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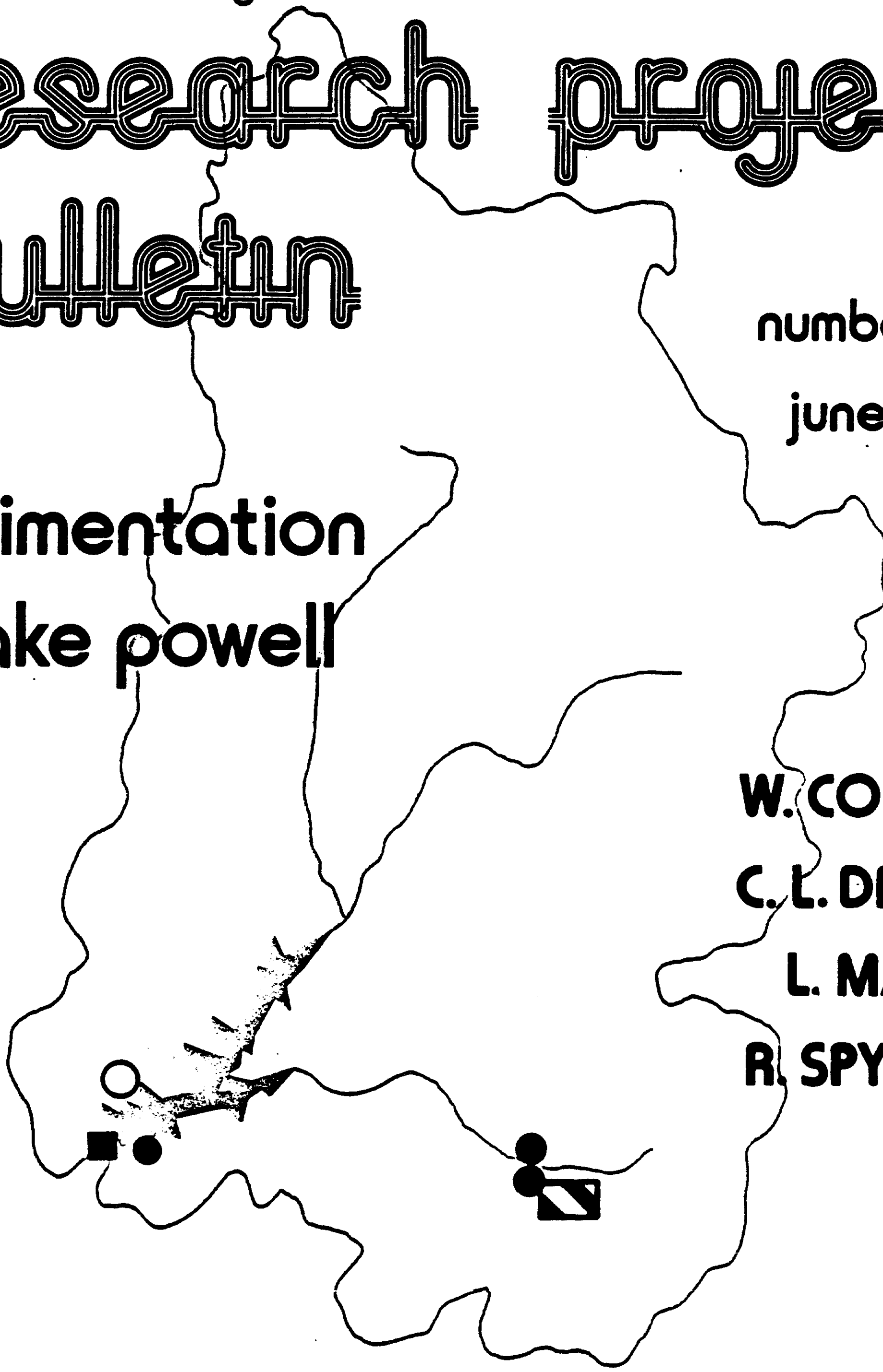
sedimentation in lake powell



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SEDIMENTATION IN LAKE POWELL

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LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

From the closing of construction of Glen Canyon Dam in 1963 through 1977, Lake Powell accumulated about 400,000 acre-feet of sediments. The major source of these sediments is suspended material brought in by the two major tributaries--the San Juan and Colorado Rivers--and most is deposited in delta-like bodies in the upper reaches of the lake. Locally, slumping has created underwater barriers as high as 60 feet (20 meters) above the old river channel. Comparison of measured sediment volume with estimates based on suspended sediment measured at the gaging stations at Bluff, Cisco, and Green River, Utah, indicates that reasonable estimates of the volume of sediments entering Lake Powell can be obtained from the gaging station data.

Chemical sedimentation is significant in times of water quality determinations but is a minor contributor to lake sedimentation. Calcium carbonate, mostly detrital, amounts only to 0.6 percent of the total sediment volume. The lack of diatom frustules in the sediments indicates that silica removed from solution by diatoms is redissolved in the hypolimnion or in the sediments. No authigenic clay minerals were found, the ubiquitous types being illite, kaolinite, and montmorillonite.

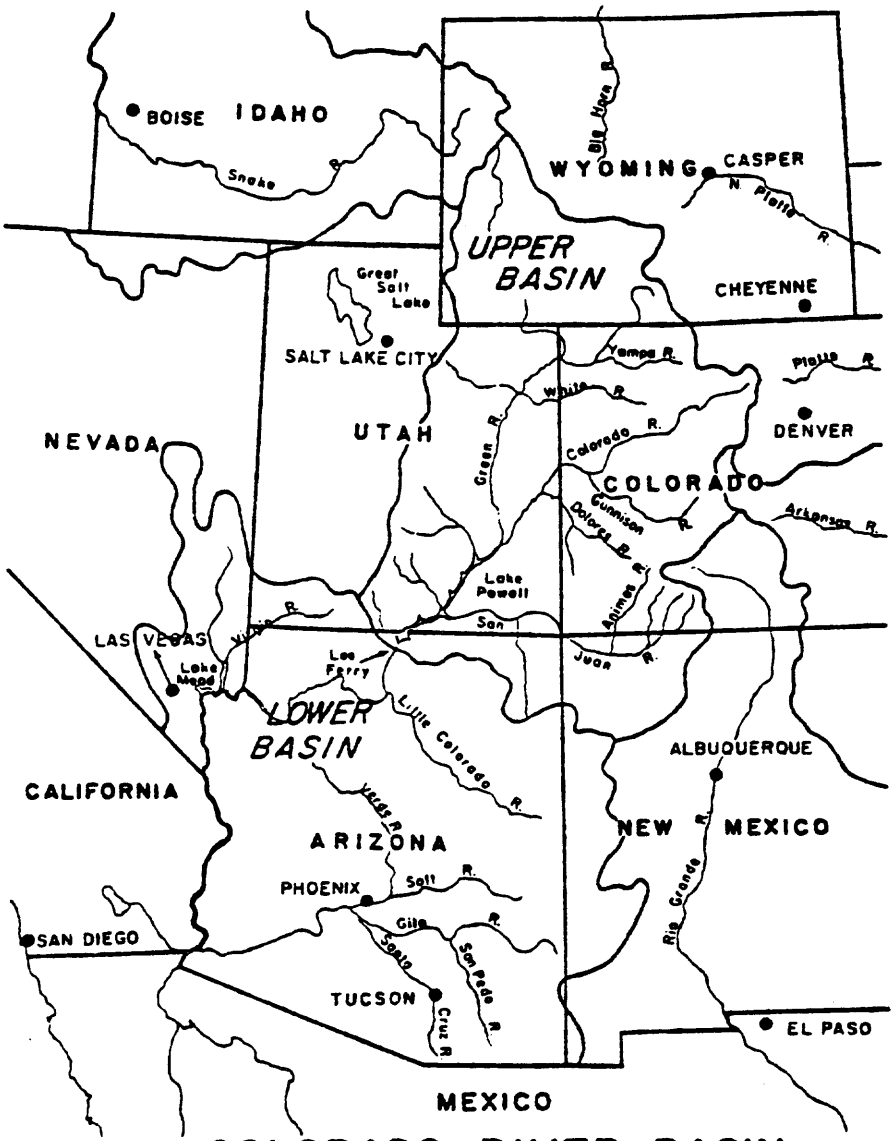
If present sedimentation rates are maintained, the minimum time for sediment infilling to the level of the penstocks would be nearly 200 years and total filling would take 1000 years

INTRODUCTION

Construction of the Glen Canyon Dam produced a water reservoir, Lake Powell, and in addition a reservoir for sediments from a number of sources. The primary sources are the two major arms of the river system, the Colorado and San Juan Rivers, with lesser contributions from smaller tributaries, from slumping, from wind-borne materials, and from chemical precipitation, sometimes influenced by biological activity.

The objective of the sedimentation studies was to determine the location of the sediments in the lake, the means by which they are being transported, the rates at which they are being deposited, their nature, and the relative importance of the different sources. The ultimate purpose of the studies was to provide an information base that would be useful in predicting the effects of the sedimentation on the uses of the lake--for power, water, recreation--and the effects that might arise from eventual developments in the Upper Colorado River Basin (UCRB) (Figure 1) or from natural variations in water supply.

The Colorado Plateau region, to which Lake Powell is central, is relatively undeveloped. It contains resources, particularly energy resources, of some magnitude, and population trends suggest that upstream demands for water will increase markedly over the next decade. The lake has been studied mostly in a filling mode, but as demonstrated in 1976 and 1977 this will not always be the case. As upstream demands increase and particularly if there is a period of protracted drought during which lake levels cannot be maintained, the distribution and nature of the sediments will significantly affect the uses and the users of Lake Powell.



COLORADO RIVER BASIN

Figure 1: Location of Lake Powell

GEOLOGIC SETTING

Lake Powell is located on the Colorado Plateau, one of the world's showplaces for both tourist and geologist. The sculpturing of the rocks by wind and water has produced geological wonders that are preserved in the many National Parks, National Monuments, and recreation areas of the region.

The Plateau escaped the major deformation that occurred in the regions surrounding it and over much of Phanerozoic time lay close to sea level--sometimes above and sometimes below. Although the Plateau behaved as a single structural unit over this time, gentle tectonic movements, predominantly vertical, have produced undulations that are reflected in such broad structural features as the Monument, Circle Cliffs, Kaibab, and San Rafael Uplifts and the Kaiparowits, Black Mesa, Paradox, and Uinta Basins. These features are usually separated by impressive monoclines, but the dip of beds elsewhere is generally no greater than 10 degrees. Igneous activity is manifested by laccolithic intrusions producing such prominent features as the Henry, La Sal, and Abajo Mountains; by diatremes, Mule Ear, Moses Rock, Hopi Buttes; by volcanic dikes or necks, Alhambra, Shiprock, Agathla; or by extensive volcanism, mostly around its edges, such as in the San Francisco and San Juan volcanic fields. The region is relatively inactive seismically compared with adjacent regions, and the few heat-flow measurements suggest low thermal activity as well. In late Cenozoic time the entire region was uplifted and the rivers and tributaries became deeply entrenched.

The stratigraphy exposed along the shores of Lake Powell ranges from the Hermosa Formation, of Pennsylvanian age, to the Jurassic San Rafael Group. The Hermosa Formation is most extensively exposed in Cataract Canyon, at the northern end of the lake, and near the axis of the Monument Upwarp and the San Rafael Group in the Wahweap-Warm Creek area at its southern extremity and on the edge of the Kaiparowits Basin. Formations as young as Cretaceous are found near the lake, particularly in the Kaiparowits and Henry Mountains Basins, but do not reach its shores. Older formations, as old as Archaen, are found downstream in Grand Canyon.

Table 1 lists the stratigraphic succession and description of the important rock units of the Lake Powell area. As is typical of the relatively flat-lying formations of this area, some are cliff-formers and some slope-formers. The cliff-formers are usually well-cemented limestones or sandstones, such as the Hermosa Limestone and the Navajo and Wingate Sandstones; the slope-formers are shaly, as the Chinle Formation, the Organ Rock member of the Cutler Formation, and the Carmel Formation. The shaly units are especially susceptible to softening and slumping in the aqueous environment of Lake Powell. The sandstone units are more resistent, but their permeability permits leakage of water from the reservoir.

Superimposed on the basic stratigraphic units are talus slopes and slump blocks, dunes of windblown sand, and perched gravels left by Pleistocene stream activity.

SEDIMENTARY SOURCES

Suspended Sediments

An overview of the water resources of the UCRB is well presented by Iorns et al. (1965) for the period prior to the

Table 1: General Stratigraphy of the Lake Powell Area

Era	Formation	Thickness	General Lithology
JURASSIC	Entrada	50-350'	Grey to reddish brown cross-bedded sandstone with minor siltstone, cliff former, somewhat massive appearance. Well exposed near Halls Crossing and at the southern end of the Lake in Wahweap and Warm Creeks.
	Carmel	0-300'	Red siltstone with interbedded shales and sandstones. Well exposed at Halls Crossing and below Bridge Canyon. Slope former.
	Navajo	300-1800'	Massive cross-bedded eolian sandstone. Forms the major cliffs and overhanging grottos of Glen Canyon. Alcoves and natural bridges result from massive conchoidal weathering of this formation along well developed joints. Water seeps in marl layers. Primary formation of Lake Powell region.
	Kayenta	0-300'	Reddish sandstone interbedded with units of shale and siltstone. Forms ledges and benches, well exposed from San Juan River mouth to Long Canyon.
	Wingate	0-400'	Light brown to reddish orange massive sandstone on fresh surface. Well jointed and particularly well covered with desert varnish in areas of long exposure to wind, rain and sun. Cliff former.
TRIASSIC	Chinle (undifferentiated)	800-1200'	Bentonitic daystone, clayey sandstone with some sandstone and limestone units. Brightly colored due to varying oxidation. Easily eroded, forms broad hillocks and frequently overlain with much talus material. Primary unit for slumping activity.
	Shinarump	0-200'	Sandstone and conglomerate. Ledge forming. Forms hard cap on Moenkopi in some areas where well exposed.
	Moenkopi	0-400'	Chocolate brown shale interbedded with brownish-red platy or massive sandstone. Forms slopes with ledges. Well exposed in Hite to Castle Butte area.
	Cutler: De Chelly ss, White Rim ss	0-1500'	De Chelly forms the steep faces of the monument in Monument Valley. Reddish-orange to brown massive sandstone unit. White Rim well exposed in White Canyon and near Hite, similar lithology to Cedar Mesa (indistinguishable with absence of Organ Rock member)
	Organ Rock	250-500'	Red to reddish brown shales, siltstones and sandstones form slopes under monuments in Monument Valley, limited exposure near Hite and Piute Farms.
	Cedar Mesa ss	0-1000'	White to light brown massive sandstone primarily cliff forming, well exposed at Hite Marina
PERMIAN	Halgaito sh	0-400'	Thinly bedded reddish brown shales, siltstones, and sandstones primarily slope forming, very limited exposure.
	Rico	300-500'	Grey to white fossiliferous limestone, some thin lenses of shale, mudstone, and sandstone. Primarily slope forming when weathered.
PENNSYLVANIAN	Hermosa	1000+	Grey cherty limestone interbedded with some units of shale and sandstone well exposed only in Cataract Canyon, abundant fossils.

(Data compiled from Baker, 1936, 1946; Cooley and others, 1969; Davidson, 1967; Iorns and others, 1965; Mullens, 1960, and O'Sullivan, 1965.)

resource development which included completion of Navajo Dam on the San Juan River and Flaming Gorge Dam on the Green River in 1962 and Glen Canyon Dam in early 1963. Table 2 presents the summary data compiled by Iorns et al. (1965) and recent data from the U.S. Geological Survey (USGS) surface water records. Comparison of pre- and post-dam gaging station data shows a halving of the sediment load of the three major rivers, but only the San Juan River showed a significant decrease in the average volume of flow after 1963. An important consideration, not shown by Table 2, however, is the velocity of the streams because the ability to entrain sediment is largely a function of the turbulence of the flow which is enhanced at high velocities. As such, impoundments at Flaming Gorge, Navajo Blue Mesa, and smaller reservoirs reduce the yearly integrated load downstream by smoothing out the natural discharge cycle. However, the effect of this factor upon sediment discharge at Green River, Cisco, and Bluff, Utah, should not be over-emphasized because the numerous tributaries below the reservoirs in question restore much of the natural periodicity to flow patterns. Another factor not accounted for is the traction load of the rivers entering Lake Powell. The difficulty of measuring this parameter has caused it to be not generally monitored. Estimation of its contribution is hampered by the fact that it too is affected by stream velocity. Dampening of the spring floods by Glen Canyon Dam, for example, has reduced the size of material transported along the bed of the Colorado River in Marble and Grand Canyons. Consequently, the bed has become armored with cobbles and the huge boulders at the mouths of side canyons causing rapids that are no longer rearranged or carried away with the spring snowmelt torrent (Dolan et al., 1974).

During the period 1914 through 1957 the suspended sediment load of the Colorado River measured near old Hite

Table 2: USGS Gaging Stations for the UCRB near Lake Powell

A. Patterns of Water Flow (data in millions of acre-feet)

Water-Year	Colorado River at Cisco, Ut.	Green River at Green River, Ut.	San Juan River at Bluff, Ut.	Colorado River at Lees Ferry, Az.
1914-1957[a]	5.141	4.067	2.028	12.71
1963	2.819	1.663	.625	2.5
1965	3.357	2.784	.792	2.414
1965	6.403	5.134	2.028	10.82
1966	3.507	3.211	1.97	7.854
1967	3.022	3.999	.919	7.797
1968	4.093	4.651	1.017	8.334
1969	4.759	4.920	1.653	8.823
1970	5.838	4.268	1.531	8.672
1971	5.633	4.057	1.34	8.591
1972	3.538	4.003	.985	9.311
1973	6.436	5.388	3.024	10.11
1974	4.514	4.468	1.065	8.266
1975	5.220	4.947	1.910	
1976	3.495	3.863	1.158	

B. Patterns of Suspended Sediment (data in millions of tons)

Water-Year	Colorado River at Cisco, Ut.	Green River at Green River, Ut.	San Juan River at Bluff, Ut.	Colorado River at Lees Ferry, Az.
1914-1957[a]	14.35	20.8	37.1	101.3
1963	4.83	5.73	12.88	15.41
1964	10.00	12.09	16.34	4.426
1965	17.41	17.88	34.83	5.977
1966	5.49	6.45	13.13	
1967	8.46	11.74	17.07	River diversion tunnels closed July 7, 1965. No sediment data after 1965 water year.
1968	11.61	7.97	20.77	
1969	9.39	8.98	31.67	
1970	9.24	7.40	23.62	
1971	5.46	5.37	15.0	
1972	3.54	5.16	13.53	
1973	14.55	15.07	72.08	
1974	4.14	10.62	3.38	
1975	7.38	10.89	16.10	
1976	2.61	4.43	3.89	

a = average

averaged about 57 million tons annually, of which some 35 million tons had passed gaging stations on the Green River at Green River, Utah, on the Colorado River near Cisco, Utah, and on the San Rafael River (a minor amount). The Dirty Devil River contributed an average of about 5 million tons per year to the load at Hite. Thus about 17 million tons of sediment entered the Colorado system within the 270 miles (435 kilometers) between these gages. Lake Powell inundates about 35 miles (56 kilometers) of that distance now so that we may reasonably estimate only 87 percent of that source to be delivered to the lake terminus. Thus the contribution of suspended sediment by the Colorado River to Lake Powell can be estimated by multiplying the sum of the Green River and Cisco gaging records by 1.4 to correct for erosion downstream. From 1963 through September 1976 this amounted to 346 million tons. For the same 14-year interval the Dirty Devil River is estimated to have carried 34 million tons, assuming the same reduction in sediment load from the long-term average as the Colorado and Green Rivers showed. Similarly, the Escalante River contribution to the reservoir is estimated to be 12 million tons through 1976. The San Juan River is last gaged at Mexican Hat, Utah (near Bluff), 50 river-miles from Lake Powell. Data from Iorns et al. (1965) suggest that an additional 5 percent to the Bluff data is a reasonable estimate for erosion within that distance. Thusly corrected, the San Juan River brought 309 million tons of sediment into the reservoir during the same period. Summing these major tributaries to the lake and subtracting the 26 million tons which passed Lees Ferry prior to the closure of the diversion tunnels in 1965, the estimated weight of suspended sediment trapped in Lake Powell through 1976 is 675 million tons.

To convert this into sediment volume, one needs the *in situ* density of the sediments. For the fine-grained silts and clays that make up most of the sedimentary material, measurements from Lake Powell (Condit, 1977) and Lake Mead (Gould, 1960) indicate that a bulk density of 1.5 grams per cubic centimeter (gm/cm^3) is a reasonable average. Using this figure, the estimated volume of post-dam suspended sediments deposited in the reservoir from these sources is about 330,000 acre-feet. This figure is considerably lower than the 14-year prediction of the Bureau of Reclamation (House Document 364, 83rd Congress, 2nd Session) of 1,187,000 acre-feet, but this estimate relies on data from 1930 to 1948 in which sediment loads were very high and it assumed that Glen Canyon Dam would be completed 3 years prior to the Flaming Gorge and Navajo projects upstream. Eng (1972) also used historical data as well as downstream data from the period prior to construction of Glen Canyon Dam to estimate a volume of 676,000 acre-feet through July 1971. Again, the historical data are biased toward the high side; assumptions about constancy of flow-suspended load ratios are not correct, and the fact that Lake Powell is a repository for sediment rather than an eroding river was not properly taken into account.

The marked decrease in suspended sediment load introduced into Glen Canyon beginning in 1963 may reflect climatic factors, but they certainly are influenced by major upstream storage projects. Storage began in Navajo reservoir, on the San Juan River, on June 28, 1962, and in Flaming Gorge reservoir, on the Green River, on November 1, 1962. These and other facilities upstream from Lake Powell should continue to keep suspended sediment loads in the lake at reduced levels.

Sediments Resulting from Shoreline Instability

Lake Powell was created in a narrow desert canyon whose walls were made up of sedimentary strata of varying degrees of competence. Some formed cliffs, which maintained their character by slumping of large blocks when undercut; others, less competent, formed slopes with angles of repose suitable for the environment. In many areas wind-blown sand formed side-hill dunes on these bedrock or talus surfaces.

Filling of the reservoir created a new environment, one in which formerly stable cliffs and slopes were no longer so. The side-hill dunes were first to feel the effects of rising waters and many have slumped piecemeal or *in toto* into the lake, leaving only a scar on the canyon walls above the water's surface (Figure 2). Similarly, the inundation of talus piles and the increased pore pressures resulting from changing lake levels have caused these to slump into the lake. Winnowing by wave action, accentuated by variations in lake level, tends to remove the sand and leave exposed either the bedrock surface or the heavier cobbles or loose rock.

The effects of this slumping are most pronounced in areas of outcrop of the variegated Chinle Formation, consisting primarily of relatively incompetent clays. Along the Colorado arm of the lake this is most noticeable near the Rincon and Good Hope Bay, along the San Juan River near Cha Canyon, and in much of the area between Paiute Canyon and Clay Hills Crossing.

The total volume of slumped material is difficult to estimate, but sounding profiles in parts of the lake where little sediment has been deposited from suspension suggest that the total volume is small compared to the volume of sediment carried in by the major tributaries. However, these slumped

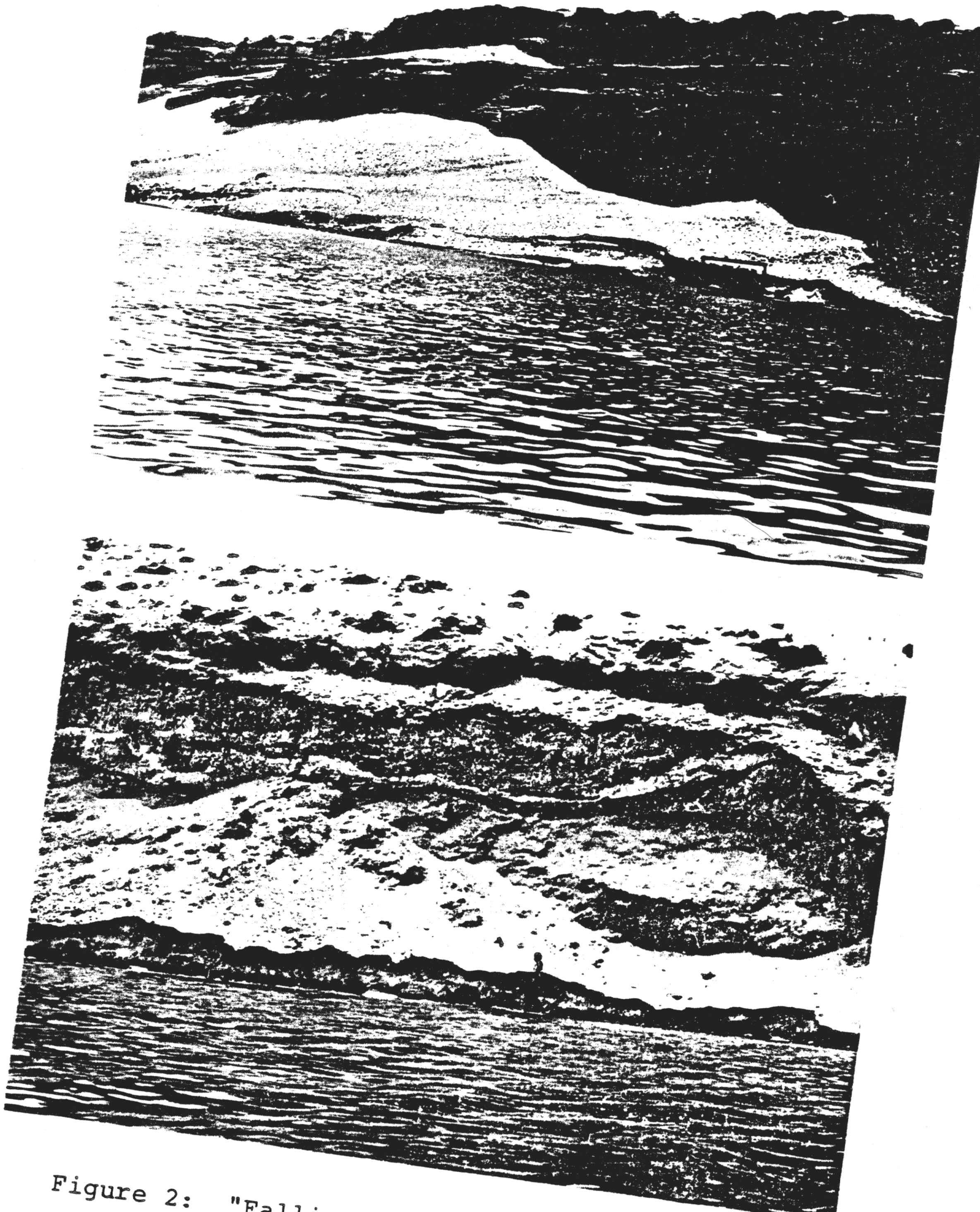


Figure 2: "Falling" Dune at the Rincon

sediments may be locally important. For example, below the Rincon at river-mile 99, where the canyon is narrow, slumping of the Chinle Formation and debris from the overlying Wingate Formation have created an underwater barrier that extends some 70 feet (21 meters) above the old river surface (Figure 3).

It has been our experience that slumping of dunes or talus into the lake is not customarily accompanied by large waves, although this may not always be the case. On the other hand, the detachment of large blocks of the cliff-forming sandstones may indeed cause major disturbances. An example is found in the vicinity of Iceberg Canyon, river-mile 102, where two rockfalls occurred (Figure 4). The first, involving a slab of rock some 20 to 30 feet thick (6 to 9 meters), 300 feet long (91 meters), and at least 300 feet high, was unwitnessed, but the second, about half this size, created a wave that drove a boat well up onto the opposite shore (L. D. Potter, personal communication). Although these were massive blocks--the largest such slumps that have occurred on the lake--their total volume was only about 75 acre-feet. The slump barrier at river-mile 99, again the largest of its type found on the lake, has an approximate volume of 2000 acre-feet, significantly larger, but quite small compared with the river influx of sediment--from about the 3700-foot (1128-meter) level--is probably less than 10,000 acre-feet; slumping from below the 3700-foot level merely rearranges the geometry of the reservoir but does not affect its capacity.

Other Sources of Sediment

Although the Lake Powell area is arid, it does occasionally receive locally heavy rainfall, particularly during summer thunderstorms. This can wash sedimentary materials

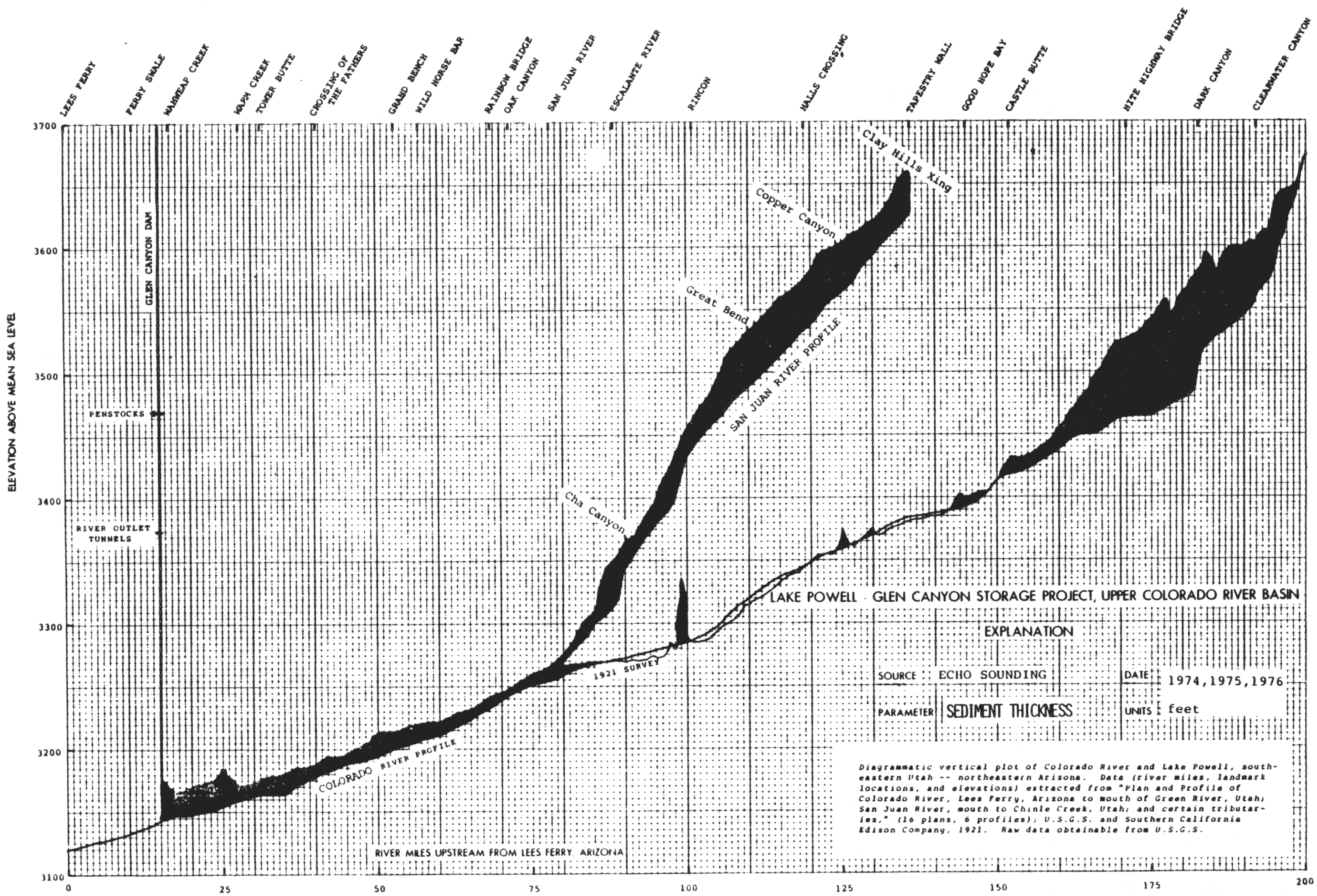


Figure 3: Diagrammatic Vertical Plot of Colorado River and Lake Powell, Southeastern Utah and Northeastern Arizona--Sediment Thickness

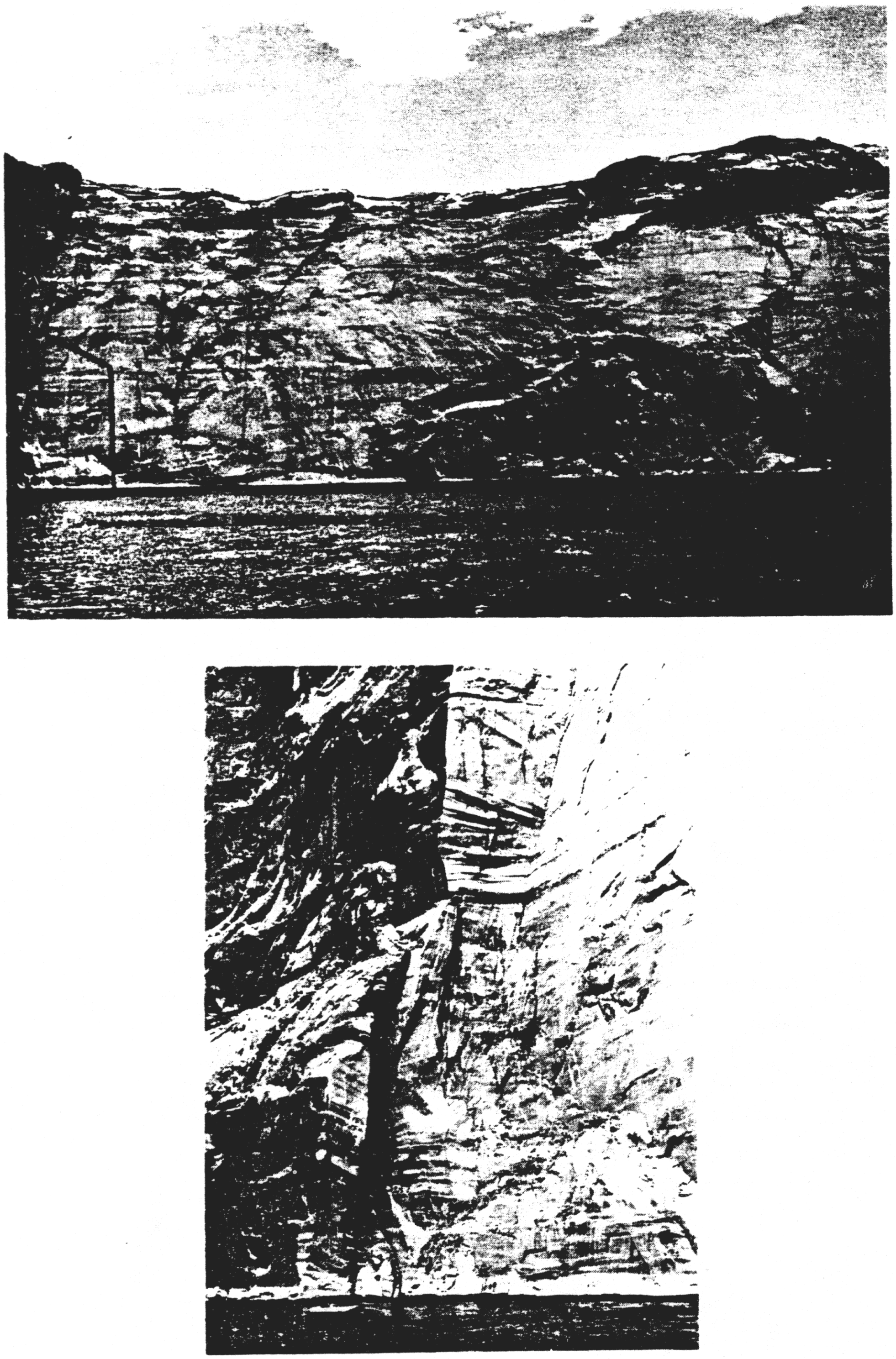


Figure 4: Result of Two Large Adjacent Rock Spalls in 1970 and 1974 Hundreds of Feet High and Wide

into the lake either through minor tributaries or by sheet wash off the sandstones. An example of the importance of this source was the measurement on October 14, 1941, of 12 million tons of sediment passing the gaging station on the San Juan River at Mexican Hat, Utah. The results of these local storms and flash floods are detected at the mouths of Navajo, Moki, and Sheep Canyons (river-miles 25, 125, and 175) where mounds of debris rise above the normal river gradient. Such debris is confined primarily to the junctures of the smaller tributaries with the old Colorado River channel.

Anderson (1972, 1974) noted a good correlation between the sedimentation rate of the 8μ to 15μ silt fraction in a remote sediment sampling device installed in Wahweap Bay and precipitation. The average rate is small, of the order of 1 centimeter per year (cm/yr). If this is typical, and given the low average rainfall for the lake, the contribution from this source must be less than 1000 acre-feet per year. The same is true of wind-borne sediments. High winds are common during certain times of the year, and a certain amount of sand and silt is carried into the lake from this source, but the total quantity is small compared to other sources.

Chemical and biological mechanisms can remove dissolved solids from the lake water and can cause them to be deposited on the lake bottom. Silica removal has been studied by Mayer (1976) who concluded that a net extraction of 13,500,000 to 16,500,000 kilograms (14850 to 18150 tons) of silica were removed from the waters of the lake between March 1975 and March 1976. If we take this as an average annual figure and assume that in its deposited form it has half the density of crystalline silica, the total contribution to the sediments over history of the lake through 1976 is about 12 acre-feet.

The other principal contribution comes from calcium carbonate. Reynolds (1974), in studying the salt flux of the lake, concluded that about 500 million kilograms (550,000 tons) of calcium carbonate were precipitated in 1974 and, prorating on the basis of reservoir volume, the contribution from this source through 1976 would approach 2,500 acre-feet.

One can conclude then that the major source of the sediments in Lake Powell is from the major tributaries and, through 1976, totalled about 330,000 acre-feet. Contributions from other sources are not negligible, but their estimated total is an order-of-magnitude smaller. The major uncertainties in these estimates result from the lack of ability to estimate accurately traction loads and the fluctuations in load that may occur at gaging stations where measurements are infrequent.

Measurement of Accumulated Sediment

Echo Sounding Methods

The narrow, steep-walled character of Glen Canyon placed some restrictions on the methods that could reasonably be employed to study sedimentation. These characteristics suggested that sonic techniques should be highly directional in order to avoid side echoes from the canyon walls, and that major sampling of the sediments should be concentrated in the main channels of the Colorado and the San Juan in order to minimize the chance of loss of equipment. Since the bulk of the sediments is in the main channels and since one can take small samples with little risk in the tributaries, this approach is not unreasonable.

During the 1971 field season, we leased an Ocean Research Equipment Sub-Bottom Profiling System and used it to measure sediment thickness (Eng, 1972). This system is low frequency, 3.5 to 7.0 kHz, has a broad beamwidth, 55 degrees, and has the capability of penetrating sediments and obtaining acoustic reflections from the bedrock surface. Unfortunately, the equipment's ability to penetrate the lake sediments was very limited, so it was used in a different mode. Since the equipment's timing accuracy is very good and since sound velocity in water can be calculated from temperature and salinity measurements (Wilson, 1959), it can provide a very accurate measure of the depth of the lake. The level of the lake surface is recorded twice daily by the Bureau of Reclamation at the dam, and leveling to benchmarks at the upper reaches of the lake indicate that the surface is tilted no more than a few inches in 150 miles. Thus the elevation of the lake bottom can be determined and compared with elevations of the river surface determined by the 1921 survey conducted by the USGS in cooperation with Southern California Edison Company. The difference will reflect the sedimentation that has occurred since closing of the dam minus the amount required to fill the old channel from river bottom to river surface.

Since acoustic penetration of the sediment did not appear to be feasible within the resources of the Sedimentation Subproject of the Lake Powell Research Project, subsequent depth measurements during 1972 to 1977 were made with a Ross Laboratories 200A Depth Finder operating at 100 kHz with a beamwidth of 22 degrees. The more directional beam was an asset in the rough underwater topography of Lake Powell, but initially the timing accuracy of the system caused error. A crystal controlled oscillator and power supply were designed and constructed at Dartmouth College to alleviate this problem and were used during the 1975, 1976, and 1977 field seasons.

Measurements of Sediment Volume

The basic data from which sediment volume in the lake was calculated were the echo sounder records. Early investigation on the study indicated that the greatest part of the sediments carried into the lake from its major tributaries and much of the sediment from other sources were deposited in the old river channels. Thus, efforts were concentrated on these channels and that portion deposited on the old canyon walls was not included.

Several BASIC computer programs were created to calculate the volume of lake sediments. Data reduction began with computation of the actual velocity of sound in the water column during sounding operations. The temperature structure of the lake, as determined monthly by the Bureau of Reclamation, is used to calculate average velocity versus depth curves. The sounding data then corrected from a machine constant of 4800 feet per second (1463 meters) to the actual value. Subtraction of the corrected depths from the lake surface elevation yields the elevation of the sediment top at each mile point of the 1921 river survey. These data are used in programs to calculate the volume of sediment in the lake for the Colorado and San Juan sections of the lake. The computer interpolates cross-section data taken from pre-dam surveys to obtain an area at each river-mile for every foot of the sediment pile. It then computes the volume of a succession of mile-long, foot-thick slabs until it reaches the top of the pile at which point it calculates the volume of a mile-long wedge, one end of which is a foot thick. The volumes of the slabs and wedges are scanned over 1-mile lengths, and the sum of these represents the total sediment volume consistent with the starting assumptions. It should be borne in mind that the pre-dam cross-sections begin at the old river surface, not its bottom, so in areas of little sedimentation negative numbers may be generated. If a mean depth of 3 feet (1 meter) is taken as being representative of the river before the lake was closed, and 400 feet (122 meters) is taken as a mean width, then some 35,000 acre-feet of sediment would be required to fill the channel to the old river surface. Negative thicknesses were found in about one-sixth of the lake, so approximately 6000 acre-feet are added to the calculated values to account for channel filling. The total volume of sediments calculated for the period 1963 to 1977 amounts to 400,000 acre-feet, of which 133,000 acre-feet are in the San Juan channel, 188,000 acre-feet are in the Colorado arm above the confluence with the San Juan, and 79,000 acre-feet are in the Colorado below the confluence. Earlier we estimated that through 1976 about 330,000 acre-feet of sediments entered the lake as suspended sediment via the main tributaries, about 10,000 acre-feet through slumping, about 1000 acre-feet from local runoff or wind-borne particles, and about 2,500 acre-feet from precipitation within the lake. Summing the above estimates yields an input of 344,000 acre-feet for the period 1963 through 1976. Addition of 25,000 acre-feet for the year 1977 in which water records are not yet available gives a total input of 370,000 acre-feet as compared to a measured 400,000 acre-feet. The agreement to within less than 10 percent is as good as can reasonably be expected. The data suggest that continued monitoring of the streamflow and suspended sediment volume at the gaging stations at Green River, Bluff, and Cisco, Utah, can yield very reasonable estimates of the majority of sediment entering and being deposited in Lake Powell.

The total capacity of Lake Powell when filled to the 3700-foot level is 27 million acre-feet. If the rate of sedimentation averaged the same in the future, it would take about 1000 years to fill Lake Powell to the 3700-foot (1128-meter) level. This assumes no aggradation upstream, no compaction, and flat-lying sedimentary deposits for the length of the lake which, of course, is not the case. The penstocks are located at 3470 feet (1058 meters) and the volume of the lake at this level is about 5,100,000 acre-feet. Given the same assumptions, it would take almost 200 years to fill the lake with sediments to this level.

Sediment Distribution

Aside from the local anomalies created by slumping, the three major repositories of sediments are in the delta-like deposits of the two principal tributaries feeding into Lake Powell and in the lower part of the lake above the dam (see Figure 3). The influence of the Colorado River delta extends about 50 miles (80 kilometers) downstream from the end of the lake to Good Hope Bay (river-mile 148) and below this sedimentary volumes are quite small except in local areas, until the Rincon, about river-mile 90. The influence of the San Juan delta is felt over the full 65 miles (105 kilometers) of the San Juan arm of the lake and may in addition be contributing to the buildup of sediment in the lower end of the lake.

The rate of sedimentation in any particular spot on the delta varies not only with the geometry of the delta, but with the filling history of the lake (Figure 5), particularly at the time of the spring runoff. During the period of the investigations reported here, lake surface level varied between 3600 and 3680 feet (1097 and 1122 meters), and the lake

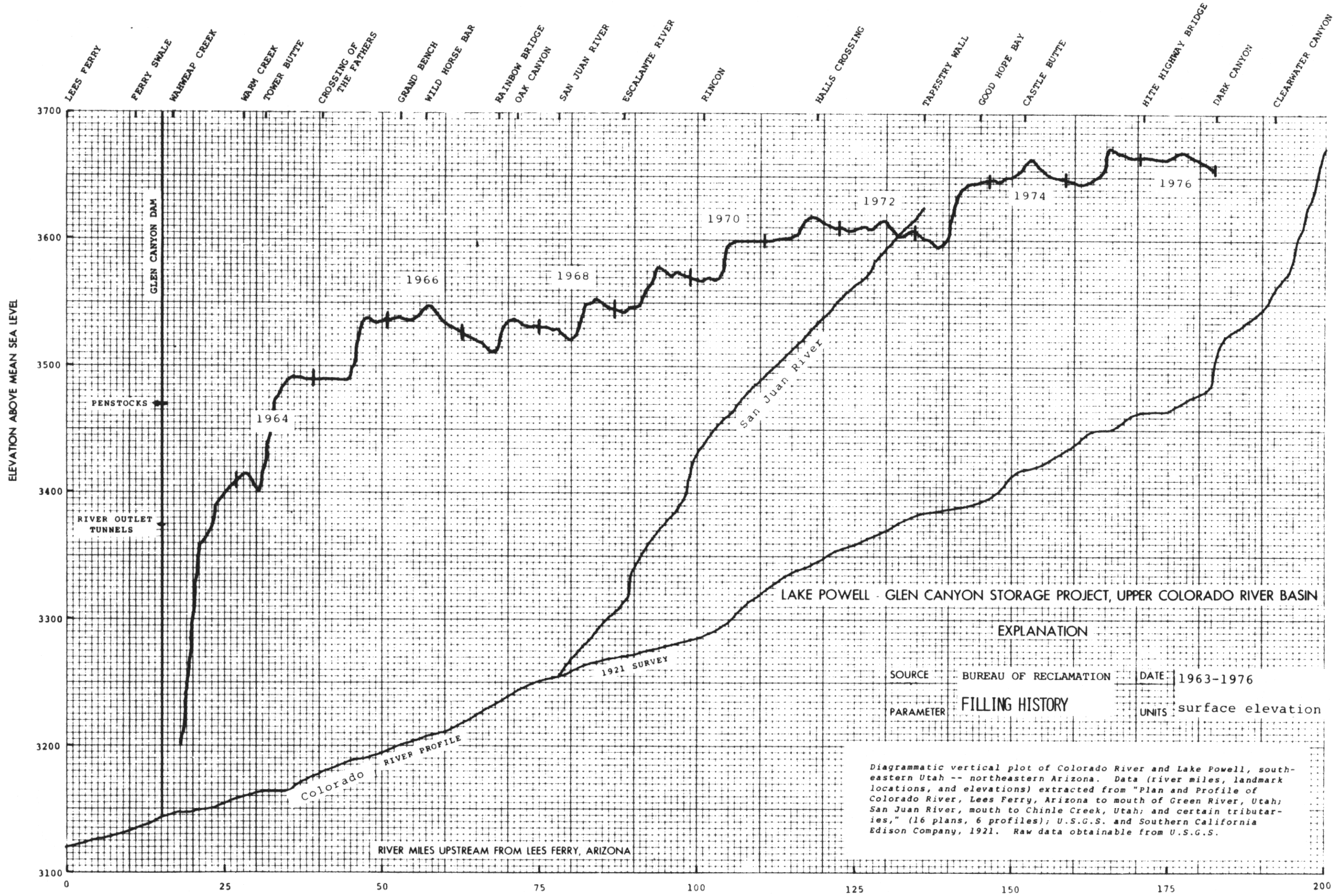


Figure 5: Diagrammatic Vertical Plot of Colorado River and Lake Powell, Southeastern Utah and Northeastern Arizona--Filling History

terminii with the San Juan and Colorado Rivers changed by as much as 15 miles (24 kilometers). When and if the lake reaches its maximum elevation and annual variations are minimized, the delta-building process should become more like that of Lake Mead, for example, where progradation was established as shown by the texture variations in the sediments (Gould, 1960).

The character of the deltas of the two rivers differs because of differences in sediment load and total flow, differences in river gradient, and because of the nature of the lake at the confluences. The San Juan River delivered only 13 percent of the water between 1964 and 1974, but it delivered close to half of the suspended sediments. The average gradient of the Colorado River between the elevations of 3550 and 3700 feet (1082 and 1128 meters) is about 2.5 times as great as the gradient of the San Juan between the same levels although the mean gradient of the San Juan in the lake area is about 25 percent greater than that of the Colorado. The confluence of the Colorado arm of the lake and the river is over 20 miles (32 kilometers) up a narrow canyon in which current is perceptible over most of the year while the confluence of the lake with the San Juan River is only a few miles up a narrow canyon and the lake then rapidly widens into a broad bay.

The results of these factors show up in several ways. First, although incoming sediment volumes on the two arms are approximately equal, sediment thicknesses are quite different. Through 1974 thicknesses average about 28 feet (9 meters) in the upper 25 miles (40 kilometers) of the San Juan arm and nearly 70 feet (21 meters) in the upper 25 miles of the Colorado arm. Rates are variable over time as depocenters shift, but maximum rates in the Colorado arm from thickness data approach 10 feet per year (3 meters) and in the San Juan arm 5 feet per year (1.5 meters). Anderson (1975) attempted to measure directly the sedimentation rates near Hite at 1.5, 4, and 22 meters (5, 13, and 72 feet) above the bottom. The bottom two devices were filled to overflowing, indicating only that rates were greater than 1 meter per year (3 feet). The topmost collector was not filled, indicating that the major sediment movement is near bottom in this area. Second, because of the physiography, migration of the depocenter is much more marked in the San Juan arm than in the Colorado arm with time and change in lake level. Third, because the waters are confined to the former canyons and tributaries and the lake is really a slow-moving river, the result of sedimentation leads more to establishment of a new bottom gradient in equilibrium with the dynamic system than to the formation of a classical delta. Thus we do not see pronounced topset, forset, and bottomset zones, but rather more an overall change in the gradient of the lake bottom, particularly in the San Juan arm.

The other significant sedimentary pile is the wedge of sediment that begins below the slump barrier near the Rincon and thickens gradually to about 30 feet (9 meters) near the dam. Although timing inaccuracies of the echo sounder caused some uncertainties in earlier records, this sediment wedge does not appear to be thickening rapidly, rather it seems to be thinning with time. This apparent thinning could be due to dewatering and compaction of the sediments. Anderson (1975) has measured sedimentation rates near the dam at less than 1 cm/yr, suggesting that most of this sedimentary wedge was produced during the construction of the dam and the early filling phases of the reservoir.

In the lower part of the lake the upper surface of the sediment wedge exhibits a double echo. The first echo is weak and at 3 or 4 feet (0.9 or 1.2 meters) greater depth a stronger echo is recorded (Figure 6). This has also been noticed near the foot of the "delta" of the Colorado arm in the Good Hope Bay area. The reflection characteristics are similar to those found in fluid muds or flocculant layers in estuaries (Einstein and Krone, 1961; Kirby and Parker, 1973, 1974). The layer in Lake Powell probably consists of flocculated clay particles, predominantly montmorillonite (Mayer, 1973).

The similarity with estuarine deposition is not surprising in Lake Powell because of the estuarine-type circulation that occurs during the spring inflow period (Merritt, 1976). This circulation consists of a downstream current of relatively fresh river water underlain by a relatively saline upstream-moving countercurrent. Observed sediment densities in estuaries are in the 1.1- to 1.4-gm/cm^3 range; thus they contain a great deal of water. If they constitute an important part of the sediments in the wedge above the dam, then dewatering and compaction of these could well explain the apparent reduction in sediments with time that we observed in the area.

Sedimentary Materials

Introduction

To complement the indirect estimates that echo sounding provides, the chemical and physical parameters described were selected at the beginning and during the course of the study with the aim of elaborating models of sedimentation which primarily were based upon the indirect evidence. For example,

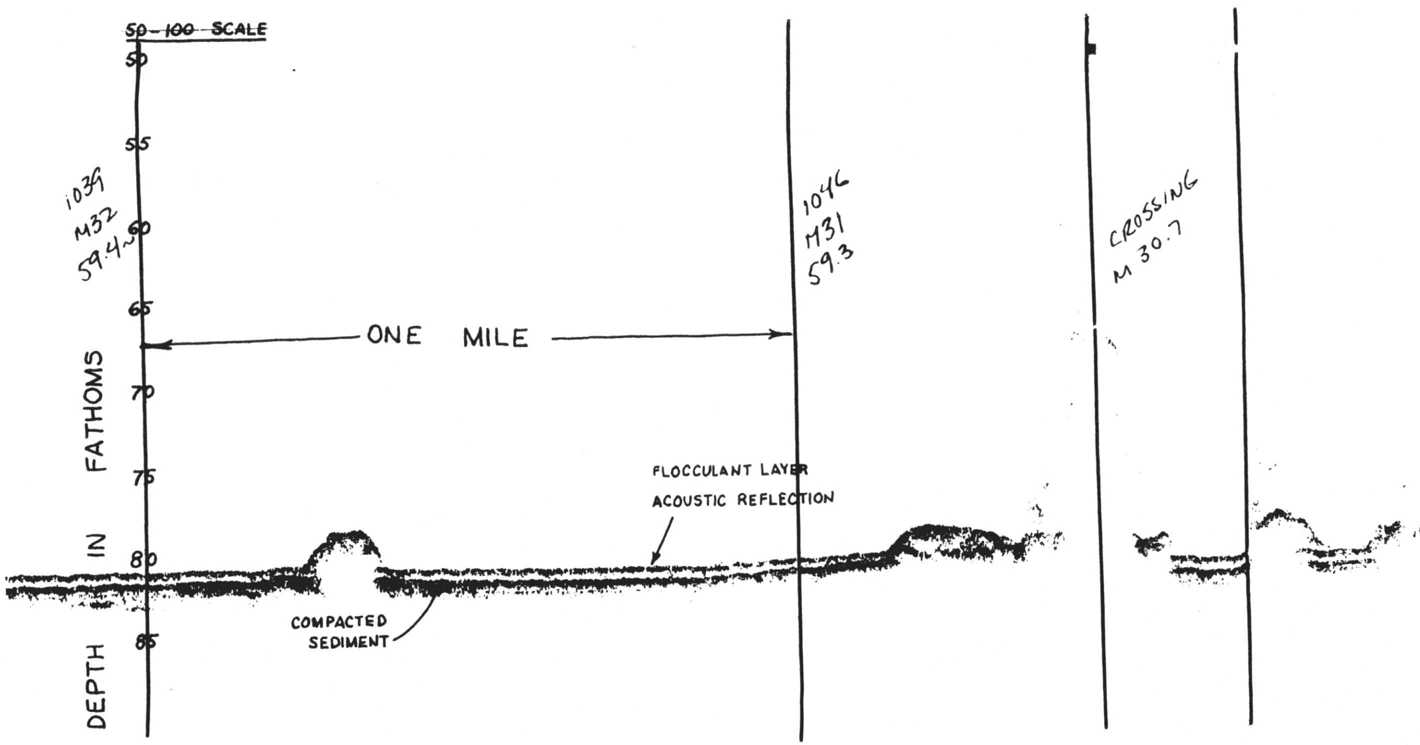


Figure 6: Echo Sounder Record Showing Flocculant Layer

measurements of the carbonate content of the muds were designed to test the hypothesis of seasonal calcite precipitation at the southern end of the lake. Organic matter contents might indicate seasonality as well. Physical properties such as texture and water content ought to indicate source areas, mechanisms of transport and deposition, and state of compaction. Color changes in the muds perhaps reflect shifts in the chemical environment of deposition.

The Sedimentation Subproject work since 1971 has included low-frequency (3 to 7.5 kHz) echo sounding (Eng, 1972), high-frequency (100 kHz) echo sounding (Spydell, 1975), and analysis of the clay mineralogy of the muds (Mayer, 1973). In addition, the chemical and physical limnology subprojects fostered work on the dissolved oxygen (Page, in preparation) and silica budgets (Mayer, 1976), the advective currents (Merritt, 1976), the geochemistry (Reynolds and Johnson, 1974), and calcite preparation (Reynolds, in press) of Lake Powell. An important conclusion gained from this previous work is that the understanding of the sedimentation regimes requires consideration of the interrelationships of the chemical, physical, and biological environments. The comprehensive study of Lake Mead (Smith et al., 1960) served as a guide because of the similarities of the two lake systems.

Field Methods

The primary sampling device used in this study was a Ewing-type piston corer fitted with a 10-foot-long by 1.5-inch-interior-diameter core tube with plastic liner. Penetrations up to 10 to 12 feet (3 to 3.6 meters) were possible in muds, but sands decreased this value. The apparatus was lowered and recovered on a 3/16-inch-diameter wire by a gasoline-powered hydraulic winch.

After recovery of the corer the liner was capped and extruded. The core was then placed vertically and the disturbed portion of the top was allowed to settle. Excess water was tapped off before the core sample was either sealed for shipment to Dartmouth College or split open and described at the lake. Notes were made of the color, texture, lamination, and hydrogen sulfide smell. A GSA color chart, based on the Munsell system of color identification, was used to standardize observations of this property. However, due to differences in time elapsed between coring and description, some samples were drier than others and thus were of lighter color value. Fine-grained texture descriptions were judged on the field of the admittedly subjective technique of feel. The plasticity of clays usually allows their distinction from silt by rubbing on the fingertips. Muds were categorized as clays, silty-clay, clayey-silt, and silt. In addition, silt with little admixture of clay, though rare, was usually laminated and thus distinguishable to the eye. For coarse-grained sediments, a sand-size comparator envelope used in conjunction with a hand-lense inspection allowed classification of roundness, sorting, and size.

Samples of the water column at depth that were analyzed for fine-grained suspended matter were recovered with a 1.8-liter Van Dorn bottle on a handline or winch. An aliquot was taken for Coulter Counter analysis on-board the houseboat (June and September 1975 cruises) or refrigerated for later analysis in the laboratory at Dartmouth.

The usual analytical scheme for sub-samples of the cores was the measurement of water content, organic matter content, and carbonate content of a 3- to 5-gram (0.1-ounce to 0.2-ounce) wet-weight split. Water content was determined by the weight loss of the aliquot after oven drying at 110°C for 24 hours and is expressed by the following equation:

$$W.C. = 100 \frac{W_w - W_d}{W_d}$$

where W.C. is the water content in percent, W_w is the weight of the wet sample, and W_d is the dry weight of the sample. Formulated as such, the water content may exceed 100 percent as it simply expresses the weight percent of pore water to the dry weight of sediment. The baked aliquot was crushed in a mortar, redried, weighed, and following the method of Dean (1974) heated to 550°C for an hour, cooled in a dessicator, and reweighed. Weight reduction is due to the oxidation of organic matter and is reported as loss on ignition. The same aliquot was returned to the furnace and heated to 1000°C for an hour, calcining the muds. Carbon dioxide is evolved from the carbonate minerals leaving oxides behind. This last weight loss divided by 0.44 (the fraction of carbon dioxide in calcium carbonate by weight) yields the weight of calcium carbonate in the split. Problems with the method are twofold. First, a significant fraction of Lake Powell sediment consists of clay minerals that contain structural hydroxyl groups. This lattice water is driven off during the second stage of heating, causing an apparent increase in the carbonate content. Secondly, the green- to gray-colored sediments contain reduced iron which is oxidized during the 550° to 1000°C run. Iron oxide oxidized to ferric oxide gains 11 percent in weight, but by analogy with Lake Mead muds iron oxide is never more than 5 percent of the dry weight. Hence, a 0.5-percent weight gain is a maximum value, somewhat balanced by the 3- to 4-percent loss due to structural water of a clay-rich mud. For some core samples we used a LECO (Laboratory Equipment Company) 70-second Carbon

Analyzer at the Woods Hole Oceanographic Institution for organic and inorganic carbon determinations (Initial Reports of the DSDP, Vol. IV, 1970, p. 745-754). The machine measures evolved carbon dioxide from combustion of the sample at 1600°C in the presence of oxygen. By measuring two aliquots of the same sample, one untreated (except for dessication) and the other pre-acidified to remove carbonate carbon dioxide, a total carbon and an organic carbon value are measured. Subtraction of the latter from the former yields carbonate carbon which is multiplied by the fraction of carbon in calcium carbonate to calculate calcium carbonate weight. Other volatile gases are scrubbed from the carrier gas so structural water vapor is not a problem.

Particle size of coarse-grained sediments was determined by dry sieving following procedures outlined in Folk (1968). A one-half ϕ sieve interval was used from 0 to 4.5ϕ (44 microns). A Ro-Tap Shaker was used for 15 minutes per nest of sieves. No wet sieving was done.

Particle size analyses of silts and clays present many problems to investigators. Swift et al. (1972) reviewed the methods in use and their inherent differences. Gibbs (1972) showed the inaccuracies that result when the most commonly used theory, that of Stokes Law settling, is applied to settling of silt-size spheres in laboratory experiments. Sizes of clay minerals are difficult to measure because of their sheet-like character and tendency to form agglomerates known as floccules.

To circumvent the above problems, an electronic particle size analyzer, the Model TAII Coulter Counter, was used. The methods used are those of Walker et al. (1974) modified to fit Lake Powell needs. The methods assume nothing about shape or density of particles, but rather measure particle volume. Sediment particles are suspended by agitation in an electrolyte solution which is passed through a small aperture across which a small electric current flows. When a particle enters the aperture it displaces a volume of electrolyte equal to the volume of the particle. If a constant voltage is maintained between two electrodes, one on either side of the aperture, then by Ohm's Law ($i = V/R$, where i = current, V = potential, and R = resistance), a current fluctuation is produced by the resistance pulse. The electronics of the instrument sort out these current pulses, which are analogs of the volumes, into 15 volume classes ranging from about 2 to 40 percent of the aperture diameter. That is, for a 100-micron aperture, the smallest particle sensed has a volume equal to that of a sphere of 1.59 microns in diameter while the largest particle sensed quantitatively has a volume equal to that of a sphere of 40.3 microns in diameter. Theoretically, very fine sizes can be discriminated with small apertures, but in practice both a diminishing signal-to-noise ratio and constant clogging made use of a 30-micron aperture impossible. Both a 100- and a 200-micron aperture tube were used in our study.

Limitations of this method found during the course of the study are twofold. First, very dilute suspensions of sediment were necessary to minimize the occurrence of two or more particles within the sensing zone concurrently and assurance of a representative mud sample from a core after several thousandfold dilution was lacking. Thus, it was decided to measure only the material in suspension in the water column.

A second limitation encountered was that the total volumetric concentration varied threefold with changes in the lake water-to-electrolyte ratio. However, the normalized curves of volume percent versus particle size were reproducible, suggesting that an electronic bias rather than true particle change was at fault.

Lastly, following procedures modified from Vollenweider (1969), subsamples of a piston core from Halls Crossing were examined for the presence of diatoms. A slurry was made of the mud, then pipetted onto a glass slide and covered with a cover slip. The slide was examined under the binocular microscope at 500X using plain light. Aliquots of surface waters gathered during the June 1975 trip were also inspected in the same manner to check for a diatom population in the water column after mud examination revealed none.

Qualitative and semi-qualitative mineralogical examination of Ekman dredge samples and piston core samples were performed by X-ray diffractometry using several preparatory techniques outlined in Mayer (1973). As the gross mineralogies were primarily a function of grain size, various size fractions were extracted and examined separately. Particular attention was paid to the less-than-2μ fraction which is composed almost wholly of clay minerals. Relative proportions of clay minerals were obtained by comparing peak heights of the 001 reflections on the X-ray records.

Physical Properties

Particle Size: Fine-Grained

Examinations of the piston cores showed that the bulk of the lake sediment is fine-grained material, i.e., silt and clay. Merritt (1976) has shown that a density contrast exists between the river and lake water such that the highly turbid but fresh and warm spring runoff flows over the cold, saline water which wintered in the reservoir. Based on USGS gaging station data (collected at Green River and Cisco, Utah) for the water-years 1965 to 1972, the suspended sediment load for the months April, May, and June constitutes 60 percent of the yearly sediment load. Thus the spring runoff water mass is the major sediment contribution to the upper reaches of Lake Powell and the transport and deposition of sediment by this current is thus of primary importance.

The suspended matter particle size measurements allow comparisons only of the modes (the most commonly occurring class) of the size distribution because all curves were normalized to 100 percent.

Figure 7a shows the range of variation in the mode observed within the surface water mass near Hite during the spring runoff of 1975. The water was streaked with alternating green and yellowish green bands in the direction of the prevailing wind. Immediate analysis of the two types yielded the average curves depicted. Previously, near Good Hope Bay (river-mile 144), a floating mat of brown algae was sampled and analysis demonstrated a very monosized population of 25 microns in diameter. In general, biological suspended matter is more narrowly size-constrained than detrital matter. Acidification yielded no dimunition of the peak and later laboratory microscopy showed the material to be diatoms. Superimposition of the three curves shows that algae are responsible for the 25- to 32-micron mode in the green surface water mixed with the small, 4-micron-diameter, mode of clay particles, whereas the yellow surface water is primarily clay. Merry (1976), from airborne spectroradiometer data, showed a correlation between intensity in the red-yellow spectral region and suspended sediment concentration.

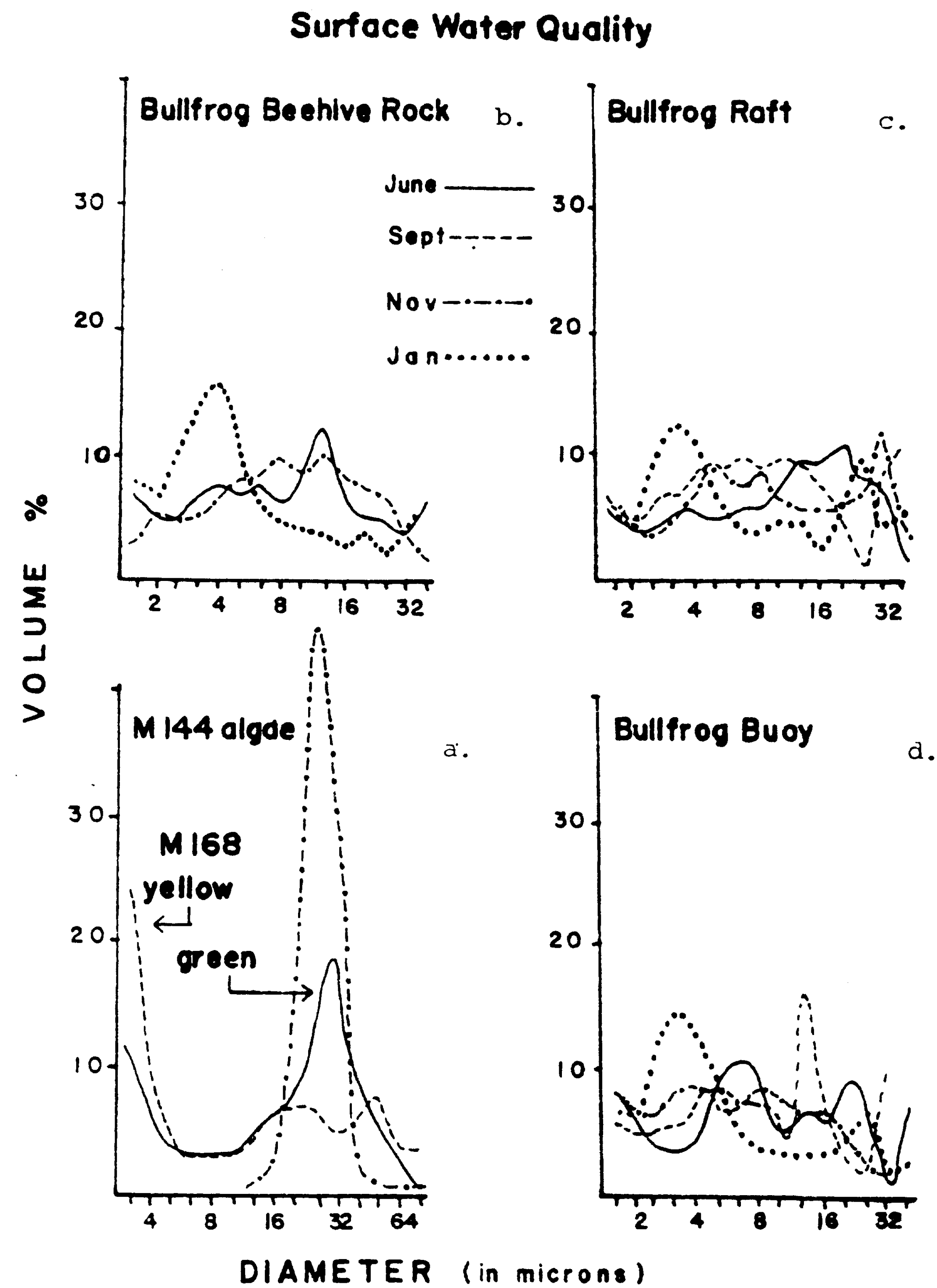


Figure 7: Suspended Matter Particle Size Versus Frequency in Water Samples from Approximately 0.5 Meter Depth

Figures 7b, 7c, and 7d depict the seasonal change in particle size in the surface waters of Bullfrog Bay, a large embayment in Lake Powell midway between the dam and Cataract Canyon. Beehive Rock, the instrument raft, and the entrance buoy sampling sites are aligned along the axis of the bay from northwest to southeast respectively. The data obtained in June 1975 for all stations reveal a mode at the coarse end of the size spectrum, attributable to algae. The buoy sample has another mode at 6 microns due to spring runoff overflow current at the bay mouth. Data obtained in September (Figures 7c and 7d only) show a prominent mode of 12 microns at the buoy, but only a broad size distribution at the raft. Anderson's 1972 collector data from Wahweap Bay show a bloom of the diatom *Fragillaria* in late September and this seems a plausible explanation of this mode in Bullfrog as well. Its absence at the raft may be due to masking by increased inorganic particulates, an hypothesis suggested by a color change observed by the aircraft spectroradiometer (unpublished data). The November data lack distinctive modes, probably reflecting the decrease of biological activity at that time. The broad distribution may be due to silt and clay influx accompanying increased precipitation during the fall months such as Anderson (1974) found in Wahweap Bay. Finally, the January 1976 data have a mode at about 4 microns diameter and a less conspicuous mode at 20 to 25 microns. The clay-size mode is fairly broad and most likely represents an inorganic suspended sediment component probably introduced by Bullfrog Creek at the head of the bay. The 20- to 25-micron mode is ambiguous. Biologic activity should be supressed by the low temperatures, and inorganic material of this size ought to settle rapidly. The answer may lie in resuspension of muds or algae such as was noted in Warm Creek Bay phytoplankton studies (Steward et al., 1974).

The preceding discussion has focused on a side bay of Lake Powell, but by far the greatest abundance of sediment lies in the old river channel. Vertical profiles of particle-size suspended matter were obtained during the June 1975 cruise for stations at Castle Butte (river-mile 151), Tapestry Wall (river-mile 136), Halls Crossing (river-mile 121), and the Rincon (river-mile 100). Figure 8 is a plot of the size-frequency curves of the first three stations. Again, the size range analyzed by the Coulter Counter is normalized to 100 percent. Castle Butte surface water shows an expected coarse mode due to algae. At 6-, 15-, and 50-foot depths (1.8, 4.6, and 15.2 meters), this mode is replaced by a sharp increase in clay-size material. This reflects the highly turbid nature of the overriding water mass (see Merritt, 1976, Figure 3) obscuring light transmission and hence algae growth. The 100-foot (30.5 meter) depth curve, however, signals a shift to a coarser particle mode. Conductivity measurements (R. C. Reynolds, Jr., personal communication) as well as turbidity show that this zone is the interface between the warm, fresh, turbid water of relatively low density (the spring runoff overflow current) above the cold, saline, and clear water of higher density which wintered in the reservoir. A net accumulation of settling particles occurs at the metalimnion because the increased density and viscosity of hypolimnetic waters causes a decrease of settling velocities. Commonly, an oxygen minimum forms here because of bacterial uptake of dissolved oxygen during decomposition of the organic matter which has concentrated at this depth (Page and Johnson, 1975). In addition, the clay minerals settling from the turbid overflow flocculate because of the shift from a fresh-water to a more saline environment, the reduction of shearing forces, the increase of viscosity, and especially an increase in the number of particles (van Olphen, 1963) at the transition zone between the "old" and the "new" water masses. The result is that the

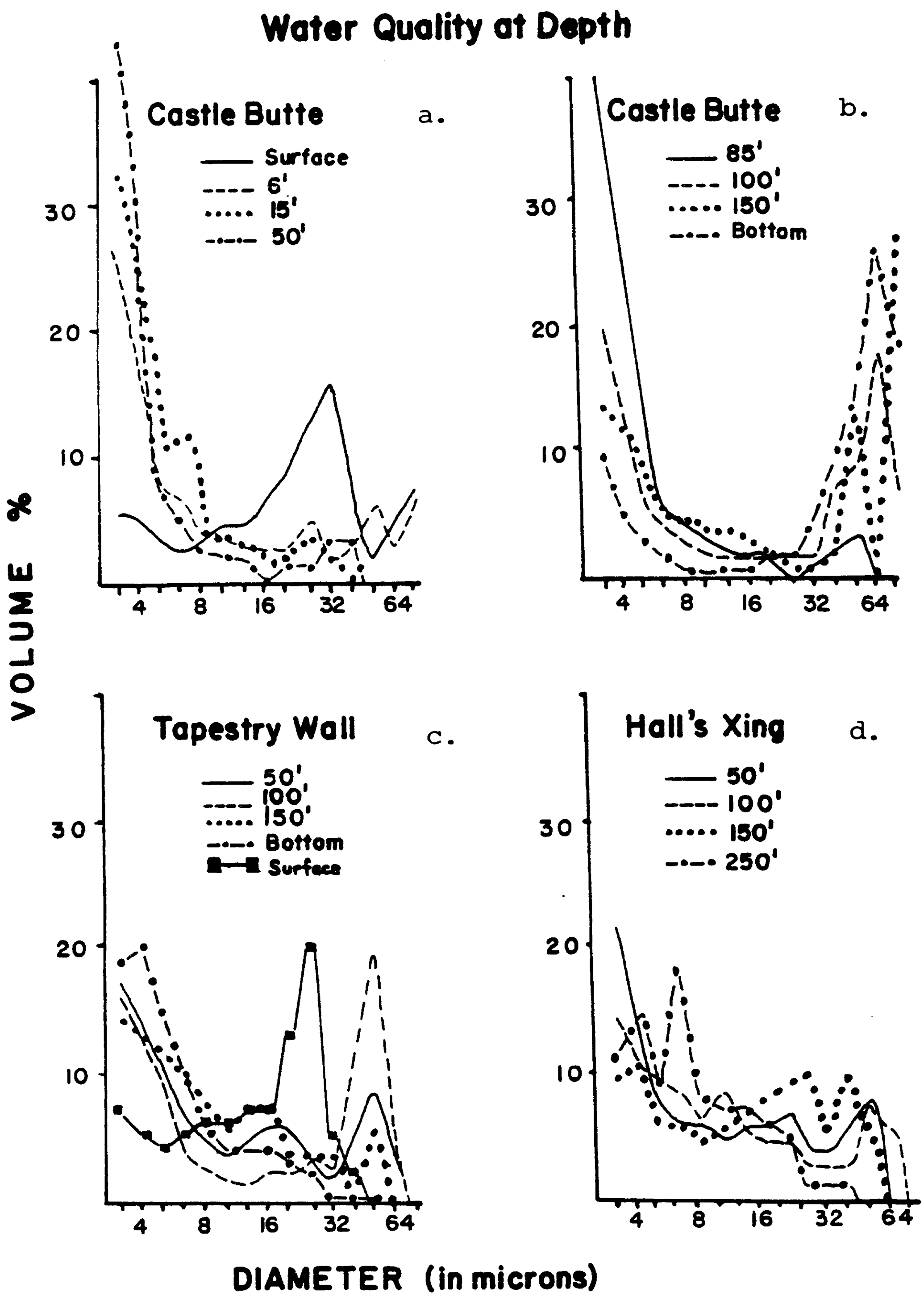


Figure 8: Suspended Matter Particle Size Versus Frequency in Water Samples from Depth Sampled in June 1975

same mass of particulate matter exists in several large-diameter floccules rather than in separate clay flakes. Sherman (1953) demonstrated that Lake Mead floccules are relatively impermeable so that when calculating their density the trapped water must be included, leading to an average value of 1.4 gm/cm^3 for constituent clay particles of 1-micron diameter. When substituting into the Stokes Law equation for settling spheres

$$U = \frac{2g(\rho s - \rho r^2)}{9\eta}$$

where g = acceleration due to gravity, ρs = density of the particle, ρ = density of fluid, r = radius of particle, η = viscosity of fluid, and U = settling velocity, it is clear that the increase of settling velocity due to changes in the particle radius outweighs the decrease due to lowered density. Thus flocculation causes the sedimentation of clays which might otherwise remain suspended during the residence time of the lake water and be passed through the penstocks.

Turbidity was determined by measuring the extinction of a collimated white light beam at a known path length (Merritt, 1976). A problem with the interpretation of the turbidity plots has been the explanation of where the highly turbid zone goes with the passing of summer (N. M. Johnson, personal communication). The size-frequency curves bear out the hypothesis that flocculation reduces the turbidity without reducing the quantity of sedimentary material. Interestingly, the Castle Butte area is one in which a flocculant layer has been observed with the echo sounder (Spydell, 1975, Figure 9).

The Tapestry Wall station (Figure 8c) 15 miles (24 kilometers) downlake shows about the same size frequency as Castle

Butte. Specifically, the large mode at the 100-foot depth marks the advection-induced metalimnion. In this instance the deeper samples show a relative depletion of the 50-micron particles. The bottom water is devoid of coarse suspended matter. It is unknown whether bottom currents sweep away the settling floccules or if undue agitation of the sample during Coulter Counter analysis disrupted them into their component particles.

Figure 8d, which depicts the particle size frequency in the main channel near Halls Crossing, reveals a much less well defined progression. This is probably due to the dissipation of the leading edge of the overflow this far downlake. To be sure, the overflow can be traced (by conductivity, see Merritt, 1975, Figure 9) almost all the way to the dam, but by this time mixing has obscured the relationships seen farther uplake. Particle size at a station downlake from Halls Crossing, near the Rincon (river-mile 101), also shifted nonsystematically.

Particle Size: Coarse-Grained

Of the 29 cores examined in our study, 17 penetrated into or through sandy horizons ranging from 1 centimeter to tens of centimeters in thickness. Textural analysis by dry sieving of a few sands proved what was readily visible upon preliminary inspection: the sand in the cores is relatively well sorted, i.e., without much of a silt and clay admixture. Conversely, the muds are nearly always free of a sand-size fraction. A discrimination based on the thickness of sand layers divided by core length shows sand percentages in the lake cores ranging from 0 to 100 (Figure 9). The distribution is biased toward the younger sediments because they are the top-lying layers readily sampled. In addition, navigation methods varied in precision in locating coring sites along the length of

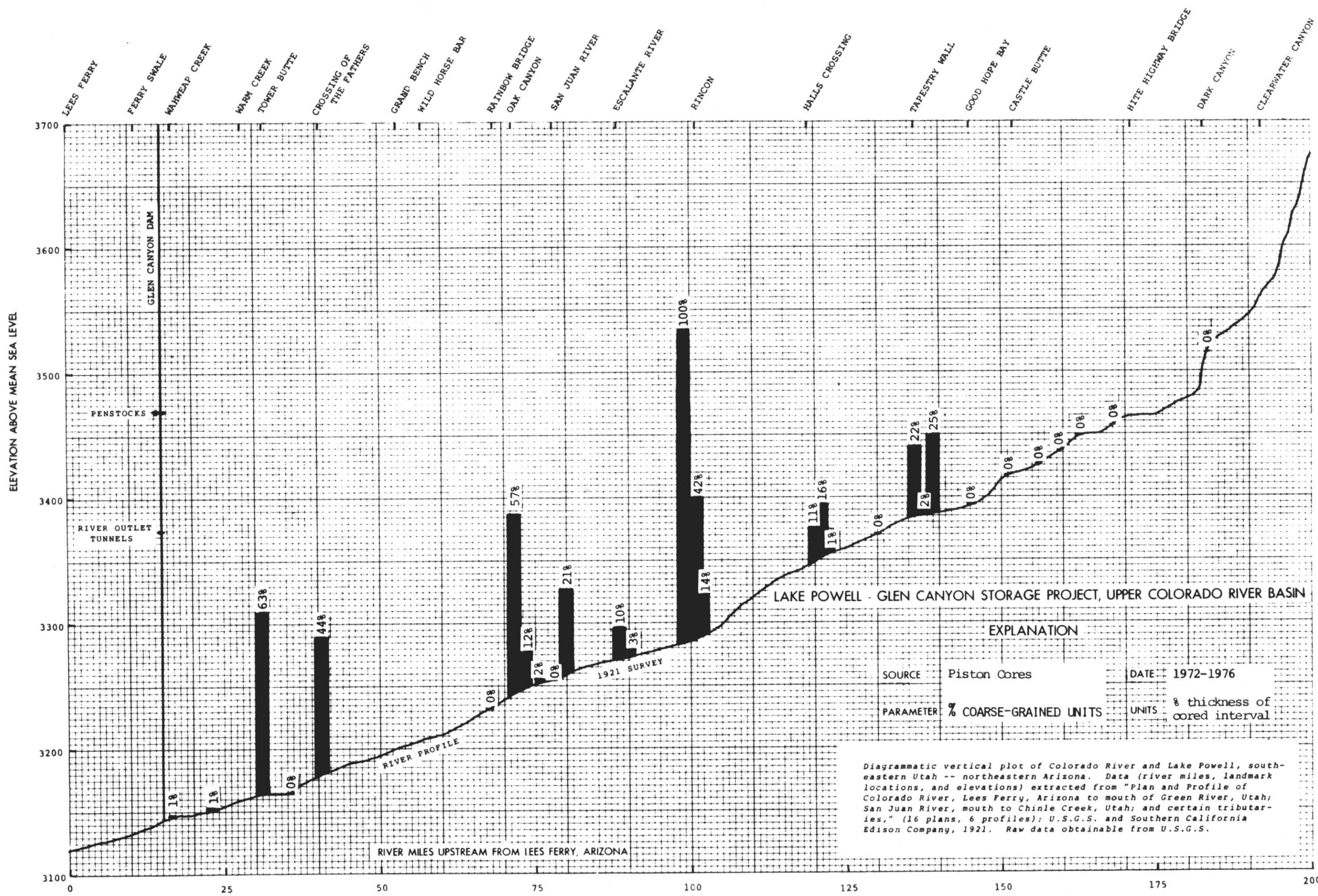


Figure 9: Diagrammatic Vertical Plot of Colorado River and Lake Powell, Southeastern Utah and Northeastern Arizona--Percentage of Coarse-Grained Units

the old river channel. For example, the cores from Halls Crossing are relatively well located by the meander-carved sandstone cliff at river-mile 118.5, yet synoptic core sampling there shows a wide variability in the amount and distribution of sands (11, 16, and 1 percent) within the lake muds. This change is greater than can be attributed to yearly sedimentation, suggesting a narrow, discontinuous nature to the sand bodies within the lake muds.

For those cores which bottom in sands, a way to discriminate between lacustrine or fluvial origin is by size and the heavy minerals content. The sedimentary rocks which fringe Lake Powell are nearly devoid of heavy minerals, whereas the igneous and metamorphic rocks far up the drainage basin contain rich heavy mineral suites. Their presence in Lake Powell sediments thus indicates relict Colorado or San Juan Rivers sands or sands deposited as topset beds of the deltas forming in the upper reaches of the lake and river migrated upstream leaving a veneer of deltaic sediments behind. However, the filling history (Figure 5) suggests the veneer of deltaic sands must be quite thin downlake and subsequent topset bed sands are confined to Cataract Canyon.

Heavy minerals were observed in sands at the base of cores from Halls Crossing (HW7-7), San Juan Mile 2 (AQ7421), San Juan Mile 3 (AQ7516), and opposite Oak Creek Canyon (AW7420 and AQ7609), leaving no doubt that these samples had penetrated the entire section of lake sediments. (The items in parentheses refer to the identification numbers assigned to each sample.) Average rates of lake sedimentation at these points are 9.9, 15.5, 6.6, 4.4, and 2.2 cm/yr respectively, as determined by simply dividing the thickness of lake sediments in the core by the time elapsed since 1963. In all cases, the median diameter is significantly larger in the river sands (0.44 to 0.15 mm) than in the lake sands. In Figure 10 the two curves marked "river sands" define a size envelope of the relict river sediment which in this core is graded upward from coarse to find sand. The contact with the overlying muds is sharp, not gradational, which implies a different origin for the muds. The sand horizons intercalated within mud horizons are finer grained with median diameters ranging from 0.16 to 0.041 mm.

The distribution of coarse-grained lake sediments seems a function of the proximity of massive sandstone formations. Where Chinle Shale forms the shoreline, these sandy deposits are generally lacking, but where Glen Canyon Group or Entrada Sandstone is at the waterline the sands are common. A notable exception is the slump barrier at river-mile 99 where side-hill dunes from sand blown over the edge of the sandstone-capped plateau mantle the Chinle Formation at the Rincon. Figure 11 is a cumulative frequency plot of sediment size from a core on the slump barrier and from two samples from the dune taken approximately 1 and 10 meters (3.3. and 33 feet) above the lake surface. The core sample has essentially the same overall size (mean) as the average of the "dune" samples. It is slightly better sorted because it lacks the coarse tail of the dune samples, which indicates a selective transport mechanism to the depositional site.

In other cores containing locally derived sands, the evidence of source area and mechanism is not as clear. A Halls Crossing core (HW7-7, Figure 10) shows the grading of grain sizes expected in a deposit laid down by a turbidity current. The base of the "turbidite" is fine sand with a 9-percent admixture of silt and clay. Midway up the deposit the median

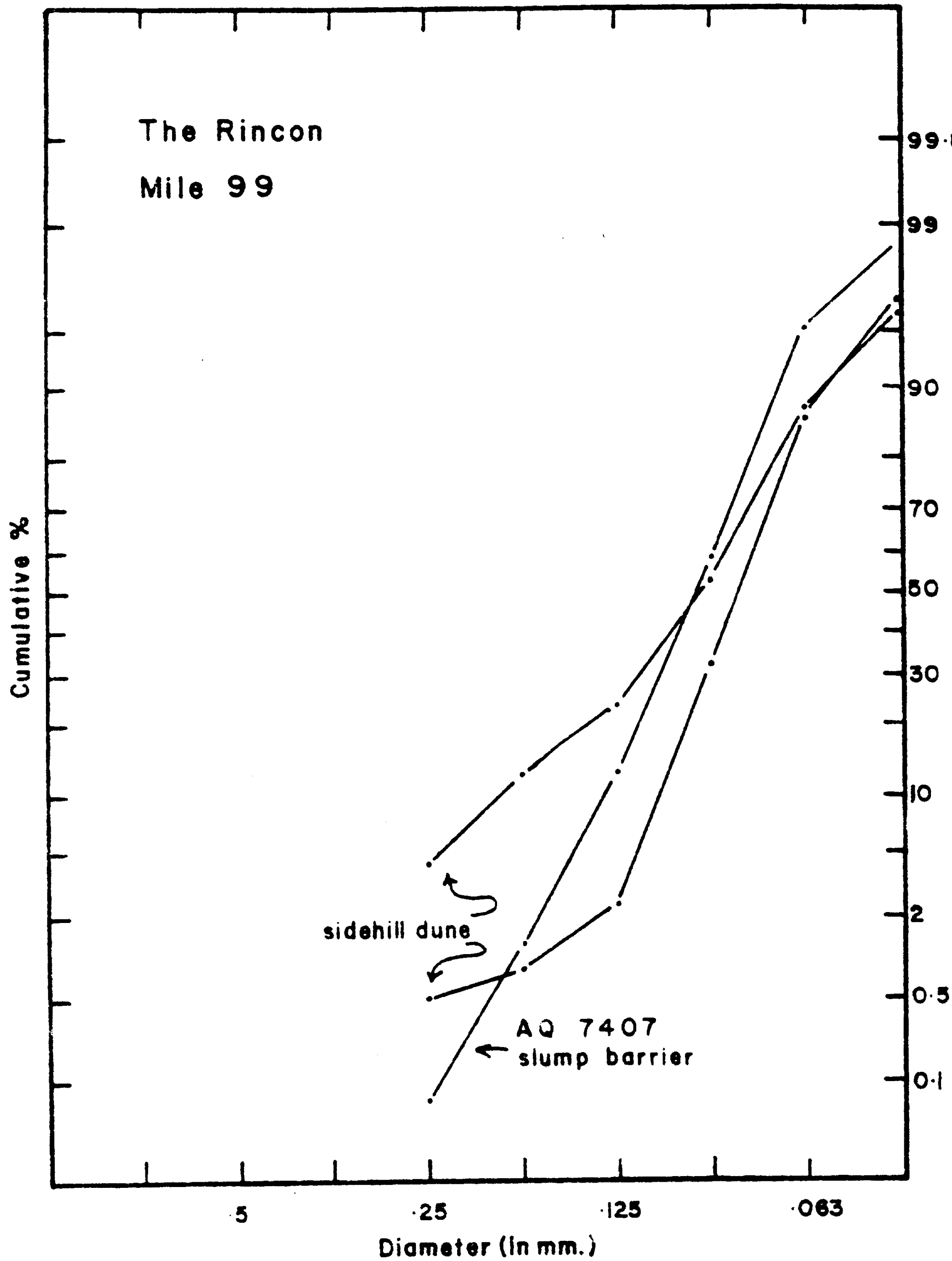


Figure 10: Grain Size Distributions of Sands Near the Rincon. Note that core AQ 7407 was entirely sand. The sample sieved is a split from the homogenized core.

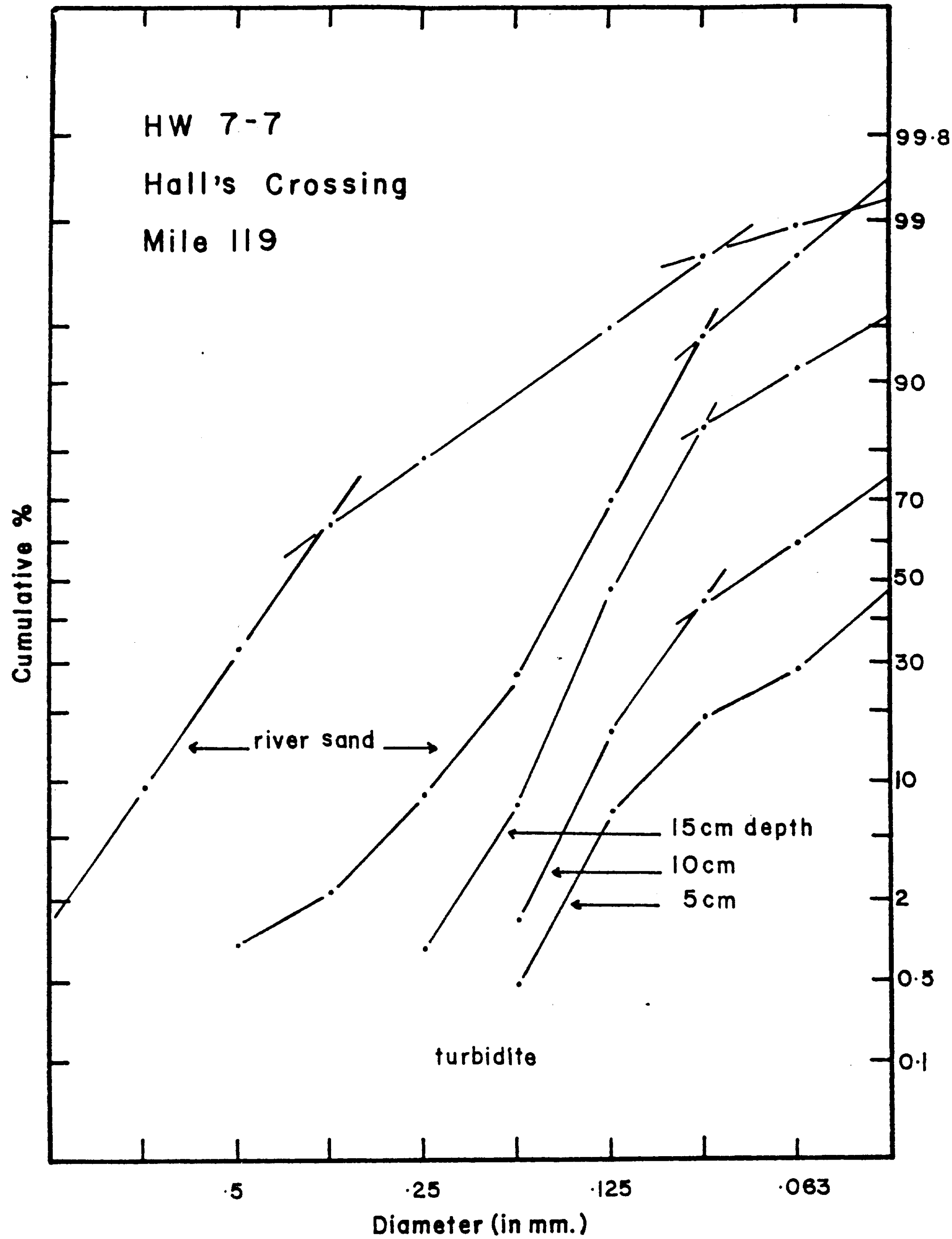


Figure 11: Grain Size Distribution of Sands Near Halls Crossing

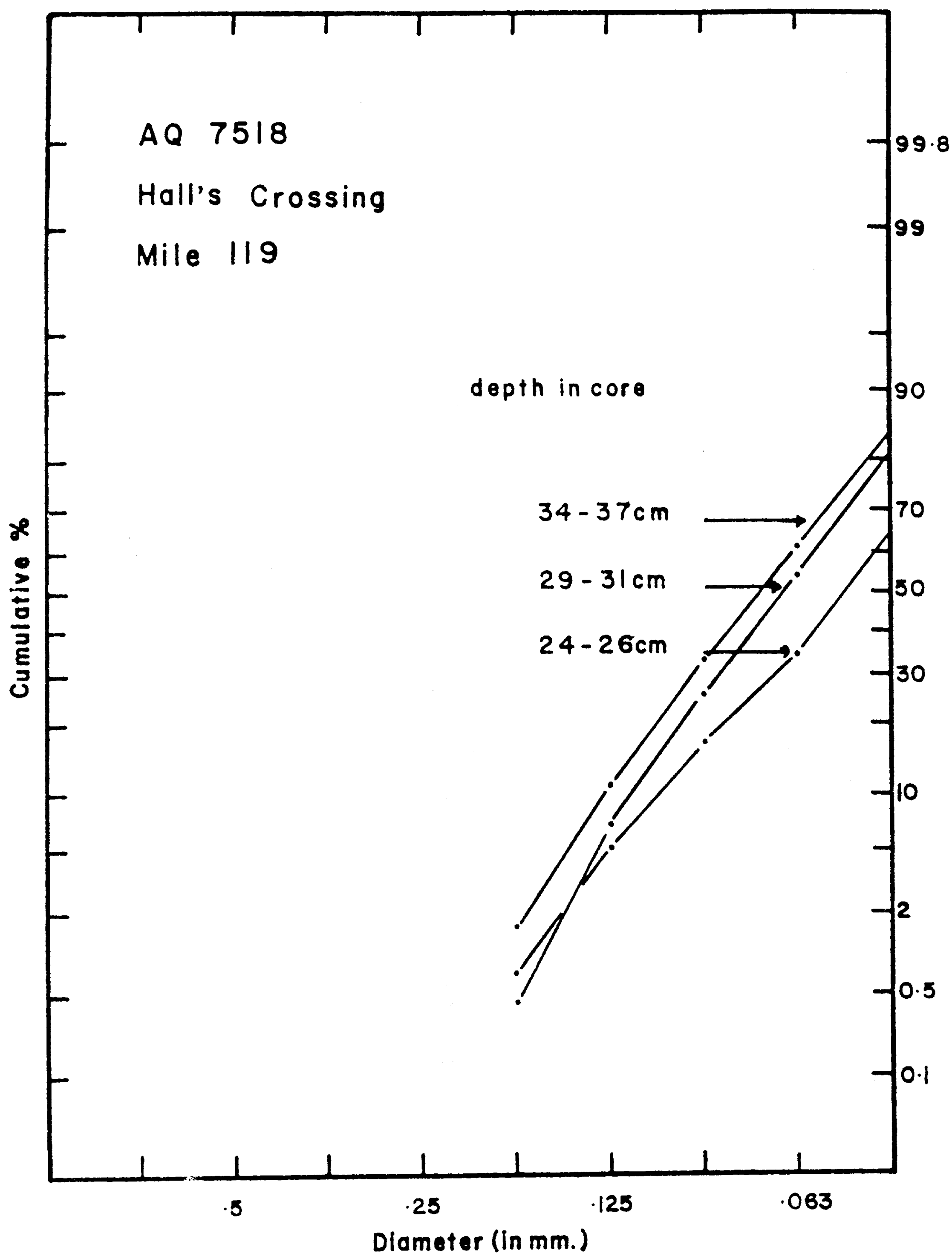


Figure 12: Grain Size Distribution of a Silty Sand in a Core Near Halls Crossing

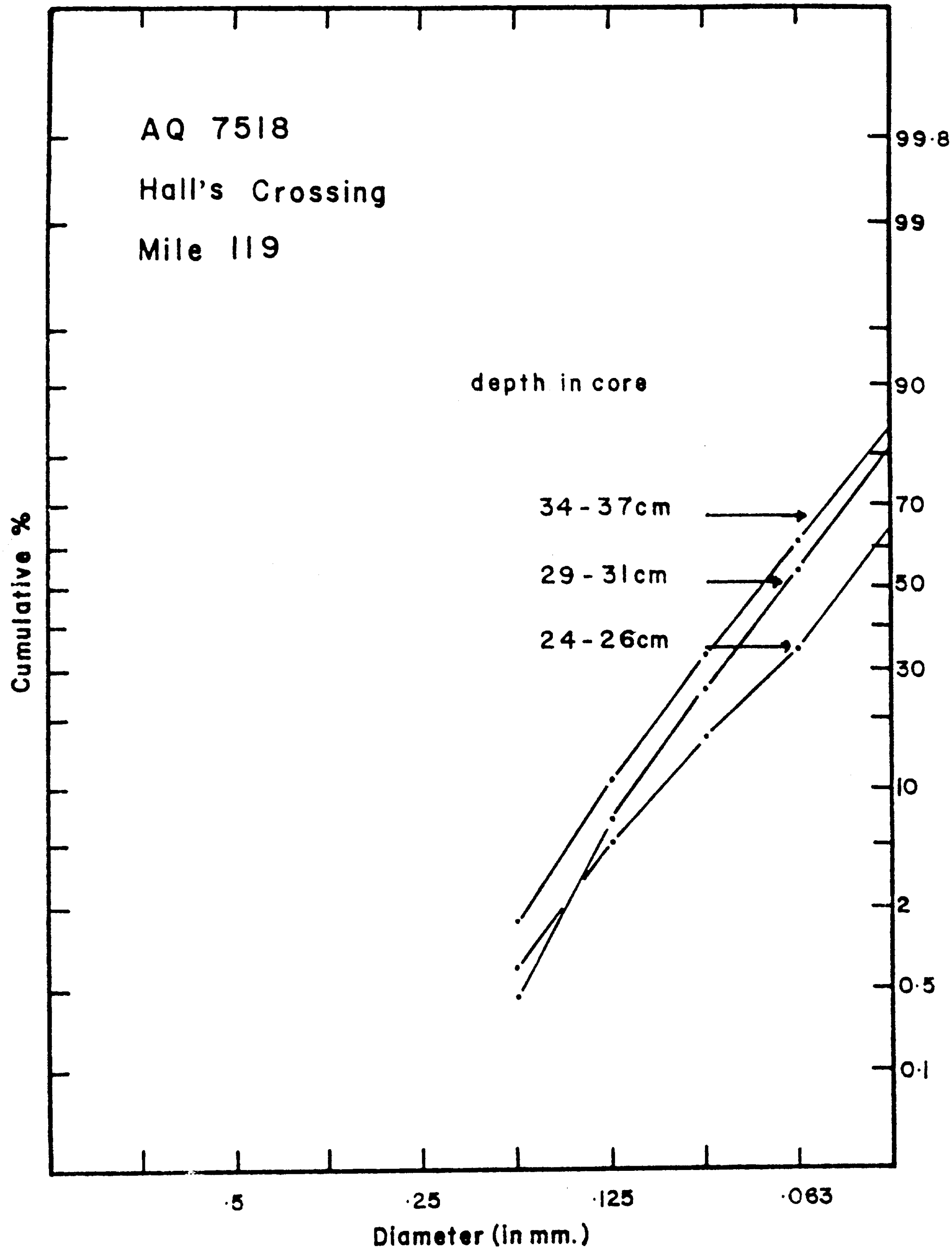


Figure 12: Grain Size Distribution of a Silty Sand in a Core Near Halls Crossing

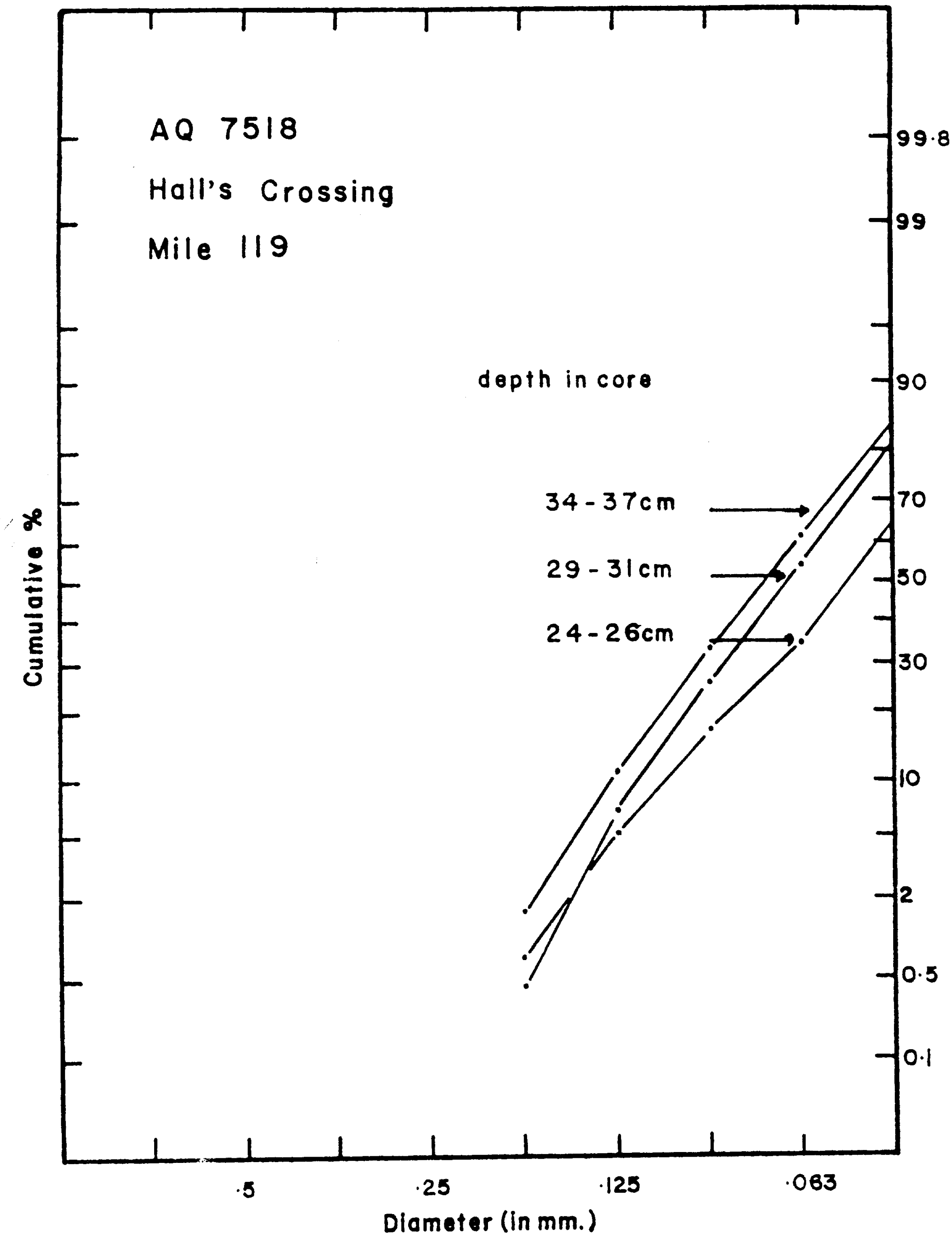


Figure 12: Grain Size Distribution of a Silty Sand in a Core Near Halls Crossing

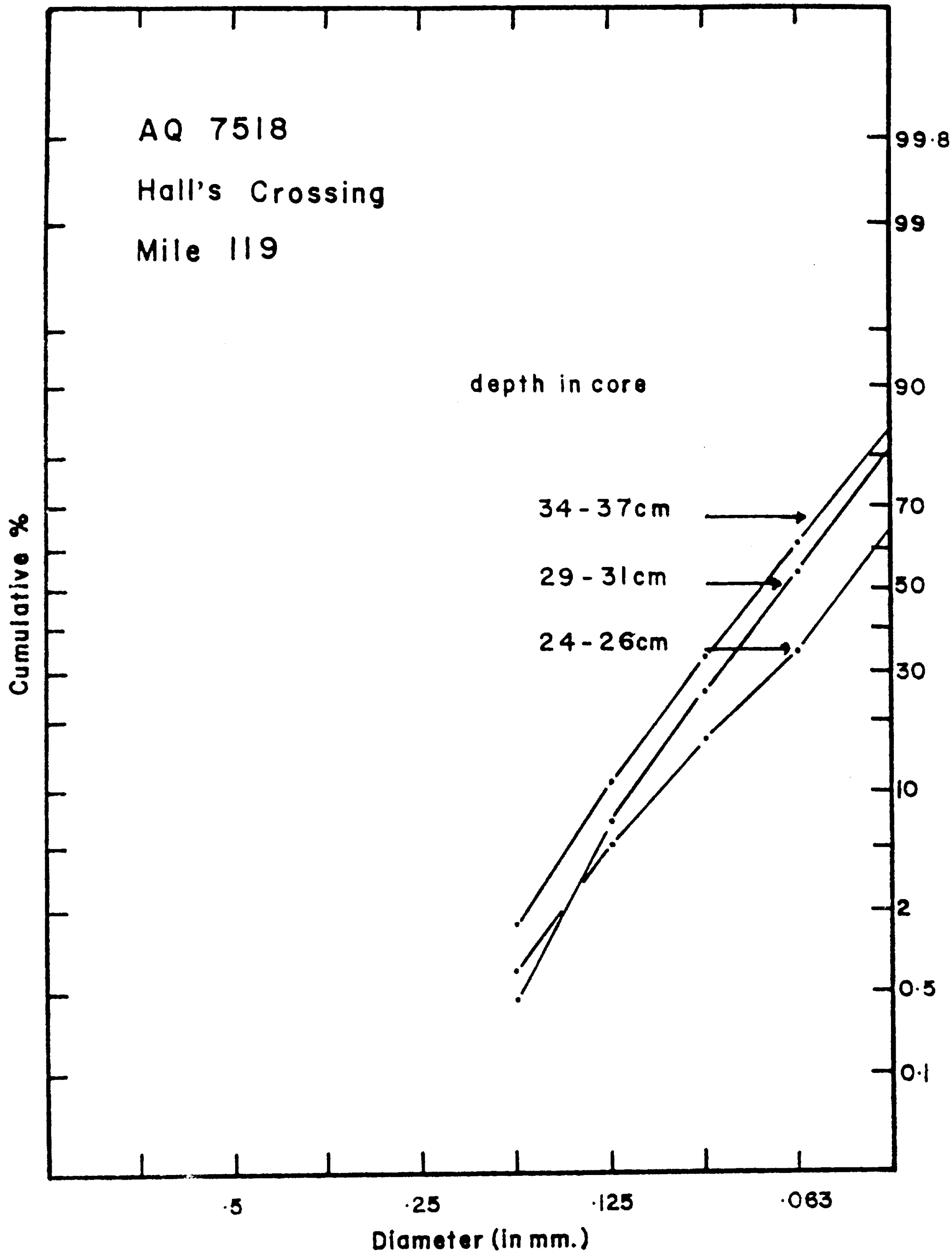


Figure 12: Grain Size Distribution of a Silty Sand in a Core Near Halls Crossing

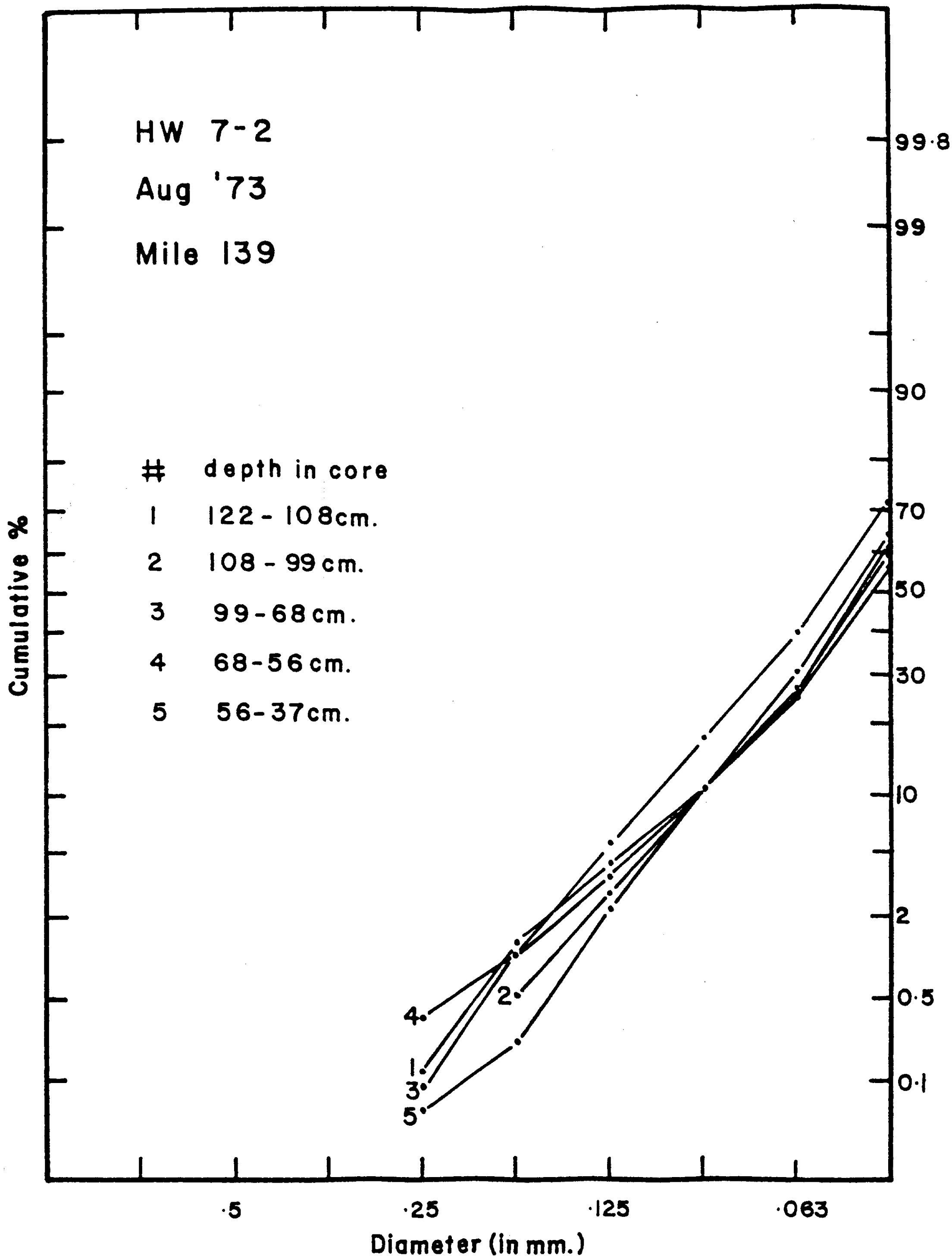


Figure 14: Grain Size Distribution of Sandy Silt from a Core at the Mouth of Sevenmile Creek Canyon

(river-mile 139), yet core HW7-2 (Figure 14) recovered 110 cm (43.3 inches) of silt capped with 12 cm (4.7 inches) of clay. Sub-samples of the bottom 85 cm (33.5 inches) are all coarse silts of median diameter 0.048 to 0.056 mm (.0019 to .0022) inches). The filling history of Lake Powell (Figure 5) shows that during the first autumn and winter the confluence of lake and river remained in the Good Hope-Castle Butte area, suggesting that the silty portion of the core was deposited by the underflow currents during that season before the lake terminus proceeded rapidly upstream during the influx of the 1964 spring runoff. If this is the case, then the top 12 cm (4.7 inches) of clay is the entire sediment record here from 1964 to 1973.

In summary, sands within Lake Powell are either relict Colorado or San Juan River sediments or are locally derived from the sandstones forming the lake basin. In the former case, the sands serve as a tool for dating the overlying lake sediments. In the latter, textural parameters are indicators of possible transport and deposition mechanisms active in the lake. The intercalated sands are products of short-term, high-energy influx and dissipation and are the record of these events in the sedimentation history.

Water Content

The percent of interstitial water was measured on selected core samples. Based on assumptions about the specific gravity of the mineral grains, porosity and bulk density values are obtained. Studies at Lake Mean (Gould, 1960) show that 2.65 gm/cm^3 is the average density of the mineral matter. Figure 15 is a plot of water content (percent of dry weight of sediment) versus bulk density and porosity (assuming no gas in the voids). Water

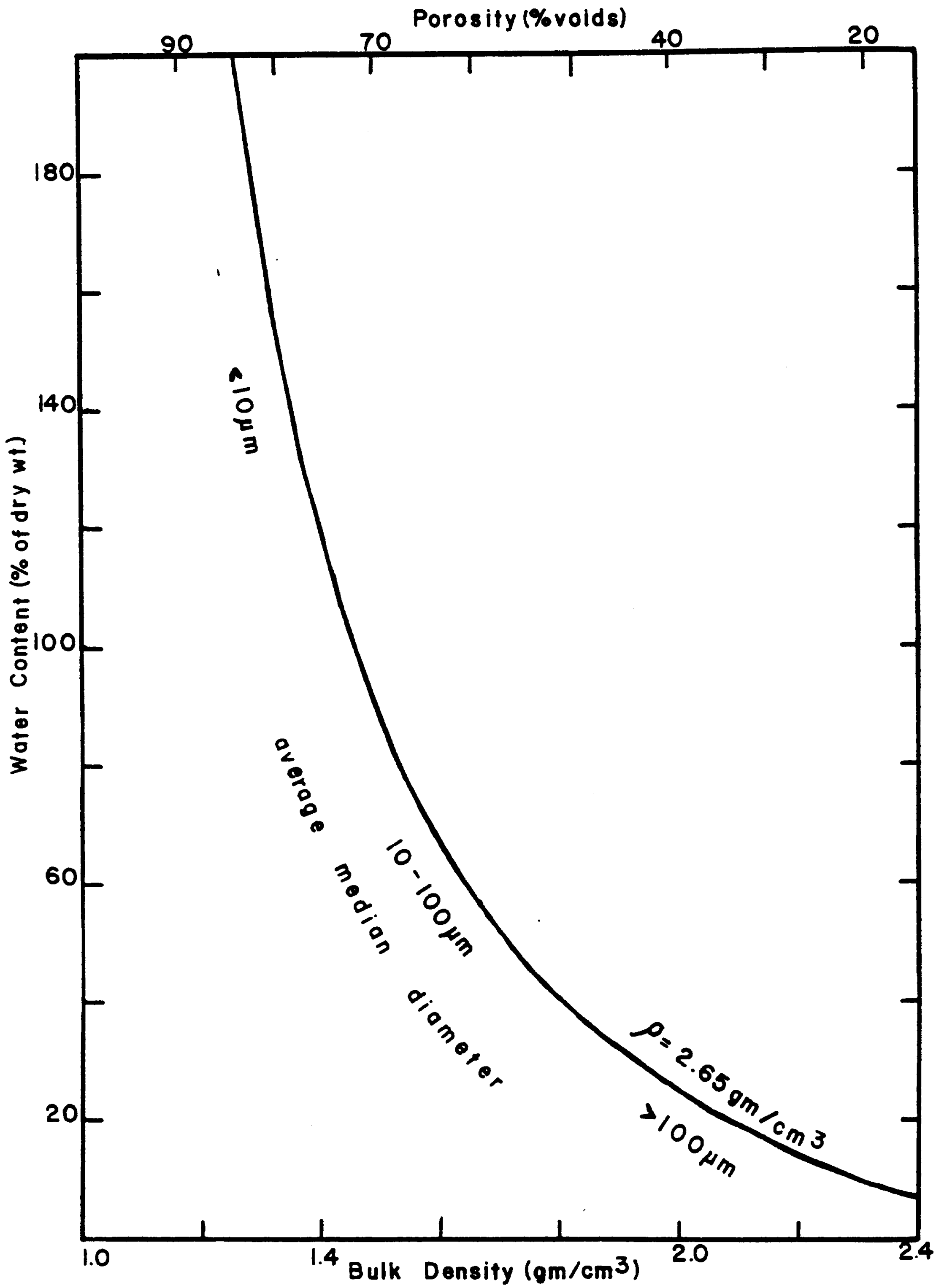


Figure 15: Nomograph for the Estimation of Porosity and Bulk Density of Sediments from Water Content Measurements. Note that the curve is for mineral grain density of 2.65 gm/cm^3.

content is a function largely of the sediment grain size distribution. The median diameter of particles measured is grossly correlated with porosity as shown (Emory, 1960).

Gravity core samples of the surficial sediments from June 1975 had the highest water content, from 97 to 167 percent, reflecting the very fine grain size of the muds and probably very recent deposition. These cores are very short, hence compaction effects must be minimal, as with the piston cores. The highest value obtained (182 percent) is from the base of piston core AQ7518, Halls Crossing (river-mile 119), 89 to 97 cm (35.0 to 34.3 inches) below the top. Figure 16 is a vertical profile of the water content in this and several other cores. The low values from 20 to 40 cm depth (7.9 to 15.7 inches) are due to the very fine sand to coarse silt described earlier. Profiles of the other cores also reveal the same scatter of values consistent with the hypothesis that textural variations cause the water content variations and that compaction by overburden is not evident at the depths to which these cores penetrate. Cores AQ7519 and AQ7521 were split and sampled immediately upon recovery, hence the values should be similar to in situ water contents. Core AQ7422 (Halls Crossing) was sampled a month after recovery. Unrealistically low values ranging from 22 to 42 percent led to the conclusion that the core liner was not sealed properly. The entire core was fine-textured mud with a deflocculated median diameter from pipette analysis of a 1-micron sample size. At Lake Mead, such fine sediment had water contents ranging from 155 to over 200 percent of dry weight (Gould, 1960), but this sample had only 37 percent.

On the basis of these measurements, with the assumption of a mineral grain density of 2.65 gm/cm^3, the use of 1.4 gm/cm^3 as an average bulk density seems warranted for at least the upper

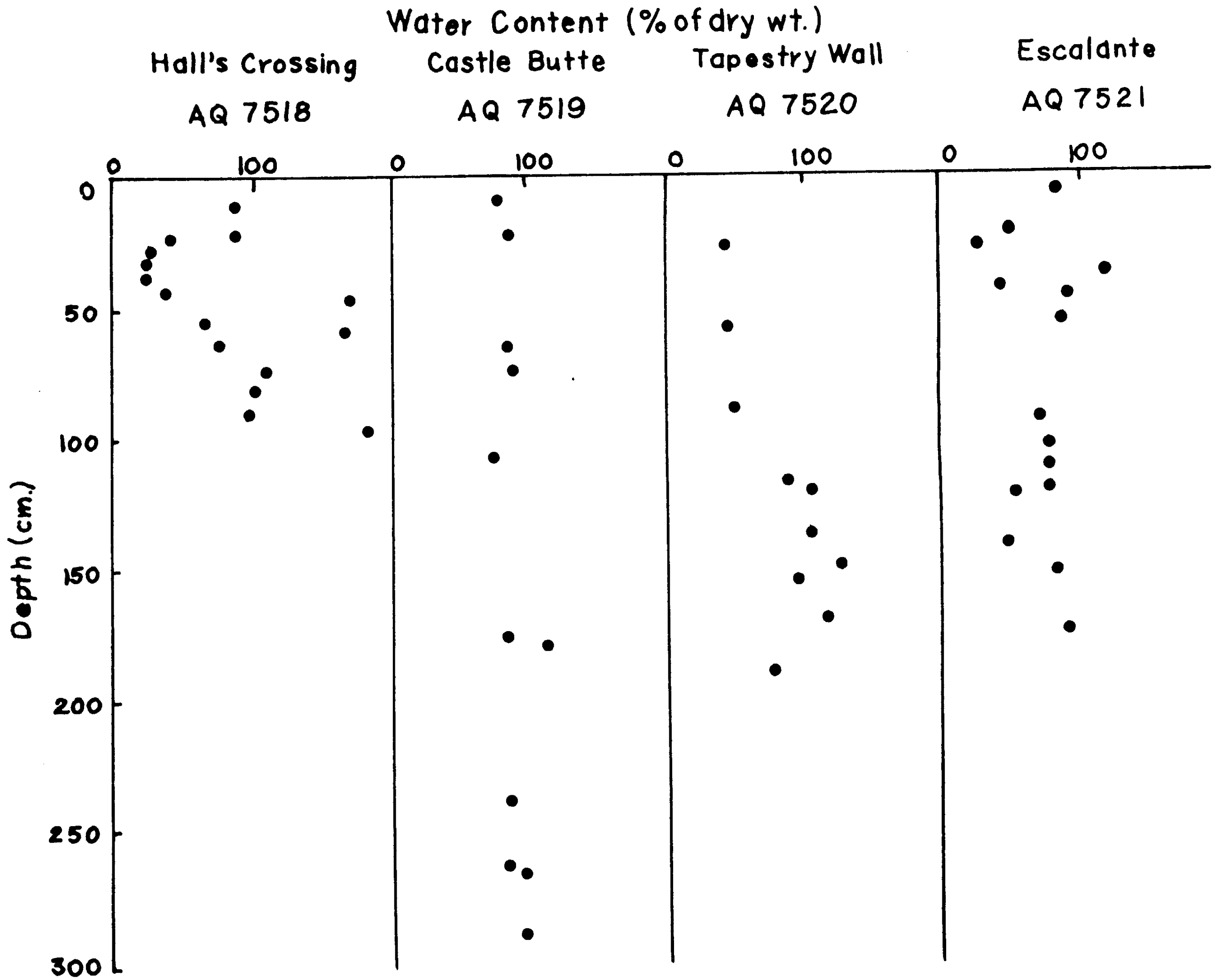


Figure 16: Water Content Profiles of Selected Cores. Note that the length of the line denotes sampled interval. Lithologic unit spacing controlled sample spacing.

few meters of sediment. This corresponds to an average water content of 86 percent and a porosity of 70 percent.

CLAY MINERALOGY

Examination of the mineralogies of the sediment in Lake Powell serves several purposes. First, it helps us if detrital minerals introduced to the lake are being changed in the lake or if new minerals are forming. Second, it provides a context for future sedimentological or geotechnical studies of the lake sediments. Third, it sheds light on past and present sediment transport mechanisms in the lake, as well as identification of sediment sources.

Qualitative analysis revealed the presence of only three aluminosilicate phases in the vast majority of surficial lake sediments. The three ubiquitous minerals are illite, kaolinite, and montmorillonite. A fourth type, found only near Navajo Creek and Castle Butte, is mixed-layer illite-montmorillonite of various expandibilities ranging from 25 to 65 percent.

At no place in the lake were any authigenic phases found such as analcite, palygorskite, etc. At the inception of this study we thought that some bay environments might create abnormally high pH or salinity conditions and thus facilitate formation of such phases. Subsequent examination of the waters in these bays showed that the lake chemistry does not change radically in them, and that conditions conducive to these phases do not arise.

The mineralogies which are found, then, appear to reflect a strictly detrital origin, because the three ubiquitous minerals are identical to the assemblage found in the suspended sediment of regional tributaries. The samples containing the mixed-layer phases are found only in areas where the Chinle Shale, which contains considerable mixed-layer illite-montmorillonite (Schrock, 1975), is known to be slumping. This finding implies that the sediments contributed by slumping remain near their source.

Semi-quantitative analysis of the relative proportions of the three detrital clay minerals does provide some information bearing on sediment transport. Samples collected along the Dirty Devil River channel show approximately the same proportions of illite, kaolinite, and montmorillonite, with no observable downstream trend in composition. This implies that flocculation does not preferentially concentrate any of the three minerals during downlake flow of a turbid suspension.

This is particularly well seen with clay mineral compositions in sediments south of Castle Butte. The Colorado and Dirty Devil Rivers probably do not introduce sediments south of this point because of sub-aqueous impoundment of the slump-dam formed by the slumping Chinle Shale. The dominant sediment contributors, then, are the San Juan River and the local ephemeral streams. Clustering of clay mineral compositions on ternary diagrams (Mayer, 1973) suggests that the San Juan and Escalante River clays can be differentiated from other sediment contributors, assuming (as was found with the Dirty Devil River samples) no differential flocculation of clays. Clays left behind by fast, turbid underflows of the type described by Grover and Howard (1938) and by Smith et al. (1960) can thus be followed stratigraphically along the course of the lake, and the provenance of turbidite layers found in piston cores can be tentatively identified. For example, in Figure 17 are shown relative amounts of illite, kaolinite, and montmorillonite, the less-than-2μ fraction from several cores taken in the lake plotted on a ternary

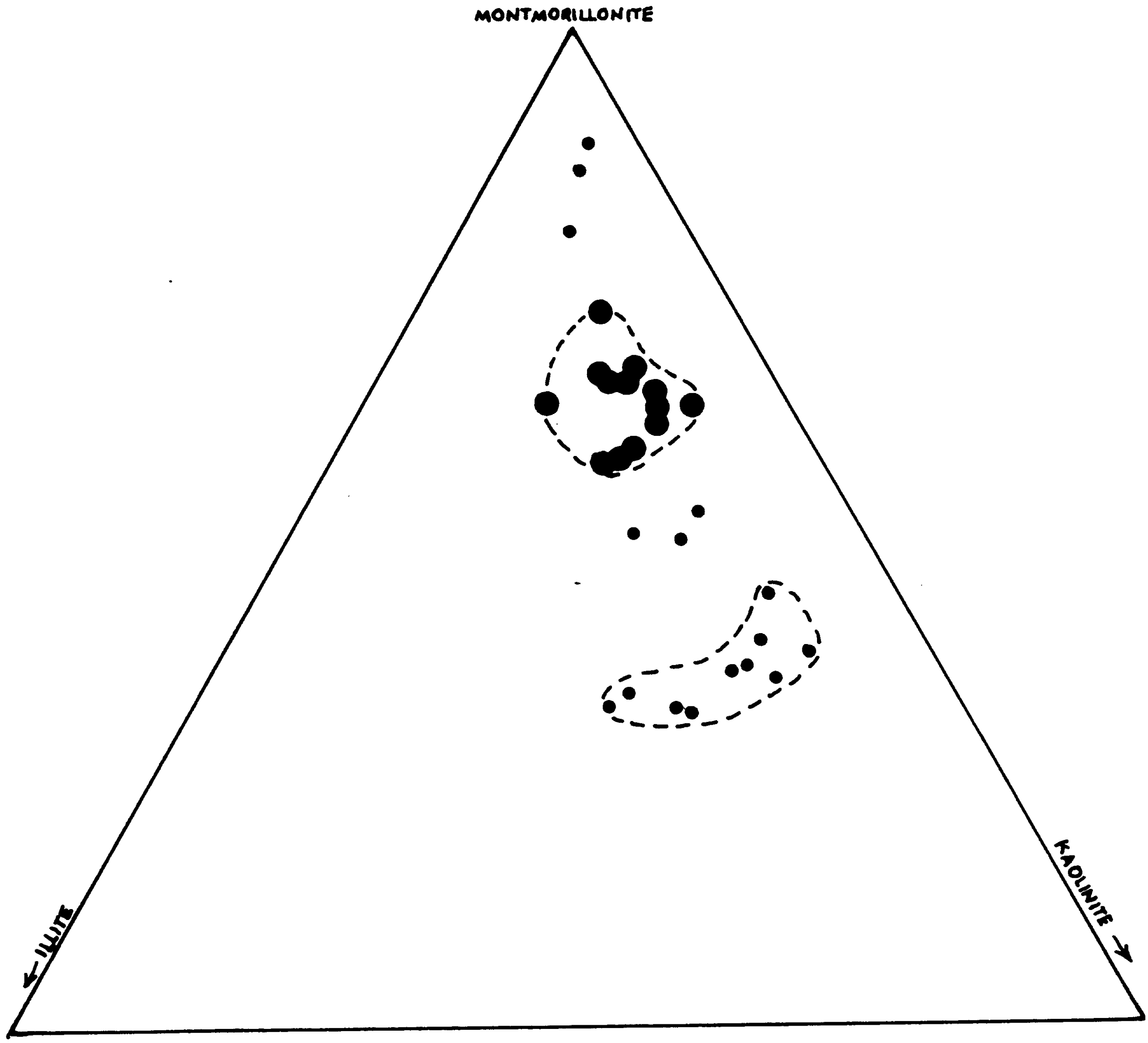


Figure 17: Clay Mineral Distribution in Cores from the Southern Part of Lake Powell

diagram. Much of the data fall into two definable clusters. The top cluster represents clays formed in several main-channel localities which probably represent deposition from Escalante- or San Juan River-derived underflows. The lower cluster, consisting of clays from several side bays (Wahweap, Warm Creek, Last Chance) with the same watershed and nearby channel sites, shows sediment contributions from the local watershed. The relative contribution of various sedimentary processes to the total siltation load at any site might thus be derived.

Chemical Properties

Carbonate Content

Reynolds and Johnson (1974) showed that precipitation of calcite in Lake Powell is a seasonal phenomenon because of several reasons: (1) photosynthetic removal of carbon dioxide by algae increases the pH of surface waters, (2) meromictic circulation during the previous winter has increased the salinity and alkalinity of the surface waters, (3) summer temperatures are higher. The first two factors are thermodynamic considerations: low H^+ and high CO_3^{--} and Ca^{++} activities favor the precipitation of calcium carbonate. Temperature is a kinetic control. The combined influence of these three factors restricts significant precipitation to the summer months. Furthermore, Reynolds (in press) has described an inhibiting effect of polyphenolic substances on the precipitation rate. Because polyphenol influx is predominantly during the spring runoff, the surface waters of the northern end of the reservoir should show only feeble calcite precipitation.

Carbonate contents of surficial sediments ranging the length of the lake were compared (Table 3) to test this model. The high values for samples AQ1075 and AQ1175 are probably attributable

Table 3: Carbonate Studies of Surficial Sediments

Sample# [a]	Location	Ical/Idol [b]	Iqtz/Ical	Wt.% $CaCO_3$ [c]
AQ 10-75	mile 183	1.6,1.3	?	21.4
" 9-75	" 175	.9,1.0	8.2,8.2	?
" 11-75	Hite Br.171	3.3,3.3	2.8,2.9	21.4
" 8-75	mile 165	2.1,2.5	3.9,3.6	?
" 7-75	" 160	1.8,2.0	5.8,5.1	15.7
" 6-75	" 155	2.2,2.2	3.7,3.8	?
" 5-75	" 150	1.9,2.2	3.8,3.3	18.3
" 4-75	" 145	1.5,1.7	3.3,3.5	17.4
" 3-75	" 140	2.2,2.1	3.8,4.0	18.2
" 1-75	" 130	2.2,2.2	5.8,6.2	?
" 12-75	Halls Xing,119	1.1,1.1	11.7,11.5	16.7
AQ1375	Wahweap Bay	1.5,1.7	4.9,5.7	19.2
76-g-15	mile 195	no cal.,dol.	133	4.9(5.4)
" 20	" 177	1.8,2.0	4.9,6.0	19.7(15.6)
" 21	Hite Br. 171	3.2,2.8	2.9,3.0	22.4(17.0)
" 34	Bullfrog Bay (sandy)	.6,.6	32,28	15.3(14.4)
" "	" " (clayey)	1.3,.9	11.5,14.7	17.1(16.1)
" 43	Hole-in-Rock,84.3	no dolomite	6.6,8.4	11.6(7.6)
" 44	S.J. mouth, 78	" "	5.8,9.7	11.2(5.8)
" 56	mile 28	2.2	6.9	19.1(15.5)
" 55	Padre Bay main ch.	7.3,7.4	4.0	? (27.5)
" 54	mile 50	6.3,6.3	3.7,3.9	? (15.1)
" 02	Wahweap Bay	6.2,7.8	2.7,2.8	? (26.9)

a= Samples AQ 1 through 12-75 are June '75 gravity corer samples
AQ1375 is a piston corer sample, but only surficial mud was recovered.
Samples labeled 76-g-# are Nov '76 Eckman dredge samples, splits of which were provided by R. McGirr.

b= Ratios of intensities of x-ray diffraction peaks, see text for discussion of technique.

c= Carbonate content obtained by method of Dean (1974) except those in parentheses, from McGirr (in prep.), obtained by analysis of LECO method.

to detrital carbonate admixture from the Hermosa Formation outcrops in Cataract Canyon, whereas the low value for 76-g-15 reflects its sandy character. Samples from Padre Bay (76-g-55) and Wahweap Bay (76-g-02) have 27 percent carbonate, but more importantly the ratio of calcite to dolomite for these samples is about 7 while a typical uplake figure is about 2. The ratio is a semi-quantitative measure of precipitated versus detrital carbonate contribution. The tabulated data suggest that the concentration of the detrital carbonate compound is dependent upon both location and texture of the sample. For example, sample 76-g-56 from the mouth of Warm Creek Bay has a carbonate content of 15.5 percent and a calcite/dolomite intensity ratio of 2.2. Thus the precipitated calcite fraction is probably small here. However, mud from the mouth of Last Chance Bay (sample 76-g-54) also has 15 percent carbonate but has a ratio of 6.3, suggesting that precipitated calcite may be important here.

To establish background values, it is necessary to measure the change with time at one specific location. By plotting carbonate content versus depth in a core, maxima represent periods of peak deposition. Anderson (1974) did this for a Wahweap Bay collector sample and showed a correlation between carbonate content and a summer bloom of the diatom Fragillaria. This same method was applied to several core samples.

Core HW6-8 from river-mile 16, near Glen Canyon Dam, was analyzed for carbonate content (by the method of Dean 1974) in the top meter of mud. Figure 18 is a vertical profile of the distribution. Note that maxima are about 25 percent and minima about 12 percent. A correlation also exists between the carbonate contents and the color of the mud. Pale brown (5YR5/2 when dry) clay has a carbonate content ranging from 11 to 16 percent, and yellowish olive gray clay (5Y7/2 when dry) to silty clay

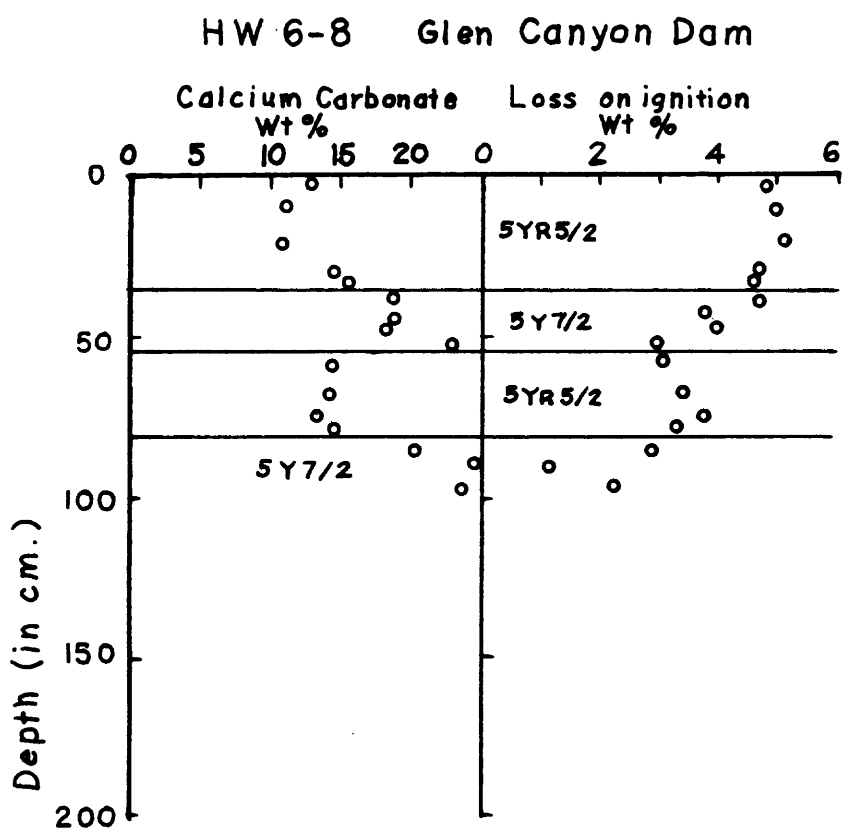


Figure 18: Vertical Distribution of Carbonate and Organic Matter in the Upper Meter of Sediments Near Glen Canyon Dam, Core HW6-8

ranges from 19 to 25 percent. The reduced muds (olive gray) have calcite/dolomite ratios near 2, and the oxidized (brown) muds range from 2 to greater than 6, with dolomite absent in three samples. Interpretation based upon maxima in the plot would ascribe the higher carbonate, olive gray muds to summertime deposition and the lower carbonate, pale brown clay to wintertime accumulation. If the color represents oxidation-reduction conditions during time of deposition, this would be expected to be seasonal also. Merritt (1976) showed that oxygenated, cold, dense, saline underflows during the winter flush out oxygen-depleted hypolimnion water. Thus, anaerobic conditions in the bottom waters have not yet occurred despite the lack of convection to these depths (450 feet) here (137 meters). In the sediments, however, the included organic matter may cause reducing conditions in the pore waters. If surficial sediment pore waters are in equilibrium with the bottom waters, we might expect them to experience the same cycle of oxygen enrichment and depletion. Echo sounding records of this part of the lake show an extremely diffuse echo, suggesting that the surficial sediments are very porous. Thus it seems reasonable that bottom and pore waters could communicate. Interpretation based on the calcite/dolomite ratio leads to the conclusion that the higher carbonate olive gray muds are deposited when calcite is not precipitating, and the lower carbonate, pale brown muds are summertime deposits. Fluctuations of the calcite/dolomite ratio of detrital material could cause this discrepancy, although it seems unlikely. Another possibility is that the surficial sediments in Wahweap Bay deposited in the summer (with high calcite/dolomite ratio) have been swept up and redeposited in the main channel.

Core HW7-7 was analyzed by the LECO method. The core bottomed river sands so the lake sediments exposed are the complete sedimentation history at this point. The muds were sampled at close intervals corresponding to color and texture changes. The lower half of the lake muds are silty but the upper part becomes more clayey, reflecting the deposition of coarser materials and thicker sedimentary units early in the life of the lake. Figure 19 is a plot of the carbonate distribution with depth. The wide range of values (7 to 22 percent) near the base of the section probably results from the deposition of alternately coarse- and fine-textured muds, fractionating the carbonate content by size. The variations diminished as the sedimentation approached a steady-state. The calcite/dolomite ratio of both a high-carbonate and a low-carbonate sample is about 2.5, indicating this ratio may be non-diagnostic here. It is tempting to assign cyclicity to seasonal precipitation of calcite, but summertime polyphenol concentrations at Halls Crossing are so high as to greatly inhibit calcite crystal growth (Reynolds, in press). Mayer (1976) noted, however, that dissolved silica concentrations were lowest in the surface waters of this section of the lake in summer because of uptake by diatoms. Although the euphotic zone is thinned by the suspended clays, the limiting nutrients for algal growth are made available by adsorption on the clays. Thus a tradeoff exists, and it is midlake that experiences high primary productivity (Kidd, 1975). The concomitant depletion of carbon dioxide might increase the pH to the point such that if enough nuclei exist the problem of polyphenol inhibition could be circumvented. The large, shallow embayments of Halls Creek and Bullfrog Bay may provide more ideal sites for precipitation. A density current mechanism such as speculated upon previously may shift the precipitated calcite-rich muds to the main channel. In support of this concept, the top of the core has been shown to be of turbidity current origin. Alternatively, the observed variation of carbonate content may simply reflect deposition of material from contrasting sources.

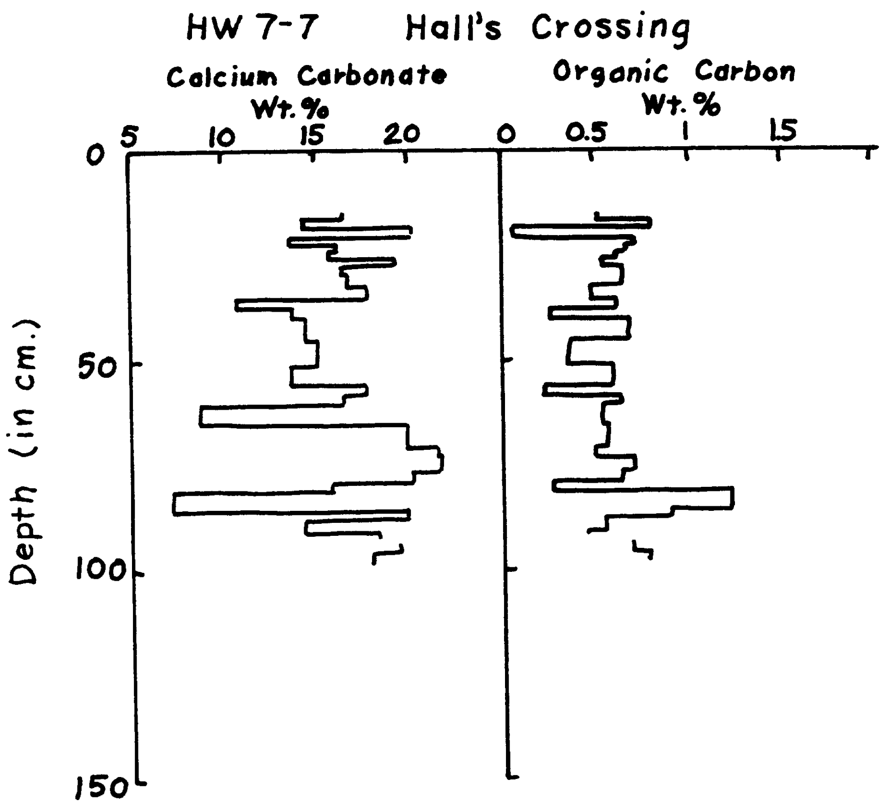


Figure 19: Vertical Distribution of Carbonate and Organic Carbon in core HW7-7. Note that the top 16 cm is a sandy turbidite and was not analyzed nor were the river sands at the base.

Core AQ7419 from the Colorado River main channel just down-lake from the San Juan arm was analyzed by the LECO method. Because of the 3-meter length (9.8 feet), the sampling interval and thickness are larger. Prominent couplets of moderate brown (5YR4/4, when wet) clay and dark yellowish brown (10YR4/2, when wet) clay were observed. Several half-centimeter-thin black "organic" layers separating the couplets also occur. The vertical profile (Figure 20) shows variations from 0 to 17 percent carbonate. The average value is 7.5 percent, much less than the previously described cores. The high-valued (17 percent) sample at 260 to 278 cm depth (102 to 109 inches) has a calcite/dolomite ratio of about 6. The echo sounding data (Figure 3) show a high sedimentation rate here. If calcite is precipitating, its effects are diluted by the detrital material. This is to be expected since the San Juan and Escalante arms of the lake are both nearby sediment contributors. Mayer (1973) noted that clays from the Escalante are "reddish-colored" while those from the San Juan are "buff-colored." The couplets may thus represent deposition alternately from these sources.

Core AQ7414 (Figure 21) from the main channel in Good Hope Bay is similar to the San Juan mouth core in that couplets of oxidized and reduced clays (dark reddish brown and dusky yellowish brown) occur. Carbonate averages 11.5 percent and ranges from 6.5 to 18.9 percent. Almost certainly, calcite precipitation must be negligible here because of the high concentration of polyphenols (R. C. Reynolds, Jr., personal communication). Thus, the profile of carbonate content must reflect changes in the percentage of calcite in the detrital load. The calcite/dolomite ratio of both a high- and a low-carbonate-content horizon was found to be about 1 and 1.5, respectively. The June 1975 surficial sediment ratio is 1.6, similar to those of Cataract Canyon muds, suggesting no precipitation of calcite. Echo sounding records from

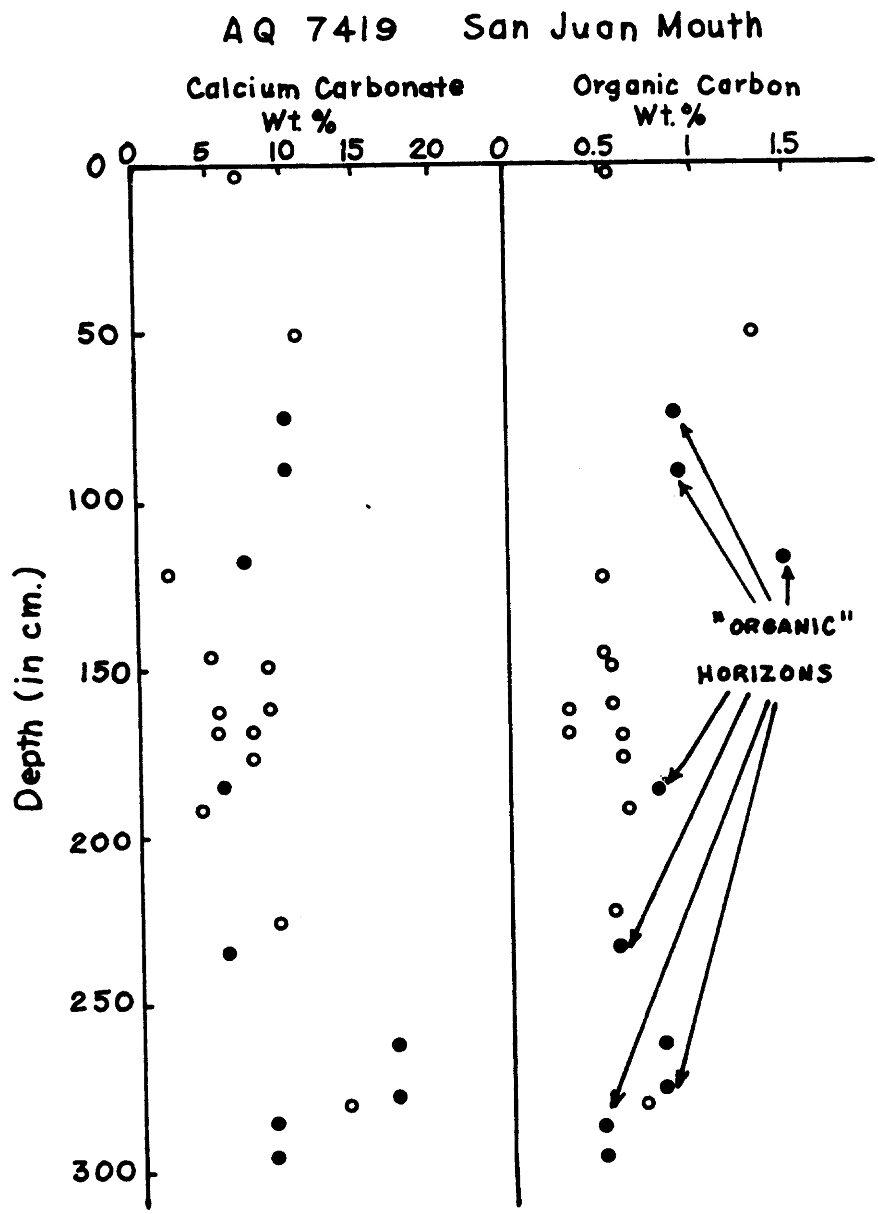


Figure 20: Vertical Distribution of Carbonate and Organic Carbon--Sample AQ7419. The points labeled "'organic' horizons" are thin layers of black amorphous sulfides not always high in organic content.

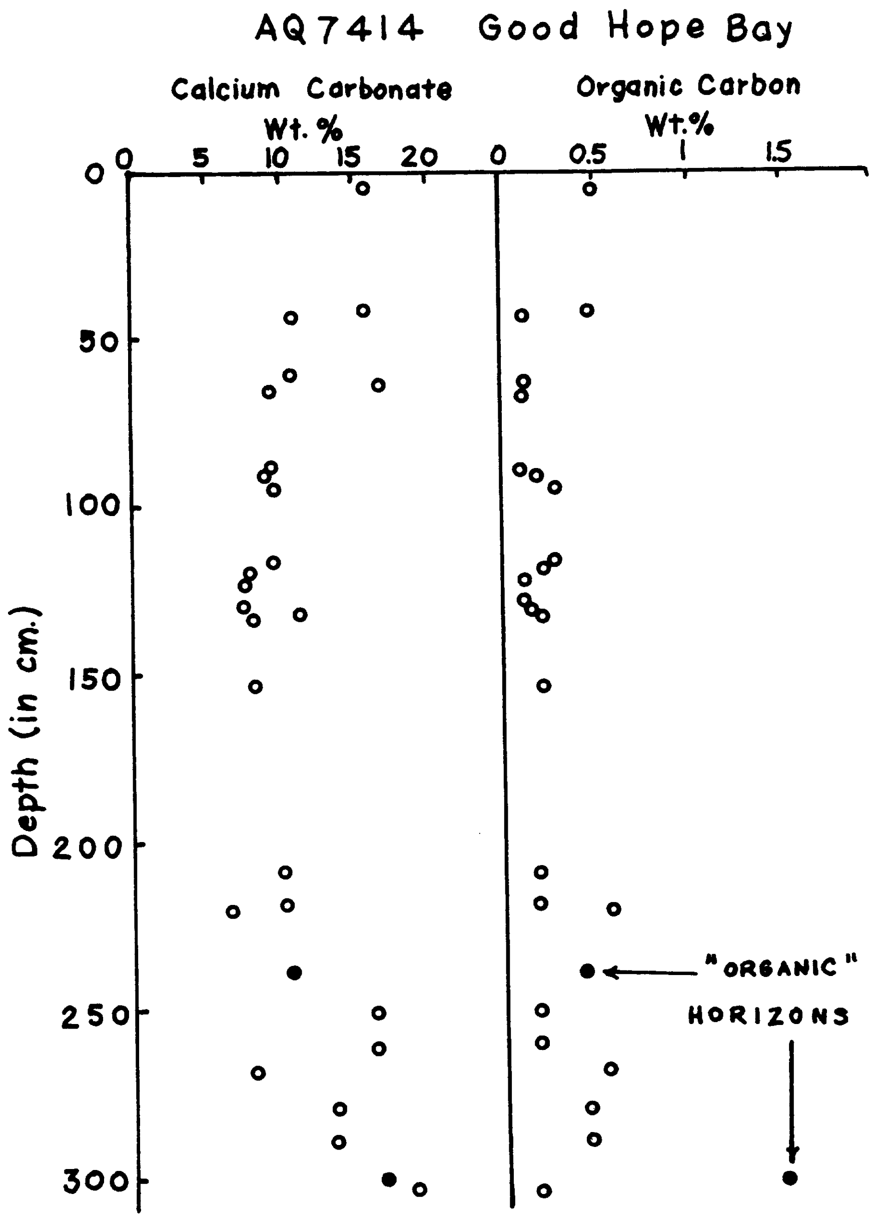


Figure 21: Vertical Distribution of Carbonate and Organic Carbon--Sample AQ7414. Note the extremely high organic content of a thin amorphous sulfide layer near the base of the core, whereas another black H_2S band is of typical background value.

here show the existence of a flooculant layer as well as at one time sediments ponded behind a slump barrier which no longer exists. A model of sedimentation here is a complex one encompassing the "pelagic rain" of suspended matter, slumping of Chinle muds and formation and destruction of flocculent layers.

Organic Matter Content and Diatom Abundance

The measurement of organic carbon, an intermediate step in the determination of carbonate content, was undertaken to aid in distinguishing seasonal sedimentation. Anderson (1974, 1975) found a correlation between organic matter content and abundance of the diatom Fragillaria in both a Wahweap Bay collector and one anchored in the main channel near Glen Canyon Dam. Core HW6-8, taken in July 1973 also near the dam, was analyzed for organic matter by the same method (from Dean, 1974) as Anderson had used. Figure 21 shows a range from 1 to 5 percent for this core, rather than the 10 to 20 percent loss on ignition of the collector samples. The highest values at the top do reflect the expected June diatom bloom, but the fourfold to tenfold discrepancy of percent organic matter between collector and core needs to be resolved. The probable cause is that preservatives (phenol-brine or formaline solution) present in the collector tubes eliminated bacterial decomposition of the organic material. The Lake Mead study (Sisler, 1960) showed that at least 1 million bacteria per gram (wet weight) of sediment exist, even near 100-foot (30-meter) depths. Their laboratory results of biochemical oxygen demand and gas evolution suggest that at least part of the observed difference between HW6-8 and Anderson's collector tube data may be attributable to preservation of organic matter. An unknown factor stems from the fact that the collector tube opening was 3 meters (10 feet) above the bottom. As such, deposition from bottom currents less than this thickness is not recorded. Therefore, the collector approach may show a bias and certainly preserves the record in an environment far different than in situ. The method does not aim to duplicate exactly the sedimentary record, but rather to "use the natural materials suspended in a water body as a recording medium for environmental changes and processes" (Anderson, 1974).

A decrease in organic matter with depth is noted which could reflect an increase of silt percentage with depth, though this was not observed when describing the core, or the older muds may simply be more decomposed. Lake Mead sediments, analyzed in another manner, showed no correlation of organic matter with depth (Gould, 1960). Furthermore, no Lake Mead sediments exceeded 1.7 percent organic matter. Thus, a considerable percentage of the loss on ignition values may be from structural water loss of clays.

The organic carbon contents of samples from cores HW7-7 (Figure 19), AQ7419 (Figure 20), and AQ7414 (Figure 21) were analyzed by the LECO method and closely resemble the range of the Lake Mead muds (0.2 to 1.0 percent organic carbon). Regression analyses of carbonate content versus organic carbon content were performed for each of these cores to test the hypothesis that precipitated calcite and organic matter are seasonally related. In none of the cores was a statistically significant (alpha confidence level greater than 95 percent) correlation found. This corroborates the findings of Gould (1960) that a predominance of the Lake Mead organic matter is finely divided allocthonous plant materials and that the plankton of the lake is a smaller contributor.

Cores AQ7414 and AQ7419 from Good Hope Bay (Figure 21) and San Juan mouth (Figure 19), respectively, illustrate another lithology seen in many of the cores we examined. Often, 0.5-cm-thick black horizons separate different color clays in a core. These were termed "organic horizons" in the field description because of the hydrogen sulfide smell associated with them. Only later did the analysis show that the organic carbon contents were not always greater than or much greater than those of the over- and underlying muds. The observation has been made throughout the lake that nearly ubiquitously a dark black hydrogen-sulfide-smelling zone lies a centimeter or so beneath the sediment-water interface. This is undoubtedly a zone where reduction of sulfate to hydrogen sulfide is taking place. In the presence of iron, hydrogen sulfide forms iron sulfide, leaving an amorphous black layer (L. Mayer, personal communication). The sulfate-reducing bacteria need both anerobic conditions and organic matter of molecular hydrogen for metabolism (Sisler, 1960), so some correlation between organic carbon and occurrence of the black reduced zone is expected. If pH conditions remain negative, however, the organic matter can be substantially decomposed, iron sulfide accumulated, and the bacteria migrated (at 1.8 cm per day at 5°C) (Sisler, 1960). Hence the "organic" layers need not be organic-rich forever. An important point is that at the migration rate reported if anerobic conditions in the pore waters persist, the sulfate-reducers can easily keep up with the sedimentation. If oxidizing conditions prevail in the pores of the new sediment the migration will cease and a "fossilized" iron sulfide zone is buried.

Finally, a note regarding the abundance of diatoms in the sediments. Several samples from core AQ7422 were examined for the presence of diatoms because Anderson's collector data showed this to be one of the best parameters to define seasonality. Also, Mayer (1976) showed that this midlake area had the highest silica depletion on the Colorado arm due to diatom fixation. The lack of any diatoms was startling. In the duplicate core that

Anderson (1977, personal communication) analyzed, he too found no diatoms or any other recognizable forms except the cladoceran Bosmina. Thus, dissolution of the diatom frustrules must be taking place in the muds. Johnson (1976) pointed out that in the marine environment introduction of clays with degraded silicate structure causes dissolution of diatoms and transfer of silica to the mineral phase. Perhaps this mechanism is at work in Lake Powell as well.

CONCLUSIONS

Establishment of average rates of sedimentation from core data is possible only when there is penetration into pre-dam sediments. At Halls Crossing, core HW7-7 yields a rate of 10 cm/yr (3.9 inches), but sample AQ7422 and sample AQ7518 give estimates of less than 22 cm/yr and less than 7.5 cm/yr, respectively (8.7 and 3.0 inches). Near the San Juan arm confluence with the Colorado arm, sample AQ7421 (San Juan River-mile 3) averaged 14.8 cm/yr (5.8 inches); AQ7420 (Colorado River-mile 71.5) measured 2 cm/yr (0.8 inch). These rates may be compared to average rates deduced by echo sounding of 200 cm/yr (78.7 inches) at Dark Canyon; 166 cm/yr (65.4 inches) at Hite Bridge; 90 cm/yr (35.4 inches) at Clay Hills Crossing; and 90 cm/yr (35.4 inches) at Glen Canyon Dam.

Particle size analysis of suspended matter suggests that the fine-grained sediments of the turbid spring runoff overflow current are concentrated at the base of this current, then become flocculated, and then settle through the hypolimnion.

Size analysis of sands and coarse silts intercalated within the muds shows that high-density turbidity current and liquefied sediment flow are the transport/depositional mechanisms moving coarse-grained sediments into the lake. Source areas are alluvium in nearby canyons, side-hill dunes, or talus slopes.

Water content measurements of piston core samples show no consistent trend with depth. This reflects a lack of compactional effects to the depths penetrated (3 meters) (10 feet), the variations being due to grain size of the sediments. Gravity-cored surficial muds from Halls Crossing to Dark Canyon have bulk densities about 1.4 gm/cm^3, based upon their water contents, and thus are essentially the same density as flocculated clay particles (with their trapped pore water). The use of 1.5 gm/cm^3 as an average bulk density for the conversion of echo-sounding-deduced volume data to gaging station weight data seems warranted on the basis of observed water contents and extrapolations.

The calcium carbonate content of the muds ranges from about 5 to 27 percent. Based upon a reduction of salinity of 20 parts per million (Reynolds and Johnson, 1974) integrated over the volume of the reservoir during the years 1964 through 1975, an estimated 4 million tons of calcite have been precipitated. Converted to volume using a bulk density of 1.5 gm/cm^3, this is but 23,000 acre-feet, or about 0.6 percent of the volume of sediments in Lake Powell. Even if all the precipitated calcite is assumed to accumulate in the main channel south of the San Juan arm confluence, it still represents but 3 percent of the accumulation. Hence, the carbonate measured is very dominantly of detrital origin. Seasonality interpretations of carbonate content versus depth graphs must therefore be made very cautiously, if at all.

Organic carbon contents of several cores are similar to values measured in Lake Mead. Correlation with carbonate content, depth, or location in the lake is not significant. Thin black reducing horizons are usually not much greater in organic matter content than are surrounding muds. The supposition is that an anerobic bacterial population is reducing sulfate to hydrogen sulfide and thence to iron sulfides in these zones.

Lack of diatoms in a core from Halls Crossing where diatom productivity in the surface water is high suggests that the dissolution of frustules is occurring in the hypolimnion or in the sediments.

The ubiquitous clay minerals are illite, kaolinite, and montmorillonite. No authigenic phases were found in the sediments. No preferential concentration of the three clays appears to occur during flocculation. Clustering of compositions on ternary diagrams suggests that major tributary sources may be distinguished from locally derived clays.

Echo sounding data corrected for sound velocity changes due to temperature effects can give accurate depths to the sediment top. Computer integration of cross-sectional data and thicknesses yields a calculated 400,000 acre-feet of accumulated sediment through June 1977. This is in close agreement with estimated inputs of 370,000 acre-feet of which 96 percent is suspended sediments brought into the lake by the perennial tributaries.

Assuming the sedimentation rates of the first 15 years to remain fixed, a minimum time for infilling to the level of the penstocks is nearly 200 years. Total filling of the reservoir would take 1000 years. Management of the lake surface elevation is a large factor in the future distribution of sediment and hence in the useful life of the reservoir for recreational purposes.

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GLOSSARY

adsorption	adhesion of molecules of gases or ions in solutions to the surfaces of the solid bodies with which they are in contact
advection	large-scale horizontal motions
aggradation	the process of building up a surface by deposition
aliquot	a sample, representing a definite part of the whole
allocthonous	not formed dominantly *in situ*; moved into its present position after deposition
alluvium	detrital deposits resulting from the action of rivers
aluminosilicate	mineral containing aluminum, silica, and oxygen; clay mineral
aqueous	pertaining to water
Archaean	the oldest geological era extending from the formation of the first crustal rocks to about 2600 million years before the present
authigenic	generated in place
bedrock	solid rock under soil, clay, sand, etc.
benchmark	a relatively permanent marker whose elevation above or below

	sea level has been accurately determined by surveying
bottomset	fine sediments deposited in front of a delta
Cenozoic	that portion of earth history extending from about 65 million years ago to the present
cladoceran	a primitive living crustacean; the common water flea
collimated	brought into line, made parallel
competence	ability of a body of moving water to transport sediments; ability of a rock formation to resist erosion
Cretaceous	a geological period extending from about 141 to 65 million years before the present
depocenter	the locus of maximum deposition of sediment
dessicator	a device for drying or removing water from a sediment sample
detrital matter	made up of mineral rock fragments
diatom	algae that secrete siliceous tests
diatremes	explosive volcanic vents
entrain	carry along with
ephemeral	transitory, short-lived
epilimnion	the upper waters in a lake, more or less uniformly warm, circulating, and fairly turbulent

estuary	that portion of a stream influenced by the tide of the body into which it flows
flocculent	aggregated into small clumps, said especially of colloids and clays
foreset	inclined beds accumulated on the front of a delta
frustules	the siliceous tests or shells of diatoms
GSA color chart	a chart of standard colors for describing sediments or rocks, published by the Geological Society of America
hypolimnion	the lower waters in a lake, deep, cold, and relatively undisturbed
igneous	rocks crystallized from a molten state
in situ	in place
integrated	combined
intercalated	one body of material interlaminated with another
interpolate	to estimate by following the trend of a curve
interstitial	filling the pores of rocks or sediments
Jurassic	a geological period extending from about 195 to 141 million years before the present

kHz	1000 cycles per second
kinetic	pertaining to motion
laccolithic intrusions	intrusive bodies that dome up the overlying strata and have a flat floor
lamination	the more or less distinct alternation of materials which differ one from the other in grain size or composition
lithology	composition and texture of geological materials
load	the material transported by a moving water body, either in suspension or driven along the bottom
meromictic	a lake in which some water remains partly or wholly unmixed with the main water mass at the circulation periods
metalimnion	the region in a lake in which the temperature gradient is steep
metastable	stable with respect to small disturbances
μ	micron, 10^{-6} meters
Munsell system	color system devised by the Munsell Color Company, 2441 North Calvert Street, Baltimore, Maryland

Ohm's Law	the relationship between electrical current and potential that defines the electrical resistance
pelagic rain	particle-by-particle sedimentation
Pennsylvanian	a geological period extending from about 310 to 280 million years before the present
penstock	the pipe or tunnel leading from a reservoir to the associated power plant
pH	the negative logarithm of the hydrogen ion activity; low numbers indicate acidity, high numbers alkalinity
ϕ	a logarithmic mean particle diameter obtained by using the negative logs of the class midpoints to the base 2
Phanerozoic	the last 600 million years of earth history during which hard-shelled organisms lived
physiography	the shape of the earth's surface
Pleistocene	the glacial epoch extending from about 12,000 to 2,000,000 years before the present
polyphenols	phenol (C_6H_5OH) derivatives that occur as plant products
progradation	lateral advance of a surface through deposition

relict	materials representing an earlier stage or assemblage that have persisted in spite of processes that might tend to destroy them
silt fraction	that part of a sedimentary mixture in the silt size range from .0625 to .0039 millimeters
slump block	a coherent block of material that has moved downhill under the influence of gravity
sounding profile	depth determinations by echo sounding along a traverse
Stokes Law	a formula to express the rates of settling of spherical particles in a liquid
stratigraphy	that branch of geology that treats the formation, sequence, and correlation of stratified rocks
talus	the sloping pile of rock fragments at the base of a cliff
tectonic	pertaining to rock structures formed in deformation of the earth's crust
ternary	having three components
wet-weight split	a water-saturated sediment sample taken for analysis
winnowing	separation of finer particles from coarser ones

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