrograms per liter for all.

TUBE #2 - QUARTZ AND CALCITE. Tube #2 determines the effect of a calcareous sandstone environment on uranyl sulphate solutions. A mixture of 90% quartz and 10% calcite was used to simulate this environment.

The pH at both A and B remains consistently around 7, (Fig. 44A). The uranium content of the solutions is extremely low at point A and is essentially the same at B. The cumulative amount of uranium passed by points A, B, and C, to D, is very low (Fig. 44B); only 4769.6 micrograms of uranium passed point A in 52 days, compared to 13923.6 micrograms in tube #1; a considerable part of this was in suspension and only 1478.0 micrograms can be credited to solution, equivalent to 60.6 micrograms per liter. Using the average leach rate as 781 micrograms per liter, a total of 25650 micrograms was lost by the source and only 7.8% of this uranium passed point A in solution. The remaining 92.2% was precipitated at the top of the calcareous sandstone as a brown encrustation on the calcite grains principally in the first two centimeters. Obviously the calcite environment exerts an influence on the solutions to cause precipitation of most uranyl ion. The calcite lowers the H ion concentration rendering the solution unable to carry the uranate ion, and also reduces availability of the SO_4 ion to diminish capacity of the solution to carry uranyl ion. Thus Ca ion effectively robs the soluble uranyl sulphate to its SO_4 ion and causes it to precipitate as yellow and brown uranic oxide. The soluble calcium sulphate passes down the remainder

Figure 45. Graphic record of changes in solution throughout tube # 3.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

of the tube. Tube #13 shows that pure quartz sand with a bed of pure V_2O_5 , lowers the SO_4 concentration by formation of vanadium sulphate, raises the hydrogen ion but precipitates the uranium. Therefore removal of SO_4 ion is considered to be the most potent single influence on lowering uranyl ion solubility.

The amount of precipitation per centimeter of calcite was calculated from the several calcite-quartz tube charges. (Table XVII). Roughly one fiftieth of the micrograms of uranium per liter will be precipitated by each centimeter of calcite sand. These values are plotted on Figure 56 giving a general graph of uranium precipitation relative to thickness of calcite sand penetrated. The graph shows that solutions have an exponential rate of decrease of their contained uranium relative to penetration.

TUBE #3 - QUARTZ AND PYRITE. Tube #3 measures the effect of a pyritic sandstone environment on uranyl sulphate solutions. A mixture of 98% quartz and 2% pyrite was used to simulate this environment.

The solutions remained at approximately pH 4 although showing a decrease of over 1/2 a pH unit as oxidation began to decompose the pyrite. (Fig. 45A). The uranium content stored between points A and B increases to a maximum and thereafter remains constant, (fig. 45B); much of this seems to have been in minute suspended particles which became filtered out. Uranium content accumulated between these two points, including the minute suspension particles, suffered a decided loss during the latter part of the 52 days in which observations were made. (See Fig-

A **B**

Figure 46. Graphic record of changes in solution throughout tube # 4.
A. Daily variation in pH and uranium content of solutions.
B. Cumulative uranium passing points A, B, C and stored in D.

ure 45B). The amount of uranium passing point A and also the amount being precipitated between points A and B during the early stages is much greater in tube #3 than in tube #2.

The uranium content in solution passing points B and C of tube #3 is so nearly the same as to suggest that much of the uranium passing point A in the early stages was transported mechanically rather than in solution and was filtered out. The pyrite oxidized extensively during the run and this became very noticeable after about 20 days; this decomposition raised the H ion concentration as is shown by the slow drop in pH. (Fig. 45A). This augmented the uranyl ion in solution by dissolving the fine carnotite suspension and Table XVI corrected for suspension shows 82 micrograms more uranium per liter at C than at B. The early uranium surplus was depleted systematically, (Fig. 45 B) and the accumulated surplus of 32 micrograms per liter is expected to disappear shortly as this experiment is continued. It appears that pyrite in a pure quartz environment accumulates uranium temporarily from uranyl solutions but the effect is small and is reversed when ferric sulphate begins to form.

TUBE #4 - QUARTZ, CALCITE, AND PYRITE. Tube #4 was arranged to determine the effect of pyrite in a calcareous sandstone on uranyl sulphate solutions. A mixture of 88% quartz, 10% calcite, and 2% pyrite was used to simulate this environment.

The pH of the solution rises to 7 between the top of the tube and sampling point A, (fig. 46A) and the uranium content, exclusive of the first 7 days, is extremely low at points A and B. The high uranium content at

A

B

Figure 47. Graphic record of changes in solution throughout tube # 5.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

A for the first few days is attributed either to mechanical transport or to calcite not being conditioned initially for reaction with uranyl sulphate. It is possible that some time is essential for the CaCO_3 to go into solution at pH 4 and absorb the SO_4 ion from the uranyl sulphate. Whatever the cause of the high uranium content at A for the first few days, amount passing A soon becomes very small at approximately 75 micrograms per day and is only 30 micrograms greater than the amount passing B (Fig. 46B). Most uranium was precipitated at the top of the sand along with a small limonite gossien formed as a result of the oxidation of the pyrite at the top of the tube. Comparison of this tube with tubes 2 and 3 shows that the calcite in the sand exerts a major influence on precipitation of uranium from the solutions. Influence of pyrite is just noticeable and pyritiferous, calcareous sandstone appears to be a slightly better accumulator of uranium in minerals than uniform calcareous sandstone. This combination duplicates conditions in the deeper workings of the Happy Jack Mine in the White Canyon area.

Tube With Modifying Formation Between Control Points

TUBE #5 - QUARTZ AND CALCITE. Tube #5 demonstrates the effect of calcareous sandstone on uranyl sulphate solutions passing into it from a uniform quartz sand. This zone is analagous to a calcite replacement zone in the Salt Wash formation; it had a mix of 90% quartz and 10% calcite.

The pH increases from 4.5 at A to nearly 7 at point B, (fig. 47) and uranium in the solutions declines between 304 micrograms per liter at

A.

B.

Figure 48. Graphic record of changes in solution throughout tube # 6.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

A to attain a low content averaging about 112 micrograms per liter at B; this represents a drop of 8.5 micrograms per cm. per liter for 304 micrograms per liter initially. The calcite zone precipitates most of the uranium between these two points. The solution drops 63% of its dissolved uranium content between points A and B. Most uranyl ion was precipitated as a brown uranium mineral at the top of the CaCO_3 zone, although the entire zone was colored faint yellow in the latter days. The calcite exerts its influence immediately and the uranium is precipitated as soon as the solutions enter the zone of calcium ions.

Effect of a Modified Source for Uranium

TUBE #6 - QUARTZ - CALCITE ZONE. URANINITE SOURCE. Tube #6 was run to determine the effect of a different source for uranium. Uraninite was substituted for carnotite and the environmental conditions were set the same as they were in tube #5 with pure quartz sand above a zone of 90% quartz and 10% calcite extending between sample points A and B.

Uraninite contributes considerably more uranium to the solution than does carnotite. (Fig. 48). The uraninite yielded 319428.6 micrograms in a period of 52 days while the carnotite of tube #5 yielded only 7319.5 micrograms. The uraninite leach yields an average (tubes 6, 9, and 13) of 6900 micrograms of uranium per liter as compared with 781 micrograms per liter from a carnotite origin (tubes 2, 5, 7, and 11).

The qualitative effect of the calcite zone on the uranyl sulphate solution was unchanged by the substitution of uraninite as a source of uran-

A

B

Figure 49. Graphic record of changes in solution throughout tube # 7.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

ium. The pH rose from approximately 4.5 to nearly 7 between points A and B; the uranium content of the solutions was reduced by almost 130,000 micrograms in 52 days or 3100 micrograms per liter. This is 40.5% of the amount passing. An additional 10% of uranium was precipitated on the quartz between points B and C. It appears that the calcite can precipitate only a limited amount of uranium in a given time as the solutions pass through it and furthermore a delay in deposition of the precipitate is identified. Later the amount precipitated will be shown to be 1/50 of the amount arriving for each centimeter of calcite. Principal uranium was precipitated as a brown uranium oxide at the top of the calcite zone and a conspicuous but diminishing yellow coloration appeared through the calcite even to the bottom of the tube.

Tubes With Modifying Bed Between Control Points

TUBE #7 - PYRITE BED IN A QUARTZ SAND. Tube #7 was run to measure the effect of a thin bed of pyritic sandstone on uranyl solutions. A mix of 90% quartz and 10% pyrite was placed midway between points A and B to simulate this condition.

The pyritic sandstone bed has no effect on the pH of the solutions, which remained approximately 4 at both A and B, (fig. 49A) but appears to have a slight effect on the total uranium content. (Fig. 49B). The large amount of uranium passing A in the first 11 days is due probably to mechanical transport of the finely powdered carnotite as in tubes #3 and #4. The general effect of the leach solution is similar to that on tube #3 but oxidation of pyrite to ferric sulphate and decrease in pH is

A

B

Figure 50. Graphic record of changes in solution throughout tube # 12.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

not so conspicuous in #7 as in #3. The pyrite may have accumulated up to 2% of the uranium passing point A which is slightly less than tube #3 but the pyritic volume is likewise less.

TUBE #12 - HYDROCARBON BED. Tube #12 was run to determine the effect of a hydrocarbon sandstone bed on uranyl sulphate solutions percolating through it. A bed of 20% hydrocarbon and 80% quartz was set midway between points A and B to simulate these conditions.

The hydrocarbon environment appears to have little effect, if any, on the pH of the solutions passing through it, (fig. 50A) and only 12 micrograms per liter are removed from solution. The uranium content graph for solutions passing point B follows rather closely that for point A (fig. 50B). Initially much more total uranium passes point A than reaches B and more passes B than reaches C. Certain irregularities in sample behavior suggest that this is due to mechanical occlusion of carnotite particles which are filtered out during their descent and do not represent a chemical precipitate. However a very pale yellow coloring around the quartz grains in the bed may be due to precipitated uranium or to migrated hydrocarbon. About 18% of the total uranium passing A is accreted on particles above C. Field occurrence of uranium with hydrocarbon in the Shinarump conglomerates appears to support the suggestion that selective physical trapping of particles may be more important than chemical precipitation. Hydrocarbon gives the appearance of removing uranium from solutions, although at a considerably slower rate than by calcite. The fact that acidity remains constant at pH 4 suggests that it

Figure 51. Graphic record of changes in solution throughout tube # 8.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

is not the hydrogen ion concentration that is the controlling factor over this sort of precipitation but some other influence.

TUBE #8 - PYRITE BED IN A CALCAREOUS SAND. Tube #8 was run to determine the effect of a pyritic zone in a calcareous sandstone environment upon precipitation of uranium. A band of pyrite was set under a zone of 90% SiO_2 and 10% CaCO_3 from the top of the tube down to sampling point B.

The zone between points A and B precipitates 86 micrograms per liter or about five eighths of the uranium in the solution passing point A. (Fig. 51 B). A large additional amount of uranium appears to have been carried mechanically in extremely fine division; the solution carried only 141 micrograms per liter past A and 54.6 micrograms per liter past B. The calcite sand between points A and B in tube #2 precipitated essentially no uranium but about 30 micrograms per liter were dropped between points B and C. The inference drawn from this comparison is first that it is very difficult to reduce the uranium in solution below 50 micrograms per liter with calcite alone and second that pyrite is a weak accumulator of uranium. The failure of pyrite to remove uranium in normal amount from tubes 4 and 7 suggests that the concentration of the pyrite in a bed has minor importance but exerts some effect. The pH of the solutions remained constant at approximately 7 between points A and B, and the uranium remained very low after the first 10 days, (fig. 51A); at the low uranium concentration being considered here, almost inconsequential errors become greatly magnified and so only the general trend of change

A

B

Figure 52. Graphic record of changes in solution throughout tube # 11.
 A. Daily variation in pH and uranium content of solutions.
 B. Cumulative uranium passing points A, B, C, and stored in D.

should be considered indicative.

TUBE #11 - HYDROCARBON UNDER A CALCAREOUS SAND ZONE. Tube #11 was run to determine the effect exerted by a hydrocarbon bed in a calcareous sand environment upon uranyl sulphate solutions. Crushed asphalt, that had been weathered for over 50 years, was diluted with 4 times its weight of quartz and was set between sample points A and B under a calcite and quartz zone to simulate these conditions.

The pH rose from 4.5 to 7 between the points A and B, and the uranium content of the solutions diminished significantly (fig. 52A). The cumulative graph form (fig. 52B) suggests that there was a large amount of carnotite carried mechanically past A between the 16th and 21st day. Seven eighths of the chemically and mechanically transported uranium that passed A was precipitated above B. Chemical transport from the 21st to the 52nd day witnessed 401 micrograms of uranium per liter passing A and 214 micrograms of uranium per liter being precipitated before reaching B so that slightly over half of the dissolved uranium was removed. Most precipitation occurred at the top of the calcite zone where a strong brownish yellow encrustation occurs on the calcite and adjacent quartz. This coating diminishes in intensity downward and the overall color becomes faint yellow. A comparison with tube #5 shows no real influence of hydrocarbon where enough calcite exists to cause precipitation. The quartz grains in the hydrocarbon mix bed acquired color which became more intense and were a light brown at the end of 52 days. It is uncertain whether this coloration is due to migrated hydrocarbon

Figure 53. Graphic record of changes in solution throughout tube # 9.

A. Daily variation in pH and uranium content of solutions.

B. Cumulative uranium passing points A, B, C, and stored in D.

or precipitated uranium.

Modified Source and Modifying Bed

TUBE #9 - QUARTZ AND CALCITE SAND, V_2O_5 BED. Tube #9 determines the effect of a bed of vanadium pentoxide in a calcareous sandstone environment on uranyl sulphate solutions bearing a large amount of uranium. Uraninite served as the uranium source.

The effect of substituting uraninite for carnotite as the source for uranium has been discussed previously in the presentation of data for tube #6. It was found that uraninite supplied approximately 9 times as much uranium to the solutions percolating through the tubes as was furnished by carnotite. This fact may be applied to tubes 9 and 13 as well as to 6 since the conditions from the top of the tubes to sample point A are identical in all three tubes.

An examination of figure 53 shows that the pH at point A varied between 4 and almost 6 but rose to over 7 at point B. The uranium content of the solutions at point A also varied from 3000 to 9000 micrograms per liter and averaged 6050 micrograms per liter. These variations appear because the top of the calcite zone is at the middle of the sampling point A. However 96.3% of all the uranium passing point A was precipitated before the solutions reached point B and only 2/3% of the uranium passing point A dropped into the beaker below C. Of this amount of precipitate, only 53% can be attributed to the calcite, (see tube #6 and figure 56). As in the other tubes with a calcareous sandstone environment, a brown precipitate formed at the top of the calcite zone indicating precipitation of

Fig. 54. Transformations in the orange V_2O_5 bed of tube # 9.

the uranyl ion at that point. However equilibrium of calcium sulphate occurs when almost half of the uranium is still in solution and the remaining extraction can be attributed to V_2O_5 .

The successive changes in the V_2O_5 band indicate the role it plays in the capture of sulphate ions and exchange of vanadium for uranium in the solutions. A reddish brown edge formed at the top of the V_2O_5 bed after two days, (fig. 54a); one day later a yellow mineral, presumably a uranium ore, formed on top of this brown edge. (Fig. 54B). The new minerals encroached more and more on the V_2O_5 as solutions continued to pass; the brown mineral always preceded the yellow and lay between the V_2O_5 and the arriving uranyl solutions. The base of the V_2O_5 began to turn black on the 5th day and this black area spread out to encompass almost all of the remaining V_2O_5 as shown in figure 54e.

The solution became a deep yellow immediately upon leaving the V_2O_5 bed and colored the entire lower part of the tube. This coloration leached away gradually and persisted only under the discharge level at the bottom of the tube. The solutions passing into the beaker, C, were bright yellow; this color intensity diminished gradually becoming essentially colorless by the 40th day. Heating the solutions during evaporation turned them colorless. However the accumulated solution kept at 1 liter volume in beaker D on the steam bath turned drab green and later bright green. A large amount of gray brown salt was left in the beaker daily at desiccation, increasing until it was almost a half inch deep after 52 days. The change in color of the solutions upon heating suggests a change in valence

A B

Figure 55. Graphic record of changes in solution throughout tube # 13.
A. Daily variation in pH and uranium content of solutions.
B. Cumulative uranium passing points A, B, C, and stored in D.

of the vanadium ion. The colorless condition of the leach solution of the 40th day suggests:

1. The amount of vanadium being leached by solutions decreased daily.
2. The vanadium carried in the solutions had changed to a different valence level.

No investigation of this problem was attempted, and this provides area for future study. The portion of the tube below the discharge level above C became a darker and darker yellow turning to dark greenish yellow or near black at the end of 52 days. In view of the small amount of uranium precipitated between B and C, this deposit probably is a vanadium mineral.

The modifying calcite zone and the V_2O_5 bed in it, precipitated almost 97% of the total uranium leached from the uraninite source. The influences operating in this precipitation will be discussed further in describing tube #13.

TUBE #13 - QUARTZ ONLY - V_2O_5 BED. Tube #13 shows the effect of a V_2O_5 bed in a uniform quartz sand environment upon solutions carrying much uranium from the uraninite source. The solution carried approximately 7000 micrograms of uranium per liter. A bed of V_2O_5 was set in a pure quartz sand environment between points A and B to simulate the field conditions. The tube was started late and the run lasted only 14 days.

The acidity of the solution increases from slightly over pH 4 at A to approximately pH 3 at B and the uranium content declined from 7000 mic-

rograms per liter to 106 micrograms per liter at B. (Fig. 55A). Almost all uranium passing point A is precipitated before reaching B, (Fig. 55B); only 1.5% remains in solution. As in tube #9, a brown mineral began to form on the top of the V_2O_5 bed during the 2nd day; likewise the solution leaving the V_2O_5 zone colored the bottom part of the tube yellow. This color was leached rapidly from most of the tube and remained only in the space below the discharge level. In the first few days the yellow solution accumulated in the beaker C, retained its color on boiling but gave a gray brown precipitate. As from tube #9 effluent, a large amount of gray brown precipitate accumulated in the beaker D on the steam bath. In later days boiling occasionally removed the yellow color and the vanadium precipitate did not form except in the concentrate on the steam bath.

Generally hydrogen ion concentration has been regarded as the controlling influence on uranium solubility. The fact that 98.5% of the uranium is precipitated between the points A and B where the pH is lowered more than 1 unit is indicative that the H ion is not the major influence on uranyl ion solubility and precipitation of uranium from solutions. The fact that the drop in uranium content is accompanied by a drop in pH and reduction in availability of SO_4 by extraction to make vanadium sulphate, suggests that it is the sulphate ion concentration which is the controlling influence. It appears that the uranium from the source at the top of the tube reacts with the sulphuric acid to form soluble uranyl sulphate which is then carried down the tube in solution. If this solution comes in contact with an ion such as Ca or V, which has a greater attraction for the

SO_4 ion than has the uranium, that ion will capture the SO_4 of the uranyl sulphate and form relatively insoluble uranic oxide or other uranic salt. The actual composition of the minerals precipitated by reduction in availability of SO_4 to the uranium has not been determined and must await X-ray analysis. Results of this laboratory experiment conforms to the observed drop in uranium content in groundwater of mines with diminution in sulphate ion. (See p.46).

Comparative Rates of Solution of Uraninite and Carnotite

Uraninite in tubes 6, 9, and 13 contributes about 6900 micrograms per liter of solution at a pH of 4 in contrast to carnotite which yields only 781 micrograms per liter. Thus the rate of redistribution of uranium from uraninite can be expected to proceed 8.8 times as fast as from carnotite. Experimentation has not indicated yet whether this relative rate of leaching is due to avidity of V_2O_5 for SO_4 as in tubes #9 and #13 or if it may be due to mechanical state of the minerals. Rate and not ultimate amount moved seems to be the only feature affected.

Available SO_4 ion concentration appears to be the controlling factor in holding uranium in a uranyl solution. The uranium oxides of the source combine with the sulphuric acid to form soluble uranyl sulphate which is carried by the solution through the various rock environments. The uranyl ion used the SO_4 ion as a vehicle, so to speak, with which to move with groundwater solutions. Any substance which can rob the uranyl ion of its SO_4 ion vehicle will precipitate it as an insoluble uranium mineral. Calcium carbonate and vanadium pentoxide take the SO_4 ion away

from the uranyl sulphate and the uranyl ion precipitates as uranic oxide. Hydrocarbon and pyrite react with the SO_4 to reduce a small amount of it to sulphide sulphur, and that may account for their behavior as weak accumulators of uranium oxides.

Effect of V_2O_5 on Uranyl Bearing Solutions

Vanadium pentoxide in either quartz sand environment or in a calcareous sand environment exerts an extremely powerful influence on the uranyl sulphate solutions. A centimeter band of V_2O_5 precipitates 98.5% of the uranium in solutions passing through it. The V_2O_5 appears to have an only slightly weaker immediate influence in the presence of calcite but the direct and delayed action account for precipitation of 99.35% of the contained uranium. Conversion of vanadium pentoxide to the soluble vanadium sulphate raises the hydrogen ion concentration of the solutions passing through it by at least 1 pH unit. Decrease in uranium solubility with decrease in availability of SO_4 ion and increase in H ion suggests that the solubility of uranyl ions is controlled by abundance of SO_4 and not by abundance of H ions.

Structural Pattern of Precipitated Uranium Minerals

Uranium minerals appear to be precipitated from solutions around calcite grains where these are present and to some extent around quartz grains. The initial and the most intense precipitate is always on the side of the modifier exposed to the arriving solutions and the change becomes progressively less pronounced in the direction of the effluent. The pattern is conspicuous on the calcite and V_2O_5 , as it is in deposits in the

field occurrences, but is difficult to detect and follow in the low content pyrite and hydrocarbon tests. Uranium is precipitated on the outside of the powdered vanadium pentoxide and as veins cutting across it. The new minerals form on the outside; increased amounts are transformed and transferred with elapse of time and almost all material had been changed in tube #9.

Interpretation of Results

The data given in the previous section of this report is considered in a number of combinations for derivation of new information and interpretation of factors effecting the precipitation of uranium from uranyl bearing solutions. It is the purpose of this section of the report to set down a summary of these combinations and interpretations. Only environments causing change in uranium content of solutions in excess of 25 micrograms per liter are considered significant; this limitation leaves a very large factor of safety since the assays were made to a sensitivity of less than 0.1 micrograms per milliliter.

Effect of Quartz on Uranyl Bearing Solutions

A uniform quartz sandstone has an effect on solutions bearing the uranyl ion which is below the limit set as significant. It does not change the pH of these solutions nor does it effect the precipitation of uranium minerals from them. This is illustrated by tube #1.

Effect of Calcite on Uranyl Bearing Solutions

A calcareous sandstone exerts a great influence on uranyl sulphate

solutions. It raises the pH of these solutions; and reacts with them to form soluble CaSO_4 . The reaction precipitates uranium as a brown mineral presumably by expropriating the sulphate ion of the soluble uranium sulphate. A zone composed of 90% SiO_2 and 10% calcite, 22.5 cms. thick will precipitate 190 micrograms per liter or $5/8$ ths of the uranium entering it (tube #5) and a meter column removes about 750 micrograms per liter (tube #2). The ability of the calcite to precipitate uranium from uranyl bearing solutions decreases with the distance these solutions travel in the calcareous environment and with reduction in the amount of uranium available for precipitation as shown in table XVII and Figure 56. Normally the solution derived from carnotite has 781 micrograms of uranium per liter at the top of the calcareous zone; this increases to 6900 micrograms per liter when a uraninite source is used. The amount of uranium precipitated per centimeter of percolation at different initial concentrations is given in table XVII.

Table XVII

Reduction in Uranium Content of a Solution per Centimeter of Calcite			
Micrograms U per liter	Data from tube	Pptd per cm.	Col. 1 Col. 3
7650	6	137.6	55.6
781	8	16.8	46.5
781	2	18.9	41.3
4550*	6	42.1*	108.0*
304	5	8.5	35.8
60 (2)	2	0.83	72.0
Average -			60.0

* This value is from relic dissolved CaCO_3 and not calcite sand. It is in an environment essentially of quartz. If the value is omitted, the average drops from 60 to 50 which probably is the correct value

Fig. 56. Uranium precipitation relative to thickness of calcite penetrated.

The product of initial uranium content of the solution in micrograms per liter and the thickness of the percolation zone, divided by 50.0 is approximately the uranium loss by precipitation from solution stated in micrograms per liter. This indicates that removal of uranium from the solution varies at a geometric rate where calcium carbonate is the modifier and that roughly $1/50$ of the uranium in a solution will be removed by each centimeter of penetration into calcite sand of the size and dilution used in the experiment. It is probable that finer sand of greater surface area per unit volume will give increased SO_4 extraction and uranium precipitation.

Effect of Pyrite on Uranyl Bearing Solutions

Pyrite exerts only slight influence on uranyl bearing solutions to cause the precipitation of some uranium but seems to store it only temporarily. (Tube 3 and 7). Tube #3 (Figure 45) showed a greater amount of uranium passing sample point A than escaped at B for the first 3 weeks, a greater amount leaving B than arrived at A for the next 2 weeks, and a nearly balanced state from then on. Tube #7 had amount passing A generally greater than that leaving at B for the first 7 weeks when the stored uranium began to be released and augment discharge at B. (Figure 49). Storage is relatively short term and release corresponds closely with initial oxidation of FeSO_4 to $\text{Fe}_2(\text{SO}_4)_3$ and hydrolysis of the sulphates. Pyrite lowers the pH of solutions passing through it by oxidizing first to ferrous sulphate, which changes to ferric sulphate before it hydrolyses to form limonite, causing thereby a higher concentration of the

hydrogen ion as in tube #3 (fig. 45). Pyrite acting in a calcareous sandstone environment (tubes 4 & 6) exerts a more powerful influence than when it acts in a uniform quartz environment (tubes 3 & 7). However pyrite reduces the effectiveness of calcite as a precipitating agent which is shown by comparison of tubes 4 and 8 with tubes 2 and 5. The delay in precipitation or coagulation of uranium precipitates is longer and more pronounced where pyrite is present than where it is absent.

Effect of Hydrocarbon on Uranyl Bearing Solutions

Hydrocarbon exerts a very minor influence on uranyl bearing solutions and causes direct precipitation of only inconsequential amounts of uranium in the limited time of experiment. A much larger amount, 190 micrograms per liter, of very finely divided uranium minerals is removed from suspension, presumably by adhesion, in contrast with only 12 micrograms per liter through direct precipitation. Some hydrocarbon is picked up by the solution and coats the lower sands and as this hydrocarbon separates, it removes 106 micrograms per liter from solution and an additional 84 micrograms per liter from suspension. The hydrocarbon seems to have unusual occlusive properties although this is not proven yet.