LA-UR-93-2165

# INFLUENCE OF HYDRAULIC AND GEOMORPHOLOGIC COMPONENTS OF A SEMI-ARID WATERSHED ON DEPLETED URANIUM TRANSPORT

by

NAOMI MIRIAM BECKER

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
(Civil and Environmental Engineering)

at the
UNIVERSITY OF WISCONSIN-MADISON
1991

# FOREWORD

Los Alamos National Laboratory throughout its almost 50-year history has been known for its open-air testing of explosives-driven devices. Such tests have been and continue to be conducted within Laboratory confines on the Pajarito Plateau. Today's explosives testing area occupies more than half of the Laboratory's 43 square miles and is considered a national resource for the research and development of explosives devices.

In retrospect, J. Robert Oppenheimer's selection of the Los Alamos site has been ideal for explosives testing. The topography of finger-like mesas and canyons has allowed the deployment of numerous testing sites in relative isolation from each other. The climate, which features low rainfall and low humidity, provides near ideal operating conditions for testing. The Los Alamos testing area to this day remains well buffered from population encroachments. The mesa tops and canyon bottoms, which serve as the explosives firing tables, are situated well above groundwater aquifers. A long-standing concern, however, has been the location and surface migration of depleted uranium that has been expended extensively and continues to be used today, albeit in smaller quantities, in Los Alamos tests.

Naomi Becker, in this dissertation treatise, describes her multi-year investigation of uranium transport in Potrillo Canyon. Potrillo Canyon drains several of the Laboratory's well exercised explosives test facilities. The study--comprising measurements, analysis, and interpretations-- provides an important assessment of the mechanisms and potentials for surface migration of uranium, up to and beyond Laboratory boundaries.

The Dynamic Testing Division, which we represent, operates the Laboratory's explosives testing area. The Division has been a strong supporter of Ms. Becker throughout her study. The Division has provided full access to its facilities and environments, detailed information as to its operations, and technical staff support for gage deployment and field measurements. It should be obvious that our Division had an intense curiosity (and some would say a vested interest) in the outcome of the study. However, we wish to state that the methodologies, protocols, models, interpretations, and findings developed in the study reside totally with Naomi Becker. Where we could, we provided motivation and encouragement. Otherwise, we waited patiently for the study's completion and conclusions. The Division considers Ms. Becker's study as an important self-assessment step in improving its environmental protection program.

As a personal note, we express our appreciation to Naomi for her scientific integrity in the conduct of the study and for completing it. In addition we, as do many of our colleagues, congratulate Naomi on succeeding to an important new level of academic achievement.

Timothy R. Neal
Leader
Dynamic Testing Division

Frank M. Jackson
Operations Officer
Dynamic Testing Division

Dennis J. Erickson
Former Leader
Dynamic Testing Division

Los Alamos National Laboratory
April 1991

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INFLUENCE OF HYDRAULIC AND GEOMORPHOLOGIC COMPONENTS OF A SEMI-ARID WATERSHED ON DEPLETED URANIUM TRANSPORT

Naomi Miriam Becker

Under the supervision of Professor John A. Hoopes

at the University of Wisconsin-Madison

Investigations were undertaken to determine the fate and transport of depleted uranium away from high explosive firing sites at Los Alamos National Laboratory in north-central New Mexico. Investigations concentrated on a small, semi-arid watershed which drains 5 firing sites. Sampling for uranium in spring/summer/fall runoff, snowmelt runoff, in fallout, and in soil and in sediments revealed that surface water is the main transport mechanism. Although the watershed is less than 8 $km^2$, flow discontinuity was observed between the divide and the outlet; flow discontinuity occurs in semi-arid and arid watersheds, but was unexpected at this scale. This region, termed a discharge sink, is an area where all flow infiltrates and all sediment, including uranium, deposits during nearly all flow events; it is estimated that the discharge sink has provided the locale for uranium detention during the last 23 years. Mass balance calculations indicate that over 90% of uranium expended still remains at or nearby the firing sites. Leaching experiments determined that uranium can rapidly dissolve from the solid phase. It is postulated that precipitation and runoff which percolate vertically through uranium-contaminated soil and sediment are capable of transporting uranium in the dissolved phase to deeper strata. This may be the key transport mechanism which moves uranium out of the watershed.

# CHAPTER 1

# THE QUESTION OF DEPLETED URANIUM TRANSPORT AND FATE IN A SEMI-ARID WATERSHED

## *Introduction*

Los Alamos, New Mexico was chosen in 1942 as the site of secret development of the first atomic bomb, during the war effort of World War II. Selected for its remote location in north-central New Mexico, war-time development and testing activities were far removed from any major population center. After the war, research activities continued at the Los Alamos installation, called Los Alamos Scientific Laboratory, later called Los Alamos National Laboratory, hereafter referred to as the Laboratory. These post-war activities focused on new nuclear weapons models as well as greater effectiveness and reliability of existing weapons.

Depleted uranium has been used in weapons testing activities at the Laboratory since the mid-1940's. Whereas natural uranium contains 99.3% Uranium-238 and 0.7% Uranium-235, depleted uranium contains 99.8% Uranium-238 and 0.2% Uranium-235. Depleted uranium is a by-product of uranium enrichment processes; it is relatively inexpensive, abundant, and substitutes well for enriched uranium during testing because it duplicates the physical characteristics of enriched uranium, but not enriched uranium's fission characteristics.

It is estimated that between 80,000 and 105,000 kg of uranium have been expended by the Laboratory since 1943. In 1983, results from the Laboratory's environmental surveillance sampling showed that tissue and gut from fish collected from a downstream reservoir on the Rio Grande contained statistically significant levels of uranium. The question arose whether these elevated uranium levels were from uranium used in Laboratory operations which had traveled offsite. This question provided the impetus to initiate a study of uranium content in runoff waters in one Laboratory watershed called Potrillo Canyon. The watershed is located within the Laboratory and receives uranium from weapons testing at firing sites. The small runoff study grew to its present form in this dissertation.

This dissertation initially aimed at defining uranium transport in a single watershed, in particular to find out where in the watershed uranium was depositing, if it was moving out of the watershed, and at what rates. Several unique aspects of this watershed became evident: 1) there is no perennial flow; 2) flow, when it occurs, is event-driven and discontinuous both temporally and spatially; and 3) although very small, less than 8 $km^2$ in area and 8 km in length, flow and sediment discharge are discontinuous through the length of the watershed for the majority of precipitation/flow events. These features caused a refocusing of the dissertation to examine the formation, stability and characteristics of the discontinuity and its effect in trapping sediment and uranium, and for infiltrating water.

A review of existing literature found no significant body of information describing this last point. For this reason, a literature review will be incorporated into the text as appropriate. Evidence will be presented, as it evolved from the field investigations, on those geomorphologic and hydrologic factors which influence uranium transport in this watershed. The hydrology shall be presented first, followed by presentation of uranium occurrence in rock, soils and sediments, uranium transport mechanisms, and the geomorphologic distribution of uranium. Several hypotheses on the fate of uranium will be offered and discussed, and a conceptual sediment transport model of the watershed presented. A generalization of the model to other valleys in this arid environment will be presented.

*Setting*

Los Alamos National Laboratory is located on the eastern flank of the Jemez Mountains in north-central New Mexico, Fig 1.1. The Jemez Mountains are a ring of volcanic and volcaniclastic rocks, surrounding a caldera (a collapse structure) of rocks ranging in age from Pliocene to Holocene (13 million years ago to less than 11,000 years ago). The most recent eruption was the Bandelier Tuff, a thick sequence of ash-flow and ash-fall deposits. These deposits nearly encircle the Jemez Mountains and form a gently dipping plateau on the eastern side known as the Pajarito Plateau (Crowe,1978). The Pajarito Plateau has been dissected into numerous, finger-like mesas separated by deep, east-southeast trending canyons. The Plateau is eroded on its eastern margin by the Rio Grande, the master stream of the region. Los Alamos National Laboratory is located entirely on the Pajarito Plateau.

The Potrillo Canyon watershed is small and steep. It is located entirely on the Pajarito Plateau, and is mostly contained within the Laboratory, Fig 1.2. It has an area of about 7.8 $km^2$, is 8 km in length, and has an average gradient of 3 percent. The watershed is characterized by flat mesa tops leading to nearly vertical canyon walls which terminate in large talus piles of tuff boulders. The valley bottom ranges

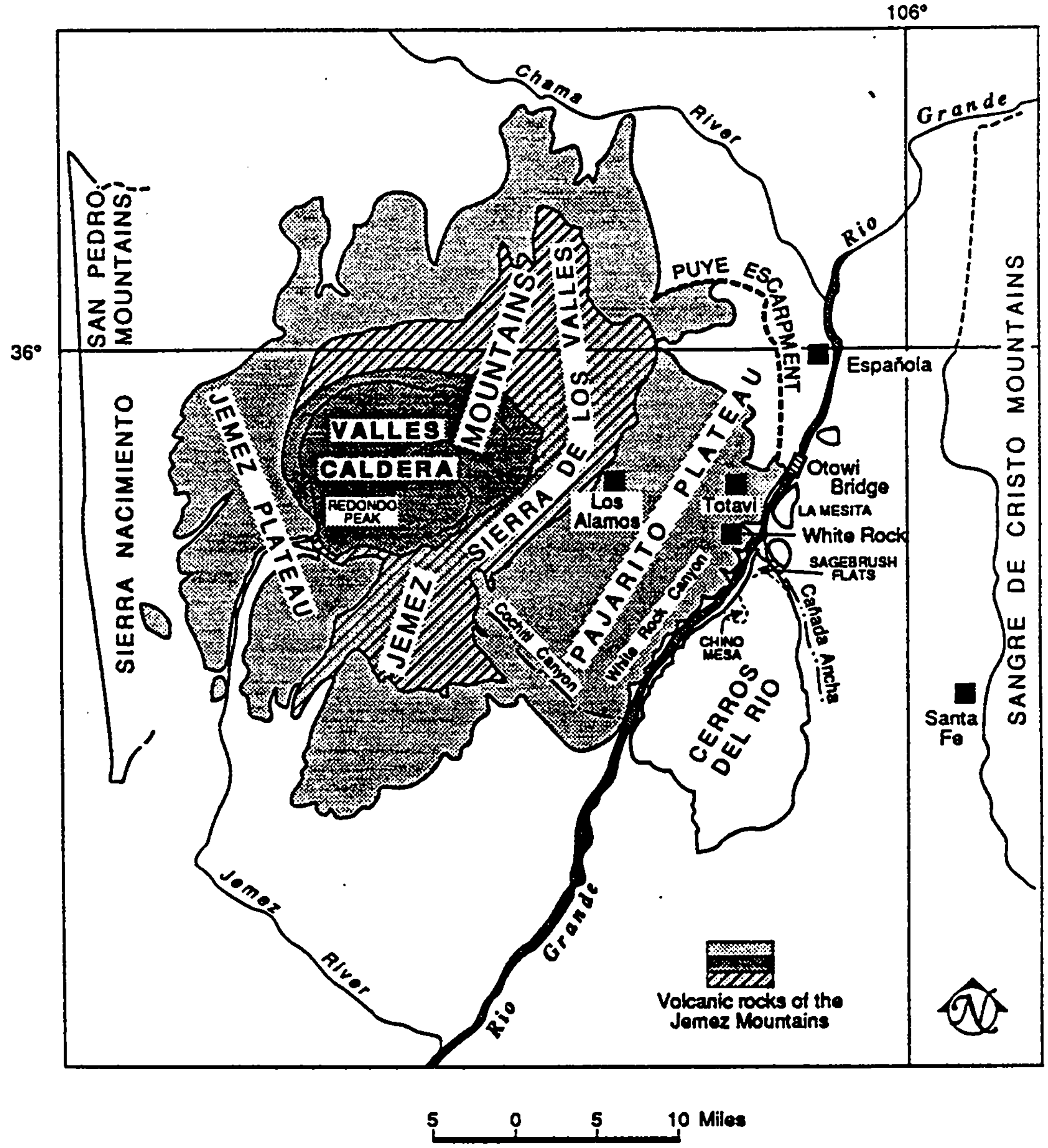



Fig 1.1. Topographic Features in the Vicinity of Los Alamos, New Mexico.

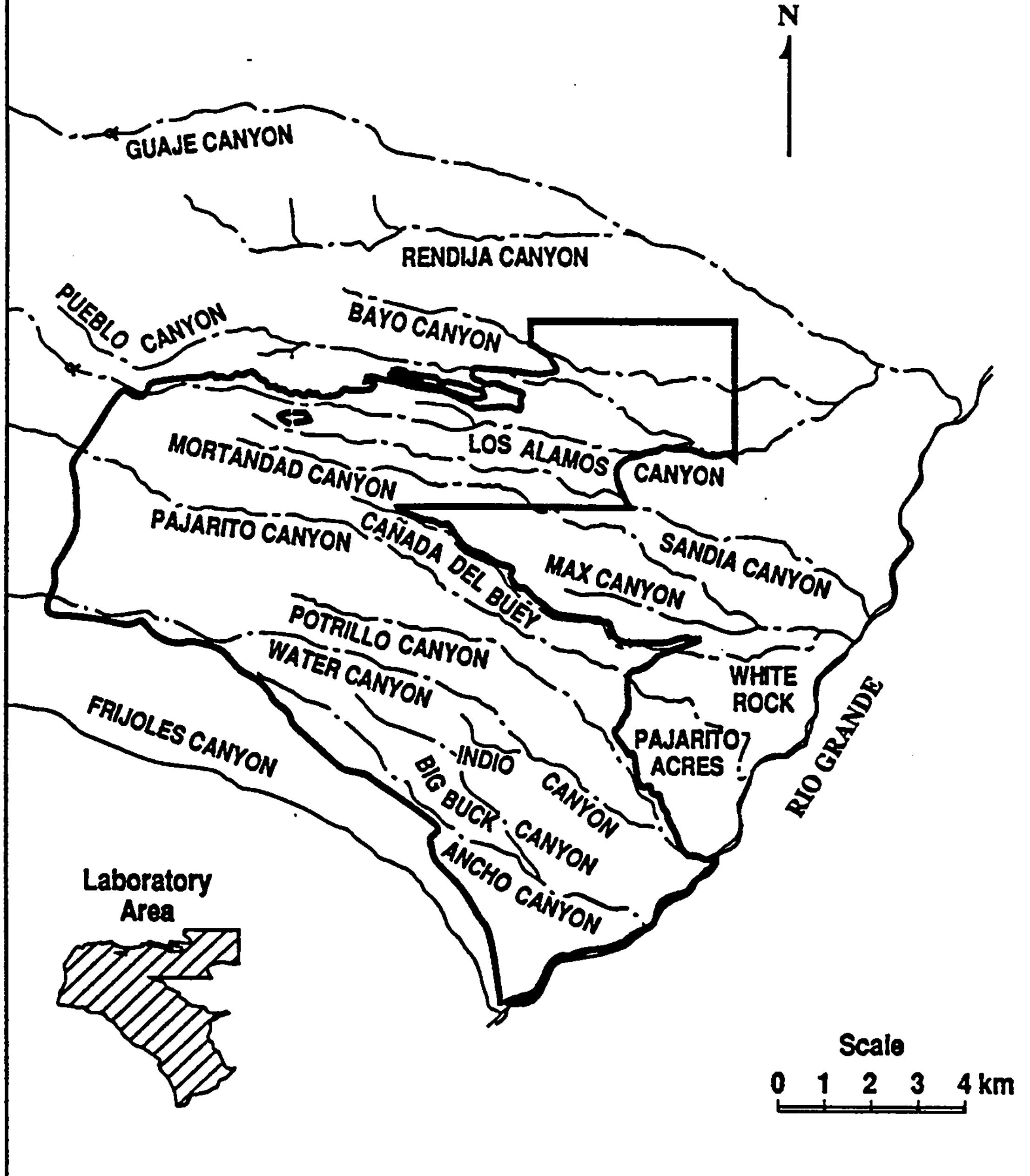



Fig 1.2. Location of Potrillo Canyon at Los Alamos National Laboratory.

from narrow in the upper end of the watershed to broad in the middle and outlet end. Vegetation varies significantly through the watershed; the upper end, which is over 2100 m in elevation, has a covering of Ponderosa pine that changes to a piñon-juniper community in the lower reaches. Soil cover on mesa tops is thin to absent, and in the valley bottom ranges from thin in the upper reaches to over 9 m in the middle and outlet. The watershed contains 4 active and 1 inactive firing sites. The inactive site has not been used for diagnostic weapons testing since April 13, 1973. Land use in Potrillo Canyon watershed is limited to development associated with firing sites: asphalt roads, firing pads and bunkers, some storage buildings. During the last 40 years land use changes have been minimal.

Los Alamos has a semi-arid climate. Average annual precipitation is 475 mm. The rapid decline in elevation, from just over 3050 m in the peaks of the Sierra de Los Valles above the town of Los Alamos (2225 m) to 1645 m at the Rio Grande, a distance of about 13 km, is echoed in the gradient of annual precipitation. The peaks receive about 750 mm of precipitation annually, decreasing to about 200 mm at the Rio Grande. Precipitation occurs predominantly in two forms, rain from summer thundershowers during July and August, and winter snowfall, which measures around 1.3 m annually in the town of Los Alamos. Evaporation and evapotranspiration are large, with potential evapotranspiration exceeding average annual rainfall.

None of the canyons traversing the Pajarito Plateau through the Laboratory contain perennial flow. Flow of water in the canyons is in direct response to rainfall events and snowmelt runoff. There are instances where perennial lenses of groundwater exist in canyons receiving effluent releases; generally these lenses are seasonal and/or of limited horizontal extent. Where shallow groundwater is present, water has perched on slightly less permeable layers within the Bandelier Tuff. Depth to deep groundwater in the main aquifer ranges from about 90 m near the Rio Grande, a groundwater discharge area, to over 485 m at the western margin of the Pajarito Plateau. This main aquifer provides the water supply for the town of Los Alamos as well as the Laboratory.

Investigations terminate at State Road 4, which coincides with the Laboratory boundary. Southeast of State Road 4 the watershed is open to public access. About 0.8 km downstream from the highway, Potrillo Canyon empties into Water Canyon, a larger watershed with headwaters in the peaks of the Jemez Mountains and which also traverses the Laboratory. Less than 1.6 km from this confluence, Water Canyon empties into the Rio Grande, Fig 1.2. The Rio Grande is public waters and used for recreation such as rafting and fishing.

*Flow Pathway Analyses in Potrillo Canyon: An Eulerian Approach*

In hydrodynamics, sampling characteristics of fluid flow at fixed points is called an Eulerian approach. In this study of uranium transport, observations of peak stage, and uranium concentration in runoff were made at points along the watershed. Cumulative runoff samplers were installed in 1983 and 1984 at five locations in the watershed, Fig 1.3. The purpose of these samplers was to collect summer stormwater runoff in order to estimate uranium movement from firing sites through the watershed and outlet and to evaluate the potential for contamination by dynamic testing entering the Rio Grande. The locations of these samplers were selected to be

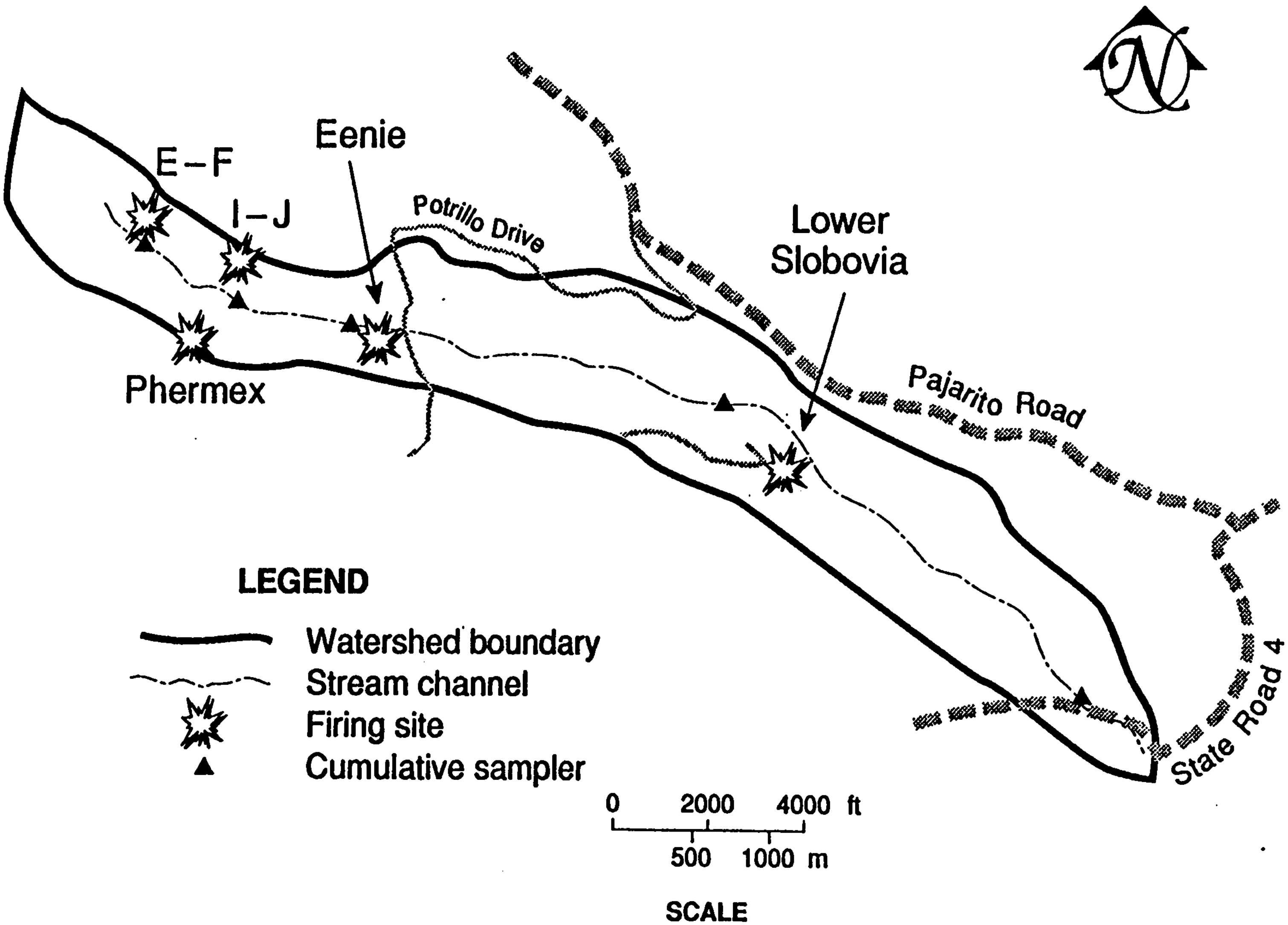



Fig 1.3 Location of Cumulative Samplers in Potrillo Canyon Watershed.

in close proximity, preferably downstream, to firing sites in order to assess the individual depleted uranium contribution from each site.

After collecting samples from a number of large rainfall events over several years, an interesting pattern became apparent. Most of the time, runoff samples were collected from the uppermost 2 or 3 samplers, and occasionally all 4 samplers upstream from Lower Slobovia, Fig 1.3. It was uncommon for all 5 samplers to be full after a runoff event. The sampler which seldom contained water is located at State Road 4, near the terminus of the watershed. It seemed the stream would flow down to the Lower Slobovia area but no farther. Discontinuity in streamflow is not uncommon in semi-arid watersheds, but was an unexpected observation in a watershed as small and steep as Potrillo Canyon.

A thorough inspection of the stream channel near Lower Slobovia corroborated this observation of flow discontinuity. A well-developed stream channel, with traditional banks and bed features rapidly changes into a wide floodplain landscape of brush, trees, bushes and grasses. About 1.2 km further downstream, a definite channel reappears. Walking along this channel it was apparent that there had not been flow for quite a while, indicated by a substantial thickness of debris covering the bed, mostly pine needles and pine cones.

Crest stage recorders confirmed the observation. A crest stage recorder was installed in 1988 about 0.5 km downstream from the Lower Slobovia bunker. Precipitation during 1988 exceeded average annual precipitation by 30 percent, precipitation during 1989 was slightly less than the annual average, and precipitation during 1990 was equal to the average. Inspection of the crest stage recorder downstream of the Lower Slobovia bunker and the channel bed after each event during 1988 through 1990 confirmed that there was no streamflow through the channel-less reach.

Many watersheds without baseflow produce runoff differentially in space. Schick (1977), in studies in the Negev desert in Israel, and Campbell (1977), in southcentral Alberta, Canada, report instances of these phenomena. During the majority of events, there is significant discharge loss in Potrillo Canyon. The area where loss occurs enables the present watershed to behave effectively as two separate watersheds, which has produced a pronounced effect on both the flow dynamics and sediment deposition. An area of flow loss is not uncommon in streams in arid areas, but there is not much literature available on the small-scale examples. One small-scale example will be described.

*Discharge Sink*

An area where inflow exceeds outflow (if there is any outflow at all), where stream velocities decrease and the flow infiltrates into the channel and valley, where there is no defined channel (only a broad valley), and where there is sediment deposition and aggradation is herein called a discharge sink. It is distinguished from areas of temporary sediment storage along the channel by the lack of flow continuity through the area. These sinks can be manmade or naturally occurring. They can be recognized by the lack of a channel through their length, an increased thickness of sediment, or a pattern of sediment fining in the distal direction. They can be, but are not necessarily, topographic depressions.

Such an area exists in Potrillo Canyon from a point approximately 0.5 km southeast of the road to Skunk Works to about 0.5 km south of the Lower Slobovia firing site bunker. There is at present no defined channel through its length, although the remains of a former channel can be distinguished primarily through floristic variation from the surroundings. This discharge sink appears to serve as a giant sponge, absorbing streamflow and trapping all the incoming sediment load. After a large runoff event, patterns of diverging flow at the upstream end can be observed, and the individual channels traced to where they end in dams of pine needles, pine cones and tree debris. All the flow infiltrates into the ground. Downstream there is no evidence of further streamflow (i.e., no deposition of fine-grained sediment, no scouring or bed forming features).

By trapping sediment, the sink serves to contain contaminants, heavy metals in particular. Uranium, with a specific gravity of 18.95, could easily accumulate in such an area. Each subsequent inflow can bring depleted uranium from upstream, and resuspend and redistribute existing uranium. Infrequent surface outflow from this area insures that the majority of the time the only mechanisms to release uranium are airborne, man-initiated, and dissolution by the infiltration water. With the Lower Slobovia firing site essentially located within this sink, one can hypothesize that the discharge sink effectively traps sediment from all 5 firing sites located in the watershed.

During July 1989, a borehole was made at the upstream end of this sink to be used for neutron moisture probe measurements. More than 10 m of unsaturated alluvium was encountered before encountering saturated alluvium. The hole bottomed at 18.6 m, still in the saturated alluvium. The total saturated thickness is unknown. Two other boreholes, one about 0.5 km upstream, and the other about 1 km downstream of this locaton, encountered no saturated alluvium; these holes were

15-19 m in total depth. The apparent spatial isolation of this saturated zone provides further evidence that streamflow preferentially infiltrates into this area. It is postulated that infiltrating streamflow percolates through the alluvium until it perches on a less permeable layer or bed or reaches the water table. A seismic survey of this sink confirmed that there was no perched-water aquifer in this reach of the canyon. The shallow seismic refraction technique used has been successful in aquifer delineation on the Pajarito Plateau in other canyons, where the observed saturated zone may be extremely localized. Such saturated zones vary in horizontal and vertical extent through time in response to runoff volume and to the spatial and temporal supply of water to the discharge sink. The stability of the discharge sink and its origin are unknown.

CHAPTER 2

# OCCURRENCE OF RAINFALL AND RUNOFF IN POTRILLO CANYON WATERSHED

## *Climatology*

Los Alamos has a semi-arid climate with an annual average precipitation of 475 mm. Precipitation amounts vary locally as the elevation changes. In the peaks of the Sierra del Los Valles, annual precipitation is closer to 750 mm, whereas at the Rio Grande, annual precipitation is about 200 mm. This gradient in rainfall occurs over a distance of about 13 km and decline of nearly 1525 m elevation. About 75% of the total annual precipitation is rain.

Forty percent of the annual precipitation falls in July and August during the monsoon season. The monsoon season, characterized by frequent thundershowers, forms when a high pressure system, called the Bermuda High, locates over the eastern United States or western Atlantic Ocean during the summer months. This high pressure permits a weak southeasterly flow of moisture from the Gulf of Mexico toward New Mexico. Other mechanisms which can transport moisture into the area are jet steam flow from the Pacific Ocean, and upper level atmosphere "cut-off lows" of low pressure (Bowen, 1989).

Summer thundershowers commonly occur in the early afternoon and early evening hours. Progressive heating of the ground begins warming the air early in the day; the warmed air, now lighter, rises. Sufficient moisture in the air, supplied from the Gulf of Mexico, permits the air to condense, form cumulus and cumulonimbus clouds, and showers develop. Frequently, cloud formation begins over the Sierra de Los Valles. The resulting rain front moves from west to east over the Pajarito Plateau, diminishing as it moves eastward. This trend is apparent in the annual rainfall gradient from west to east along the Plateau.

Snow is common during the winter months. The average annual accumulation is about 1300 mm. It is common to have accumulations in excess of 100 mm with an individual storm, but mild temperatures and intense solar radiation usually melt heavy snow cover rapidly. Many years have little springtime snowmelt runoff due to high evaporation and sublimation rates in the winter.

*Precipitation Statistics in Los Alamos*

Weather records have been recorded in Los Alamos since November 1910. Records exist for 81 years, although years 1916, 1917, 1918, 1920, 1922, 1923, 1943, and 1945 are incomplete, and there are no records for 1921. The gage has been moved a number of times. Table 2.1 summarizes the different locations and period of record. A double mass curve was prepared, comparing records from the Los Alamos gage with Santa Fe records, Fig 2.1. The purpose was to determine if the Los Alamos data has been affected by the gage movement. Only years with complete precipitation records at both stations were used.

There is a break in slope in the double mass curve between 1915 and 1919. Other slope deviations occur during the periods 1938-1941 and at 1951, but neither persisted for at least 5 years, and therefore are not considered significant (Chow, 1964). Examination of the Los Alamos records between 1915 and 1919 reveal no change in the gage location during that period. As the difference in slopes is slight, it

Table 2.1
Locations of the Los Alamos Raingage
1910-1990

| Time Period | Location |
| --- | --- |
| November 1910 - March 10, 1946 | Los Alamos Ranch |
| March 19, 1946 - April 30, 1950 | Townsite |
| May 1, 1950 - December 31, 1951 | Airport |
| January 1, 1952 - March 20, 1956 | H/Administration Bldg (now the site of Los Alamos Inn) |
| March 21, 1956 - August 31, 1956 | LANL, TA-3, SM-43 roof |
| September 1, 1956 - 1978 or 1979 | LANL, TA-3, SM-43 on ground near southwest end of bldg |
| 1978 or 1979 - June 1987 | LANL, TA-59, OH-1 on ground near southeast end of bldg |
| June 1987 - 1990 | LANL, TA-59, OH-1 roof |

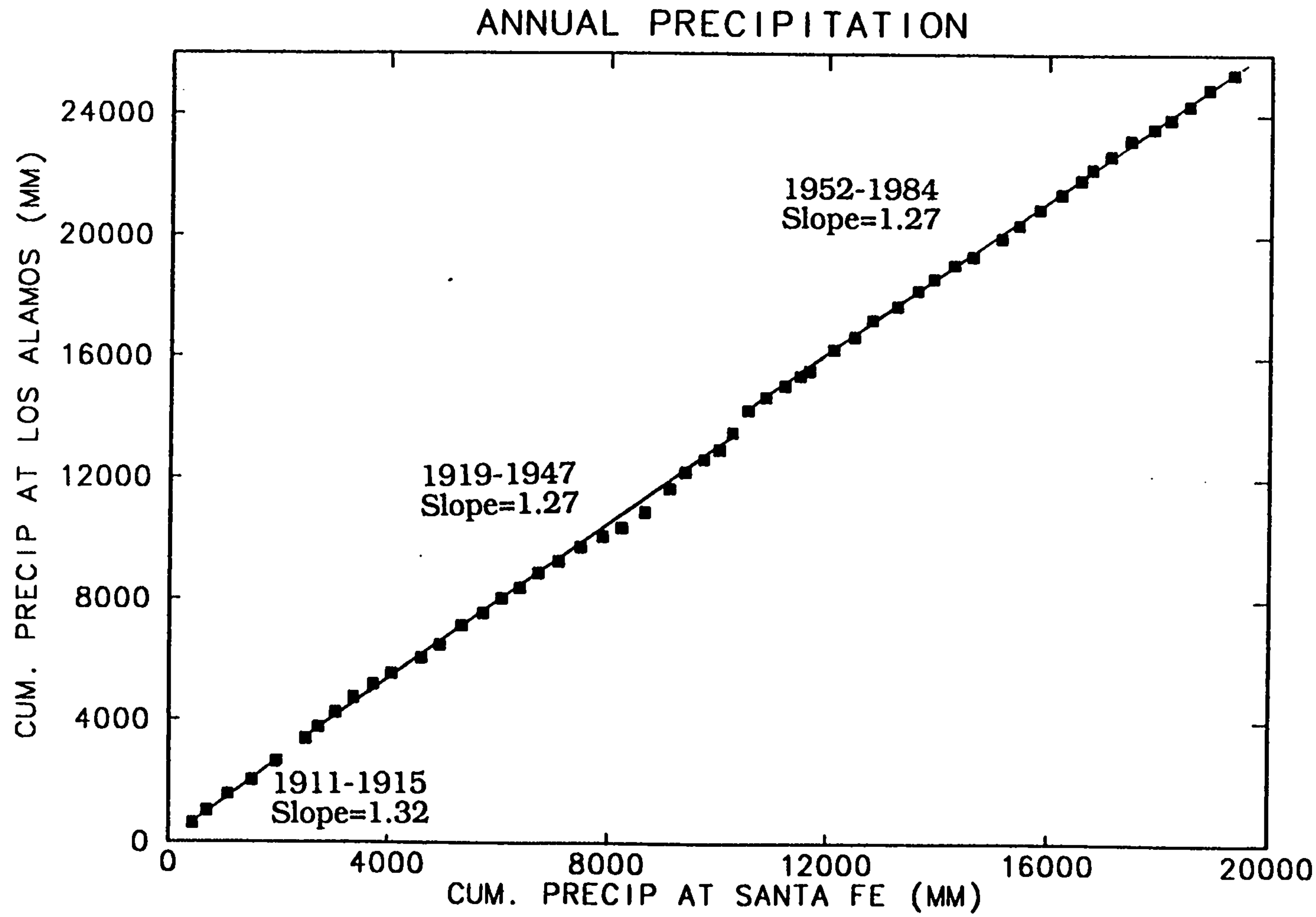



Fig 2.1 Double-Mass Curve.

will be assumed that the change in the gage location has not affected the precipitation record.

Daily rainfall is plotted in Fig 2.2. The maximum daily value recorded was 88.4 mm on October 5, 1911. Annual and monthly precipitation statistics are compiled in Table 2.2. The annual mean and standard deviation are based on the entire record of complete years. The mean annual rainfall, using a record length of 70 years, is 474.0 mm, with a standard deviation of 117.4 mm. The maximum annual precipitation was 770.6 mm in 1941, the minimum was 172.7 mm in 1956. The wettest mean month is August, with 92.0 mm, and the driest mean month is February, with 20.6 mm. The largest monthly rainfall occurred in 1952, when 281.4 mm of rain was measured during August.

*Rainfall Monitoring in Potrillo Canyon Watershed*

Los Alamos National Laboratory maintains a number of weather stations around the Laboratory, but there are none in the Potrillo Canyon watershed. The closest collection station is located on the mesa top of Mesita del Buey, 1.2 km north of the watershed boundary, and has been operating since 1980. It is common in the summertime for rain clouds to form over the Sierra de Los Valles. The clouds drop rain as they move east and southeast over the Pajarito Plateau, the amount of precipitation decreases in the eastward direction. Because the watershed trends northwest-southeast, similar to the Los Alamos area precipitation gradient, it is difficult to make inferences whether individual storms measured at the Laboratory's main station also produced rainfall at Potrillo Canyon, or predict which portion or all

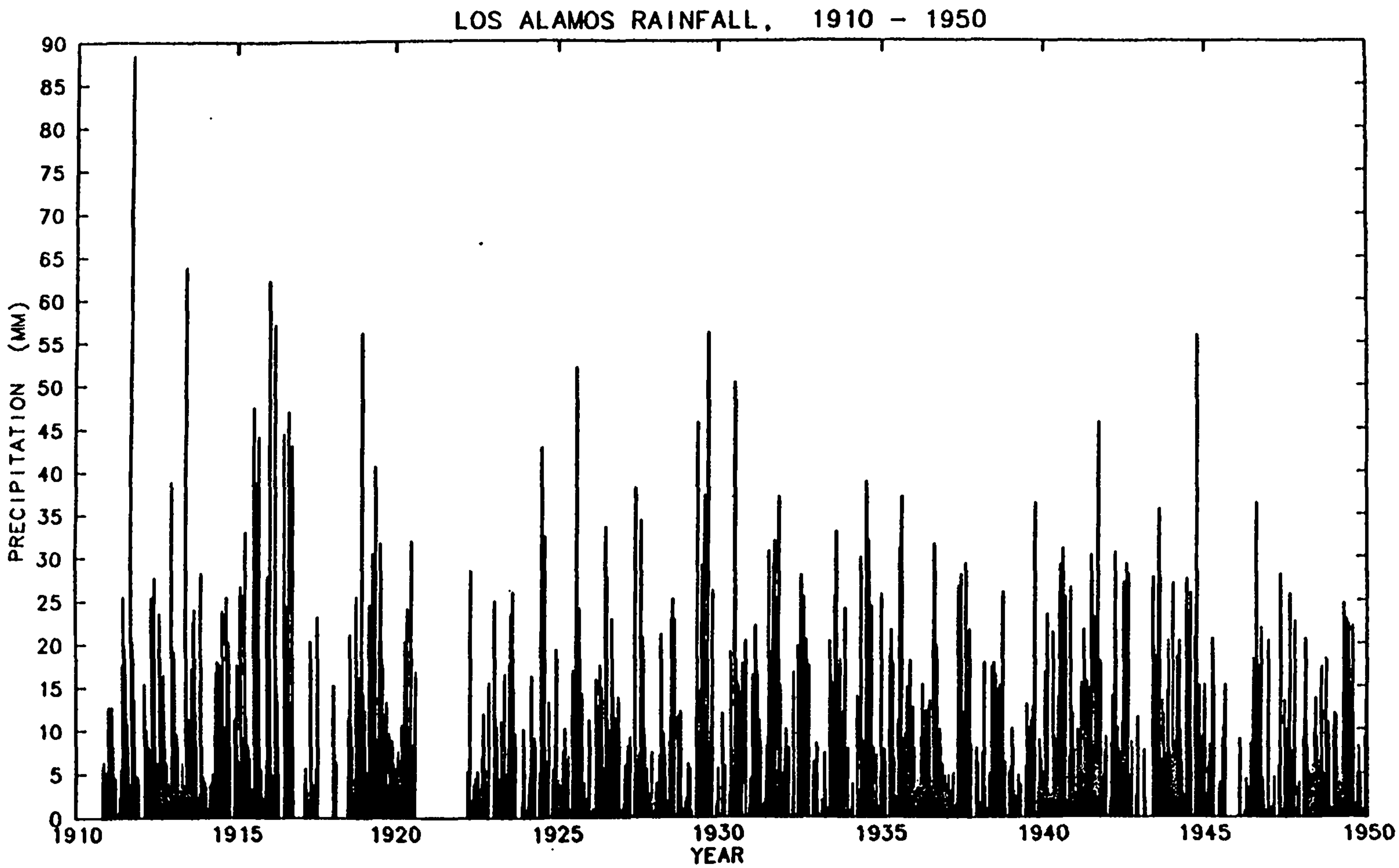



Fig 2.2 Los Alamos Rainfall 1910-1950.

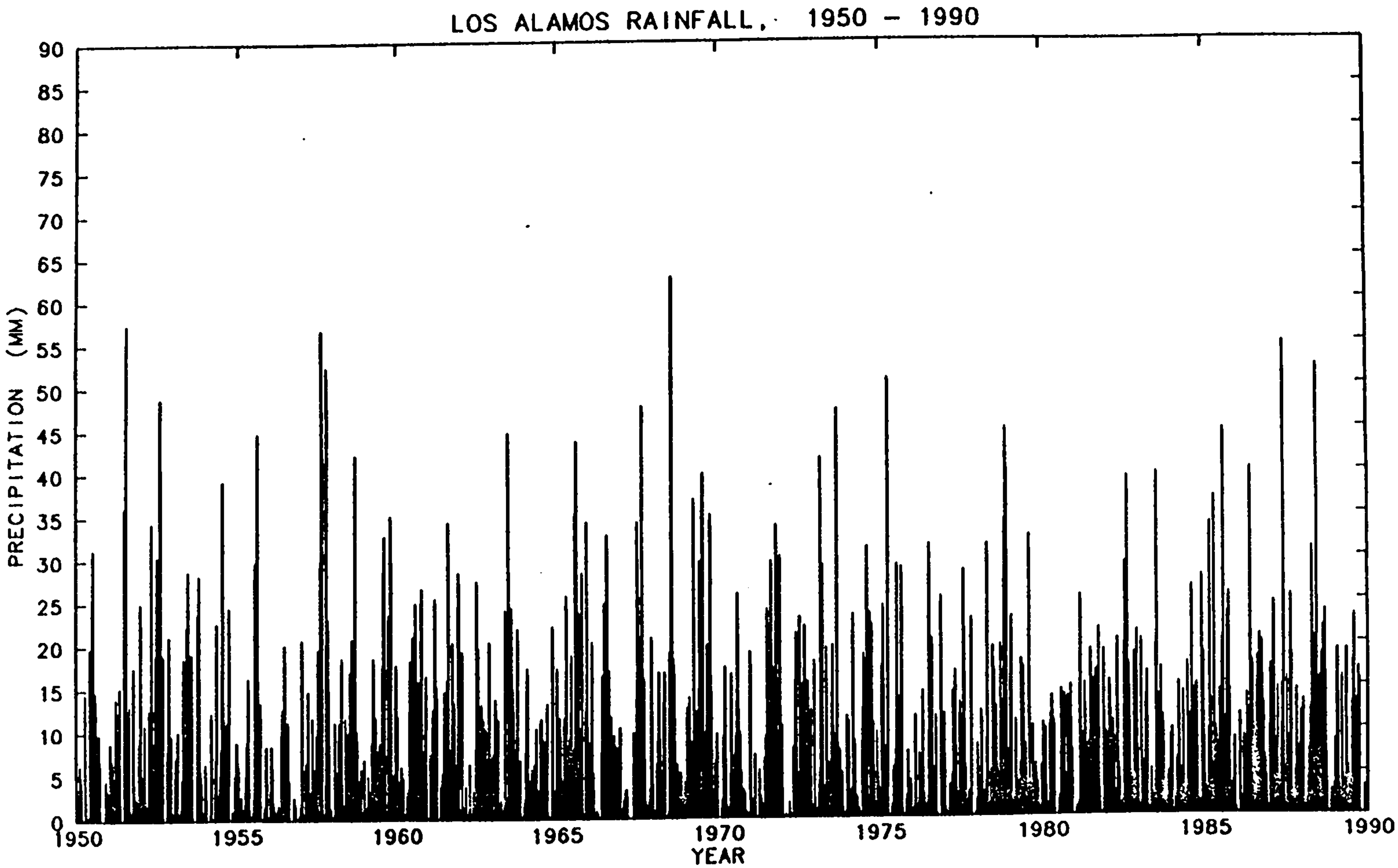



Fig 2.2 (con't). Los Alamos Rainfall 1950-1990.

TABLE 2.2
ANNUAL AND MONTHLY PRECIPITATION STATISTICS (MM)
FOR LOS ALAMOS

| | Mean | Standard Deviation | Number of Years | Maximum (Year Occurred) | Minimum (Year Occurred) |
|---|---|---|---|---|---|
| Jan | 21.84 | 23.62 | 76 | 171.45 ('16) | 0.00 ('12,'22,'28 '42,'46) |
| Feb | 20.57 | 25.15 | 77 | 198.12 ('51) | 0.00 ('22,'43,'54) |
| Mar | 26.67 | 21.34 | 77 | 104.39 ('73) | 0.00 ('22,'34,'46) |
| Apr | 26.67 | 25.15 | 76 | 117.86 ('15) | 0.00 ('25,'29, '30,'67) |
| May | 33.53 | 25.15 | 76 | 113.54 ('28) | 0.00 ('45) |
| Jun | 35.81 | 33.78 | 77 | 143.26 ('86) | 0.00 ('16,'29, '51,'80) |
| Jul | 81.53 | 41.66 | 78 | 201.42 ('19) | 8.89 ('80) |
| Aug | 91.95 | 46.74 | 77 | 281.43 ('52) | 12.95 ('22) |
| Sep | 50.55 | 30.99 | 75 | 147.07 ('41) | 0.00 ('53,'56) |
| Oct | 39.37 | 36.07 | 74 | 174.75 ('57) | 0.00 ('52) |
| Nov | 20.83 | 24.64 | 74 | 167.64 ('78) | 0.00 ('14,'32,'37 '42,'50,'56) |
| Dec | 23.62 | 21.59 | 74 | 94.49 ('18) | 0.00 ('30) |
| Annual | 473.96 | 117.35 | 70 | 770.64 ('41) | 1722.72 ('56) |

of the watershed received rainfall based on the Mesita del Buey measurements. Rainfall is often extremely localized.

There are cooperative observer measurements of rainfall and snowfall in the watershed. Measurements have been made one time or another at I-J site, Eenie site, and Meenie site, all which are located on mesa tops. They consist of daily totals. No measurements have been taken on weekends or holidays, and there have been periods of months where no measurements were taken. To obtain hyetographs within the watershed, two tipping bucket raingages were installed in the canyon bottom in the summer of 1989. These were connected to data loggers to provide a continuous record of rainfall. One gage is located near the I-J cumulative sampler station and the other near the Lower Slobovia cumulative sampler, Fig 1.3.

*Occurrence of Runoff by Cumulative Runoff Samplers*

Beginning in 1984, 5 cumulative runoff samplers were installed in Potrillo Canyon watershed, and a sixth installed in a small side canyon to Mortandad Canyon to provide background data. A cumulative runoff sampler is a buried bottle in the stream channel with a tube emanating from the neck pointed upstream to collect streamflow. The bottle is anchored to a particular spot through attachment to a heavy angle-iron set into the channel bed. After a runoff event, the bottle is removed and replaced. This method does not require an operator to be present, is inexpensive, and usually robust for collection in locations with intermittent streamflow.

The five collection stations were located according to two criteria. The first criterion was that the location be downstream from a firing site, and the second criterion was that the station be in a channel suitable for emplacement, collection, and sampler stability. The locations are shown in Fig 1.3. The locations of the five collection stations have remained fixed during these 7 years, with the exception of the I-J station. The I-J station was located in a reentrant canyon below I-J firing site from 1984 until mid-1987, when it was moved into the main channel.

The number of runoff events in any given year was found to be variable; from 1984 through 1989 the number of events has ranged annually from a high of 11 in 1986 to a low of 3 events in 1987. In discussing streamflow characteristics through the entire watershed length, only years 1988 through 1990 will be considered, due to the spatially discontinuous record at I-J station.

During 1988 there were 9 runoff events, beginning in July. The majority of the streamflow was concentrated in the upper portion of the watershed. All of the events included runoff at one or all of E-F, I-J, and Eenie sites. Only 2 of the 9 events included runoff at all 5 stations.

There were 8 runoff events in 1989. Seven of the 8 events included runoff at one or all of E-F, I-J, and Eenie sites. Only 1 event included runoff at all 5 stations. One event produced runoff only at State Road 4. Two events produced runoff in the upper portion of the watershed (E-F, I-J, or Eenie) and at State Road 4, but not the middle of the watershed at Lower Slobovia. Two events produced runoff down through the Lower Slobovia station, but not the lower portion of the watershed at State Road 4.

Initial examination of these runoff patterns promoted the idea that there are occasional occurrences during the summer runoff season when rainfall events create sufficient streamflow to traverse the watershed from the top to the outlet at State Road 4. Data from the crest-stage recorders discussed in the following section revealed that there has been no flow through the channel reach in the vicinity of the Lower Slobovia bunker during the study period 1988-1990. The area downstream of Lower Slobovia can at times cause sufficient runoff to produce flow at State Road 4, while the runoff upstream of Lower Slobovia infiltrates into the canyon alluvium at the discharge sink near Lower Slobovia. Cumulative samplers were found to be efficient water quality collection devices which operated successfully without supervision; however, in this watershed, inferences made about streamflow in other portions of the watershed based on data from the cumulative samplers were found to be misleading. Cumulative samplers reflect flow in the vicinity of the sampler but cannot be extrapolated to inferences of continuous flow between samplers.

*Crest Stage Monitoring, Hyetographs and Hydrographs*

Crest stage recorders were installed at the beginning of the summer of 1988 at 5 locations throughout the watershed. Four of the 5 locations coincide with the cumulative samplers, at the E-F site, I-J site, Skunk Works site and State Road 4 locations. The other crest stage recorder was installed downstream from the discharge sink, where the channel had reestablished. The purpose of the crest stage recorders was to determine the peak runoff discharge in locations along the channel in the watershed. Crest stage recorders consisted of aluminum standpipes 0.9 to 1.3 m in height, perforated along the bottom 0.3 m. These were sunk into the channel bed with about half of the length protruded above the bed, located in the center of the active channel. Crushed cork was placed inside. The holes in the pipe allow for the water to statically rise inside of the pipe to the same elevation as the flowing water. A high water mark of crushed cork delineates the maximum static height of water in the channel. After an event, measurements were collected for each recorder, and the cork inside washed down to the bottom.

All crest stage recorders indicated that there was flow at one time or another during 1988, 1989 and 1990 at all locations; however, the crest stage recorders were not maintained during the winters, so that the indicated flow occurred during the spring, summer, and fall runoff seasons. The crest stage recorder downstream from the flow sink recorded flow for the first time since installation in the late summer of 1990. Interestingly, the source of the flow did not come through the main channel or through the discharge sink, but from a side tributary headcut draining a small sub-area on the west side of the stream from a new construction site. The lack of rise in the cork in this recorder during 1988-1990 provided positive evidence that there was no flow through the flow sink during the that period.

Peak discharges were calculated from stage data using the Manning Equation, which in SI units is:

$$Q = (1.0/n)\ A\ R^{2/3}\ S^{1/2}$$

where $Q$ = discharge in $m^3s^{-1}$

$n$ = Manning roughness coefficient

$R$ = hydraulic radius in m

$A$ = cross-sectional area in $m^2$

$S$ = channel slope, dimensionless.

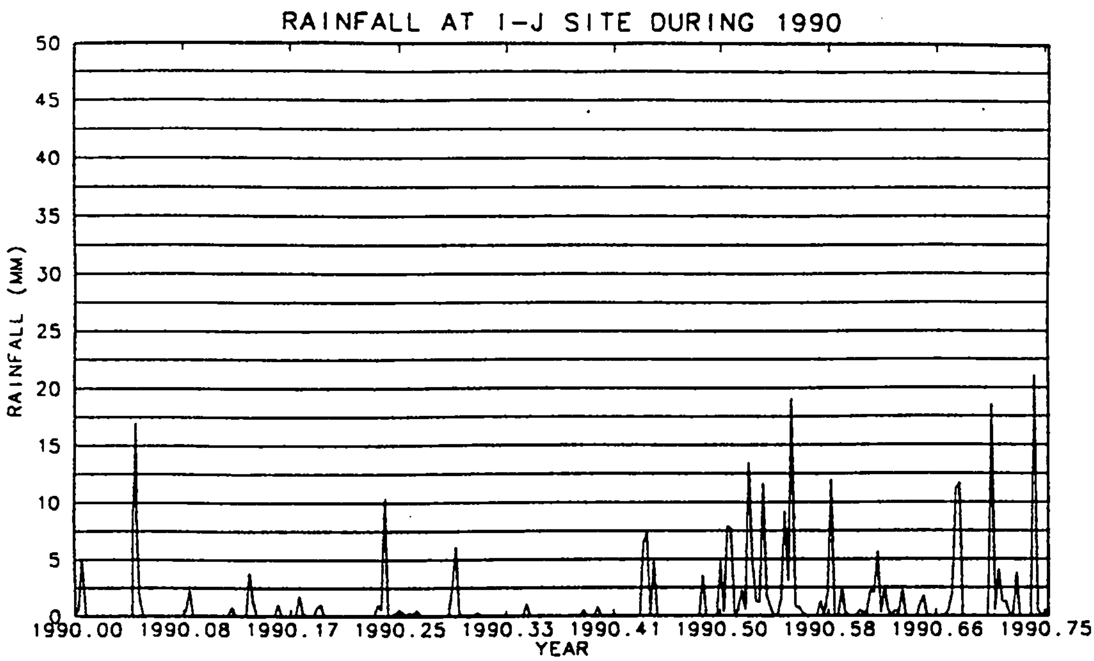
The area and wetted perimeter were derived by measuring the channel cross section at the selected location and computing the channel area and wetted perimeter as a function of water depth. The slope was obtained with a transit. The Manning n was selected through comparison with Manning n values derived for channels in Barnes (1967).

Peak discharges from data collected at the I-J and Skunk Works crest stage recorders in 1988 varied from a low of 0.002 $m^3/s$ to a high of 0.87 $m^3/s$. In every instance where flow was recorded at both locations during 1988, the Skunk Works discharge was greater than at I-J.

In the summer of 1989, the crest stage recorders at the I-J and Skunk Works locations were modified by attaching access ports containing Druck PDCR 903/TI series pressure transducers to measure the static rise. These transducers replaced the manual servicing of the crushed cork and were found to provide a history of the flow rise and fall, unlike the cork. A tipping bucket rain gage was installed at both locations. Both the rain gages and the pressure transducers were linked to a Campbell Scientific CR10 data logger, which enabled continuous recording of rainfall hyetographs and flow stage hydrographs.

Daily rainfall amounts for the I-J and Skunk Works Sites are shown in Fig 2.3. Each division is one month. Data for the months of January through March are from the TA-59 raingage, located 4.3 km northwest of the I-J gage. These data were used because the tipping bucket raingages in Potrillo Canyon are not equipped with heaters and therefore cannot accurately measure snowfall or water equivalent of snowfall. The year 1990 began fairly typically, with the majority of precipitation falling during the summer months of July and August, and in September.

During 1990, the Skunk Works site received slightly more than 17 mm of rain than the I-J site during the months April through September; the excess occurred during April and September. The I-J site received 17.5 mm more rain than Skunk



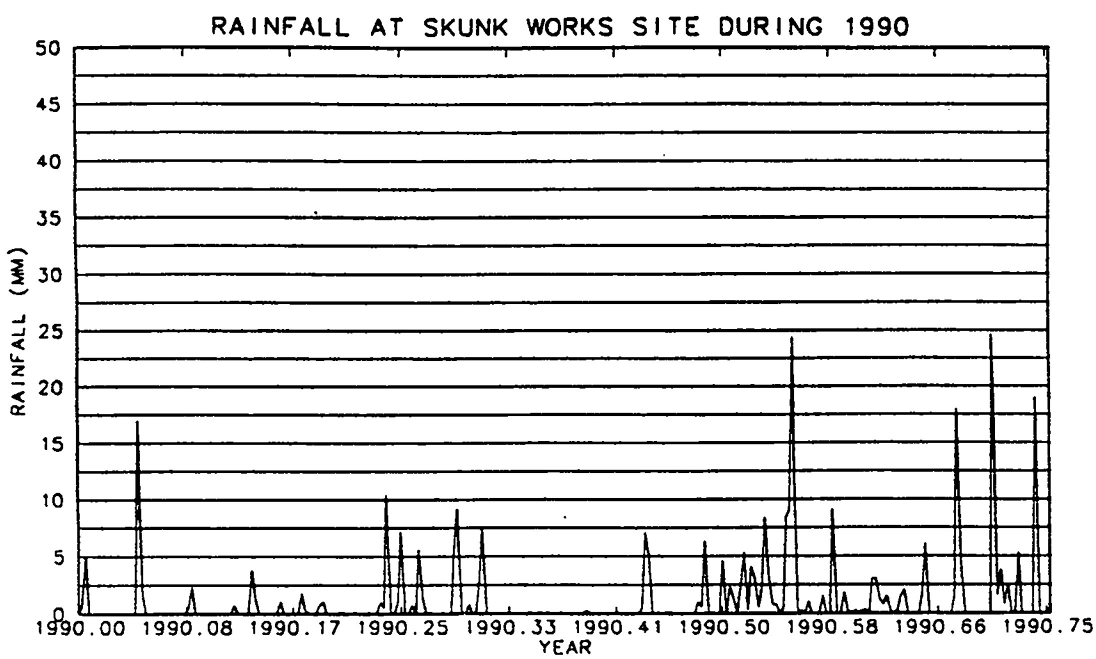




Fig 2.3. Rainfall at I-J and Skunk Works gages, January through September 1990.

Works during May, June, July, and August. This follows the expected trend of summer rainfall patterns, with greater amounts falling closer to the Sierra de Los Valles, and diminishing in the distal direction. Note that this pattern is distinguishable even though the two gages are separated by a distance of only 3.05 km.

Daily rainfall amounts were generally small, with totals less than 25 mm. Five rainfall events were examined in greater detail because each produced runoff hydrographs at I-J site, and in two instances, at the Skunk Works site. These events occurred on July 22, August 2, September 6, September 7, and September 28th. Hydrographs and hyetographs for these events are presented in Fig 2.4 through 2.8. The total rainfall amounts, and duration of events are presented in Table 2.3. All these events are of relatively short duration. The longest duration rain measured 20.3 mm in slightly less than 5 hours at I-J site. The shortest event lasted 57 minutes at Skunk Works, where 24.4 mm fell. At times, rainfall intensity was great; as much as 1.5 mm was measured in a 1 minute period. In general, these events can be described as fairly short duration and relatively high intensity.

Information on the resulting hydrographs is presented in Table 2.3. The hydrographs can be characterized as sharply peaked, with durations frequently less than an hour, and rise times occurring shortly after the onset of rainfall. At I-J site, the duration of the hydrographs varied from over 15 hours (the longest) to just 19 minutes. At Skunks Works, one hydrograph lasted 83 minutes and the other just short of 4 hours. Hydrographs volumes were calculated using graphical integration techniques.

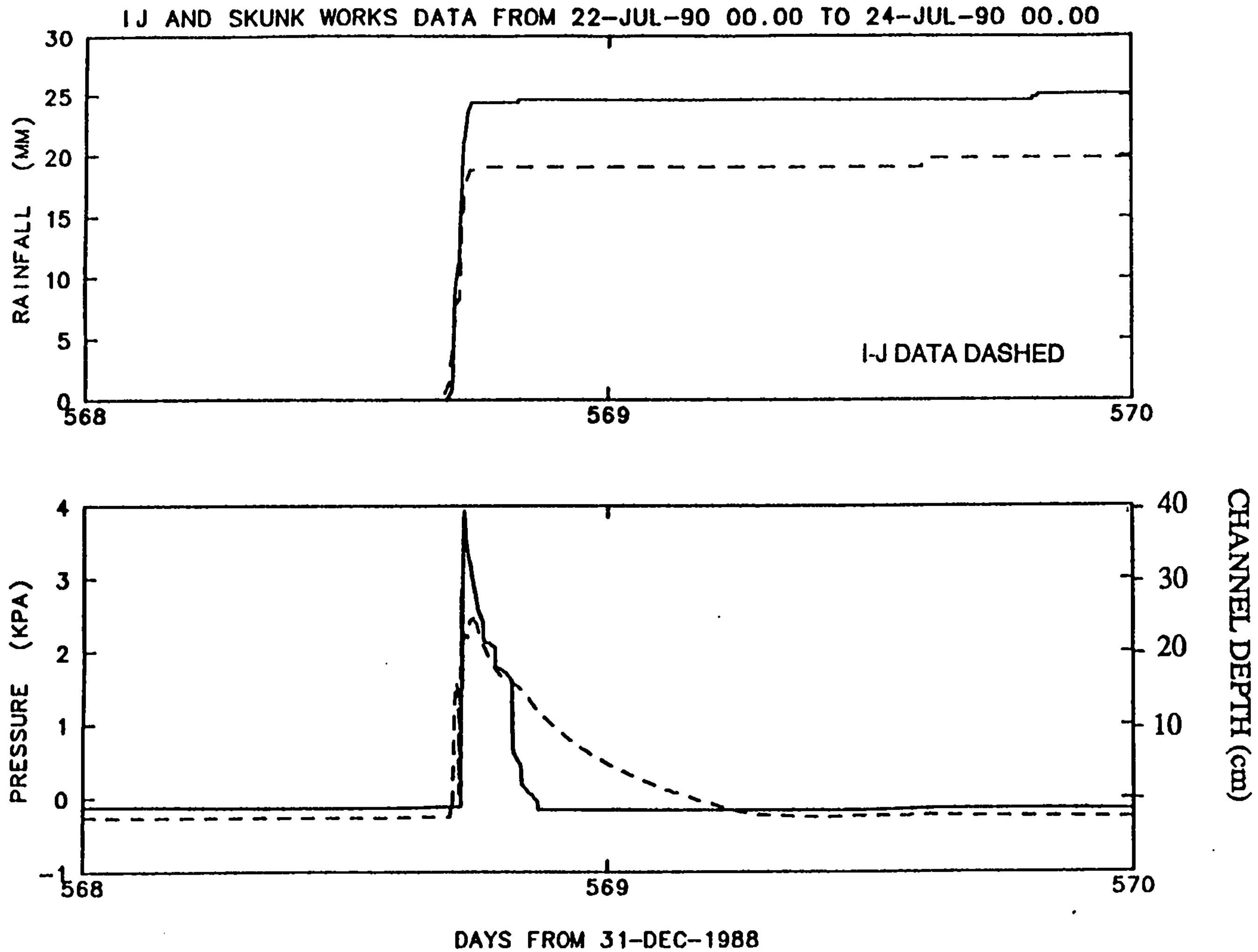



Fig 2.4 July 22, 1990 Hyetographs and Hydrographs.

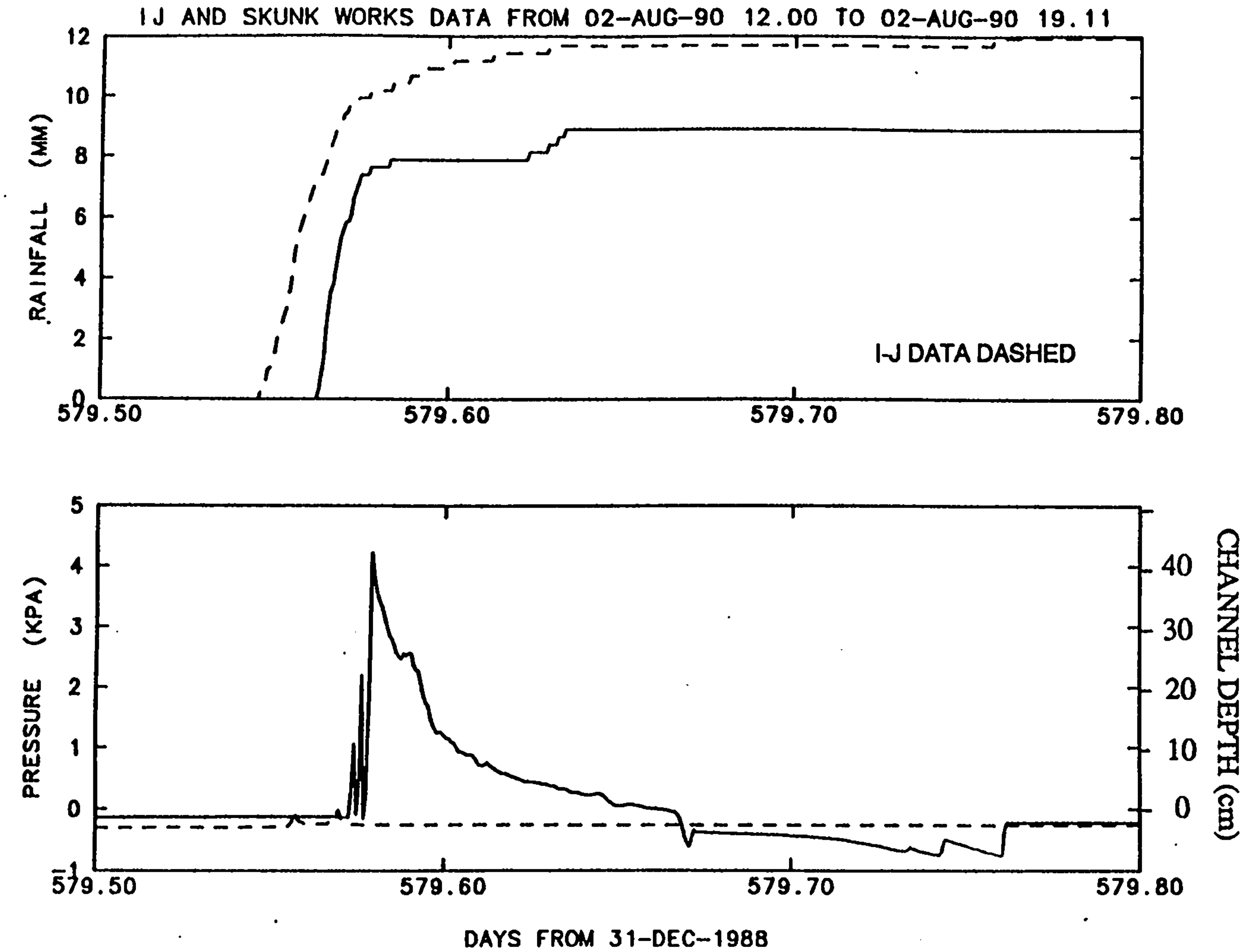



Fig 2.5 August 2, 1990 Hyetographs and Hydrographs.

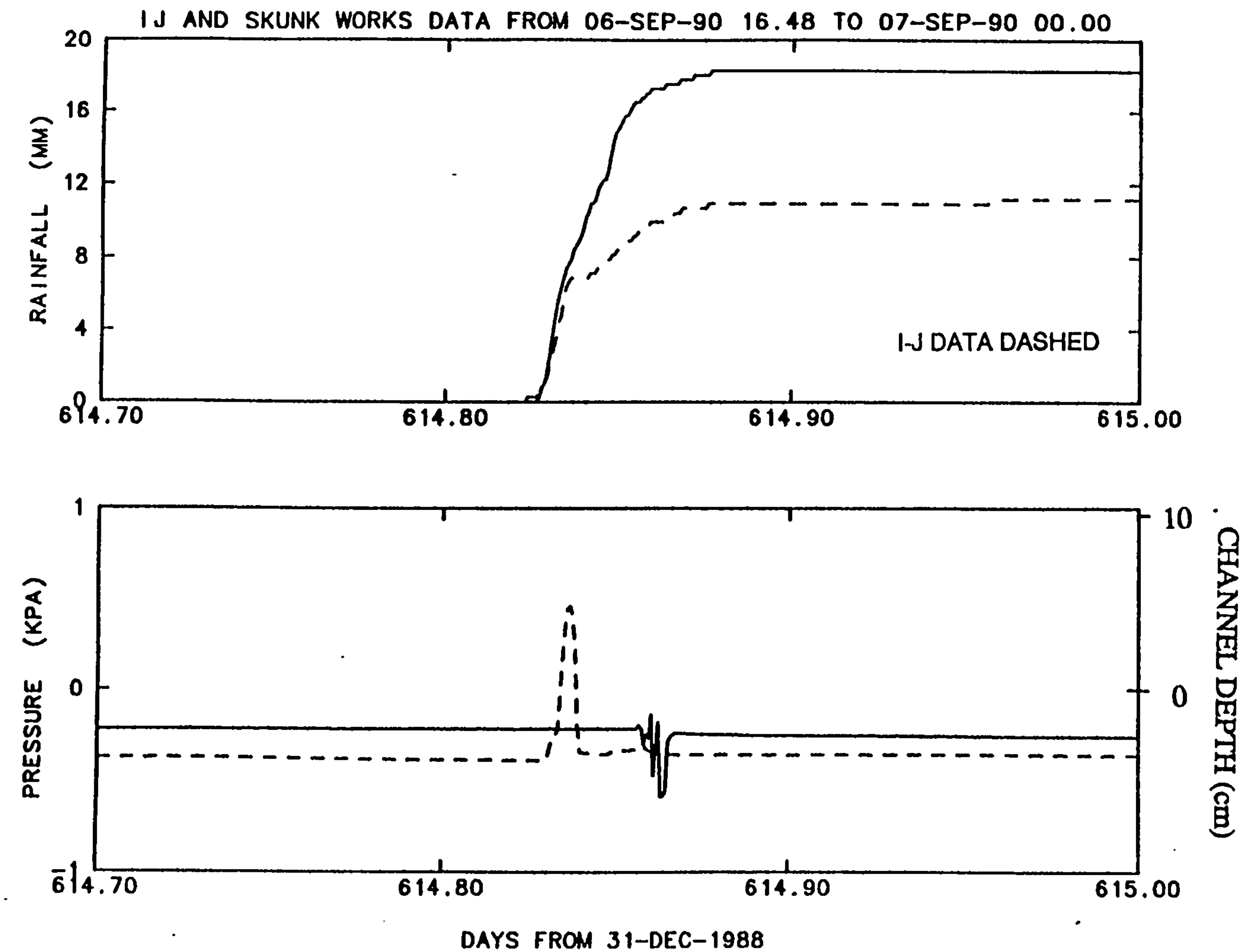



Fig 2.6 September 6, 1990 Hyetographs and Hydrographs.

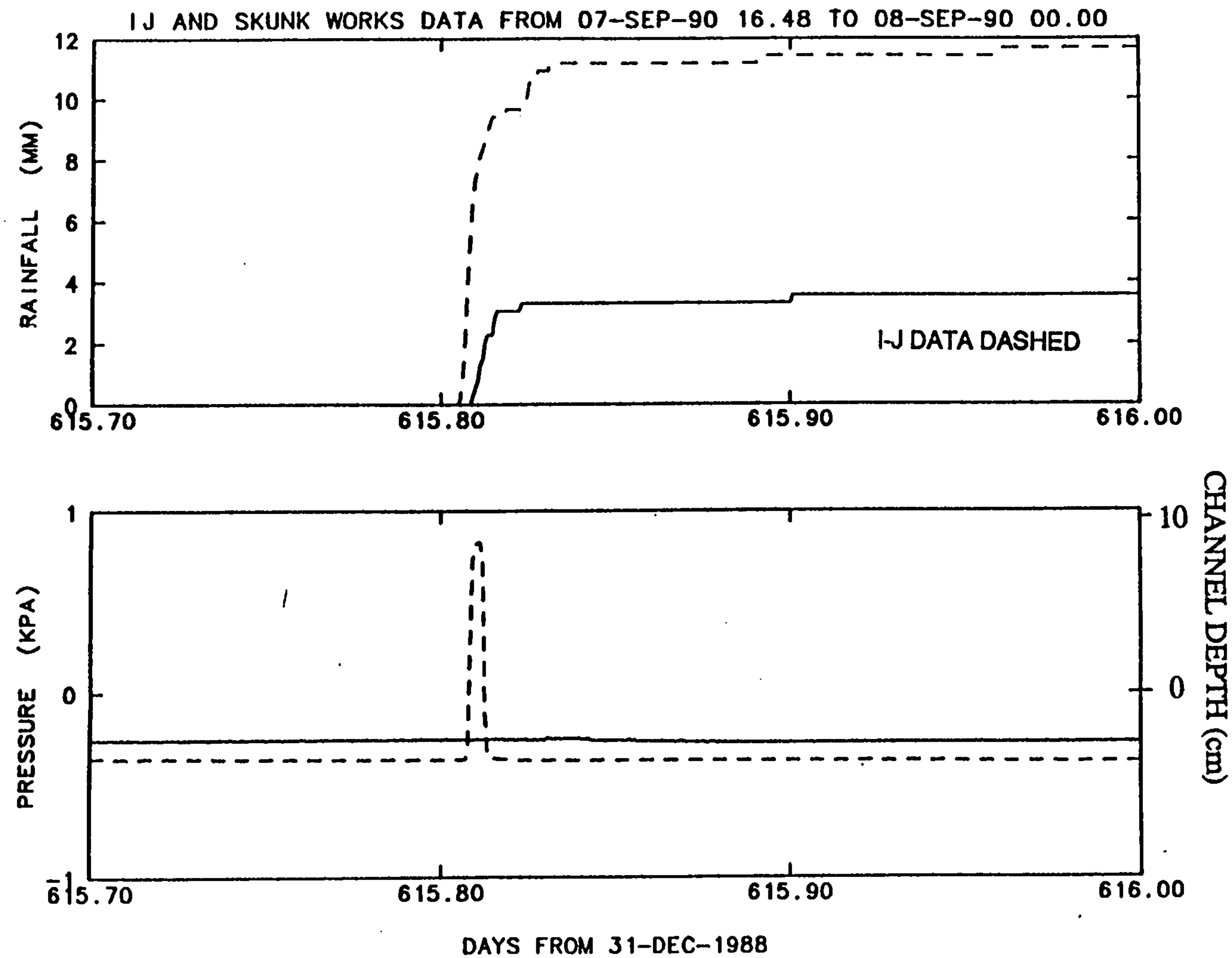



Fig 2.7 September 7, 1990 Hyetographs and Hydrographs.

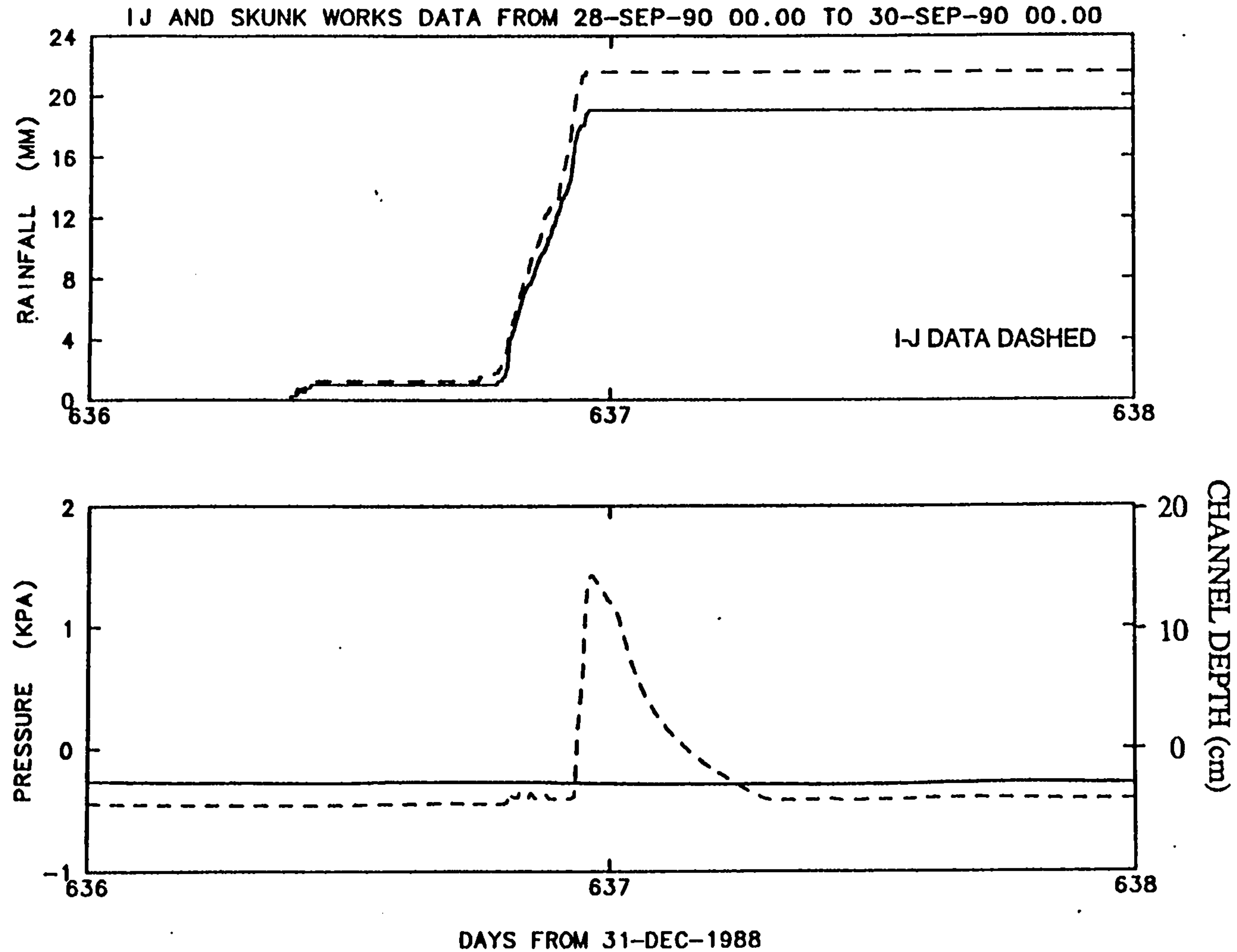



Fig 2.8 September 28, 1990 Hyetographs and Hydrographs.

Table 2.3

1990 Rainfall and Runoff in Potrillo Canyon Watershed

**RAINFALL**

| Date | Amount (mm) | | Duration (min) | |
|---|---|---|---|---|
| | I-J | Skunk Works | I-J | Skunk Works |
| July 22 | 19.05 | 24.38 | 96 | 57 |
| August 2 | 11.68 | 8.89 | 119 | 102 |
| September 6 | 10.67 | 18.29 | 61 | 71 |
| September 7 | 11.18 | 3.30 | 37 | 20 |
| September 28 | 20.32 | 17.78 | 298 | 255 |

**RUNOFF**

| Date | Hydrograph Volume ($m^3$) | | Peak Discharge ($m^3/s$) | | Duration (min) | | Time to Peak (min) | |
|---|---|---|---|---|---|---|---|---|
| | I-J | Skunk Works | I-J | Skunk Works | I-J | Skunk Works | I-J | Skunk Works |
| July 22 | 6689.31 | 3778.86 | 0.85 | 1.33 | 927 | 239 | 66 | 31 |
| August 2 | 0.98 | 1392.32 | 0.002 | 1.63 | 46 | 83 | 21 | 14 |
| September 6 | 15.85 | - | 0.025 | - | 59 | - | 10 | - |
| September 7 | 15.44 | - | 0.062 | - | 19 | - | 7 | - |
| September 28 | 1775.34 | - | 0.30 | - | 496 | - | 61 | - |

The maximum volume measured occurred from the July 22 event at I-J site. Over 6600 $m^3$ (over 1.7 million gallons) passed through the gage. Nearly 3800 $m^3$ (about 1 million gallons) were measured at Skunk Works. The I-J site hydrograph peaked in 66 minutes with a peak flow rate of 0.85 $m^3/s$. The Skunk Works site peaked 26 minutes before the main peak at I-J. Peak flow at Skunk Works from this event was 1.33 $m^3/s$ and occurred after 31 minutes of flow (41 minutes after it began raining there). Consequently it appears that all of the Skunk Works flow up to the peak was from localized runoff and not flow which passed through the I-J gage. Flow at Skunk Works between the time of peak and the end of flow probably has been recorded at I-J, and equalled about 2700 $m^3$ over a 2.8 hour period. The time from I-J's first peak to Skunk Works' first break in slope on the falling limb (labeled "A" and assumed to be the peak from I-J) was about 45 minutes. The distance between the two gages is about 3 km, implying a travel time of 1.1 m/s. The amount of flow past I-J gage after time 20:51 on July 22, 1990, probably infiltrated into the channel between I-J and the Skunk Works gage, because there was no flow recorded at Skunk Works after that time. The volume of that portion of the I-J hydrograph is about 570 $m^3$. Therefore, nearly 60 percent of the flow recorded at the I-J gage appears to have infiltrated or evaporated. Because no flow was measured by the crest stage recorder downstream from the Skunk Works gage, all flow past this gage is assumed to have infiltrated into the discharge sink. Field inspection of the flow path was made after this event in the discharge sink and the terminus was delineated approximately 105 m downstream from the beginning of the sink. There was no evidence of flow out of the sink. This was the first discharge event in the watershed during 1990, even though there had been rainfall previously (it had rained nearly every day of the month up to July 22nd).

A second event which created runoff at both gages occurred on August 2. Rainfall amounts were modest; there was 11.7 mm measured at I-J in about 2 hours, and 8.9 mm measured in a 1.7 hour period at Skunk Works. Very little flow was produced at I-J, as indicated by the small volume and peak discharge (0.98 $m^3$ and 0.002 $m^3/s$, respectively). In contrast, nearly 1400 $m^3$ (over 1/3 million gallons) passed through the Skunk Works gage in an 83 minute period with a peak flow of 1.63 $m^3/s$. This flow is assumed to have been produced between the two gages. Inspection of the downstream crest stage recorder and visual observation within the discharge sink provided evidence that all flow infiltrated into the discharge sink about 150 m distance downstream from the beginning of the discharge sink.

Three other rainfall events created runoff at I-J site, but runoff was not produced at Skunk Works. The September 6 and 7 events created small volumes of runoff at I-J, Table 2.3. The September 6th storm produced 18.3 mm of rainfall at Skunk Works, but apparently the soil had dried out sufficiently so that all rainfall infiltrated the overland and channel segments upstream from Skunk Works. Hence there was no flow past the Skunk Works gage. Likewise, there was no flow at Skunk Works from the September 7th rain event. The September 28th event of 20.3 mm at I-J site produced a runoff volume of 1775 $m^3$ with a peak flow of 0.3 $m^3/s$. There was no measurable flow registered at the Skunk Works gage, although inspection of the channel in the vicinity of the gage afterwards showed that there had been some extremely low flow due to the event. There was some redistribution of heavy metals on the channel floor, but no runoff had collected in the cumulative sampler located about 15 m downstream. Therefore, it appears that all runoff which flowed past the I-J gage infiltrated into the channel before reaching Skunk Works. It also appears that any runoff produced between the I-J and Skunk Works gages infiltrated into the overland and channel portions of the watershed between the two gages.

*Infiltration Studies*

In August 1989, three monitoring wells were installed in the vicinity of the discharge sink to monitor vertical moisture movement using a neutron moisture probe. The three wells were located upstream from (#1), at the upstream head (#2), and near the downstream edge (#3) of the discharge sink, Fig 2.9. All were located in the active channel.

Three 10.2-cm diameter boreholes were drilled to accommodate the 5.1-cm diameter aluminum casings. Well #1 was drilled at the Skunk Works road crossing. The hole was augered to 15.2 m, and 14.3 m of aluminum casing installed. Although the depth is uncertain, changes in drilling pressure indicated that a change in lithology occurred between 8.2 and 9.1 m depth, from alluvium to a weathered tuff. Moisture contents in the cuttings in this hole were low; no excess moisture was observed in the cuttings. The weathered tuff appeared as a silty clay.

Well #2 was drilled down to 18.6 m, and 16.4 m of aluminum casing was installed. Over 2 m of collapse occurred at the bottom of the hole between the time the auger was pulled and the casing installed. From the surface down to 3.0 to 3.6 m alluvium was encountered; weathered tuff was found to the bottom of the hole. The moisture content in the cuttings was dry (10-20 percent by volume) until a depth of 10.7 m. There the cuttings showed saturated conditions down to the bottom of the

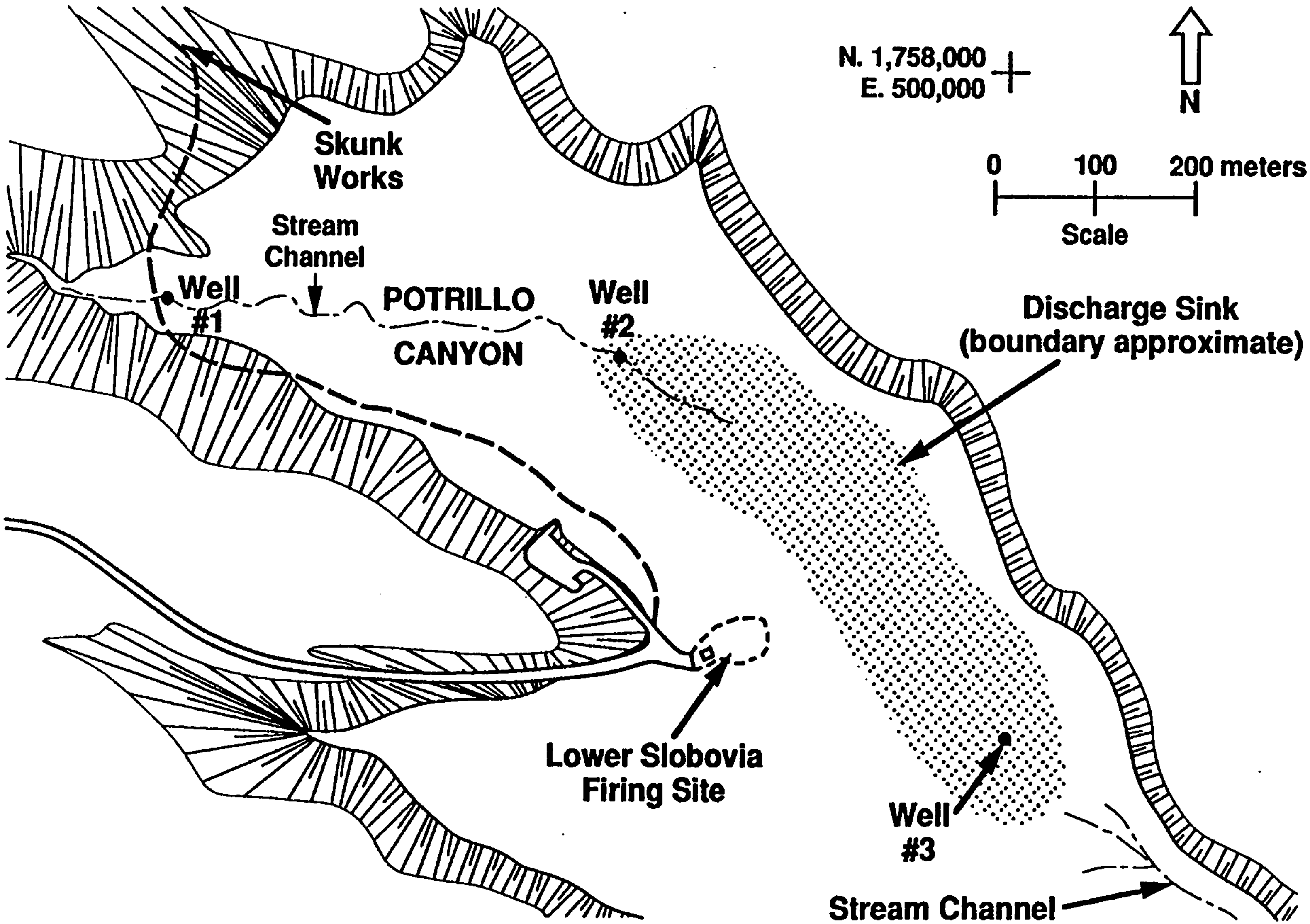



Fig 2.9 Location of Neutron Moisture Access Wells.

hole. The grainsize of the cuttings increased with depth to a silty sand (although still a weathered tuff) at the bottom of the hole.

Well #3 was drilled to a depth of 15.8 m, and 14.6 m of casing was installed. The lithology showed 0 to 4.6 m depth was alluvium, and from 4.6 to 15.8 m weathered Bandelier tuff was encountered. Moisture contents in the hole closely resembled those in Well #1.

In each well, the upper 1.5 to 3 m of casing are cemented up to the ground surface to prevent water from the channel flowing down the casing and producing spurious results. Therefore, to investigate moisture content in the near surface region a shallow well, from 1.5 to 2.7 m in depth, accompanies each deep well.

A Campbell Pacific neutron moisture probe, Model 503DR, was calibrated using the test calibration facility operated by the U.S. Geological Survey at the U.S. Department of Energy's Nevada Test Site. The calibration facility consists of three test tanks 1.2 m diameter and 1.5 m high filled with silica flour and silica sand mixture. Each tank had a unique volumetric moisture content; they were 20.7, 13.8, and 7.7 percent. A linear relationship between the probe's count rate and volumetric moisture content was developed by fitting a first order polynomial equation derived using the method of least squares. To adjust the curve to insitu conditions at Los Alamos, a field measurement was made, and the volumetric moisture content measured on a representative soil sample collected at the site of the probe measurement. The relation between count rate and volumetric moisture content, adjusted for Los Alamos alluvium conditions, was determined to be:

$$Y = 0.007\,X - 45.55$$

where Y = Volumetric moisture content in percent

and X = Probe count rate.

Although there is a linear relationship between the volumetric moisture content and count rate in the moisture range of 7.7 to 20.7 percent (Klenke and others, in press), the relationship is probably not linear below 7.7 percent. Applying the linear relationship to Los Alamos data below 7.7 percent predicted negative moisture contents. The same result was verbally reported by a geologist (Dan Blount, personal communication) from Raytheon Services of Nevada (a contractor to the U.S. Geological Survey in Nevada). Therefore, to obtain moisture contents below 7.7 percent (corresponding to about 7600 counts) separate field calibration studies need to be performed.

Moisture measurements were taken after the wells were installed on August 23, 1989, and again after 2 rain event sequences on September 7, and October 6, 1989. August 23 represents a relatively dry background condition; there was 0.5 mm rain on August 21, and no rain for several days before August 21. Prior to September 7, rainfall measured on September 2 was 13.2 mm, 5.6 mm on September 3, 1.0 mm on September 4, and 10.7 mm on September 5, totalling 30.5 mm. Before the October 6 reading, rain measured on October 2 was a trace, 13.0 mm on October 3, 15.8 mm on October 4, 12.7 mm on October 5, and a trace on October 6, totalling 41.5 mm before the measurement. Runoff was observed at the Skunk Works cumulative sampler on August 14 ( it washed out the cumulative sampler) and after the October 2-6 sequence.

Results from neutron moisture probe logging from Well #1 are presented in Fig 2.10 through 2.12. In all plots, the solid boxes represent moisture measurements from the shallow well and open boxes are the deep well measurements. Neutron probe measurements are made every 0.3 m down to the bottom of the shallow wells and every 0.6 m from the last shallow well measurement to the bottom of the deep well. In the background log on August 23, Fig 2.10, the moisture content was 34 percent and 29 percent at 2.4 m and 2.7 m depths respectively. Moisture content then drops to below 7.7 percent from 2.7 to 11.6 m, increases to 11 percent at 11.6 m, decreases to 8 percent at 12.2 m and increasesto 16 percent at 14.0 m. On September 7, Fig 2.11, the volumetric moisture was 25 percent at 2.4 m, 15 percent at 2.7 m, below 7.7 percent from 2.7 to 10.7 m, increased to 15 percent at 11.3 m, was below 7.7 percent from 11.9 to 13.7 m, and increased to 29 percent at 14.3 m. On October 6, Fig 2.12, volumetric moisture exceeded 7.7 percent at: 2.4 m with 18 percent, 11.3 m with 13 percent, and 14.3 m with 30 percent. In summary, there appeared to be three zones which consistently exhibited moisture content above 7.7 percent; they were at 2.4 m, 11.3 m, and 14.3 m. Initial moisture content in the August 23 reading at the 2.4 m depth was 34 percent. The moisture declined at this depth to 25 percent in September, and to 18 percent in October. Moisture content at the 11.3 m depth remained relatively constant through the three readings, varying between 11 and 15 percent. The percent moisture at the 14.3 m depth increased from 16 percent in August to 30 percent in October. Increased moisture readings at these three depths consistently through the August-October period is probably related to some lithologic change, for example a slight increase in the clay content, along with a downward moisture flux from the surface region. Moisture, in general, declined

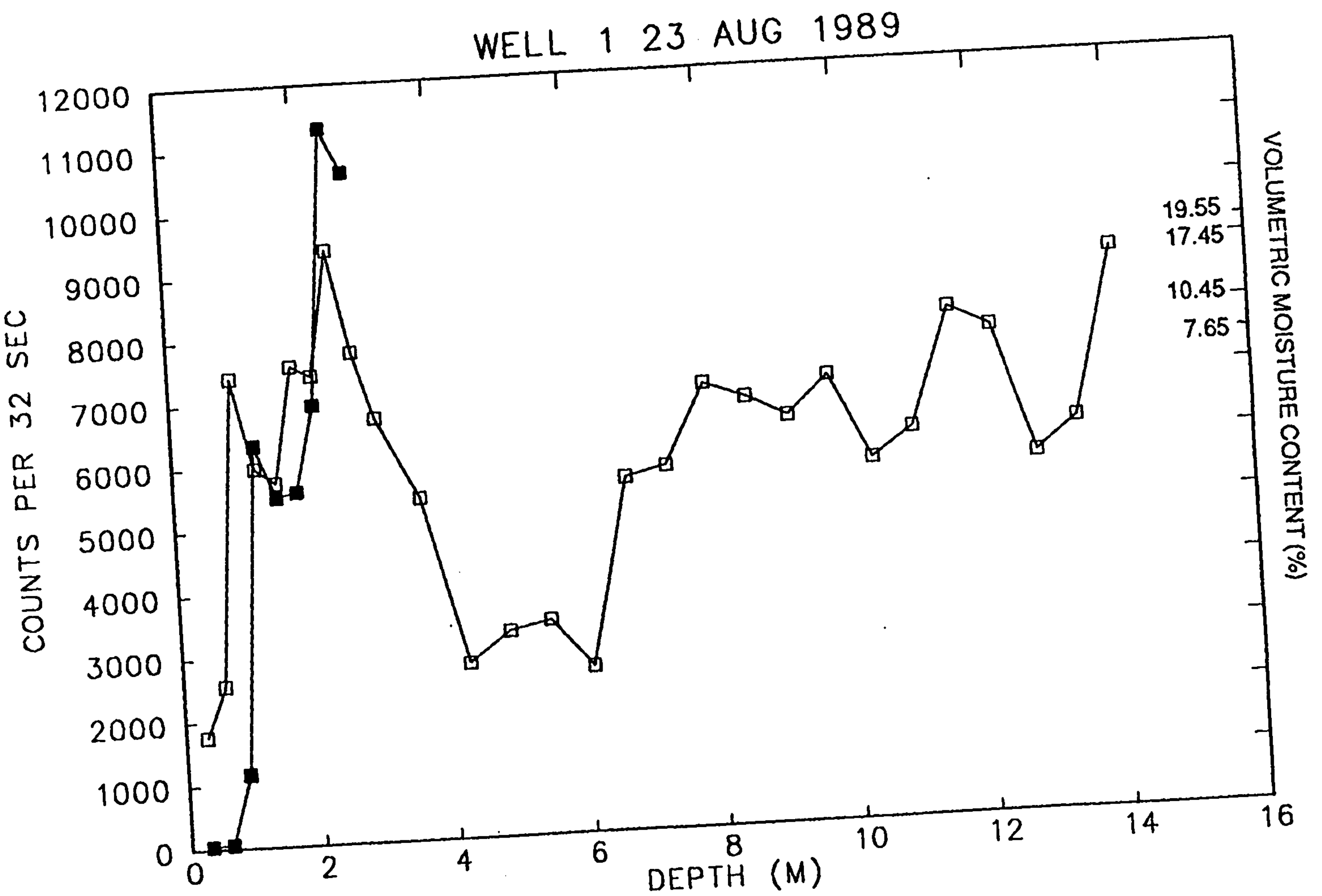



Fig 2.10 Moisture in Well #1 August 23, 1989 (Solid Box-shallow well reading, open box-deep well reading).

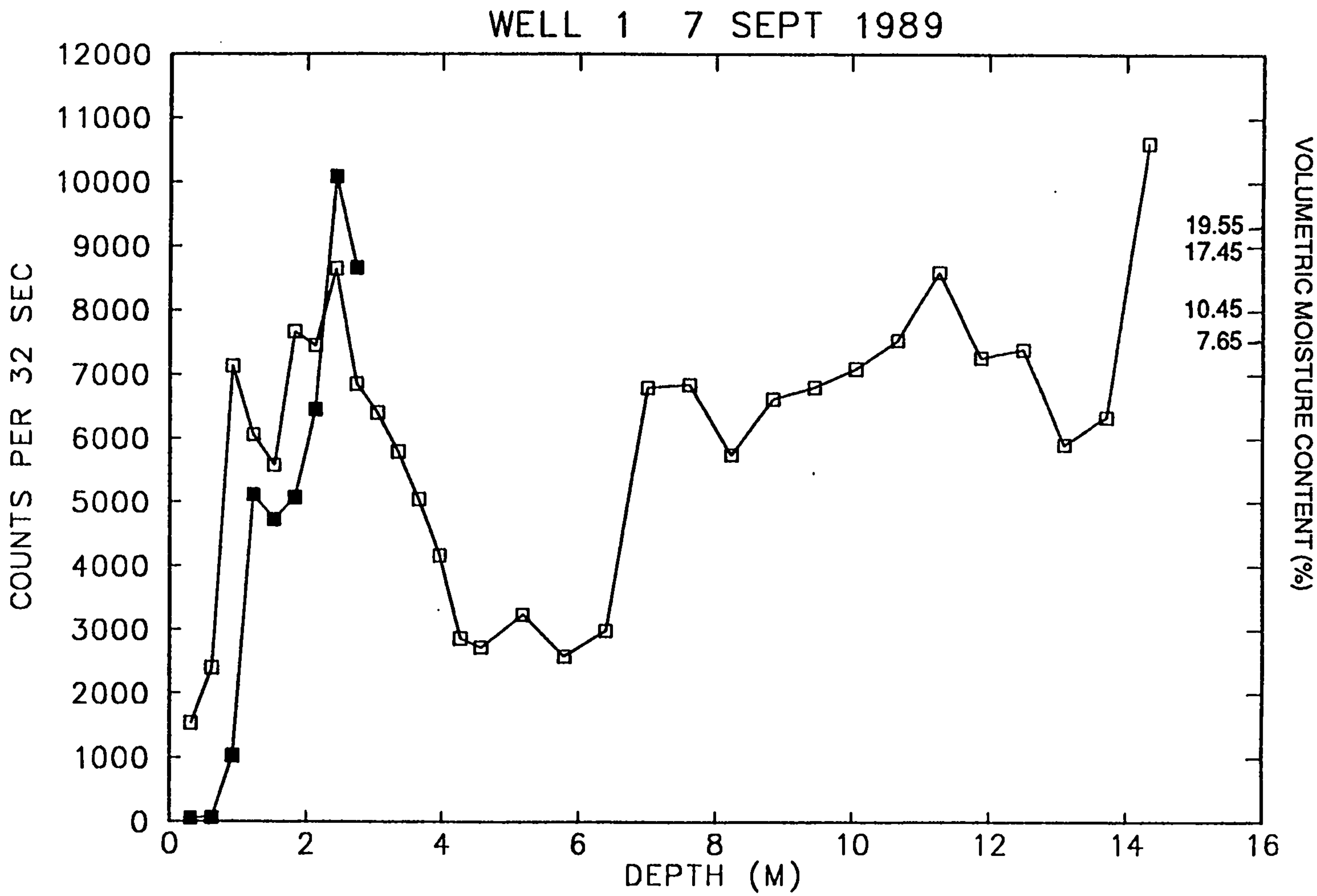



Fig 2.11 Moisture in Well #1 September 7, 1989 (Solid Box-shallow well reading, open box-deep well reading).

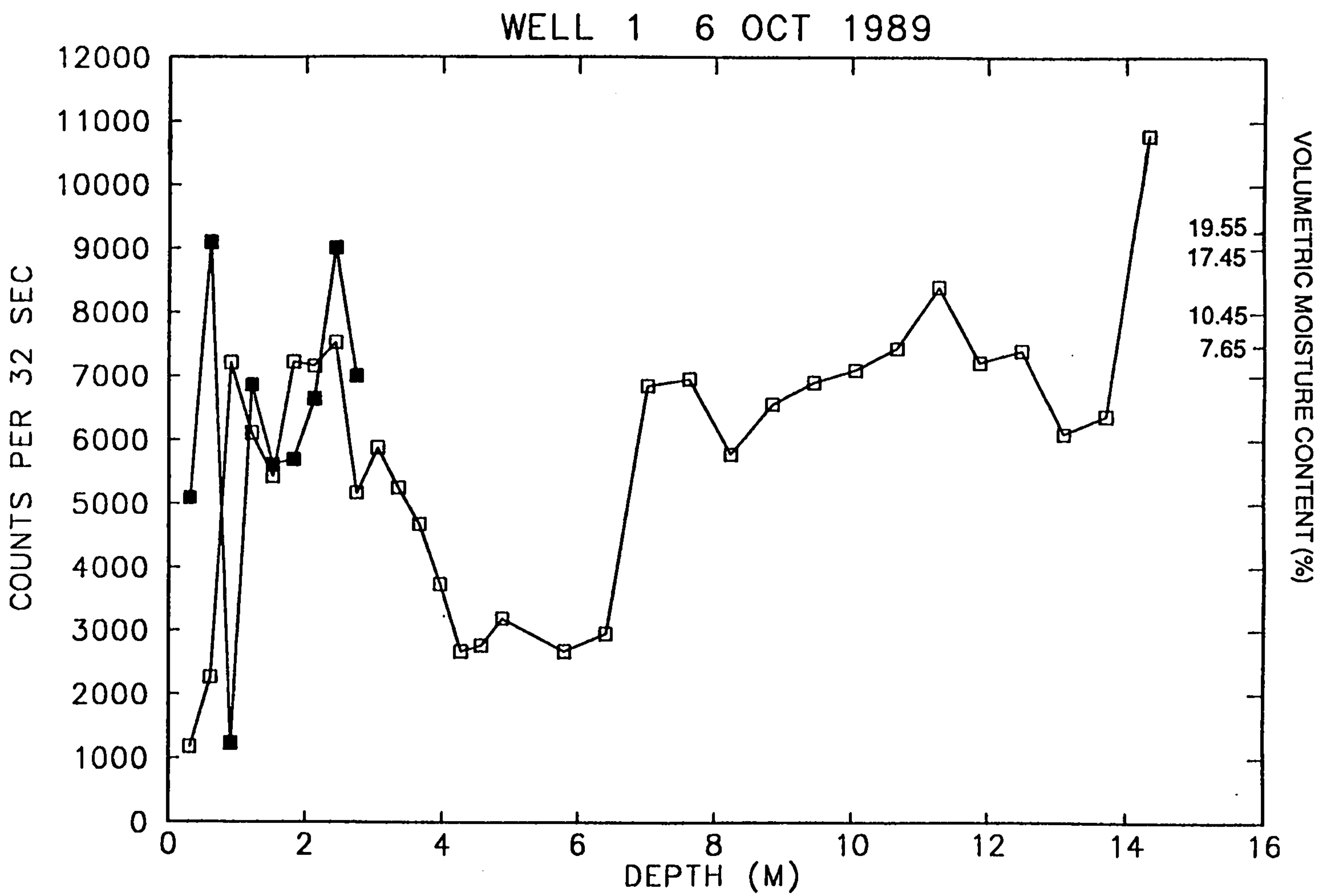



Fig 2.12 Moisture in Well #1 October 6, 1989 (Solid Box-shallow well reading, open box-deep well reading).

in the shallow zone and increased in the deep (14.3 m) level, reflecting a flux of moisture downward.

The moisture content in well #3 is shown in Fig 2.13 through 2.15. All moisture readings in this well were below 7.7 percent except for a reading of 18 percent at the 0.3 m depth level on October 6, Fig 2.15. There is evidence of an increase in moisture content with increasing depth in each log, although the moisture logs for September 7 and October 6 below 0.9 m depth are nearly identical, and the moisture log from August 24 varies only slightly from the later logs. The lack of variation in moisture content in this well indicates that there was little to no moisture flux recorded.

Volumetric moisture contents in Well #2 are shown in Fig 2.16 through 2.18. The moisture variation with depth was similar for all three dates. The moisture at most depths varied from 14 to 20 percent. Increased moisture above this range was consistently observed at three depths: at 0.6 m, at 2.7-3.0 m, and at 14.6-14.9 m. Moisture at 0.6 m varied from 29 percent on August 24 to 26 percent on September 7 and October 6. At the 2.7-3.0 m depth, the moisture varied from 29 to 32 percent on August 24 and declined to about 26 to 29 percent on October 6. At 14.6-14.9 m level, the moisture content remained constant at 31 percent for all three dates.

Well #2 is the most sensitive to moisture fluctuations due to its position in the discharge sink. It lies at the upstream end of the sink, in the path of nearly all runoff events and at the upstream end of the infiltration area. As shown in Table 2.3, significant volumes of water infiltrate in this region, on the order of thousands

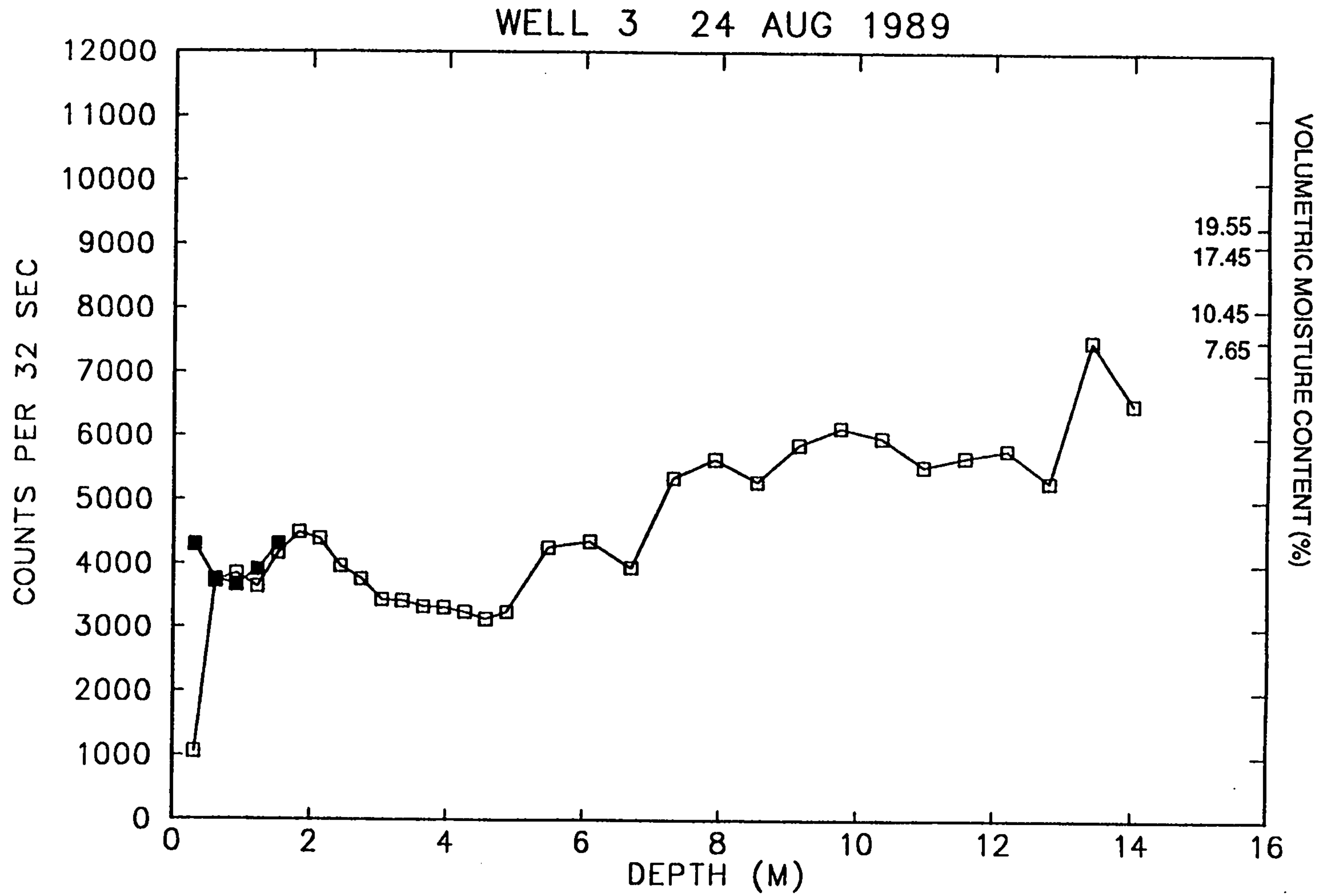



Fig 2.13 Moisture in Well #3 August 23, 1989 (Solid Box-shallow well reading, open box-deep well reading).

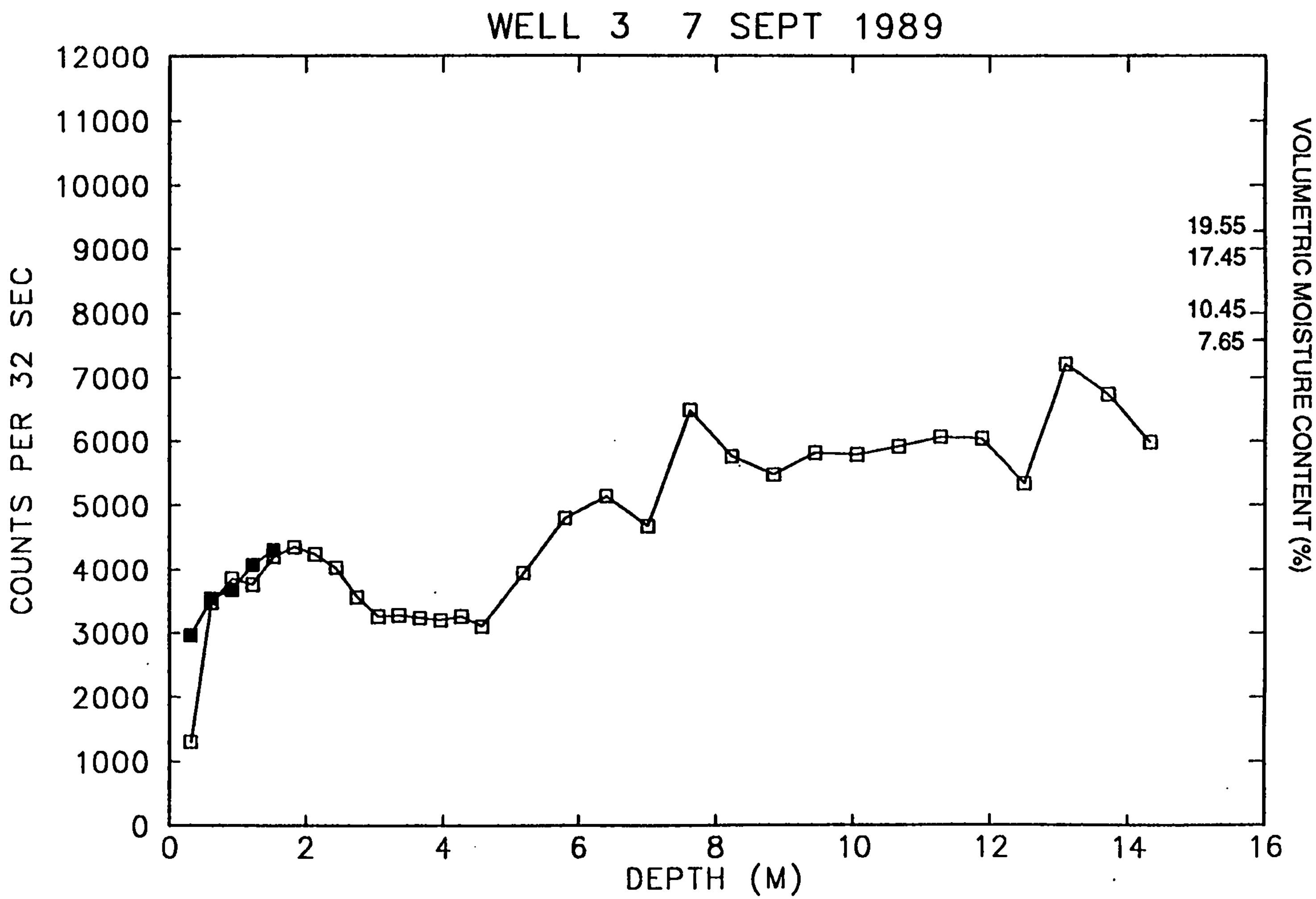



Fig 2.14 Moisture in Well #3 September 7, 1989 (Solid Box-shallow well reading, open box-deep well reading).

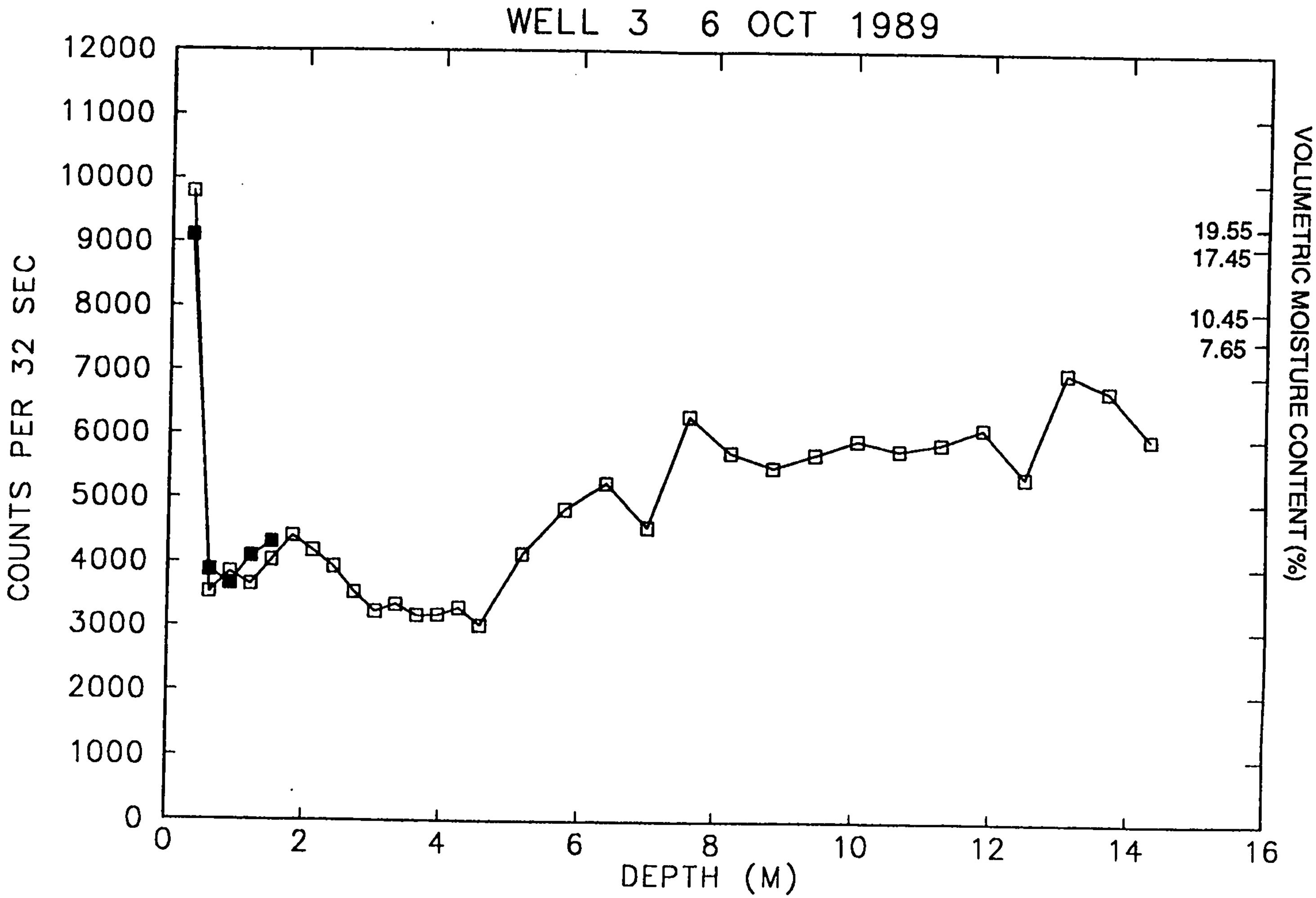



Fig 2.15 Moisture in Well #3 October 6, 1989 (Solid Box-shallow well reading, open box-deep well reading).

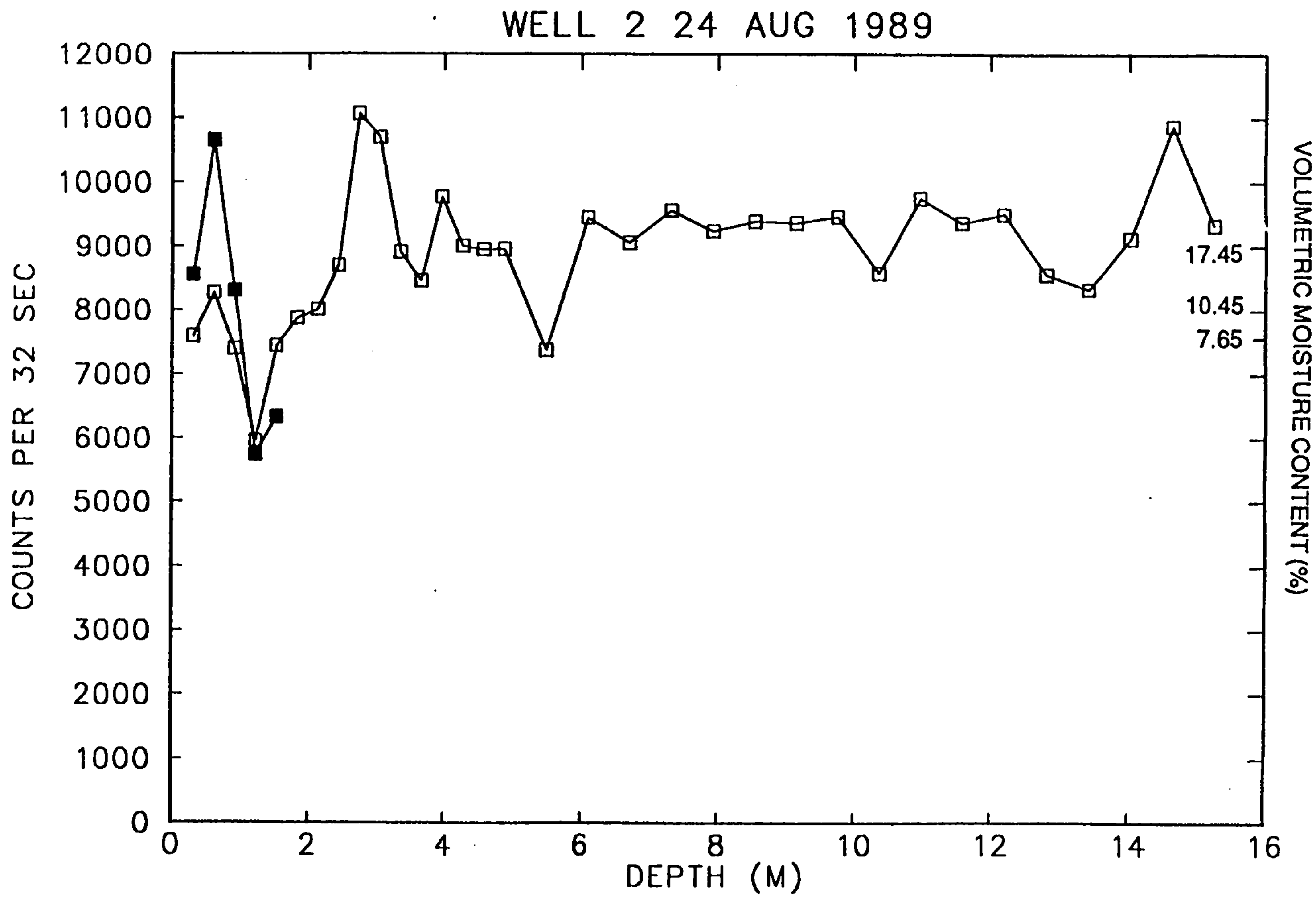



Fig 2.16 Moisture in Well #2 August 24, 1989 (Solid Box-shallow well reading, open box-deep well reading).

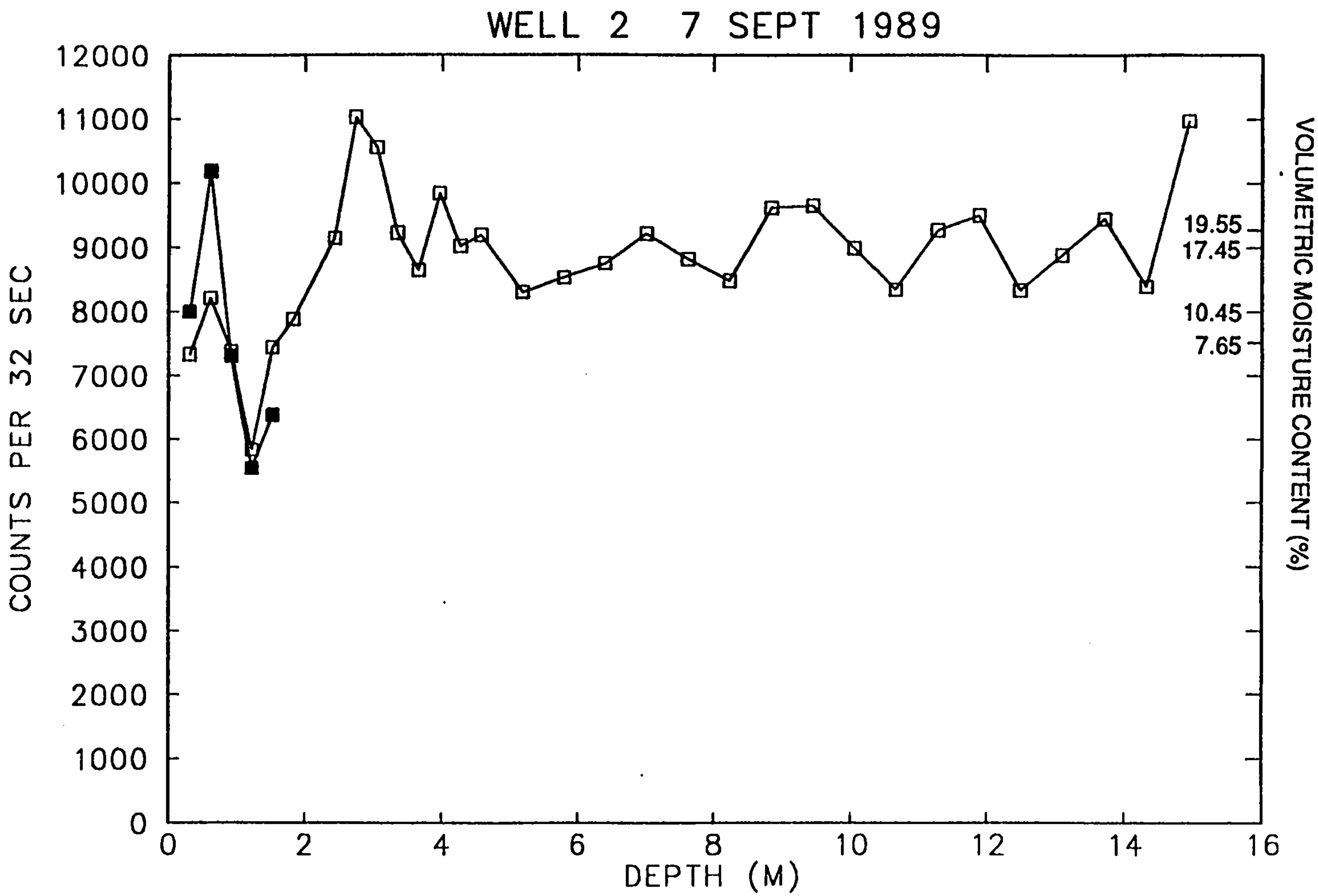



Fig 2.17 Moisture in Well #2 September 7, 1989 (Solid Box-shallow well reading, open box-deep well reading).

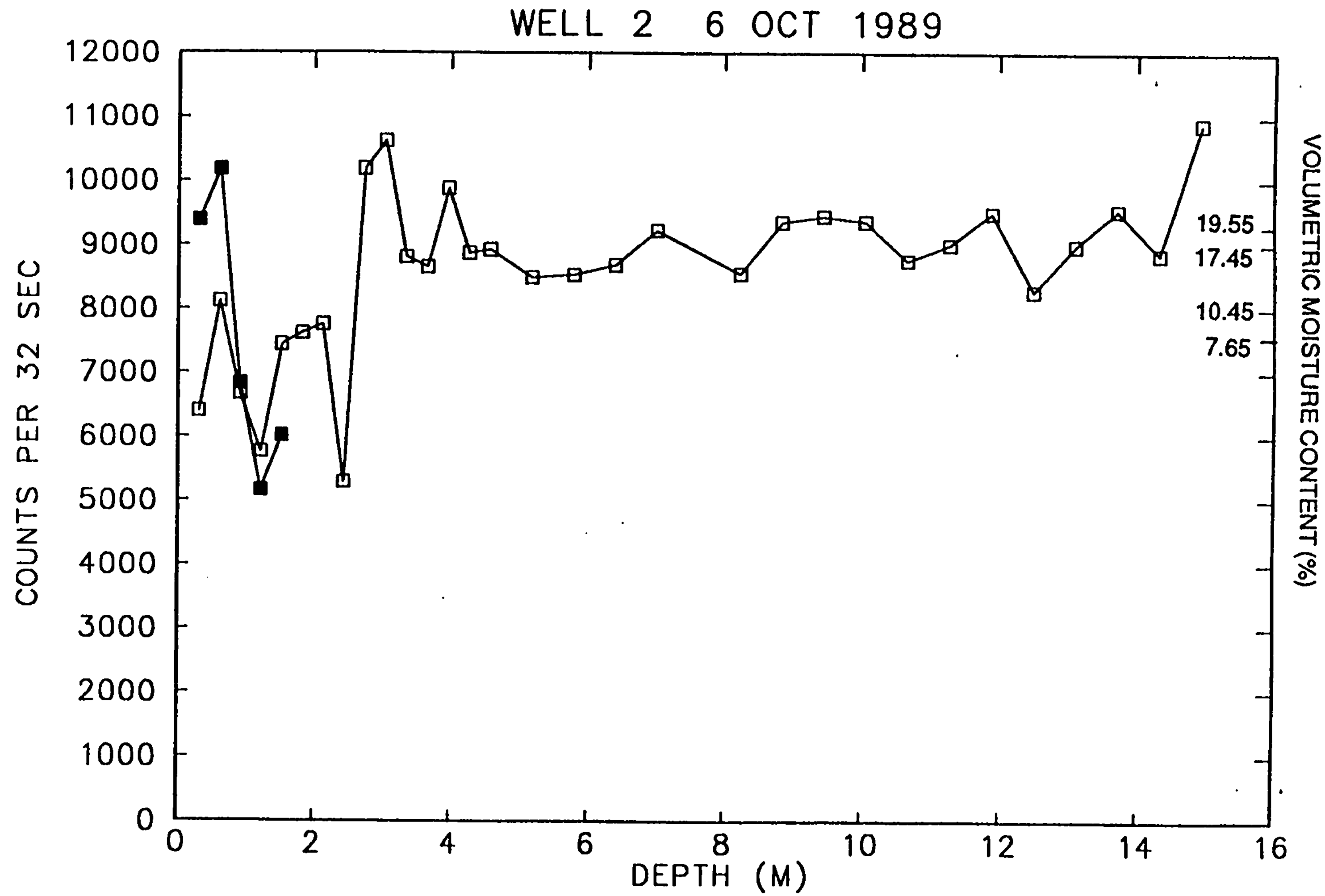



Fig 2.18 Moisture in Well #2 October 6, 1989 (Solid Box-shallow well reading, open box-deep well reading).

of cubic meters; therefore one would expect to see vertically moving moisture fronts in this well. Each well was logged one or two days following a runoff event. The nearly uniform moisture content with depth indicates that rates of moisture infiltration must be very rapid, on the order of hours. Moisture does not appear to be retained in the profile down to 15 m, but to be percolating to deeper depths, possibly to the water table.

# CHAPTER 3

# OCCURRENCE OF URANIUM THROUGHOUT POTRILLO CANYON WATERSHED

## *Historic Use of Depleted Uranium at Los Alamos National Laboratory*

It is estimated that amounts as much as 80,000 to 105,000 kg of natural and depleted uranium have been expended at the Laboratory since 1943. This number assumes that the 45,000 kg of uranium reported used from 1943-1953 is all depleted uranium, but the lack of records from this period precludes the ability to separate depleted uranium from natural uranium usage, since both were used. An estimated 32,500 kg of depleted uranium were expended between 1954 and March 1971 collectively into Potrillo, Pajarito, and Fence Canyons. Again, it is difficult to accurately estimate the amount which was expended into the Potrillo Canyon watershed. If one assumes that one half of that amount was used in Potrillo Canyon Watershed, because Potrillo contains 4 of the 8 firing sites present in these three canyons, and that the uranium usage in the 1970's and 1980's was less than 20,000 kg, a conservative estimate of the total uranium source term in Potrillo Canyon is in the neighborhood of 35,000 kg.

## *Background Levels of Uranium in Country Rock*

The Bandelier Tuff consists of two sequences of air-fall and ash flow deposits, the lower Otowi Member, dated at 1.4 Ma, discomformably overlain by the upper Tshirege Member, dated at 1.1 Ma. Bandelier Tuff has been characterized geochemically and petrographically by Crowe and others (1978). Uranium was one of the trace elements analyzed. Values of 38 samples collected in three composite locations in Los Alamos County varied between 4.0 and 11.35 ppm; the mean value was 7.83 ppm with a standard deviation of 2.02 ppm. Uranium concentrations in country rock are bimodal, with concentration maxima at around 4.5 and 8-9 ppm, Fig 3.1.

Bandelier Tuff was sampled in 1983 for uranium, Table 3.1. Each member and its individual subunits was sampled, in some instances more than once. Values ranged from a high of 11.02 ppm to a low of 3.08 ppm; the mean concentration was 5.74 ppm with a standard deviation of 2.25 ppm. These values are comparable to those published by Crowe and within the range of global soil values (Watters, 1983). Notice that the older deposits, the Otowi Member and Units 1A and 1B of the Tshirege Member have nearly twice the uranium concentrations as the younger deposits in the Tshirege, Units 2A, 2B, 3A, and 3B. This probably explains the bimodality observed in Fig 3.1. It is reasonable to assume that sediments derived from Bandelier tuff will have natural uranium compositions similar to their parent rock, and reflect the uranium composition of the individual units. Potrillo Canyon is cut into units 1A, 1B, 2A, and 2B.

*Background Uranium Concentrations in Sediments*

Channel sediments were collected in 1983 from the ephemeral streams which cross the Pajarito Plateau and analyzed for total uranium, Table 3.2. The streams listed in Table 3.2 are located both on the Laboratory as well as U.S. Forest Service and San Ildefonso Indian Reservation land, and the sample locations designated by

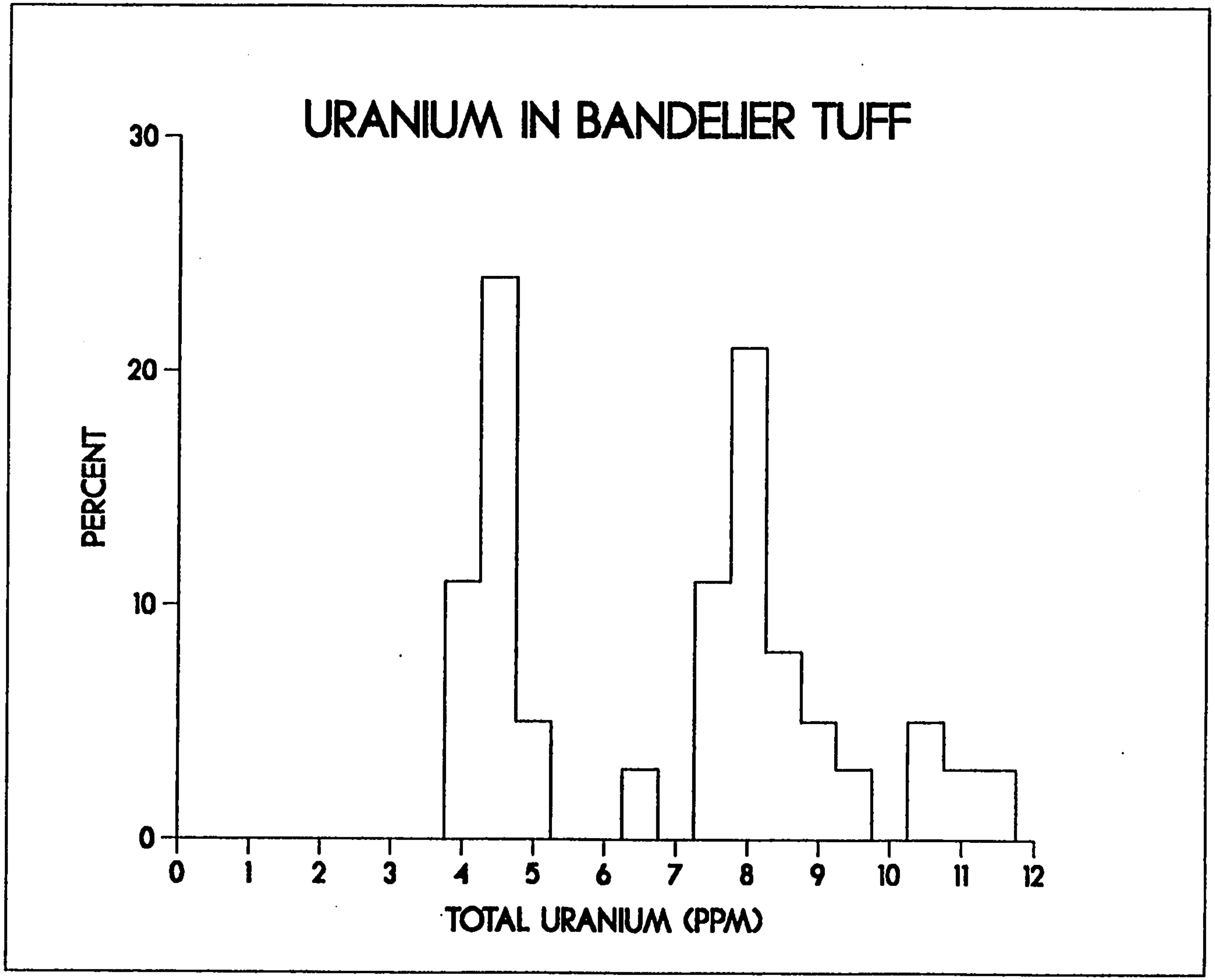



Fig 3.1. Total Uranium in Bandelier Tuff Samples (from Crowe and other, 1978).

TABLE 3.1
URANIUM IN OUTCROP SAMPLES
(μG/G)

| Unit | Member | Total Uranium |
|---|---|---|
| Guaje | Otowi | 11.02 |
| Otowi A | Otowi | 5.99 |
| Otowi B | Otowi | 6.71 |
| Unit 1A | Tshirege | 8.12 |
| Unit 1B | Tshirege | 7.91 |
| Unit 2A | Tshirege | 8.46 |
| Unit 2B | Tshirege | 4.70 |
| Unit 2B in Ancho Canyon below well DT-9 | Tshirege | 3.83 |
| Unit 2B in Big Buck Canyon below well DT-10 | Tshirege | 4.32 |
| Unit 3 | Tshirege | 3.77 |
| Unit 3A in Ancho Canyon below well DT-9 | Tshirege | 4.21 |
| Unit 3A in Big Buck Canyon below well DT-10 | Tshirege | 3.51 |
| Unit 3B in Ancho Canyon below well DT-9 | Tshirege | 3.08 |
| Unit 3B in Big Buck Canyon below well DT-10 | Tshirege | 3.80 |
| Pumice-Otowi at type section | Otowi | 5.87 |
| Pumice-Otowi in Ancho Canyon | Otowi | 6.61 |

TABLE 3.2
TOTAL URANIUM IN CHANNEL SEDIMENTS IN STREAMS CROSSING THE PAJARITO PLATEAU
(μg/g)

| Location | Undifferentiated | Fine Sand | Silt/Clay |
|---|---|---|---|
| Rendija at Guaje | 2.89 | 2.65 | 4.13 |
| Guaje at Well 5 | 2.78 | 2.28 | 7.24 |
| Barrancas Canyon at Guaje | 2.87 | 2.74 | 5.36 |
| Bayo Canyon at State Road 4[a] | 2.45 | 2.28 | 4.98 |
| Pueblo Canyon at the "Y"[b] | 1.70 | 2.43 | 8.26 |
| Los Alamos Canyon at the "Y"[b] | 1.78 | 1.81 | 5.42 |
| Sandia Canyon at State Road 4[c] | 3.35 | 2.41 | 5.84 |
| Mortandad Canyon at State Road 4[d] | 2.60 | 2.42 | 6.01 |
| Cedro Canyon at State Road 4 | 2.75 | 2.70 | 4.80 |
| Max Canyon at State Road 4 | 2.90 | 3.19 | 5.42 |
| Canada del Buey at State Road 4[e] | 2.12 | 2.88 | 3.96 |
| Pajarito Canyon below Area G[f] | 2.35 | 2.74 | 4.85 |
| Potrillo Canyon at State Road 4[f] | 2.51 | 2.45 | 4.12 |
| Water Canyon at State Road 4[f] | 2.58 | 2.16 | 5.86 |
| Indio Canyon at State Road 4 | 3.29 | 2.77 | 6.65 |
| Big Buck Canyon at State Road 4[f] | 4.43 | 5.15 | 9.73 |
| Ancho Canyon at State Road 4[f] | 1.65 | 1.96 | 5.34 |
| Ancho Canyon below well DT-9[f] | 1.92 | 1.58 | 5.13 |
| Big Buck Canyon below well DT-10[f] | 1.88 | 1.69 | 4.84 |
| Potrillo Canyon at confluence with Water Canyon[f] | 1.52 | 1.42 | 4.36 |
| Water Canyon at confluence with Potrillo Canyon[f] | 3.05 | 2.62 | 5.97 |

Notes:

[a] Natural and depleted uranium used upstream at TA-10; decommissioned and decontaminated in 1963.
[b] Possible uranium release upstream from TA-45 and DP sewage treatment plants .
[c] Possible uranium release upstream from TA-20 firing sites; decommissioned in 1985.
[d] Possible uranium release upstream from TA-50 sewage treatment plant
[e] Possible uranium release from Area G, an active radioactive waste disposal site.
[f] Possible uranium release upstream from active or inactive firing sites.

a solid triangle, Fig 3.2. Five of the sites are located in watersheds whose source of uranium is from either the host rock or from fallout. The remaining sites could have potentially received uranium from either former or active firing site activities, or from former or ongoing waste treatment activities.

Levels of uranium in these channel sediments (undifferentiated) ranged from 1.52 to 4.43 µg/g, with a mean of 2.54 µg/g, Table 3.2. These levels of uranium are, on the average, lower than levels measured in the host rock. Although isotopic ratios were not measured on these samples, these levels do not appear to represent elevated levels associated with contamination of sediments of watersheds which may have received uranium input from Laboratory activities. Levels are comparable and in instances lower than natural uranium levels in the parent rock. In a separate study, Purtymun and others (1987) made measurements of uranium in sediments along the Rio Grande upstream and downstream of the Laboratory between 1979 and 1986. Purtymun's mean concentration result of 2.6 µg/g from a total of 59 samples is essentially the same as were measured on the channel sediments.

*Earlier studies of Uranium Distribution in Potrillo Canyon Watershed*

Earliest soil studies of uranium in Potrillo Canyon watershed began in 1974 (Hanson and Miera, 1976). Soil samples on locations along transects located at E-F firing site and the Lower Slobovia firing site were collected both on the surface and down to 10 cm depth. Firing site locations are shown in Fig 1.3. Uranium concentrations were shown to decline with distance from the target areas in both layers at E-F firing site. Soil sampling was repeated in 1976 at E-F firing site in a polar coordinate sampling layout which incorporated depth sampling via cores down

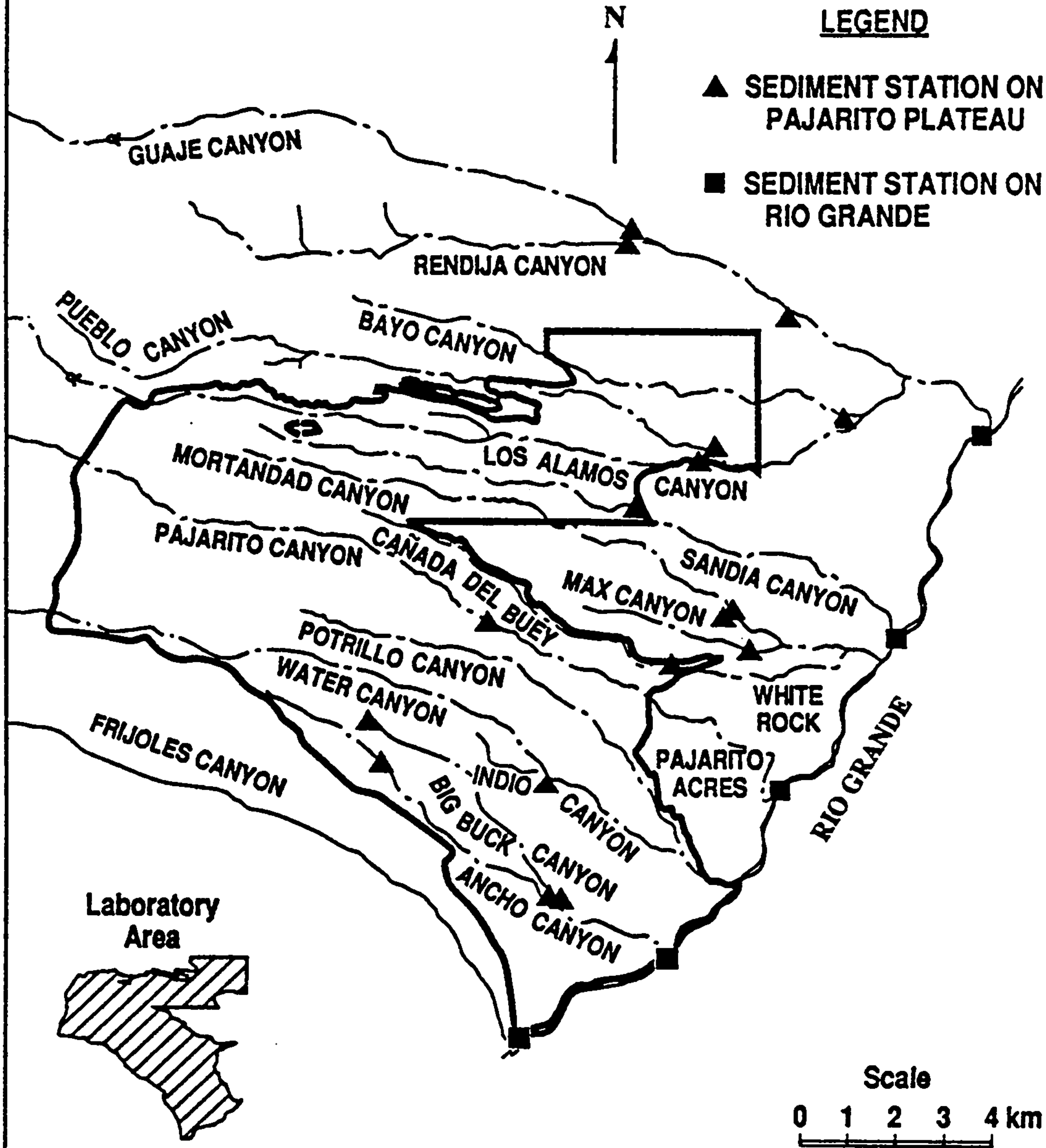



Fig 3.2. Location of Sediment Sampling Stations.

to 30 cm, as well as samples of soil and sediment collected in a side canyon (3 samples) and in the Potrillo canyon channel to a distance of 9000 m from E-F firing site (7 samples) (Hanson and Miera, 1977). From these data, estimates of 70,000 kg of uranium present in the canyon system were calculated. Measurements of uranium in standing water and runoff water led Hanson to state that storm runoff was "an important vector in transporting uranium from E-F site" (Hanson and Miera, 1977).

Later, Hanson and Miera (1978) studied uranium concentrations by particle size at E-F firing site, redistribution mechanisms of uranium by surface creep, saltation and resuspension, and comparison of two methods of inventory calculations at E-F firing site. They concluded that: 1) uranium in the particle fraction smaller than 53 μm predominated within 10 m of the target; 2) uranium in the particle fraction 1-2 mm were important at 20 - 50 m distances; and 3) smaller particles predominated at farther distances. Redistribution by suspension of fines was seen as an active mechanism when the sampling height exceeded 0.5 cm above the ground surface. Estimates of uranium inventory in surface soils in the vicinity of the former E-F firing pad determined that nearly 4500 kg of uranium was deposited within 200 m, and that the greatest uranium concentrations were at distances ranging between 125 and 175 m.

Other soil sampling for uranium at E-F site consists of unpublished data collected by the Environmental Science group at the Lab in 1985. Soils were collected along transects, along with some depth data down to 15 cm in the vicinity of the firing point. They also collected ponded water, snow, and soil moisture samples at the firing site, and measured uranium in the water and suspended sediment. Uranium levels in soils were elevated, as were levels in the dissolved phase. Uranium levels in soil water were also elevated. Uranium was apparently concentrating in the soil water as the moisture content dropped and as the snow melted, evaporated or sublimated.

Soil sampling at I-J firing site was conducted in 1982, associated with emissions characterization of shaped charges of depleted uranium munitions (Gunderson and others, 1983). Polar grid sampling to distances of 61 m from the firing pad and depths to 0.1 m was conducted.

Soil sampling at the PHERMEX firing site was conducted in 1987 by the Environmental Surveillance group in association with preconstruction activities for a new diagnostics center (unpublished data). One hundred forty-five surface soil samples were collected on a grid adjacent to PHERMEX and three core holes were drilled to a maximum depth of just over 3 m to sample for, among other constituents, uranium.

During the spring of 1988, the Department of Energy's Environmental Survey team collected 20 surface soil samples (which were composited into 5 samples) at the Lower Slobovia firing site and 3 samples at the Lower Slobovia burn pit. Samples were analyzed for uranium, as well as other constituents (U.S. Department of Energy, 1989).

There have been few aerosol investigations of depleted uranium. An aircraft outfitted with a high volume air filtration system and wing mounted cascade impactor sampler flew through detonation clouds of dynamic test experiments in 1974 (Dahl and Johnson, 1977). The results indicated that 10% of the uranium was contained in the debris cloud (aerosolized). In another study of air and fallout emissions from testing of shaped charges of depleted uranium munitions (Gunderson and others, 1983), high volume air samplers and fallout samplers placed on the ground adjacent to the firing pad could not distinguish between uranium from the detonation of the device of interest and resuspended uranium left over from previous tests. Other studies reported that uranium was aerosolized but the amount was not quantified (Elder and others, 1976), and that aerosolized mass following penetrator detonation in a confined vessel amounts to tenths of a gram quantities from a several hundreds gram penetrator (Hanson and others, 1974). This compares to 20% aerosolization of plutonium in the Roller Coaster experiment (Dewart and others, 1982).

In 1982, EG&G flew an aerial survey of E-F, I-J, and PHERMEX firing sites to measure the extent of Protactinium-234m (Pa-234m) (Fritzsche, 1986). Pa-234m is a daughter of uranium-238 and can be used to infer uranium-238 contamination. Assuming a vertical distribution into the surface profile, EG&G estimated 4 to 23 Curies of Pa-234m, which implies considerable (order of Curies) uranium-238 activity in the soil. The major concentration of Pa-234m was centered over E-F firing site.

*Inventory Sampling of Surface Soils*

During August 1987, 122 soil samples were collected within Potrillo Canyon watershed. The purpose of this sampling was to establish levels of uranium throughout the watershed, especially in locations other than firing pads or within the watercourse. All samples were collected in the upper 5 cm of the soil profile and analyzed for total and isotopic uranium. Sample locations were randomly generated, although firing pads were excluded. By chance, there were no samples located within the stream channel or on the banks.

Values for total uranium are shown in Fig. 3.3. Background levels for total uranium are 4-5 µg/g. Background samples were collected in non-firing site areas at the Laboratory and at a second location south of Los Alamos County near Cochiti Lake. The contour interval for total uranium is 10 µg/g. The major areas of elevated uranium concentration are associated downgradient from E-F firing site and PHERMEX. The maximum value measured was 66 µg/g, although the majority (84%) of the samples were at or below 5 µg/g. Six samples measured over 10 µg/g, and 4 out of the 6, or 3.3% of the total, registered over 20 µg/g. These highest uranium values were found adjacent to and in the canyon below E-F firing site, adjacent to PHERMEX, and near the canyon head to the south of the storage magazine road at R-Site.

Isotopic uranium levels are shown in Fig 3.4. Using information from the quality control samples, if one assumes that background isotopic ratios are 0.0072 +/- 0.0008 at the 95% confidence level, then samples whose isotopic ratio are below 0.0064 are depleted. With this criterion, 84% of the samples represented natural uranium. Contamination, as designated by diminished isotopic ratio, was present mostly below E-F firing site, and between Eenie and Meenie firing sites, Fig 3.4.

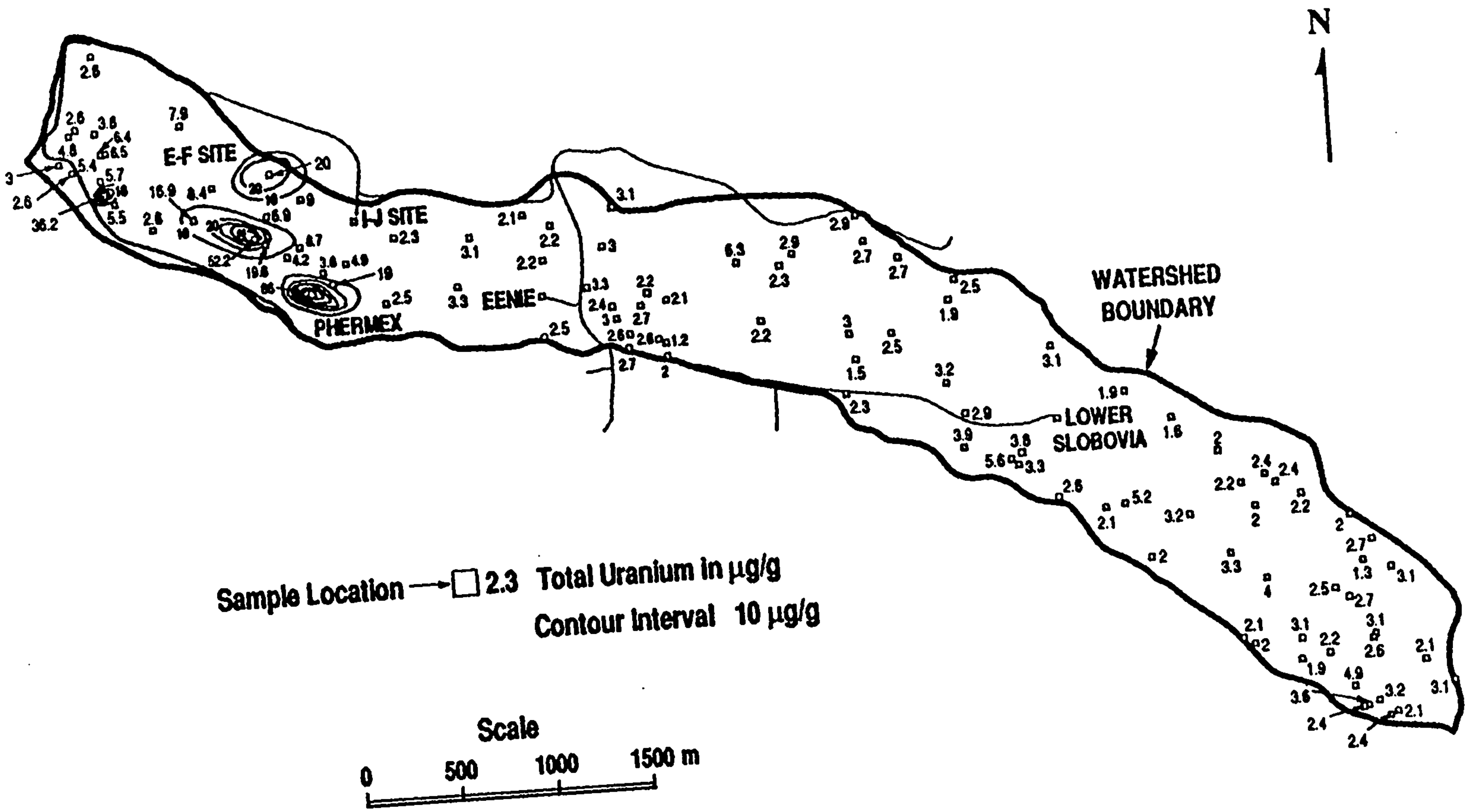



Fig 3.3 Total Uranium in Surface Soil Samples in Potrillo Canyon Watershed.

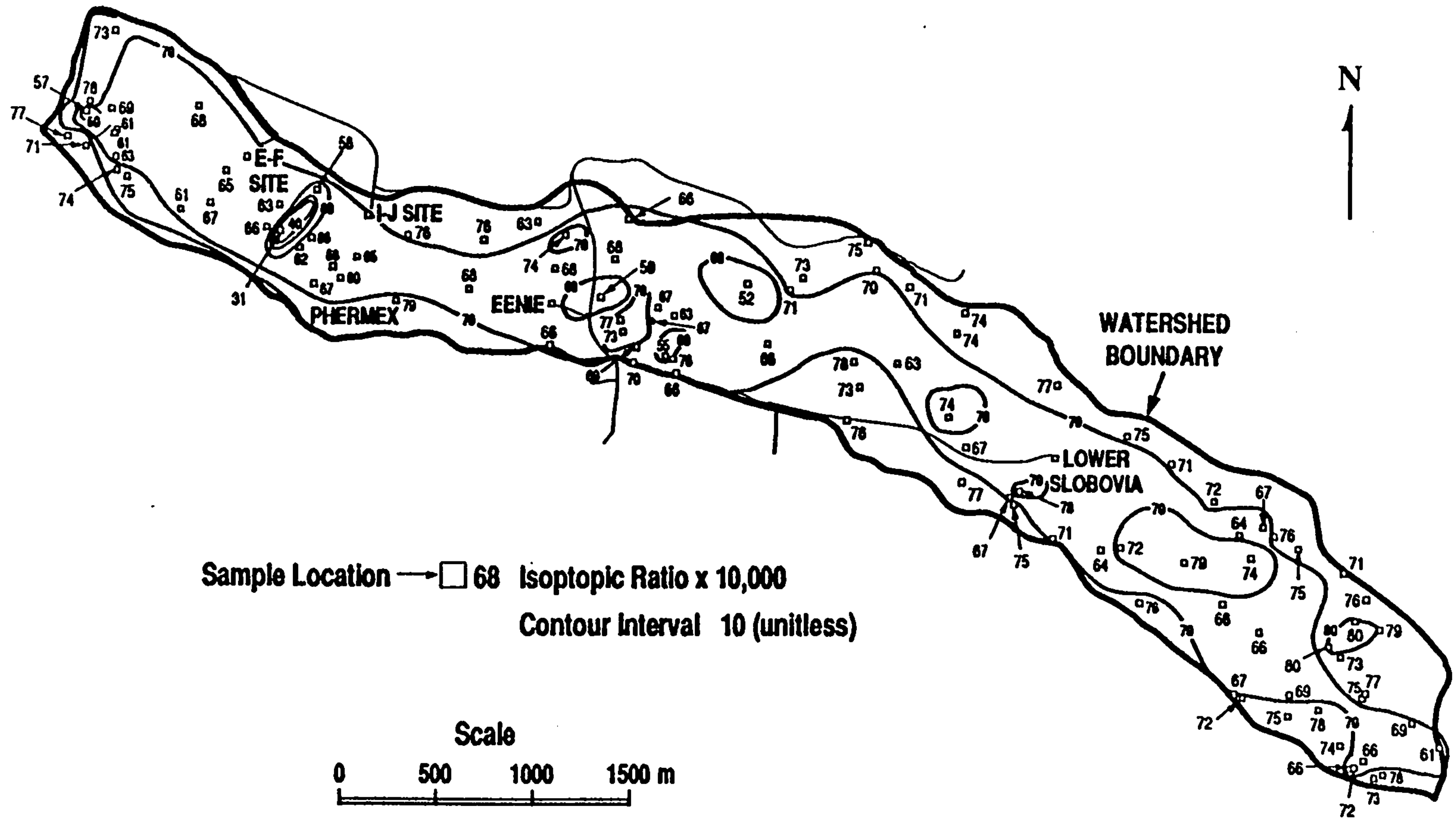



Fig 3.4 Uranium Isotopic Ratio in Surface Soil Samples in Potrillo Canyon Watershed.

# CHAPTER 4

## MODES OF URANIUM TRANSPORT

### *Fallout sampling*

Fallout studies were initiated to determine the effect and magnitude of airborne transport on uranium movement in Potrillo Canyon watershed. Uranium becomes airborne during dynamic testing, as ascertained by air sampling at a firing site during a test (Gunderson and others, 1983) and has been estimated to comprise 10% of the total uranium used in an individual dynamic test (Dahl and Johnson, 1977). Redistribution of uranium-contaminated soil at the pad of a former firing site at heights of 0.5 cm was observed by Hanson and Miera (1978). The following study was designed to evaluate the magnitude of fallout transport throughout the watershed, in contrast to the cited evaluation techniques performed directly on, or adjacent to, or above the firing pad.

On September 7 and 10, 1984, 10 fallout buckets were installed in Potrillo Canyon watershed, and one in the Mortandad Canyon watershed (the background location). Each bucket was embedded halfway into the ground. Although the buckets stood nearly 0.3 m above the ground surface, many of the buckets received a small amount of sediment due to rainsplash up the bucket sides and into the interior. In addition a number of buckets collected insects, and one bucket trapped and drowned two ground squirrels. All the buckets remained in place for about 9 months. The buckets were then removed and submitted for analyses of total uranium and isotopic ratio.

Of the 11 samples collected, 7 were located within the watershed valley. Valley fallout samples were collected below E-F and I-J firing sites, between E-F and I-J firing site, between I-J and Eenie firing sites, between Eenie and Lower Slobovia firing sites, below the Lower Slobovia firing site, and nearby State Road 4. Three samples were collected on mesa tops: one near I-J firing site, another above the Eenie firing site, and the third between Meenie firing site and Moe magazine. The eleventh sample was located on a mesa top in a small watershed which drains into Mortandad Canyon and was used as the background sample. Sample locations are shown in Fig 4.1. None of the fallout buckets were located in runoff drainage channels.

Collected volumes of fallout were small. Although the buckets stood out for 9 months, in most instances the bottom of the bucket was barely covered with sediment at the end of the period.

Samples were analyzed using delayed neutron activation (DNA). DNA assumes that all the uranium is natural; that is, U-235/U-238 = 0.0072±0.0008. If a sample contains depleted uranium, then the DNA result must be adjusted by the ratio of natural uranium's isotopic ratio to the depleted sample's isotopic ratio. It was assumed that samples with isotopic ratios less than 0.0065 were depleted. Samples were adjusted by multiplying the reported total uranium value by the quotient of the natural uranium isotopic ratio (0.0072) to the reported isotopic ratio.

The results are summarized on Table 4.1 and in Fig 4.1. Values of adjusted total uranium varied from less than 1 to over 7 μg/g. These values fall into the range of naturally occurring uranium in the host rock. Eight samples had isotopic ratios

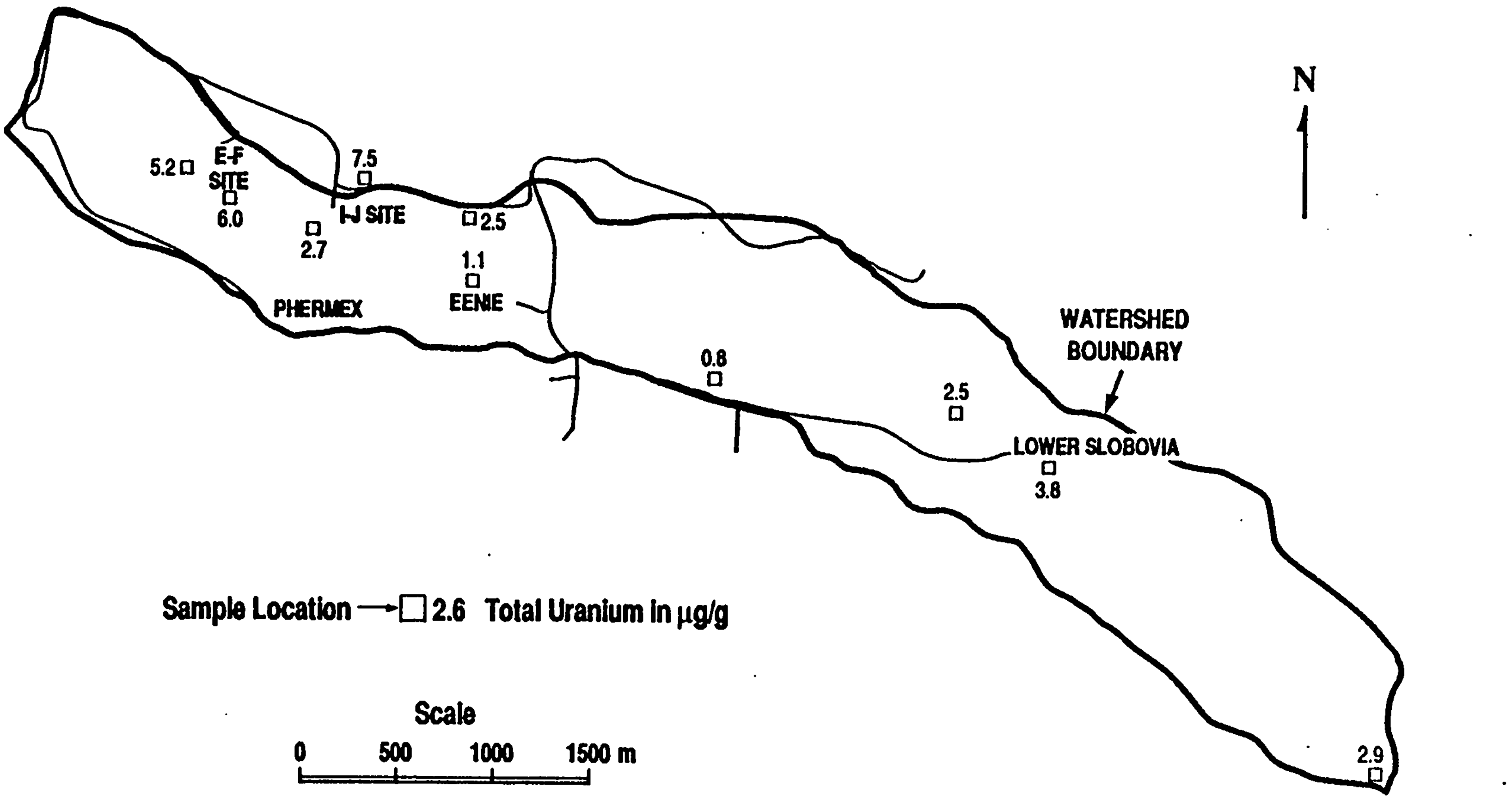



Fig 4.1 Uranium Fallout Concentrations by Weight in Potrillo Canyon Watershed.

TABLE 4.1
Fallout Uranium in Potrillo Canyon Watershed
September 7, 1984 to June 24, 1985
(μg/g)

| Location | Reported Total Uranium | Isotopic Ratio | Adjusted Total Uranium |
|---|---|---|---|
| E-F | 5.2 | 0.0069 | 5.2 |
| Between E-F and I-J | 4.6 | 0.0055 | 6.0 |
| I-J | 2.4 | 0.0064 | 2.7 |
| Eenie | 1.1 | 0.0073 | 1.1 |
| 0.5 km from hilltop | 5.6 | 0.0054 | 7.5 |
| 1.1 km from hilltop | 1.9 | 0.0056 | 2.5 |
| Meenie-Moe | 0.8 | insuff. data | 0.8 |
| Skunk Works | 1.5 | 0.0043 | 2.5 |
| Lower Slobovia | 3.3 | 0.0062 | 3.8 |
| SR4 | 2.0 | 0.0051 | 2.9 |
| Mortandad Canyon | 2.5 | 0.0044 | 4.2 |

TABLE 4.2
Uranium in Air Samples*
($pg/m^3$)

| Year | Regional Mean | Perimeter Mean | Onsite Mean |
|---|---|---|---|
| 1988 | 159 | 56 | 62 |
| 1987 | 74 | 33 | 31 |
| 1986 | 60 | 26 | 26 |
| 1985 | 46 | 28 | 32 |
| 1984 | 39 | 28 | 29 |
| 1983 | 39 | 37 | 26 |
| 1982 | 61 | 44 | 52 |
| 1981 | 27 | 47 | 36 |
| 1980 | 60 | 49 | 50 |
| Mean | 63 | 39 | 38 |
| Low | 27 | 26 | 26 |
| High | 159 | 56 | 62 |

* Data from Environmental Surveillance Group, 1981-1989.

less than 0.0065, indicating that depleted uranium from weapons testing was present in fallout or in insects. Uranium present in surrounding soils are presumed to have been deposited either by overland flow (sheet wash) or through fallout mechanisms.

Possible sources of uranium redistribution in fallout particles are from the settlement of small particles in plumes created by dynamic tests of weapons components, and from the resuspension of contaminated soil. Locations of wind distributed contaminated dusts and particles would be dependent on the local topography and prevailing wind direction and magnitude. The prevailing wind direction in the vicinity of Potrillo Canyon watershed is from the south-southwest (Bowen, 1990). If wind redistribution were significant, then one should expect to see the valley samplers contaminated by material from PHERMEX, and mesa top samplers contaminated by Meenie and Minie firing sites. Inspection of the isotopic ratio data revealed some evidence of this, but the pattern is not consistent. Total uranium levels are at or slightly elevated above background values of both soil and dust particulates. Background values of total uranium in sediments are about 2-4 μg/g, as discussed in Chapter 3.

Calculations were made for the uranium loading in air samples collected in the routine environmental monitoring for the laboratory in order to compare to the fallout values. Years 1980 through 1988 were examined for uranium measured in air samplers at regional stations in northern New Mexico, at stations at the Laboratory boundary (perimeter sites), and at onsite locations, Table 4.2. The mean of the annual means for the regional, perimeter, and onsite locations are 63, 39, and 38 pg of uranium/$m^3$ of air, respectively. The lowest value measured was 26 pg/$m^3$

at both the perimeter and onsite stations, and the highest was 159 $pg/m^3$ at the regional station. Using the lowest and highest annual values and an average measured particle loading of 25 μg of $particles/m^3$ of air (Environmental Surveillance Group, 1988), the range of uranium content in dust in the air from all stations from 1980 through 1988 was between 1 and 6 μg of uranium per g of dust, which is comparable to soil and fallout values. Therefore, only the fallout sampler on the mesa top near the I-J firing pad showed levels of total uranium above local soil and air sampling values (7.5 μg/g total uranium). These results indicate that air distribution is not a significant uranium transport mechanism.

*Summer Runoff*

Cumulative samplers collected summer runoff water from established locations in the main channel below E-F site, I-J site, Eenie site, at Skunk Works, and at State Road 4, Fig 4.2. These samplers were buried in the channel under a dam of channel-fill material. When runoff began, flow would pond behind the dam. When the water level rose to the level of the sampler inlet tubing, the sampler bottle would begin to fill. In most instances, the bottle would completely fill before the pressure of the ponded water and/or height of rise would overtop and erode the dam. Afterwards, usually the next day, the sampler bottle would be dug out, replaced, and the runoff sample submitted for radiochemical analyses. At times, the force of the moving water would be sufficient to completely wash out the sampler with the bottle. When this occurred the sampler was lost, and the bottle broken. This scenario

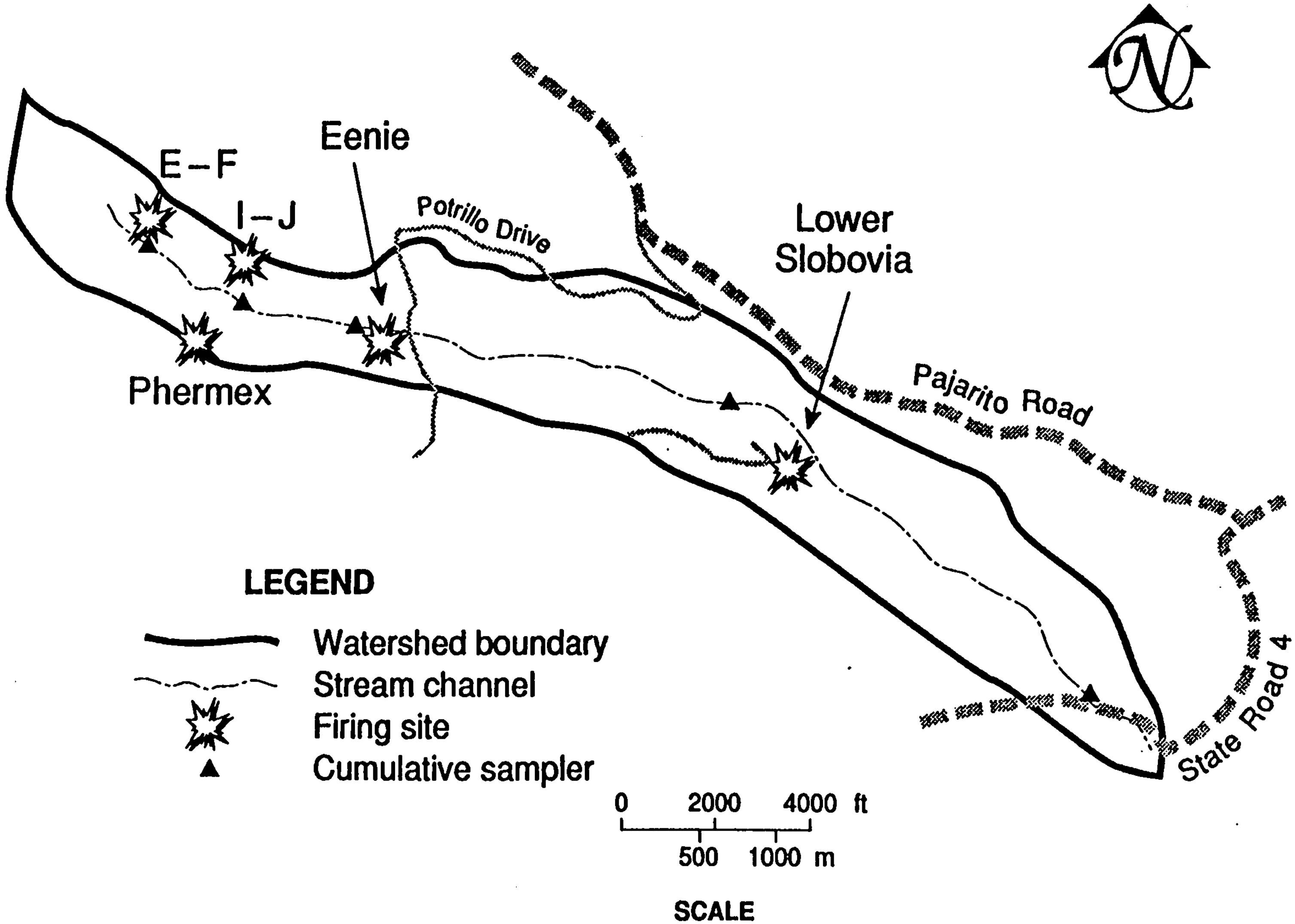



Fig 4.2 Location of Cumulative Samplers.

occurred most frequently at the Skunk Works location and is the reason why there are less runoff results there.

Each runoff sample was filtered through a 0.45 micron filter; the liquid was analyzed for dissolved total uranium, and the suspended sediment collected on the filter analyzed for total uranium and isotopic ratio. Means and standard deviation were computed for the dissolved and suspended sediment components. Maximum likelihood estimation (Helsel and Cohn, 1988) permitted inclusion of data less than detection limits. A log normal distribution would be an alternative, appropriate given the data distribution and avoid negative values. Background levels of uranium are in the 1-2 ppb range dissolved in water and in the 2-4 μg/g range in sediment particulate phase.

The total uranium dissolved in runoff as a function of time are shown in Figs 4.3 through 4.7. At E-F site dissolved uranium values were uniformly elevated above background. The total uranium ranged from 3.0 to 654 ppb for runoff events from 1983 to 1989, Fig 4.3, with a mean value of 48.2 ppb and a standard deviation of 122.1 ppb. At I-J site, the total uranium dissolved in runoff from 1985 through 1989, and one value collected in 1990 ranged from below the detection limit of 1 ppb to 194 ppb, Fig 4.4, with a mean of 7.7 ppb and a standard deviation of 48.4 ppb. Dissolved uranium collected at Eenie between 1983 and 1989 ranged from 0 to 31 ppb, Fig 4.5, with a mean of 2.2 ppb and a standard deviation of 5.6 ppb. At Skunk Works, dissolved uranium in runoff was measured from 1984 to 1990. Only 16 samples were collected during that interval even though there were more runoff events. There were quite a few samples lost due to the sampler being washed away. Of those samples collected, the dissolved total uranium ranged from 0.1 to 18 ppb,

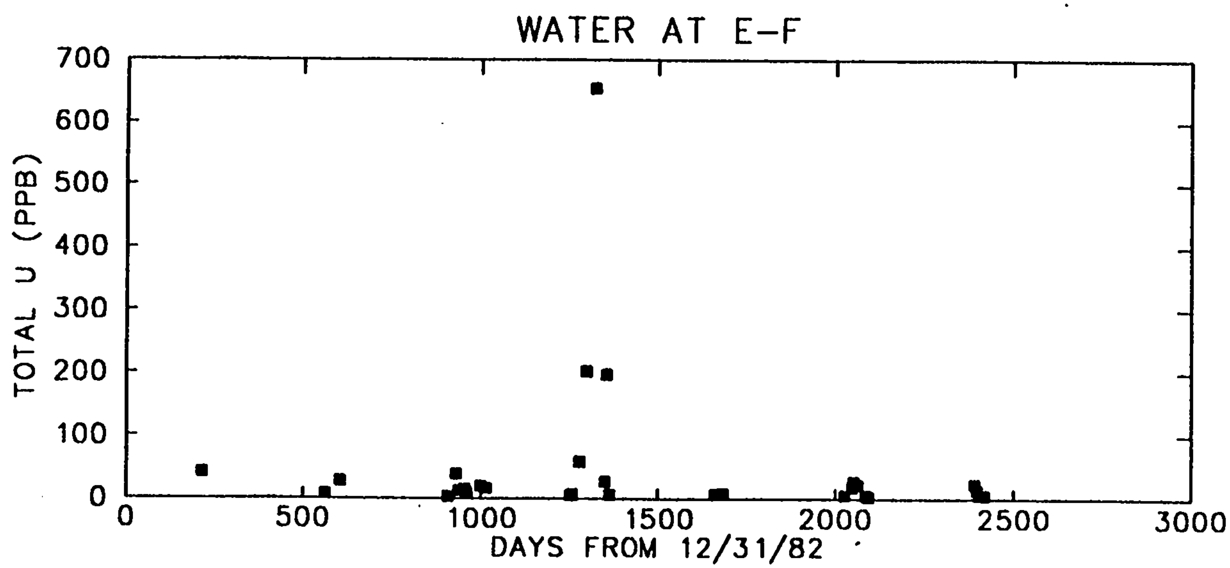



Fig 4.3 Total Uranium in Runoff Water at E-F Cumulative Sampler Site.

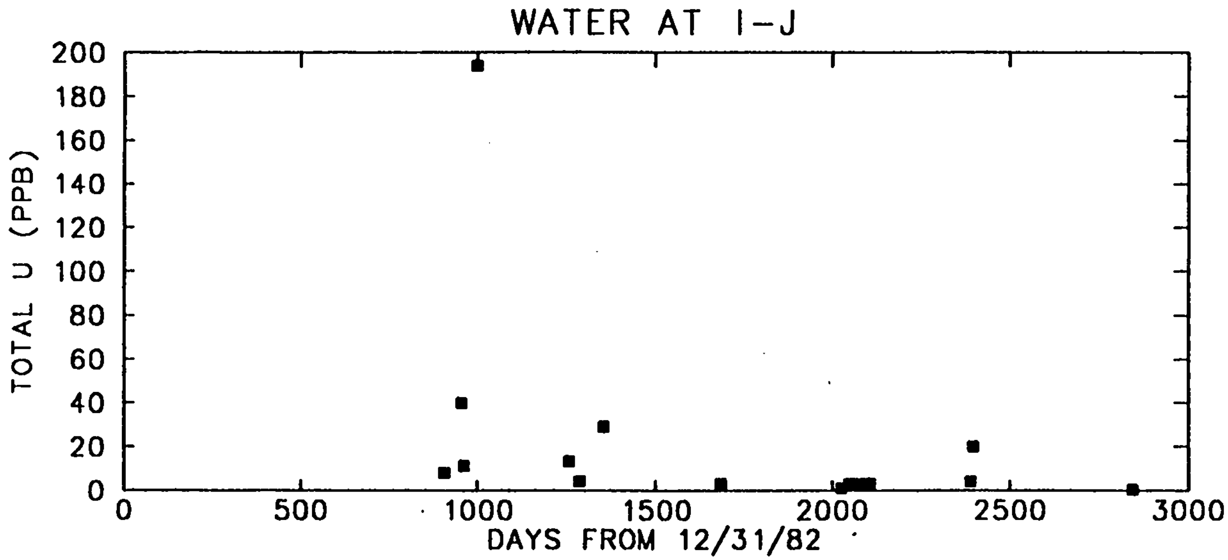



Fig 4.4 Total Uranium in Runoff Water at I-J Cumulative Sampler Site.

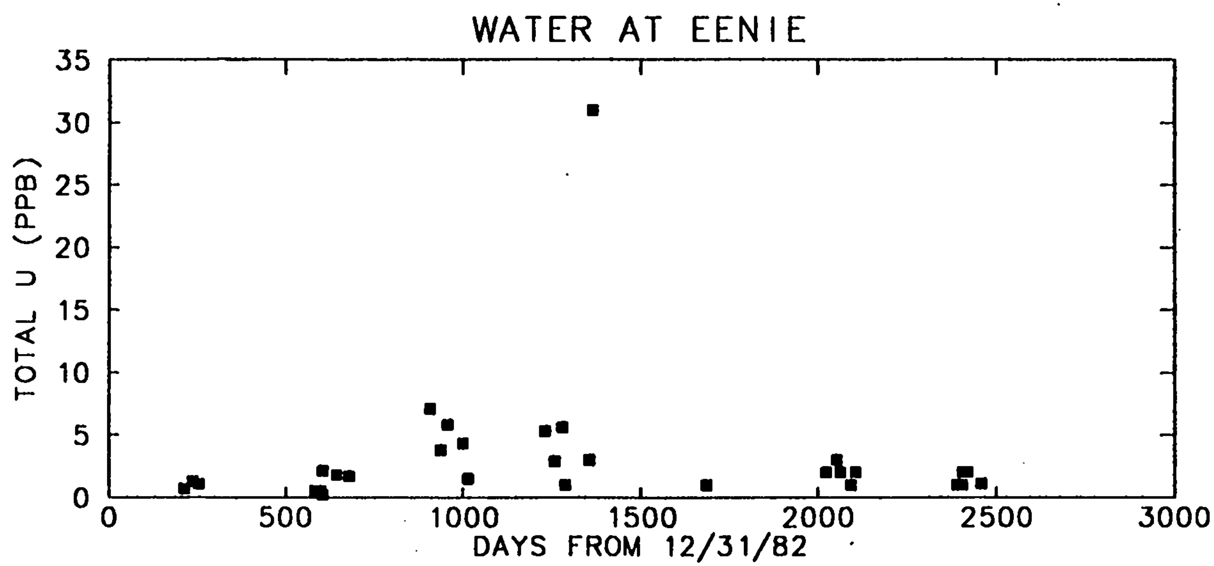



Fig 4.5 Total Uranium in Runoff Water at Eenie Cumulative Sampler Site.

Fig 4.6, with a mean of 1.9 ppb, and a standard deviation of 5.6. Dissolved uranium in runoff at State Road 4 was measured between 1983 and 1990; the range was 0-72 ppb, Fig 4.7; with a mean of -0.9 ppb and a standard deviation of 17.5. A mean below zero was possible because 1) data below the detection limits were included in the calculations and 2) the maximum likelihood technique used to calculate the means assumes a normal distribution about a central value, which could be negative.

Values for total uranium in the suspended sediment carried in the runoff followed similar trends to uranium in the dissolved phase, Fig 4.8 through 4.17. At E-F site, the total uranium in suspended sediments ranged from 2.61 to 404.9 µg/g, Fig 4.8, with a mean of 137.6 µg/g and a standard deviation of 90.5 µg/g. The isotopic ratios associated with these samples ranged from 0.0019 to 0.0057, Fig 4.9, indicating all samples were depleted.

At I-J site, total uranium in suspended sediment in runoff ranged from 5.5 to 99.3 µg/g, Fig 4.10, with a mean of 33.1 µg/g, and a standard deviation of 26.2 µg/g. The isotopic ratios associated with these ranged from 0.0023 to 0.0064, Fig 4.11, indicating that nearly all samples contained depleted uranium. The sample with the isotopic ratio of 0.0064 had an accompanying total uranium value of 22 µg/g, indicative of uranium contamination.

Suspended sediments at Eenie contained total uranium ranging from 1.3 to 60.9 µg/g, Fig 4.12, with a mean of 15.1 µg/g and a standard deviation of 11.7 µg/g. The corresponding isotopic ratios varied from 0.0018 to 0.0076, Fig 4.13, although the 0.0076 was associated with a total uranium value of 28.8 µg/g, which is above background.

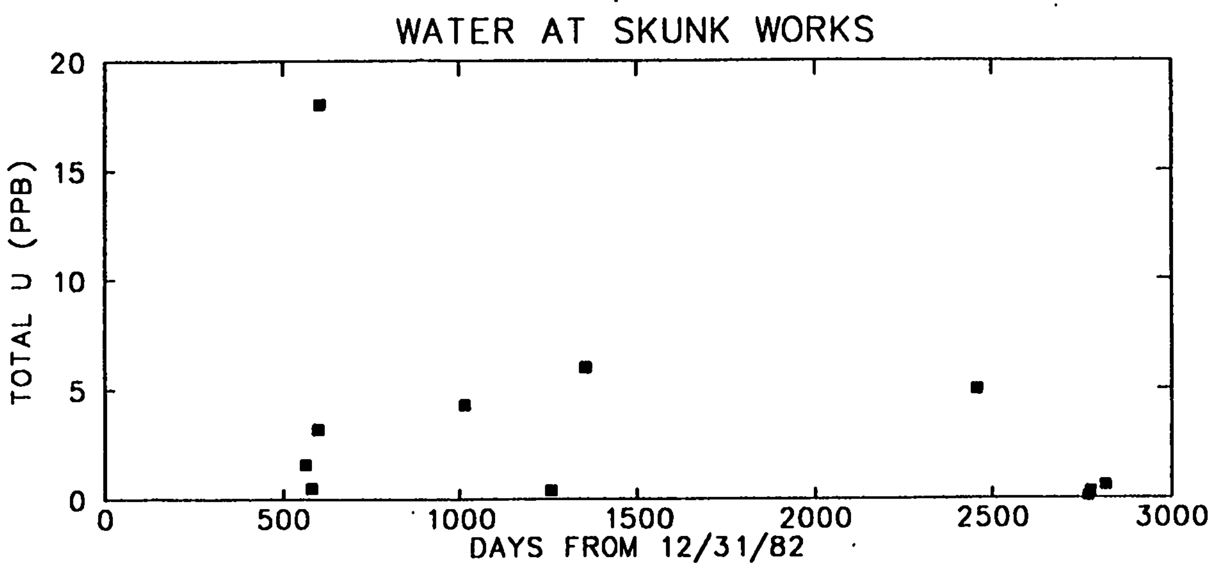



Fig 4.6 Total Uranium in Runoff Water at Skunk Works Cumulative Sampler Site.

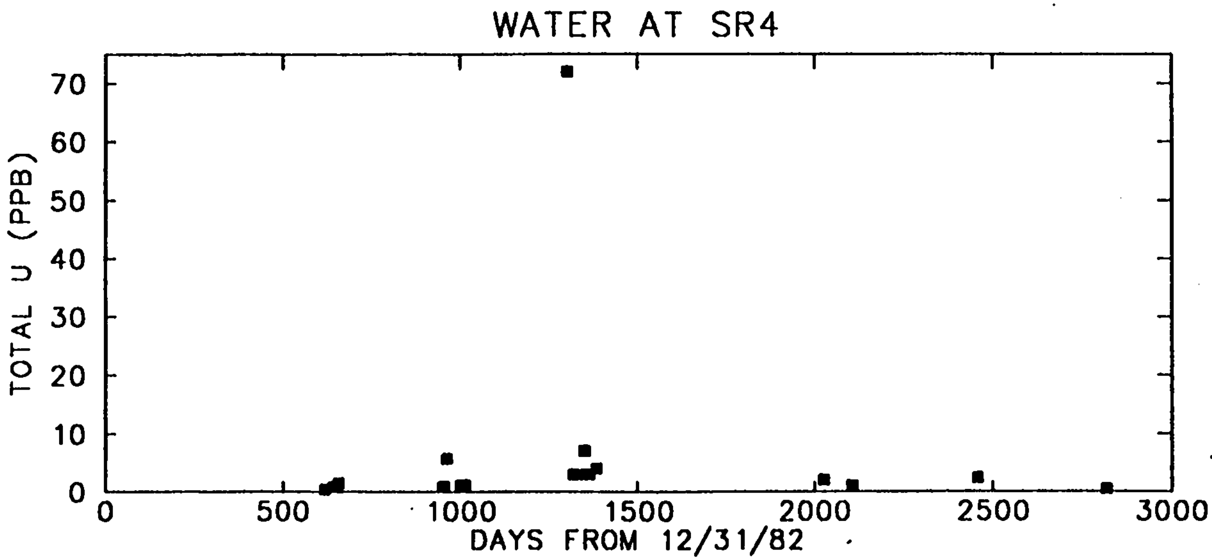



Fig 4.7 Total Uranium in Runoff Water at State Road 4 Cumulative Sampler Site.

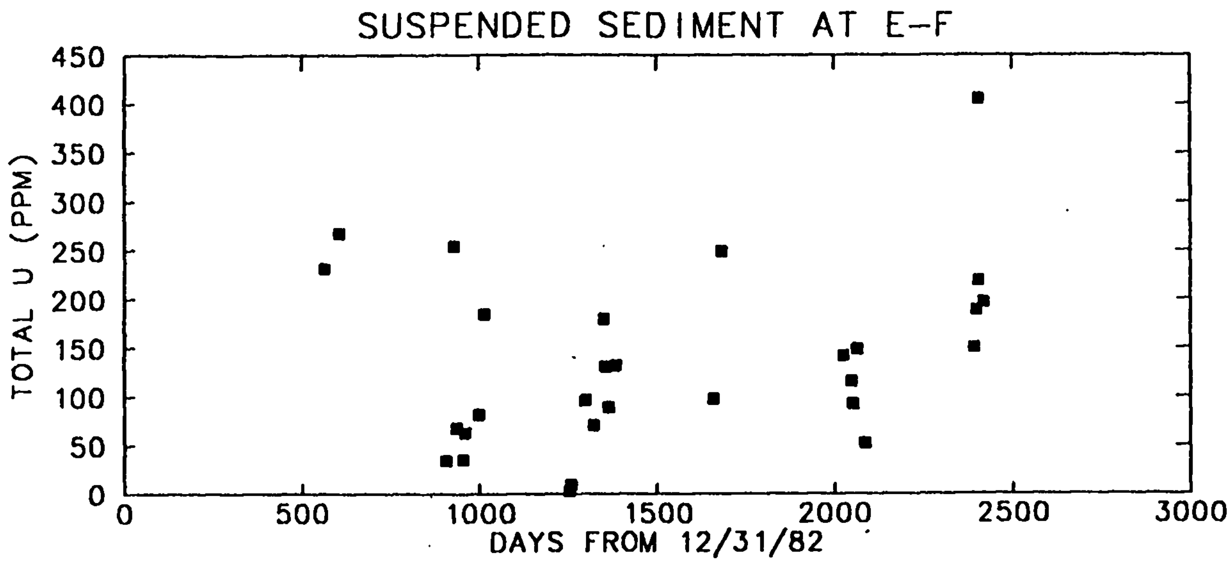



Fig 4.8 Total Uranium in Suspended Sediment in Runoff at E-F Cumulative Sampler Site.

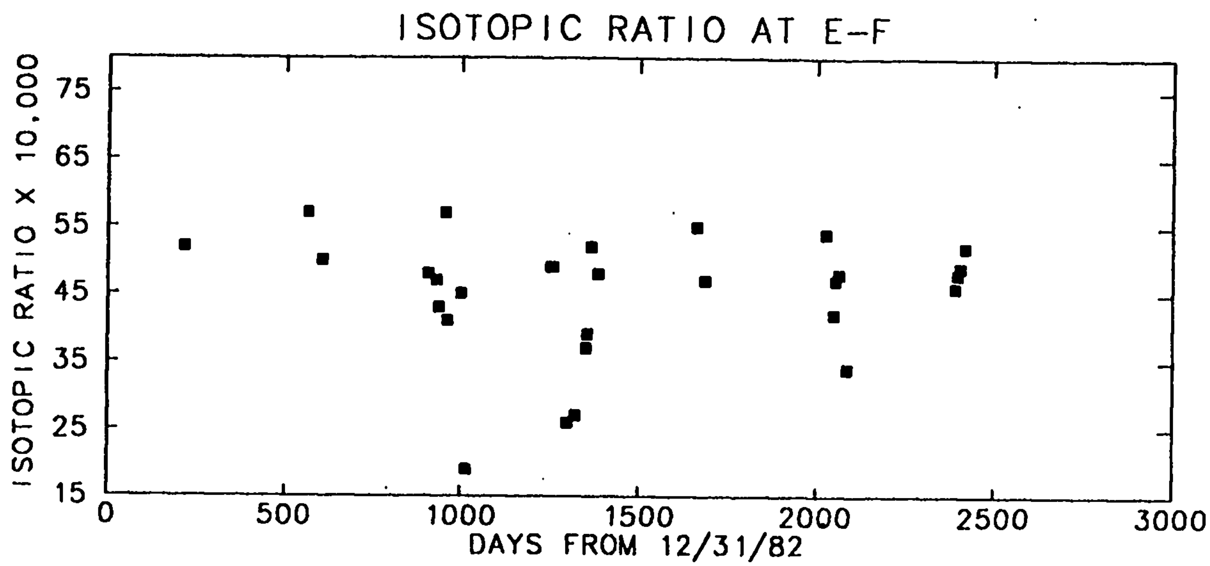



Fig 4.9 Isotopic Ratio of Suspended Sediment in Runoff at E-F Cumulative Sampler Site.

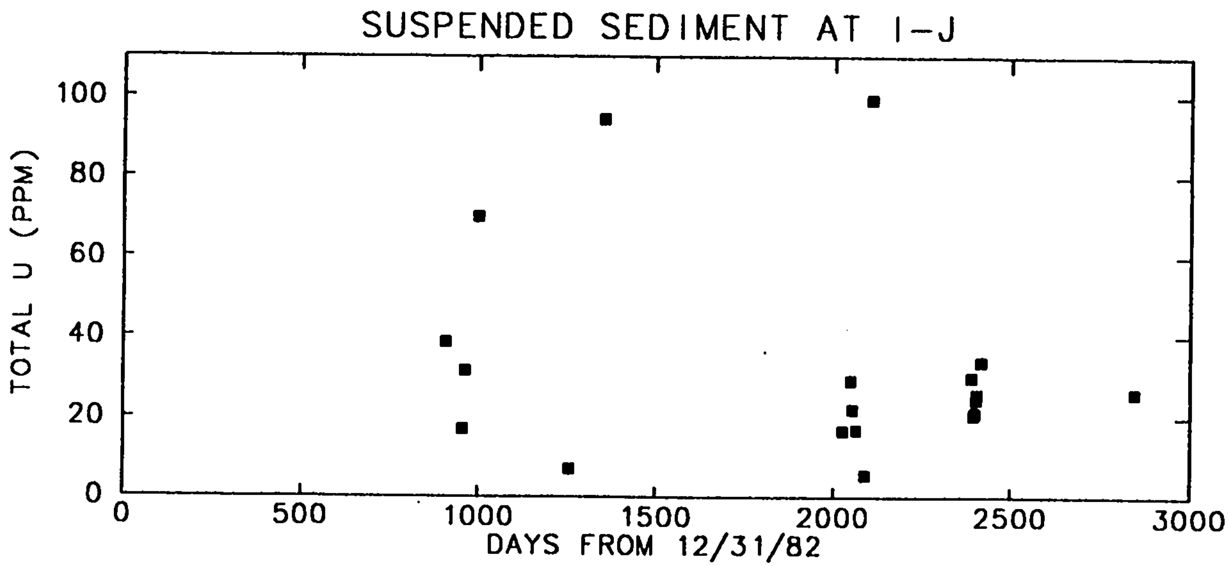



Fig 4.10 Total Uranium in Suspended Sediment in Runoff at I-J Cumulative Sampler Site.

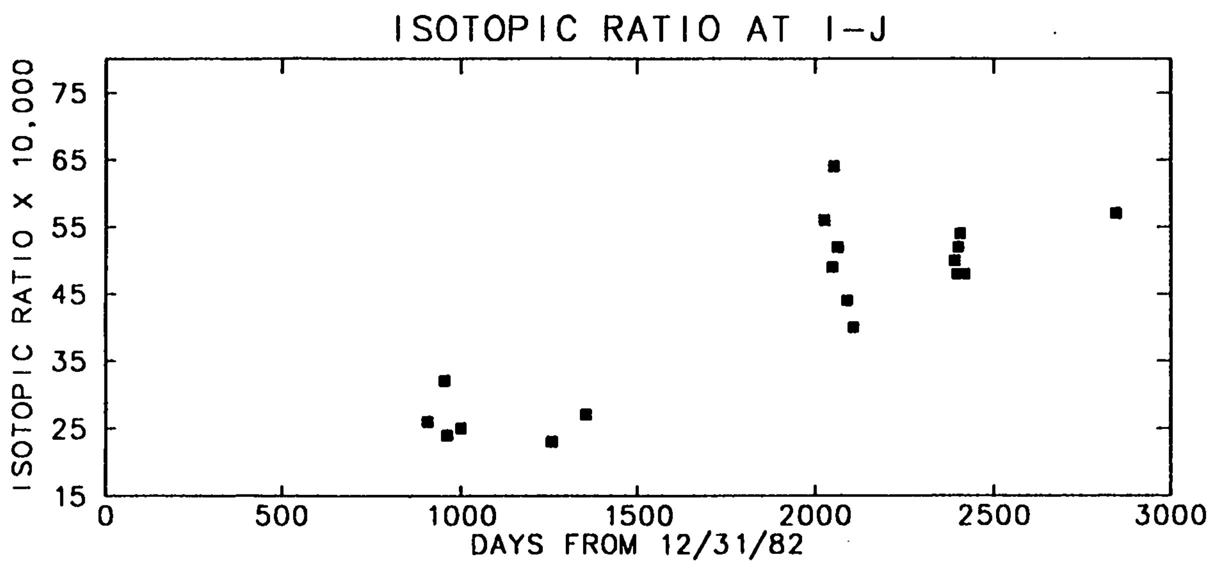



Fig 4.11 Isotopic Ratio of Suspended Sediment in Runoff at I-J Cumulative Sampler Site.

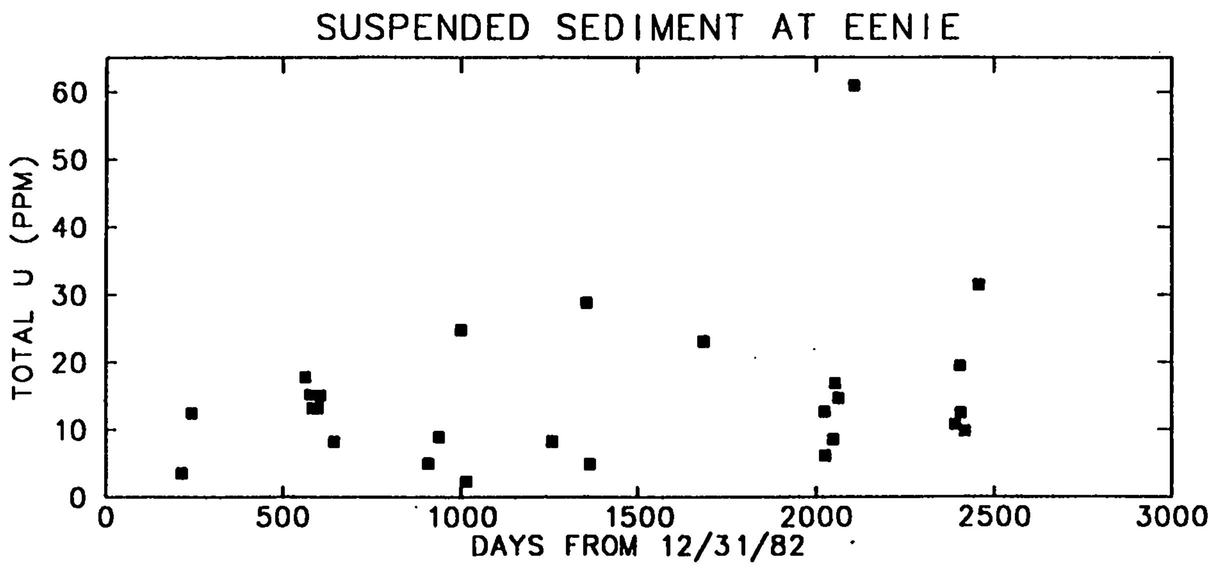



Fig 4.12 Total Uranium in Suspended Sediment in Runoff at Eenie Cumulative Sampler Site.

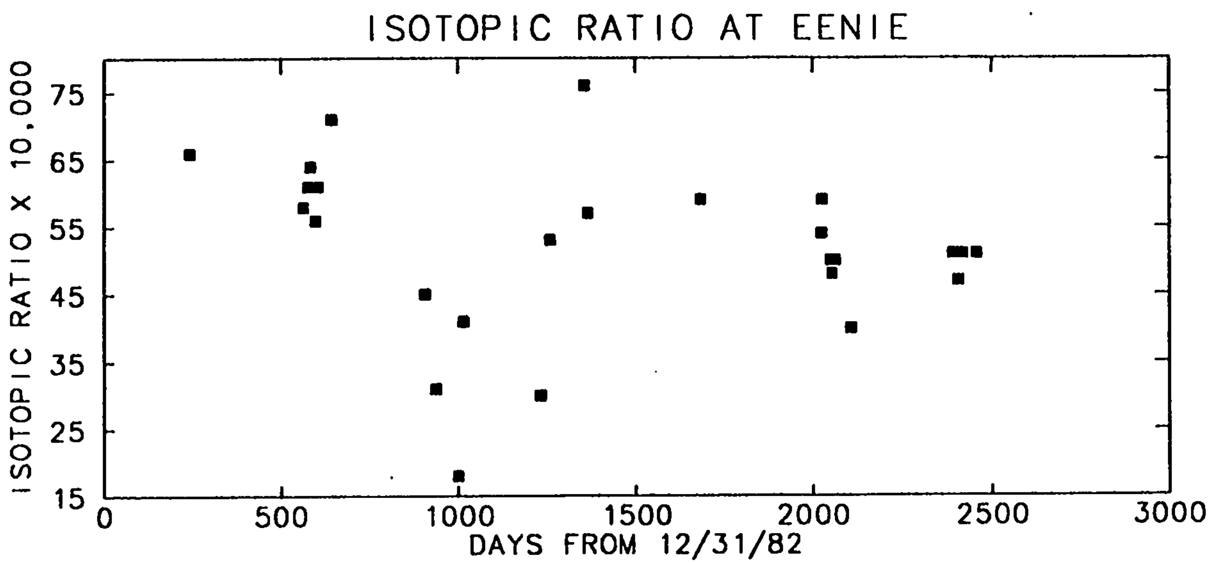



Fig 4.13 Isotopic Ratio of Suspended Sediment in Runoff at Eenie Cumulative Sampler Site.

The total uranium in suspended sediments collected at Skunk Works ranged from 1.1 to 20.3 µg/g, Fig 4.14, with a mean of 8.01 µg/g and a standard deviation of 5.9 µg/g. The isotopic ratio of these sediments ranged from 0.0026 to 0.0070, Fig 4.15. Through inspection of both the isotopic ratio and total uranium only 2 of the 15 samples could be considered within background values.

At State Road 4, total uranium in suspended sediments ranged from 0.5 to 114.4 µg/g, Fig 4.16, with a mean of 7.5 µg/g and a standard deviation of 22.3 µg/g. The isotopic ratio varied from 0.0019 (associated with 114.4 µg/g) to 0.0079, Fig 4.17. Only 3 samples of the 25 measured had isotopic ratios indicative of depleted uranium.

A number of conclusions can be drawn from these data. First, the large standard deviations for all data indicates the wide range in observed concentrations. Because there are no flow data associated with these concentrations available, it is not possible to separate out the flow magnitude effect on the uranium concentrations. Second, there is evidence of a decline in concentration with distance downstream from the top of the watershed, both in the dissolved and suspended sediment phases. Sizeable infiltration losses along the channel (estimated to be nearly 60 % of the hydrograph, discussed in Chapter 2, *Crest Stage Monitoring, Hyetographs and Hydrographs*) permits flow loss and results in deposition and storage of uranium in the fluvial deposits. Dilution by background sediment load and runoff also occurs along the watershed length; it is not possible to separate out these two effects.

All results were examined for trends with time using a non-parametric test of correlation, Kendall's Tau and a test of significance z. This technique

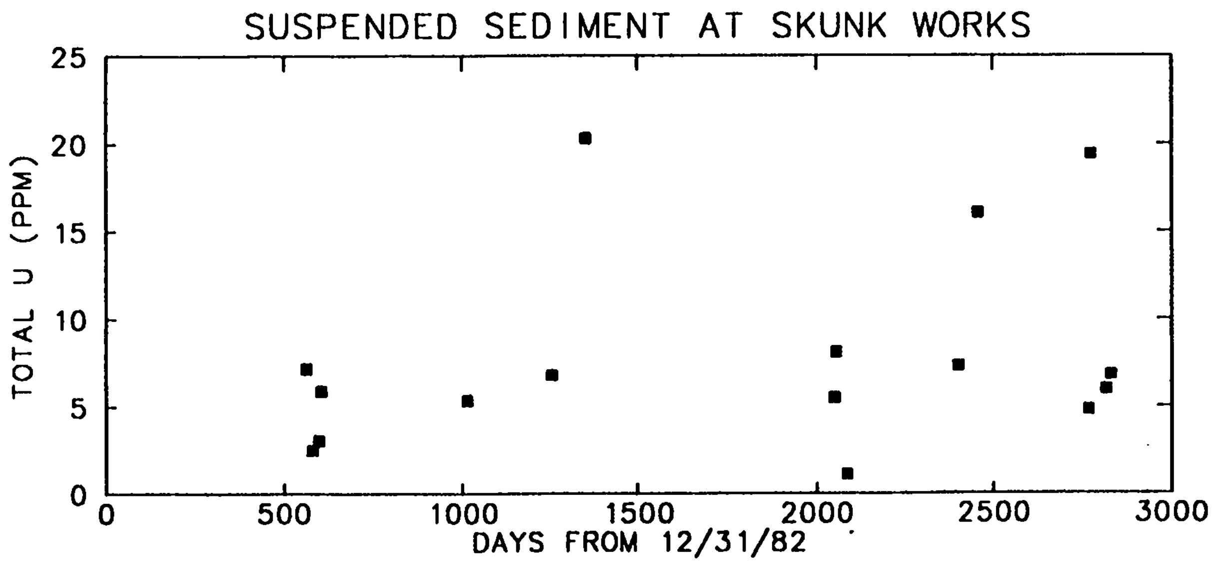



Fig 4.14 Total Uranium in Suspended Sediment in Runoff at Skunk Works Cumulative Sampler Site.

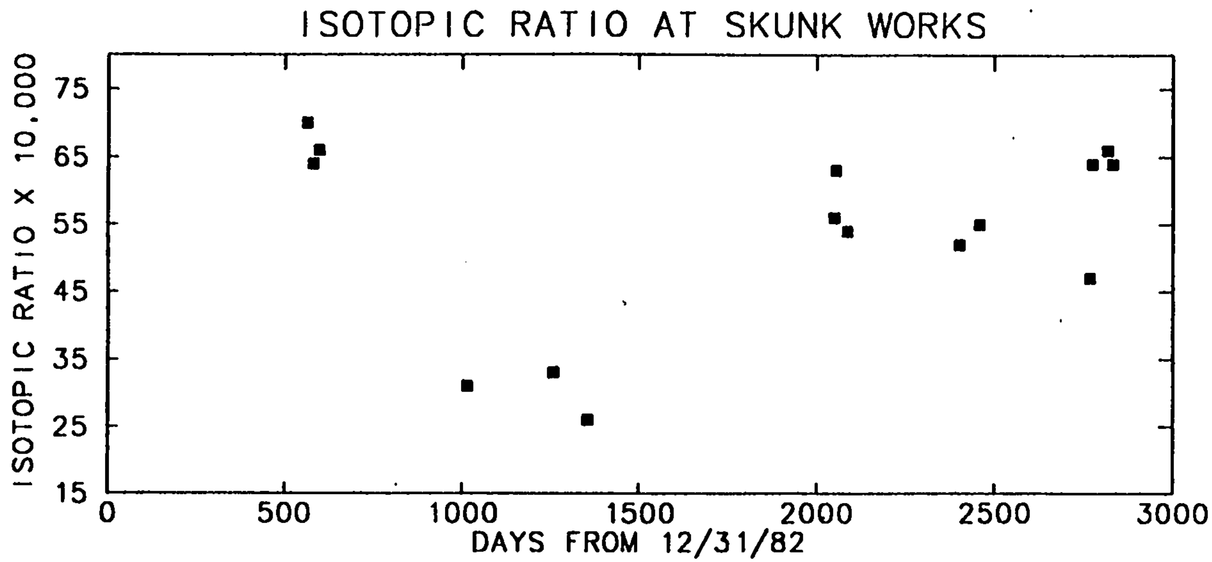



Fig 4.15 Isotopic Ratio of Suspended Sediment in Runoff at Skunk Works Cumulative Sampler Site.

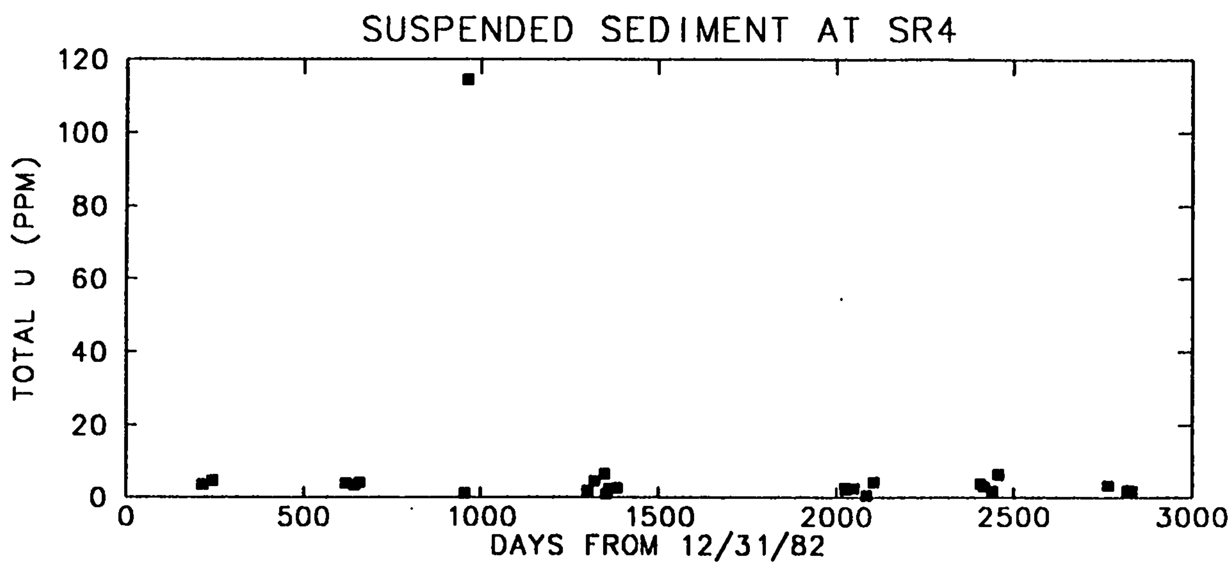



Fig 4.16 Total Uranium in Suspended Sediment in Runoff at State Road 4 Cumulative Sampler Site.

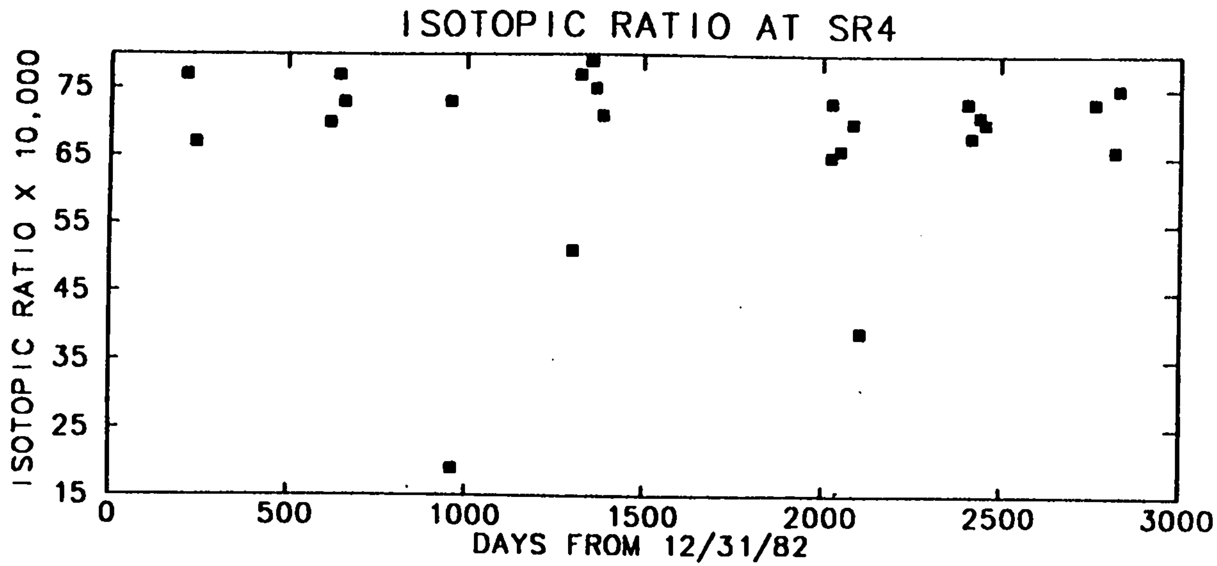



Fig 4.17 Isotopic Ratio of Suspended Sediment in Runoff at State Road 4 Cumulative Sampler Site.

has been used to examine water quality data for trend analyses (Hirsch and others, 1982). Kendall's Tau was computed for each set; the criteria for significance of a trend was that the probability for the trend being due to randomness was less than 10 percent.

Cases in which trends were observed were: uranium in sediment from E-F cumulative sampler; uranium in water from E-F cumulative sampler; uranium in water from I-J cumulative sampler; the isotopic ratio associated with the sediment from I-J cumulative sampler; and the isotopic ratio associated with the sediment at the Eenie site.

Uranium in suspended sediment at the E-F cumulative sampler is shown in Fig 4.8. There appeared to be a trend of increase in uranium with increasing time, with 4 chances in 100 that the observed tau is due to randomness.

Uranium in water at the E-F cumulative sampler is shown in Fig 4.3. There was a 7.5 percent chance that the observed tau value is due to randomness. The tau value was negative, implying that there is a general decline in uranium concentration in water with time at this site.

Uranium in water at the I-J cumulative sampler is shown in Fig 4.4. There was less than 1 percent chance that the observed tau was due to randomness. The tau value was negative, implying that there is a decline in uranium concentration with time.

Isotopic ratio of uranium in suspended sediment at I-J site is shown in Fig 4.11. There is a 1 percent chance that the observed tau was due to randomness and the tau value was positive, implying that the isotopic ratio at this site has been increasing in time.

The isotopic ratio of uranium in suspended sediment at Eenie site is shown in Fig 4.13. There was a 1.7 percent chance that the observed tau is due to randomness. The tau was negative, implying the isotopic ratio at Eenie site is declining.

In summary, it appears that the concentration of uranium in sediment at E-F site is increasing with time, that the uranium concentration in runoff water is declining with time at the cumulative samplers at E-F site and I-J site, that the isotopic ratio of suspended sediments at I-J site is increasing, and that the isotopic ratio of suspended sediments at Eenie site is declining. This suggests that there may be a trend in long-term movement of contaminants away from E-F and I-J cumulative sampler sites toward the Eenie cumulative sampler site, which is interpreted to mean surface water transport and fluvial deposition are actively modifying the spatial distribution of uranium in the watershed.

*Uranium Transport in Snowmelt*

Snowmelt samples were collected in the spring of 1985, 1986 and 1987 to study uranium transport by snowmelt. Snowmelt discharge in general tends to be small with a water depth of less than 1 cm in the channel. During years of light snowpack or when snowfall occurs primarily in the spring months, there may be no snowmelt runoff in the channel. This was the case during 1989 and 1990. The reason for light to no runoff is that the snow sublimates or melts and infiltrates or evaporates before reaching the channel, or melts and reaches the channel but infiltrates into the channel without creating continuous streamflow. Snowmelt was collected in the main channel below E-F site, below I-J site, near Eenie site, at Skunk Works, and at State Road 4, Fig 4.18. Samples of running water were collected and

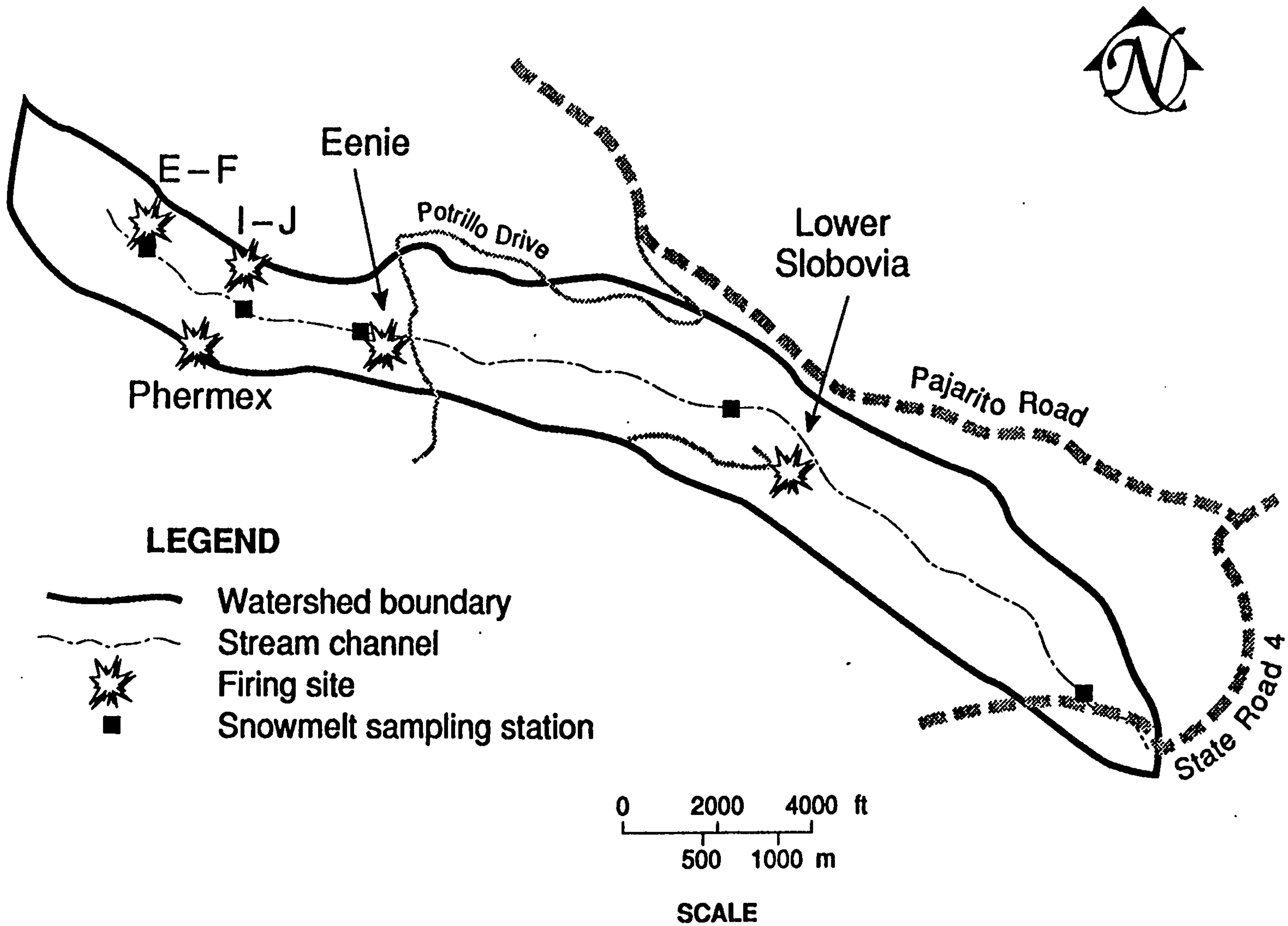



Fig 4.18 Location of Snowmelt Sampling Stations.

analyzed for total uranium in the dissolved fraction and for total uranium and isotopic ratio of the suspended sediment, Tables 4.3 and 4.4.

Results from analyses of the dissolved component showed high levels of dissolved uranium at the E-F and I-J locations in all cases. Concentrations of dissolved uranium were lower by about an order of magnitude at the Eenie location, (mostly 3-6 ppb), but still above background levels of about 1 ppb. Dissolved uranium levels were elevated at Skunk Works, with 1.5 and 5 ppb measured. At State Road 4, the dissolved uranium concentrations were at background levels.

Results from the uranium associated with the suspended sediment component followed a similar pattern. Total uranium in sediment values at the E-F location were 85 and 119 µg/g, which were of the same magnitude as suspended sediment transported during summer runoff events. The isotopic ratio of 0.0067 and 0.0066 for these samples may indicate natural uranium as the source of contamination. The total uranium content dropped to 28 µg/g at the I-J location, and contained depleted uranium, with an isotopic ratio of 0.0052. Samples collected at Eenie were mostly within background values although there was one sample of 133 µg/g and another at 36 µg/g. In quite a few instances, total uranium values were not available due to analytical chemistry difficulties and are designated NA in Table 4.4. However, the isotopic ratios of all Eenie samples ranged from 0.0022 to 0.0064, indicating the presence of depleted uranium. Results from two samples collected at Skunk Works indicated low total uranium levels, with depleted uranium present (isotopic ratios of 0.0020 and 0.0045).

TABLE 4.3

DISSOLVED URANIUM IN SNOWMELT
(ppb)

| Location | Date | Total Uranium |
|---|---|---|
| Below E-F Site | 5-3-85 | 15.8 |
| | 5-29-87 | 60.0 |
| Below I-J Site | 5-29-87 | 34.0 |
| Below Eenie Site | 3-5-85 | 3.6 |
| | 3-13-85 | 3.4 |
| | 3-18-85 | 3.5 |
| | 3-27-85 | 3.9 |
| | 4-1-85 | 3.9 |
| | 4-10-85 | 3.2 |
| | 4-16-85 | 6.5 |
| | 4-22-85 | 4.5 |
| | 5-2-85 | 5.6 |
| | 5-6-85 | 6.2 |
| | 3-25-86 | <1.0 |
| | 4-4-86 | 0.5 |
| | 5-29-87 | 3.0* |
| | 5-29-87 | 27.0 |
| Skunk Works | 3-28-85 | 1.5 |
| | 5-3-85 | 5.0 |
| State Road 4 | 4-1-85 | 0.6 |
| | 5-9-85 | 0.4 |

* Ponded

TABLE 4.4

URANIUM IN SUSPENDED SEDIMENTS IN SNOWMELT
(μg/g)

| Location | Date | Total Uranium | Isotopic Ratio |
|---|---|---|---|
| Below E-F Site | 5-3-85 | 85.1 | 0.0067 |
| | 5-29-87 | 118.7 | 0.0066 |
| Below I-J Site | 5-29-87 | 28.2 | 0.0052 |
| Below Eenie Site | 3-13-85 | 2.60 | 0.0044 |
| | 3-18-85 | 4.03 | 0.0027 |
| | 4-1-85 | NA | 0.0037 |
| | 4-10-85 | NA | 0.0050 |
| | 4-16-85 | NA | 0.0022 |
| | 4-22-85 | NA | 0.0056 |
| | 5-2-85 | NA | 0.0025 |
| | 5-6-85 | NA | 0.0055 |
| | 3-25-86 | <1.0 | 0.0022 |
| | 4-4-86 | 2.2 | 0.0064 |
| | 5-29-87 | 132.9* | 0.0026* |
| | 5-29-87 | 35.7 | 0.0025 |
| Skunk Works | 3-28-85 | 1.76 | 0.0045 |
| | 5-3-85 | NA | 0.0020 |
| State Road 4 | 4-1-85 | NA | 0.0053 |
| | 5-9-85 | NA | 0.0069 |

* Ponded

Suspended sediment in snowmelt at State Road 4 showed the presence of depleted uranium in one sample in 1985 and no depleted uranium in the other. Total uranium results were not available at this station for the same reason as at the Eenie location.

Samples collected at the Eenie location present the most complete suite of uranium variation in snowmelt runoff during a snowmelt season. Weekly snowmelt samples were collected during the months of March and April and part of May, 1985. Due to analytical chemistry problems, only a complete history of the dissolved uranium and the isotopic ratios are available. Examining the dissolved phase, there was a discernable rise in the dissolved uranium concentration at Eenie as the snowmelt season progressed. The concentration at the beginning of March was 3.6 ppb. This level continued through to the end of March, and rose to 3.9 ppb at the end of March and beginning of April. The concentration fell to 3.2 ppb at the beginning of the second week in April and then rose to 6.5 ppb by the middle of April. There was fluctuation in the concentration between 4.5 and 6.2 ppb until the end of collection on May 6. Unfortunately, there is no total uranium in sediments data to compare this observed trend in the dissolved phase.

A number of possibilities may explain the observed rise. It could be due to the length of time of runoff duration which permitted increased uranium leaching into the snowpack from contaminated soil and sediment particles. There could be an apparent increase in the uranium concentration due to concentrating effects in the declining volume of snowmelt as the season progressed. Or, the rise could be due to the delayed effect of snowmelt flushing through the contaminated surface layer by infiltration creating an interflow which reached the channel later than overland flow from direct snowmelt.

*Leaching Investigations*

Leaching investigations were conducted on a channel sediment sample collected in the main channel below the I-J firing site in 1990, Fig 4.19. The purpose of this investigation was to examine rates of uranium leaching from contaminated sediments by rainwater. In particular,, leaching rates from individual particle sizes were of interest to determine if there were differences present due to particle size. A sample split was made; one-half of the sample was sieved into 8 particle fractions. These fraction were pebbles (#4 sieve), granules (#10 sieve), coarse sand (#20 sieve), medium sand (#40 sieve), medium-to-fine sand (#60 sieve), fine sand (#100 sieve), very fine sand (#200 sieve), and the pan fraction, which represented silt and clay. Each fraction was washed to remove silt and clay adhering to larger particles. Water and suspended sediments from the washing water were collected and analyzed. The washing water had a dissolved uranium concentration of 2.1 ppb, while the suspended sediment had a uranium concentration of 86.1 μg/g and an isotopic ratio of 0.0048.

For the leaching study deionized water was adjusted to a pH of 4.65 to 4.75 to simulate the pH of natural rainwater measured in the Los Alamos area. Ten grams of sample in each particle size was mixed with 1200 ml of the pH-adjusted water and then placed in a rotating horizontal mixer. There was insufficient sample in the pebble and pan fractions to make up 10 g samples; 6.3 g and 8.5 g samples,

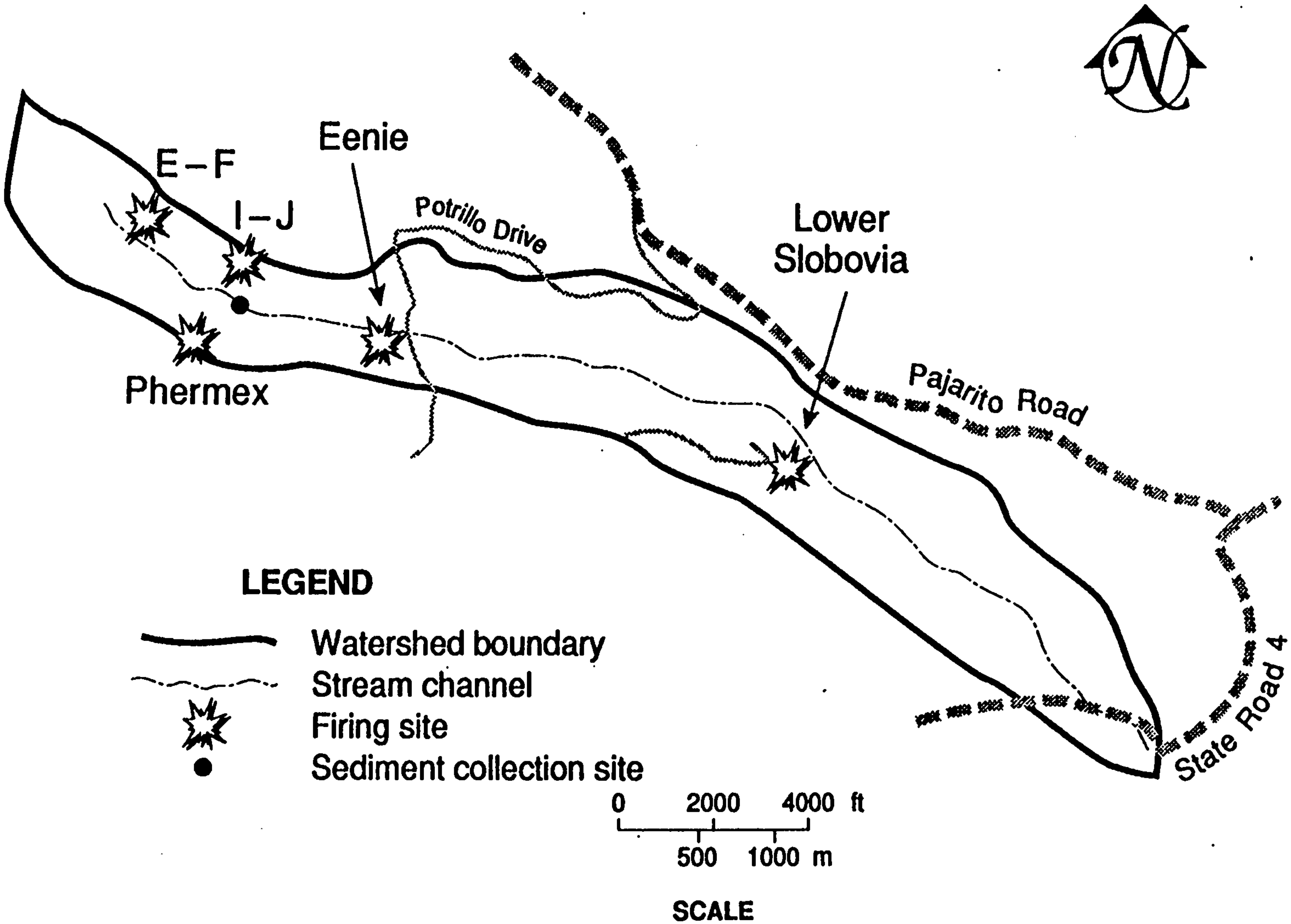



Fig 4.19 Location of Channel Sediment Used in the Leaching Experiment.

respectively, were used. An undifferentiated sediment sample was used as the 9th leaching sample to determine the combined grainsize case.

The sediment-water solutions were continuously mixed, except during the designated collection times when the mixers were stopped. The collection schedule in hours after the beginning of mixing was 1 hr, 2 hr, 4 hr, 8 hr, 24 hr, 48 hr (2 days), 96 hr (4 days), 192 hr (8 days), and 216 hr (9 days). Fifty ml of solution were collected and immediately drawn through a 0.45 micron filter in order to separate the sediment and halt the dissolution reaction. The filtered water was then submitted for total uranium analyses. There were insufficient volumes for isotopic ratio analyses.

The results for the leaching experiment are graphed in Figs 4.20 through 4.28. The limits of detection were 1 ppb. Data points of zero were used to designate results that were below the limits of detection. The level of uncertainty for all samples was +/- 1 ppb.

Fig 4.20 shows the results for the undifferentiated sample. The initial concentration of the sample was 1.89 μg/g of soil and the isotopic ratio was 0.0060, indicating the presence of depleted uranium. The dissolved uranium concentration was 3 ppb after the first hour. The concentration then dropped to 1 ppb, rose to 2 ppb after 8 hours, and attained steady-state of 1 ppb after 24 hr.

Fig 4.21 shows the results for the pebble size fraction. The initial concentration of the sediment was 5.82 μg/g soil and the isotopic ratio was 0.0058, indicating the presence of depleted uranium. The dissolved uranium concentration after 1 hour was 3 ppb, dropped to 2 ppb at 2 hour and 4 hours, rose to 3 ppb at

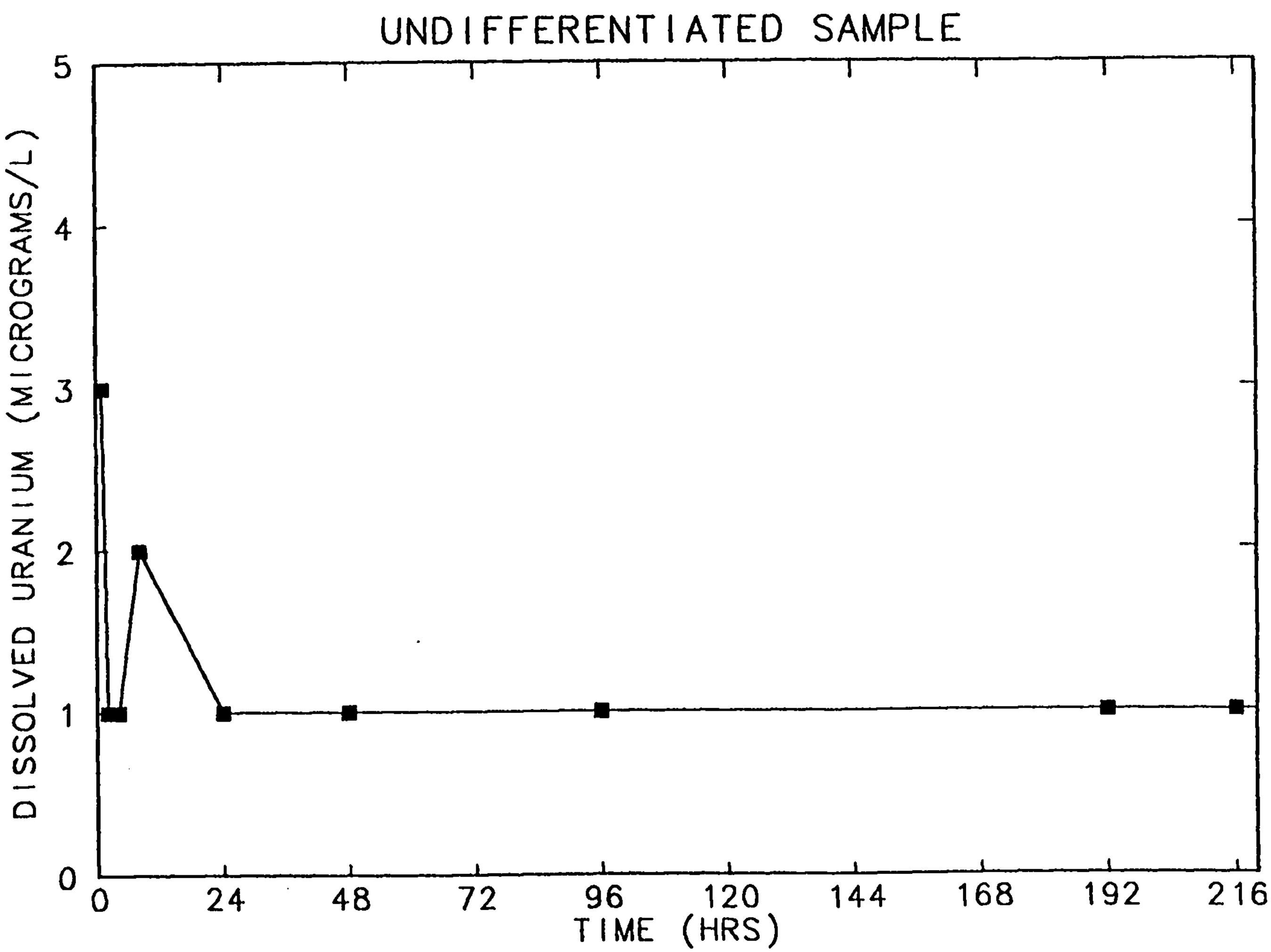



**Fig 4.20 Uranium Dissolution in the Undifferentiated Fraction.**

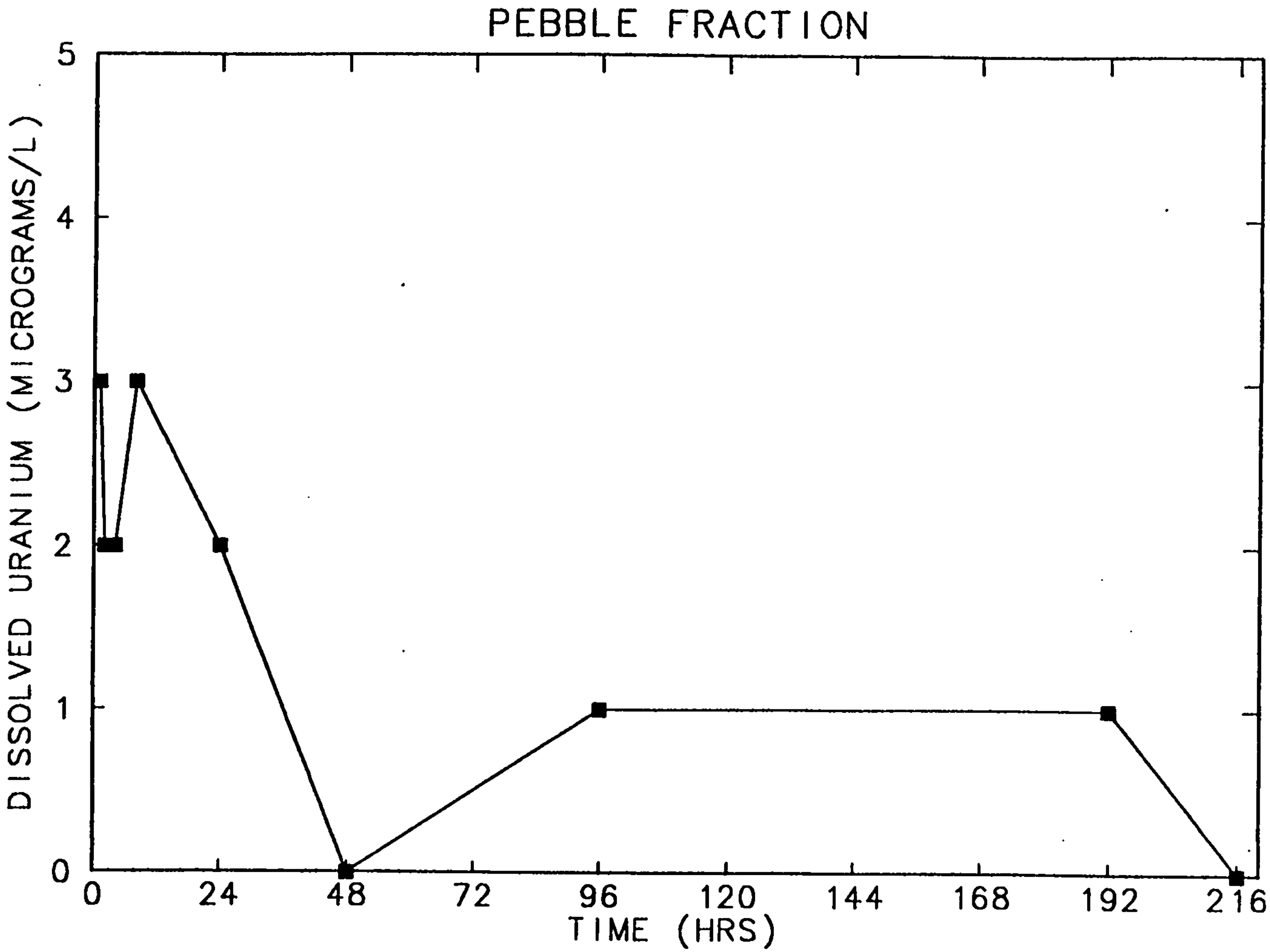



Fig 4.21 Uranium Dissolution in the Pebble Fraction.

8 hours, and then achieved a steady-state of about 1 ppb at 48 hours.

Fig 4.22 shows the results for the granule fraction. The initial concentration of the sediment was 3.92 μg/g of soil and the isotopic ratio was 0.0061, indicating the presence of depleted uranium. The dissolved uranium concentration was 4 ppb after 1 hour, dropped to 2 ppb until 48 hours, and then dropped to a steady state value of 1 ppb, assumed to be steady-state.

Fig 4.23 shows the results for the coarse sand fraction. The initial concentration of the sediment was 1.83 μg/g of soil, and the isotopic ratio was 0.0060, indicating the presence of depleted uranium. The dissolved uranium concentration was 2 ppb after 1 hour, dropped to 1 ppb after 2 and 4 hours, rose to 2 ppb after 8 hours, dropped to 1 ppb after 24 hours, rose to 2 ppb after 48 and 96 hours, and then dropped to 1 ppb after 192 hours, and then dropped below the detection limits. It appears that steady-state was not achieved until 192 hours.

Fig 4.24 shows the results for the medium sand fraction. The initial concentration was 3.1 μg/g of soil, and the isotopic ratio was 0.0057, indicating the presence of depleted uranium. The dissolved uranium concentration rose slowly from 1 to 2 to 3 ppb after 48 hours, then slowly declined to 1 ppb after 192 hours. At 216 hours, the level of dissolved uranium dropped below the detection limits.

Fig 4.25 shows the results for the medium-to-fine sand fraction. The initial concentration was 17.6 μg/g of soil, and the isotopic ratio was 0.0055, indicating the presence of depleted uranium. The dissolved uranium concentration was 3 ppb after

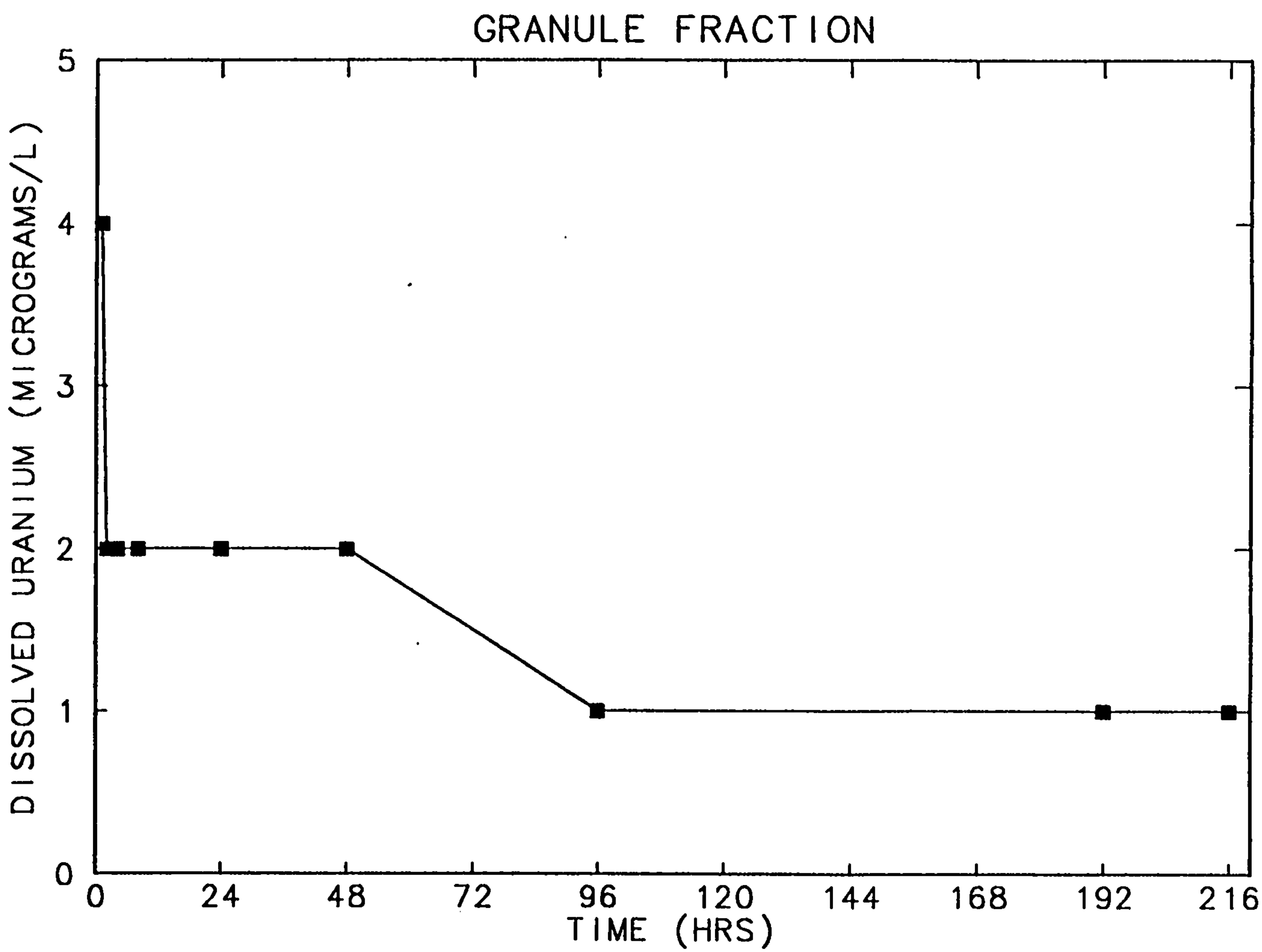



Fig 4.22 Uranium Dissolution in the Granule Fraction.

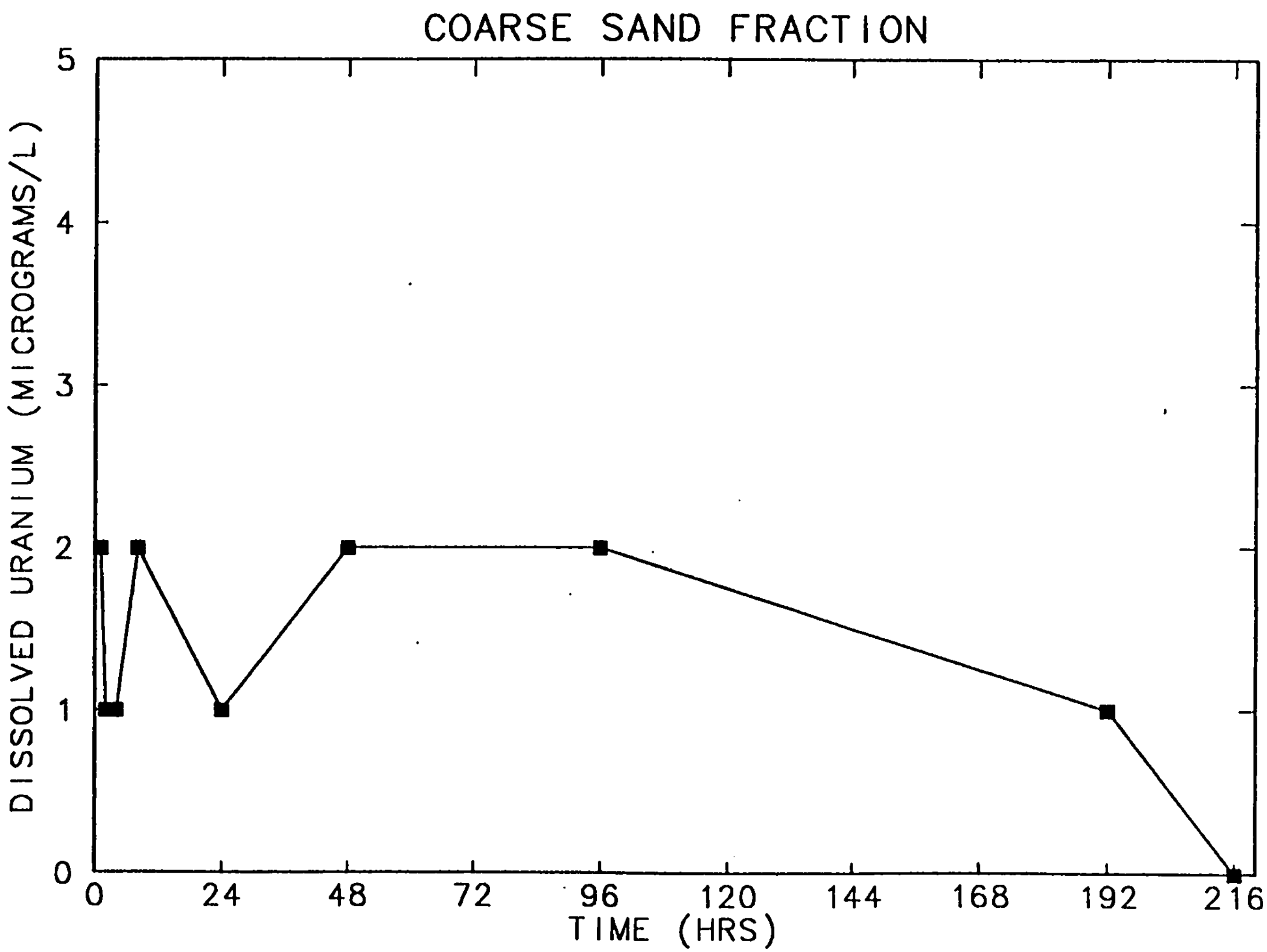



Fig 4.23 Uranium Dissolution in the Coarse Sand Fraction.

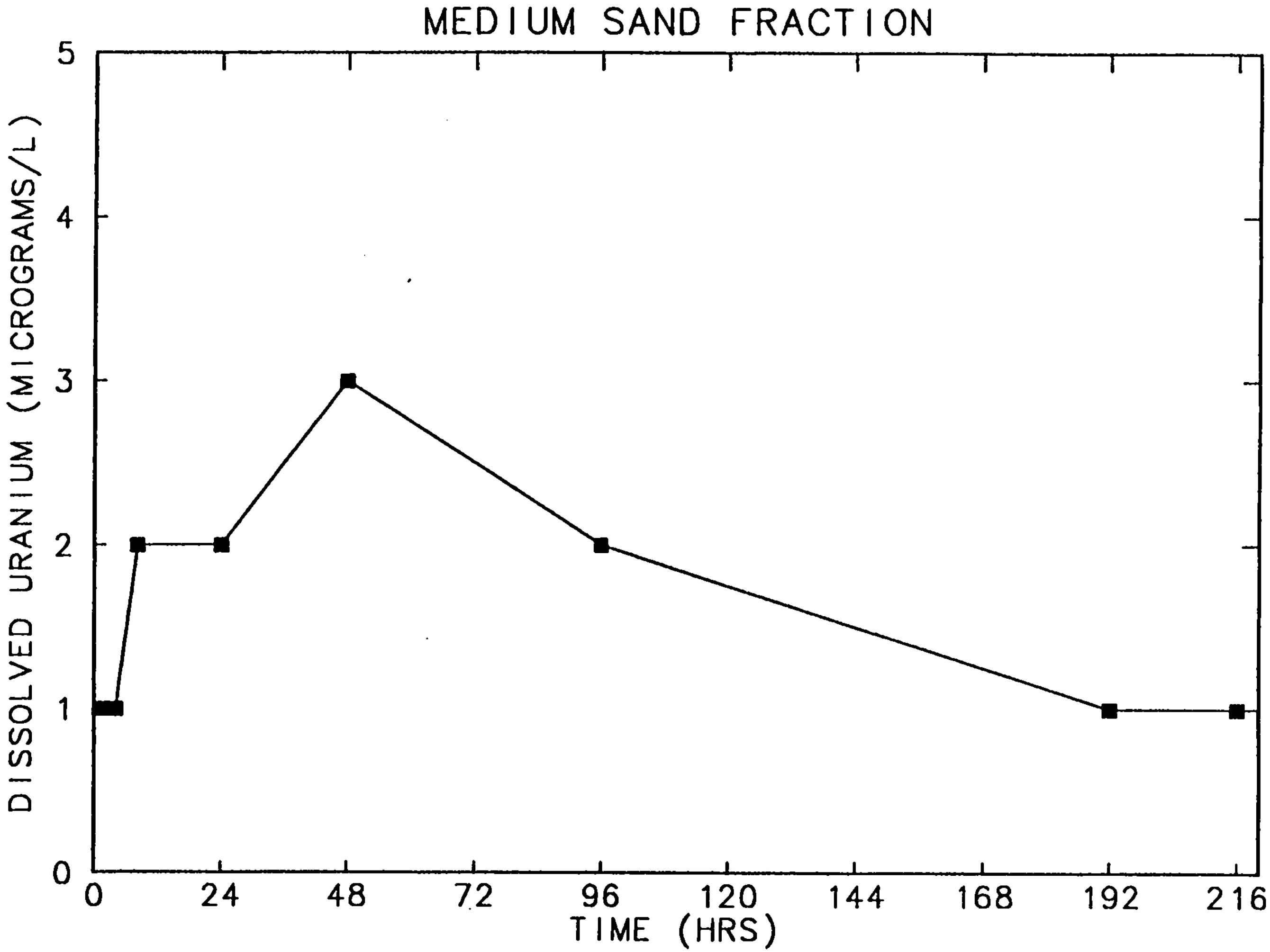



Fig 4.24 Uranium Dissolution in the Medium Sand Fraction.

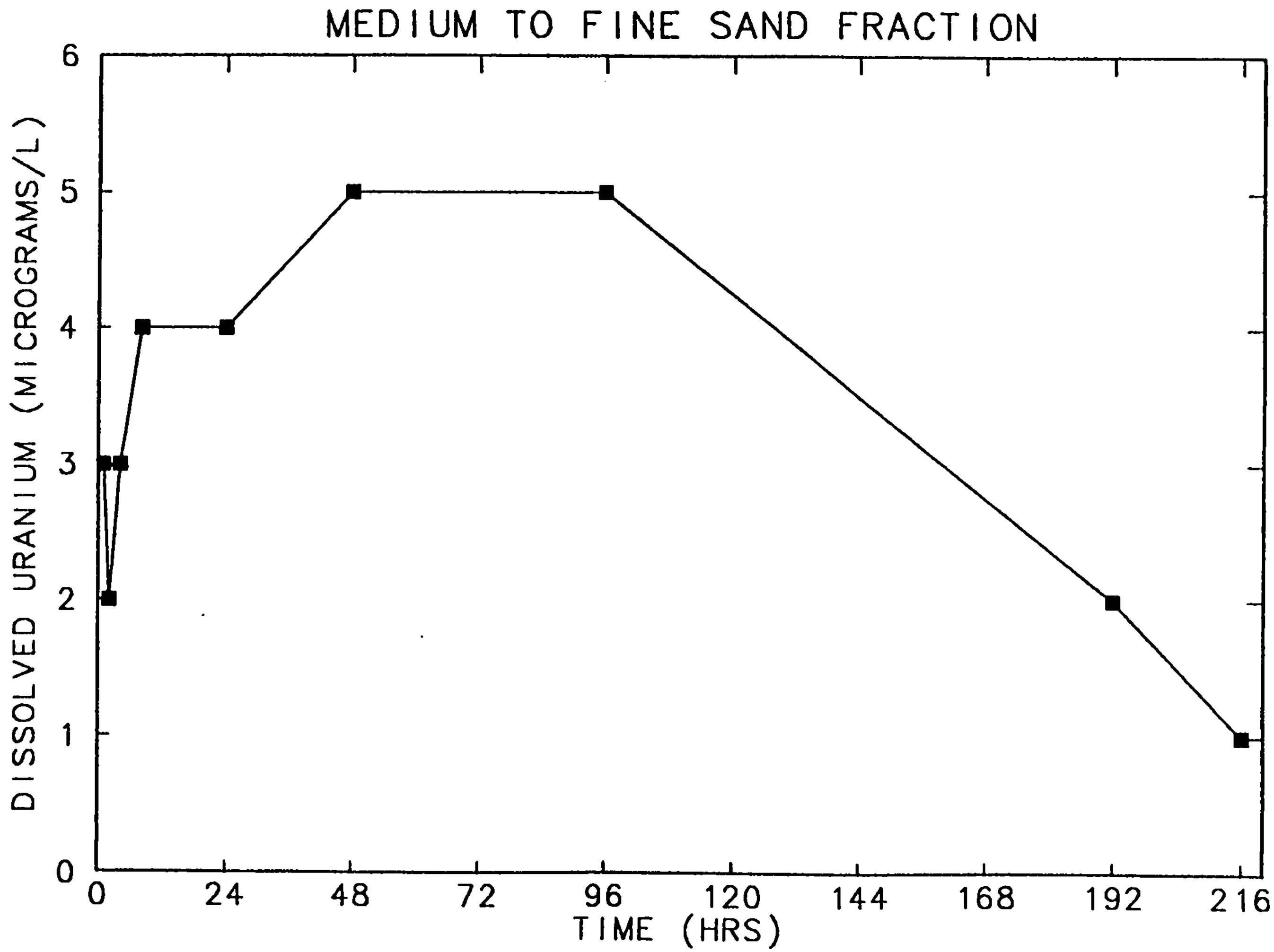



**Fig 4.25 Uranium Dissolution in the Medium to Fine Sand Fraction.**

1 hour, fell to 2 ppb after 2 hour, then rose to 5 ppb for 48 and 96 hours, then fell to 2 ppb after 192 hours, and then 1 ppb after 216 hours.

Fig 4.26 shows the results for the fine sand fraction. The initial concentration was 4.05 μg/g of soil and the isotopic ratio was 0.0049, indicating the presence of depleted uranium. The dissolved uranium concentration was 2 ppb for 1 and 2 hours, fell to 1 ppb after 4 hours, rose to 3 ppb after 8 hours, fell to 2 ppb after 24 hours, rose to 3 ppb after 48 hours, and then slowly fell to 1 ppb after 192 hours, which was assumed to be steady-state.

Fig 4.27 shows the results from the very fine sand fraction. The initial concentration was 10.2 μg/g of soil, and the isotopic ratio was 0.0053, indicating the presence of depleted uranium. The dissolved uranium concentration was 3 ppb after 1 and 2 hours, rose to 5 ppb after 8 hours, slowly dropped to 3 ppb at 96 hours and finally to a steady-state of 1 ppb after 192 hours.

Fig 4.28 shows the results from the silt and clay fraction (pan). The initial concentration was 18.5 μg/g of soil, and the isotopic ratio was 0.0047, indicating the presence of depleted uranium. The dissolved uranium concentration was 3 ppb after 1 hour, dropped to 2 ppb at 2 and 4 hours, rose to 4 ppb at 8 hours, and then slowly dropped to 2 ppb at 192 hr, the assumed steady-state level.

Although the levels of dissolved uranium were not highly elevated, a number of conclusions can be drawn. Depleted uranium was present. In general, more uranium leached into solution from samples with elevated initial concentrations. At the beginning of the leaching study, the solution is assumed to be undersaturated with respect to uranium. Uranium will leach from the particulates (solid phase) to the dissolved phase until an equilibrium between the two phases is reached. When this

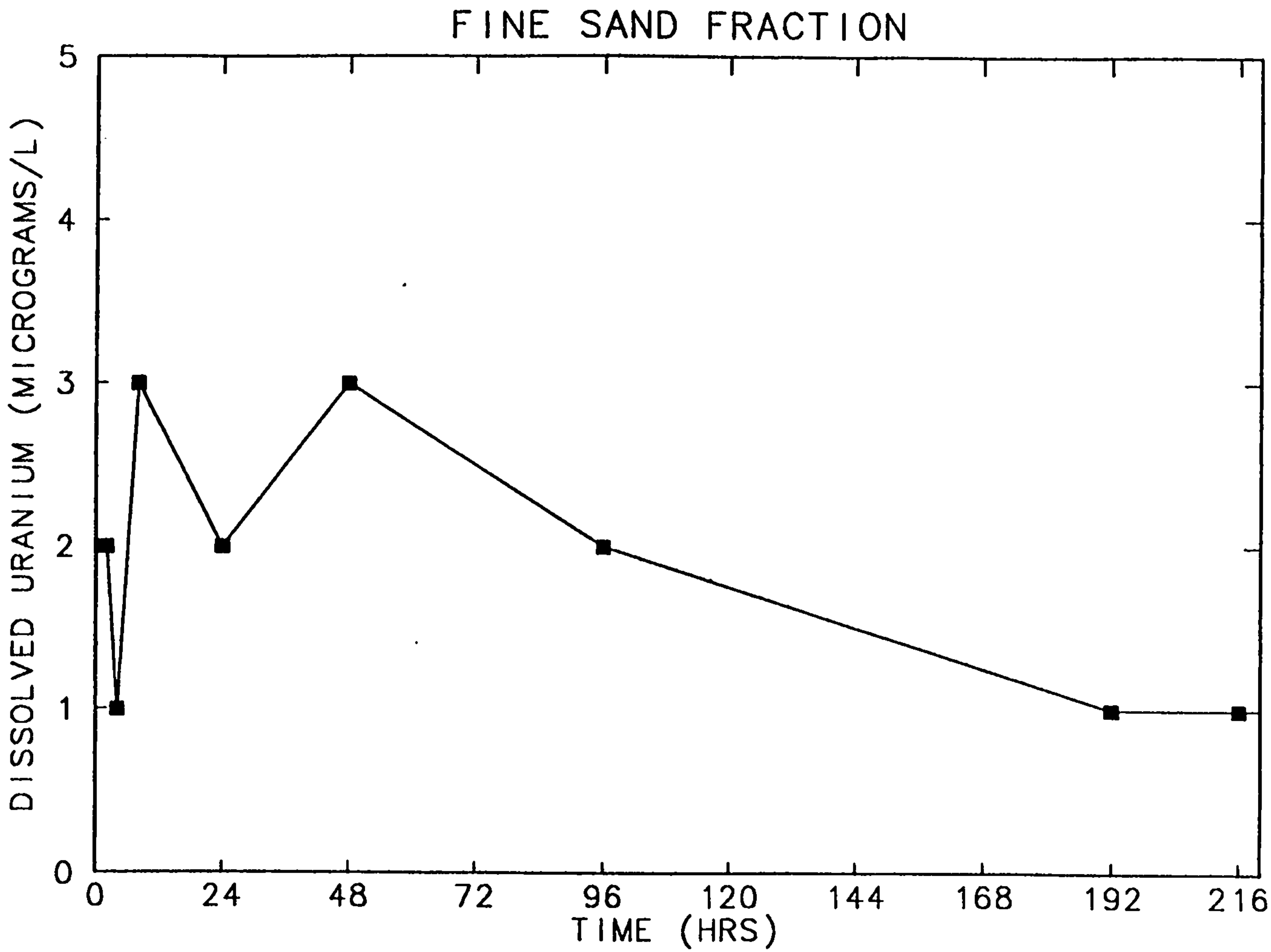



Fig 4.26 Uranium Dissolution in the Fine Sand Fraction.

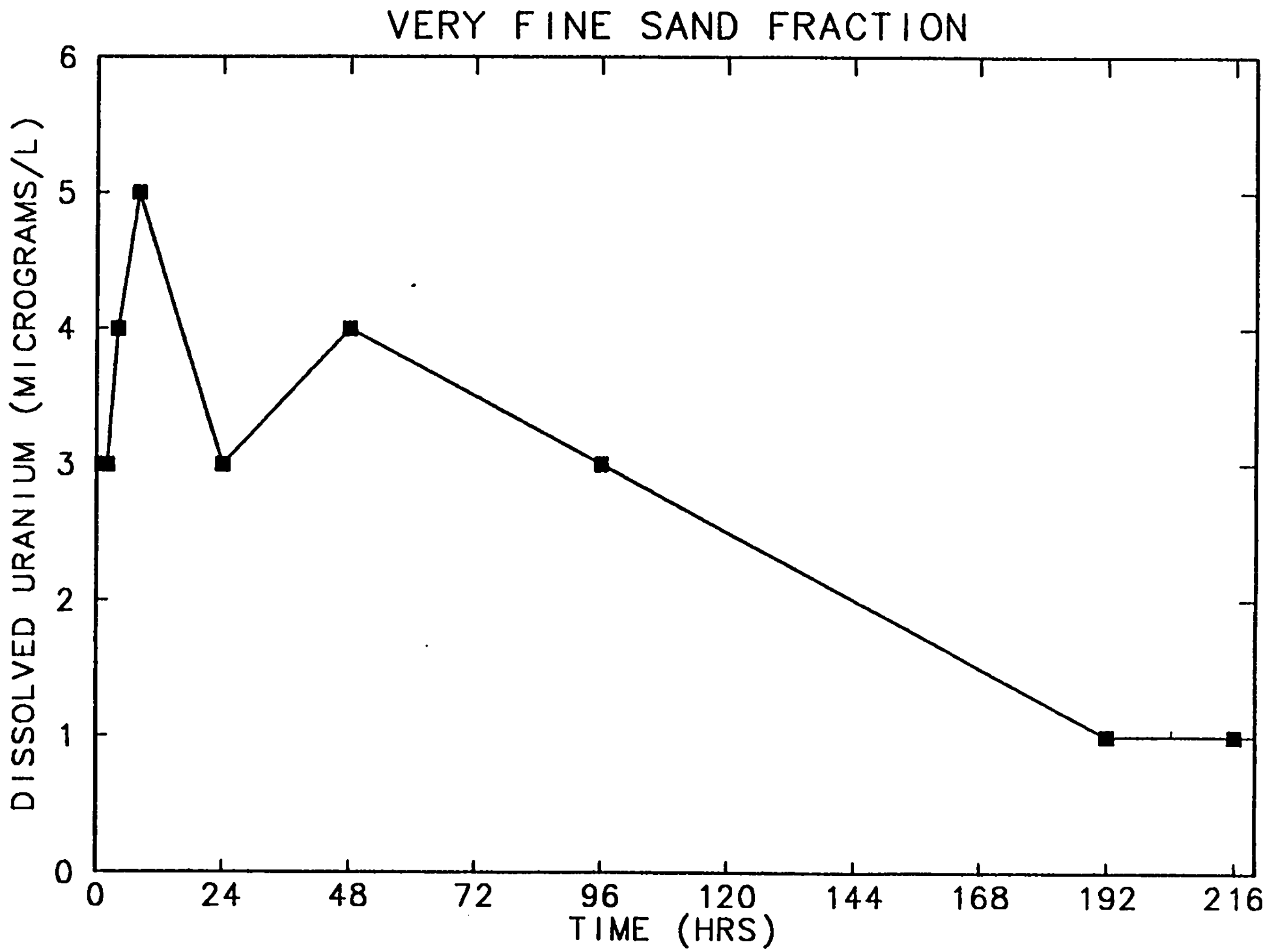



Fig 4.27 Uranium Dissolution in the Very Fine Sand Fraction.

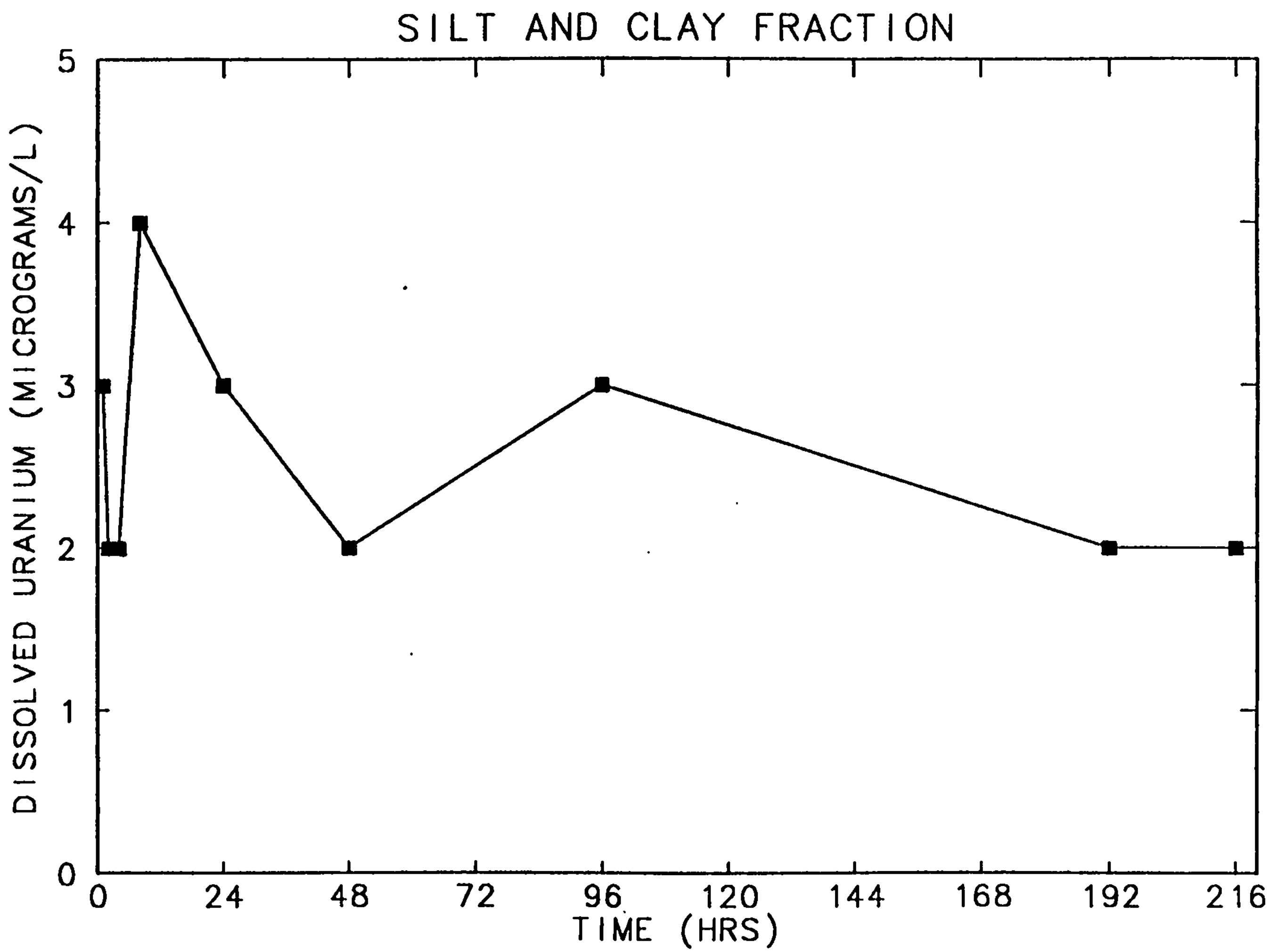



Fig 4.28 Uranium Dissolution in the Silt and Clay Fraction.

steady-state condition is reached no further change in the uranium concentration with time is expected. Decline in uranium concentration after steady-state is achieved can be attributed to other effects, e.g. biologic uptake. In this study, the smaller particle size fractions had the highest, initial total uranium concentrations, and correspondingly, the highest dissolved uranium in solution. The largest initial sediment concentration was 18.5 μg/g, and the highest dissolved uranium concentrations was 5 ppb in the medium-to-fine and very fine particle fractions. Smaller particle sizes, in general, have higher initial concentrations than larger particles, and can therefore dissolve more uranium.

Second, most of the uranium dissolution occurred within the first four days of mixing, and much occurred during the first 24 hours. The samples were highly diluted, with 10 g of sediment in 1.2 L of water, and therefore this effect is subtle. These two effects can be seen more dramatically in leaching results from a clayey soil collected inside a dynamic testing area at Eglin Air Force Base in Florida, Fig 4.29. This soil, which was not subdivided into individual particle sizes, registered an initial total uranium concentration of 451 μg/g. Within the second hour of the leaching experiment, the dissolved uranium concentration rose to over 3000 ppb and remained at that level for 4 days (Becker and Vanta, in preparation). The larger initial concentrations in the soil resulted in larger concentrations in the dissolved phases at steady-state compared to samples having lower initial uranium concentrations.

Third, steady-state was achieved in the I-J channel sediments after 4 days in most instances and by 8 to 9 days in all instances. The implication is that given a

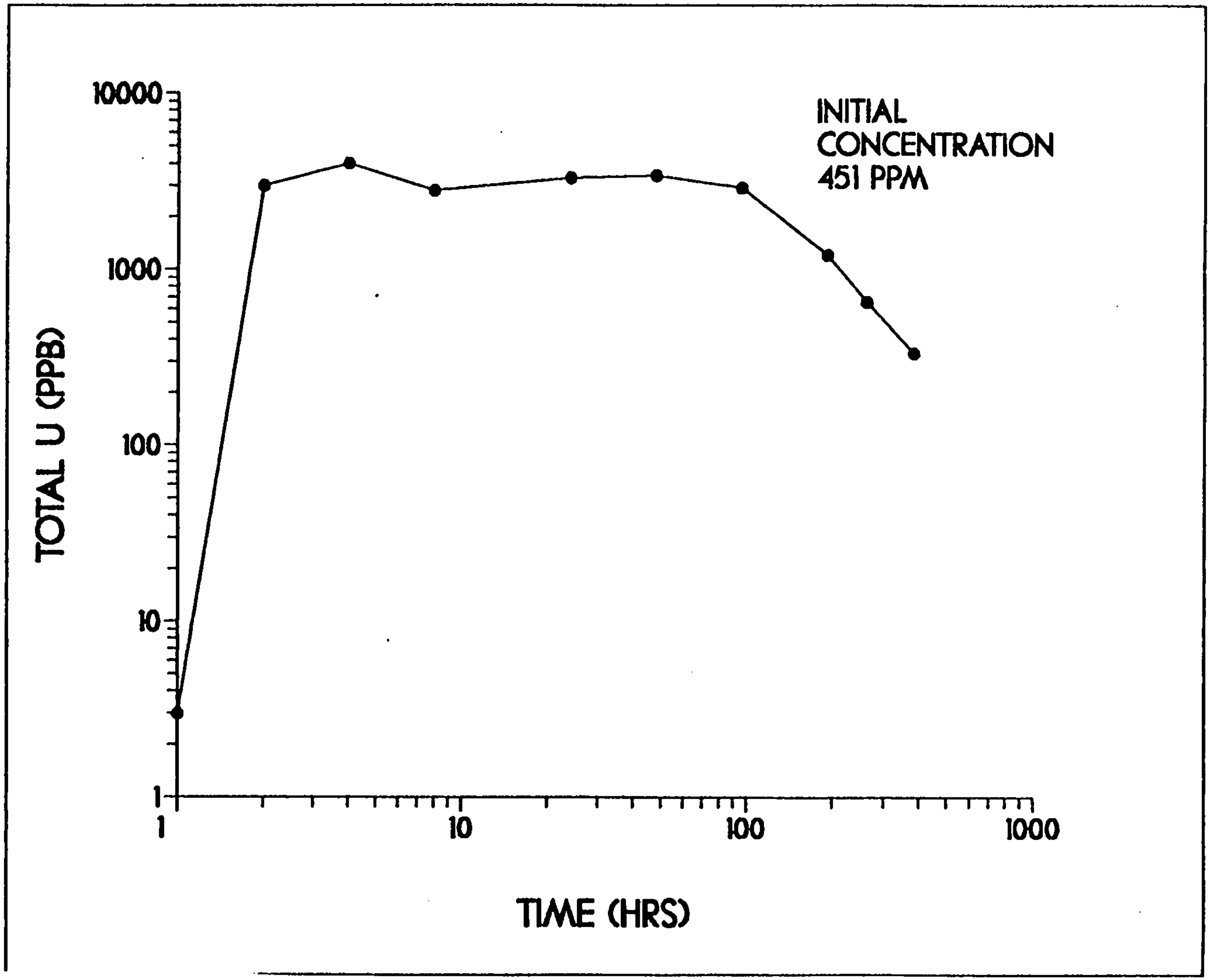



Fig 4.29 Uranium Dissolution from Soil at Test Area C-64, Eglin Air Force Base, Florida.

sufficient supply of uranium in a soil, infiltrating water from precipitation can dissolve the uranium and mobilize it for surface or subsurface transport. In an area of elevated uranium in a soil, elevated levels of uranium moving in the dissolved phase towards the water table would be expected.

*Grainsize Distribution Studies*

Grainsize distributions were performed on firing site samples randomly collected at Minie firing site, I-J firing site, and at the Sled Track at Lower Slobovia, Fig 4.30. The purpose of this sampling was to define the level of total uranium in individual particle sizes in order to characterize the source term. Each sample was sieved through a nest of 7 screens. The screen sizes in mm were 8, 2, 0.84, 0.42, 0.25, 0.149, and 0.074, corresponding to screen numbers 4, 10, 20, 40, 60, 100, and 200. The grain descriptions corresponding to these screens are pebbles, coarse sand/granule, coarse sand, medium sand, medium fine sand, fine sand, and very fine sand, respectively. Material which passed the #200 screen was collected in a pan (referred to as Pan).

Each fraction was weighed before analyzing for total uranium and isotopic ratio. Sieves #4 and 10 were grouped together under the category "gravel", sieves #20, 40, 60, 100, and 200 were grouped under the category "sand", and the Pan fraction was called "silt/clay". The percent of each fraction at firing sites is shown in Fig 4.31. The majority of material at each firing site fraction is sand, comprising between 70 and 80 percent of each sample. Gravel makes up between 18 and 20 percent, and the silt/clay fraction, less than 10 percent.

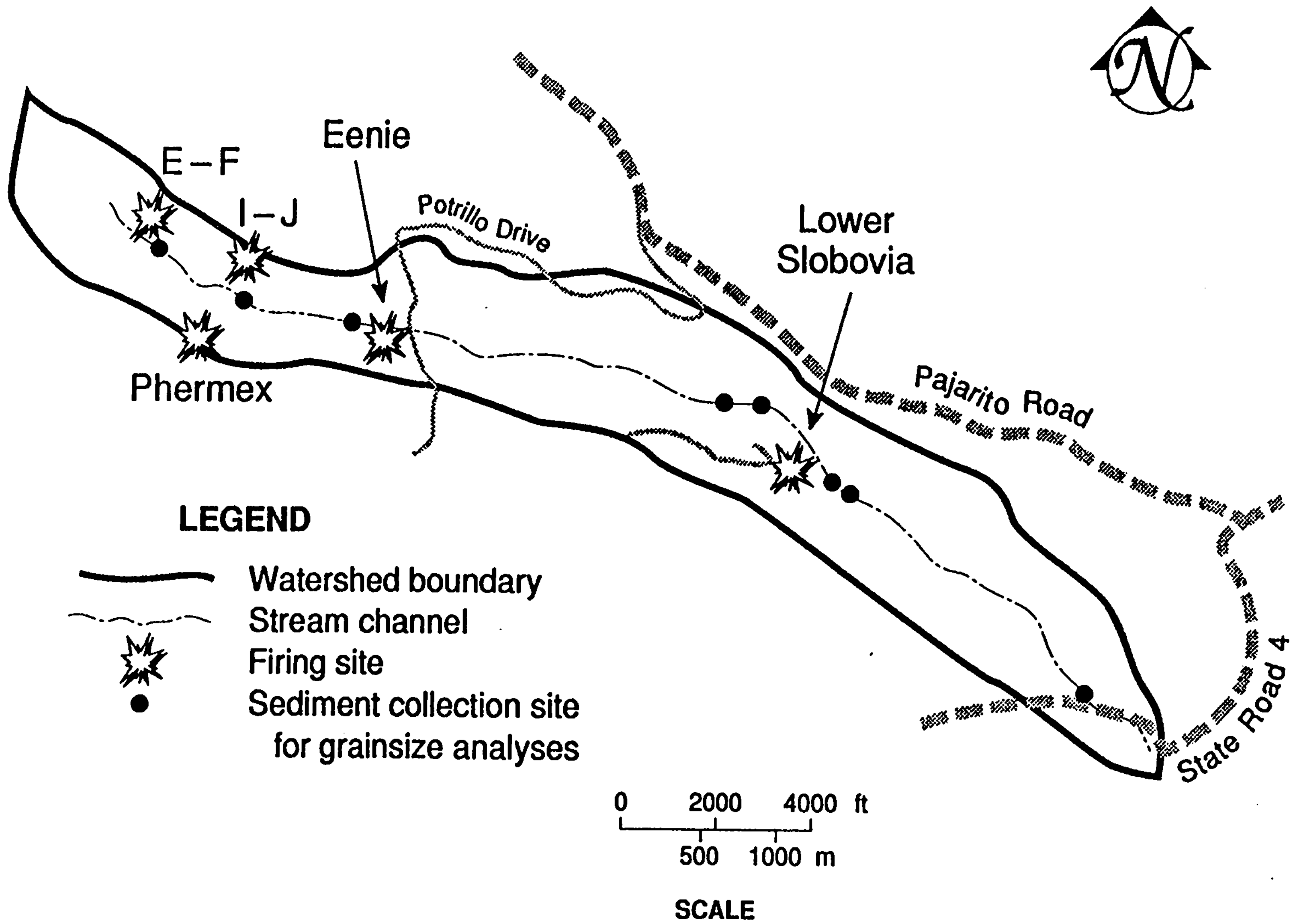



Fig 4.30 Location of Samples Used in Grainsize Distributions.

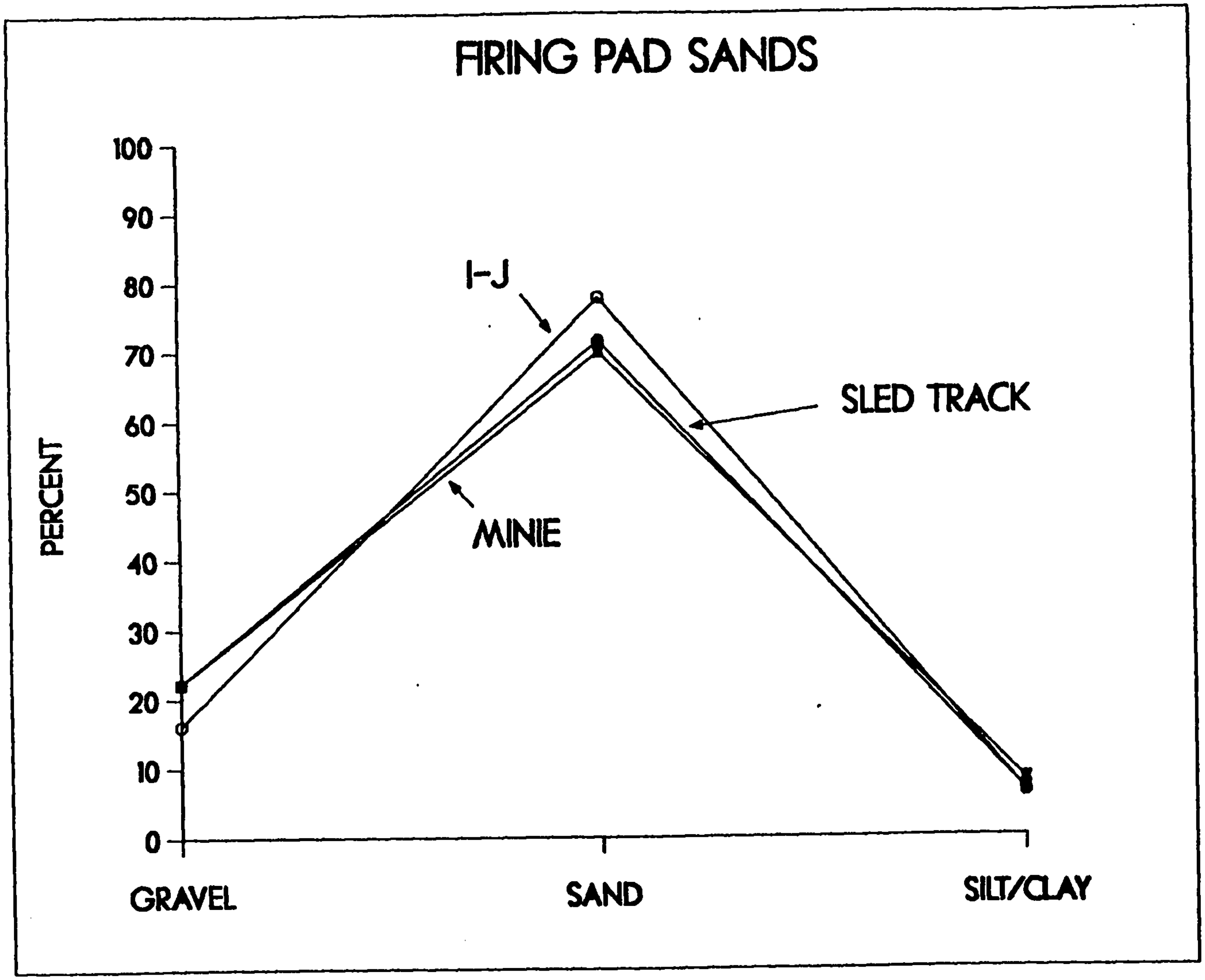



Fig 4.31 Grainsize Distribution of Sands from Firing Pads.

Each sieve fraction was individually analyzed for total uranium and isotopic ratio, Table 4.5. Natural uranium has a background concentration level of about 2-4 µg/g. Depleted uranium has an isotopic ratio of 0.0020, based upon the isotopic composition of the firing site sands. A sample wholly composed of depleted uranium will have an isotopic ratio of 0.0020, whereas a sample which contains a mix of depleted uranium and natural uranium will have an isotopic ratio between 0.0020 and about 0.0064. Although natural uranium's isotopic ratio is 0.0072, the range of values between 0.0064 and 0.0080 was used to define natural uranium to include the analytic range of uncertainty. Samples whose isotopic ratio is above 0.0080 are considered to contain enriched uranium. All firing site samples in sieves sizes #10 and greater contain significant levels of depleted uranium. The pebble size (#4 sieve) at Minie Site and the Sled Track at Lower Slobovia are composed of a mix of depleted and natural uranium or entirely natural uranium, respectively. The natural uranium in these samples is probably due to the firing site sands being bought from a local sand-and-gravel operation, which contains indigenous natural uranium.

Total uranium values ranged from a low of about 7 µg/g to a high of 2000 µg/g. All samples were elevated above the natural background levels of 2-4 µg/g. The lowest values are in the pebble, granule, and coarse sand fraction, and range from 7 up to 632 µg/g. Levels of total uranium in the medium to very fine sand fraction ranged from 206 to 806 µg/g. Total uranium values in the pan, or silt and clay ranged from 912 to 2000 µg/g.

There are several general trends in these data. One trend is that there is an increase in total uranium with decrease in particle size. This could be biased in

TABLE 4.5
GRAINSIZE DISTRIBUTION OF TOTAL URANIUM AND ISOTOPIC RATIOS
AT FIRING SITES DURING 1988

Total Uranium
(µg/g)

| Sieve Size | #4 | #10 | #20 | #40 | #60 | #100 | #200 | PAN |
|---|---|---|---|---|---|---|---|---|
| Minie | 19.7 | 11.2 | 340 | 420 | 392 | 329 | 806 | 2000 |
| I-J | 32.3 | 20.9 | 28.9 | 206 | 268 | 336 | 676 | 1600 |
| Sled Track | 6.8 | 8.2 | 632 | 276 | 301 | 109 | 589 | 912 |

Isotopic Ratio

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Minie | 0.0050 | 0.0026 | 0.0020 | 0.0021 | 0.0019 | 0.0022 | 0.0020 | 0.0020 |
| I-J | 0.0023 | 0.0023 | 0.0023 | 0.0022 | 0.0022 | 0.0022 | 0.0022 | 0.0022 |
| Sled Track | 0.0068 | 0.0024 | 0.0024 | 0.0020 | 0.0019 | 0.0020 | 0.0020 | 0.0021 |

part to the nature of firing site operations. During a shot, a component containing a mass of depleted uranium is explosively detonated on top a wooden structure. After the shot, there is an attempt to clean off the largest visible pieces of depleted uranium, removing the larger particles although there still may be some chunks left on the pad. Because of the explosive nature, one might expect all sizes of uranium particles to be present. Uranium is present in all particle sizes at the firing pad; however, the largest uranium concentration is in the silt and clay fraction, even though the silt and clay fraction represents the smallest weight fraction. Decreased particle size results in large surface areas, presenting a large number of sites for surface adsorption. There also may be greater ion exchange capacity. Both factors could explain a preferential association with small particle sizes. Uranium concentration may be viewed as present in three populations; pebble and granule/coarse sand having total uranium in the tens of µg/g, medium and fine sand having total uranium in the hundreds of µg/g, and the silt and clay having a total uranium concentration in the thousands of µg/g range.

A second trend is that in general, there is little difference in total uranium concentration between firing sites. The only difference between firing pads is that there is slightly less uranium at the Sled Track. This is not surprising since the Sled Track began firing depleted uranium in October 1987, whereas I-J and Minie sites have been firing since the 1950's. The difference in total uranium concentration between the Sled Track and the other two sites does not appear to be significant.

Total uranium and isotopic ratio analyses were performed on grainsize distributions of sediments collected in the Potrillo Canyon watershed channel at 8 locations and on the banks at 6 locations, Fig 4.30. The locations termed headcutting and headcutting+60 refer to two positions downstream from the discharge sink and the Lower Slobovia bunker where the channel resumes an active channel appearance with a distinct bed and banks. The purpose of the sampling at those locations was to assess the magnitude of movement of sediment out of the discharge sink. The grainsize groupings for gravel, sand, and silt/clay fractions were the same as those described for the firing site samples and are shown in Fig 4.32. The percent gravel in the channel samples varied from about 6.5 to 25.7 percent. The largest percent gravel (25.7 %) was at the E-F location, at the top of the watershed, while the smallest percent (6.5 %) was at the Skunk Works location. A similar value of 6.8 percent gravel was present at the State Road 4 location. The percent sand in channel samples varied from a high of 87.9 percent at Skunk Works to a low value of 55.6 percent at the E-F location. A similar value of 87.6 percent sand was present at the State Road 4 location. The percent silt/clay in channel sediments varied from a high value of 19.0 percent at the headcutting location downstream from Lower Slobovia to a low of 4.22 percent at Eenie site.

The variation of the percentage of silt- and clay-sized particles with increasing distance downstream from the top of the watershed is shown in Fig 4.33. The percent of silt and clay decreases in the downstream direction; then increases slightly, and then dramatically increases followed by subsequent decrease. The high percent of silt and clay near the top of the watershed can be explained by sedimentation theory of textural maturity. Immature sediments contain amounts of silts and clays over 5 percent because streamflow velocities are weak or

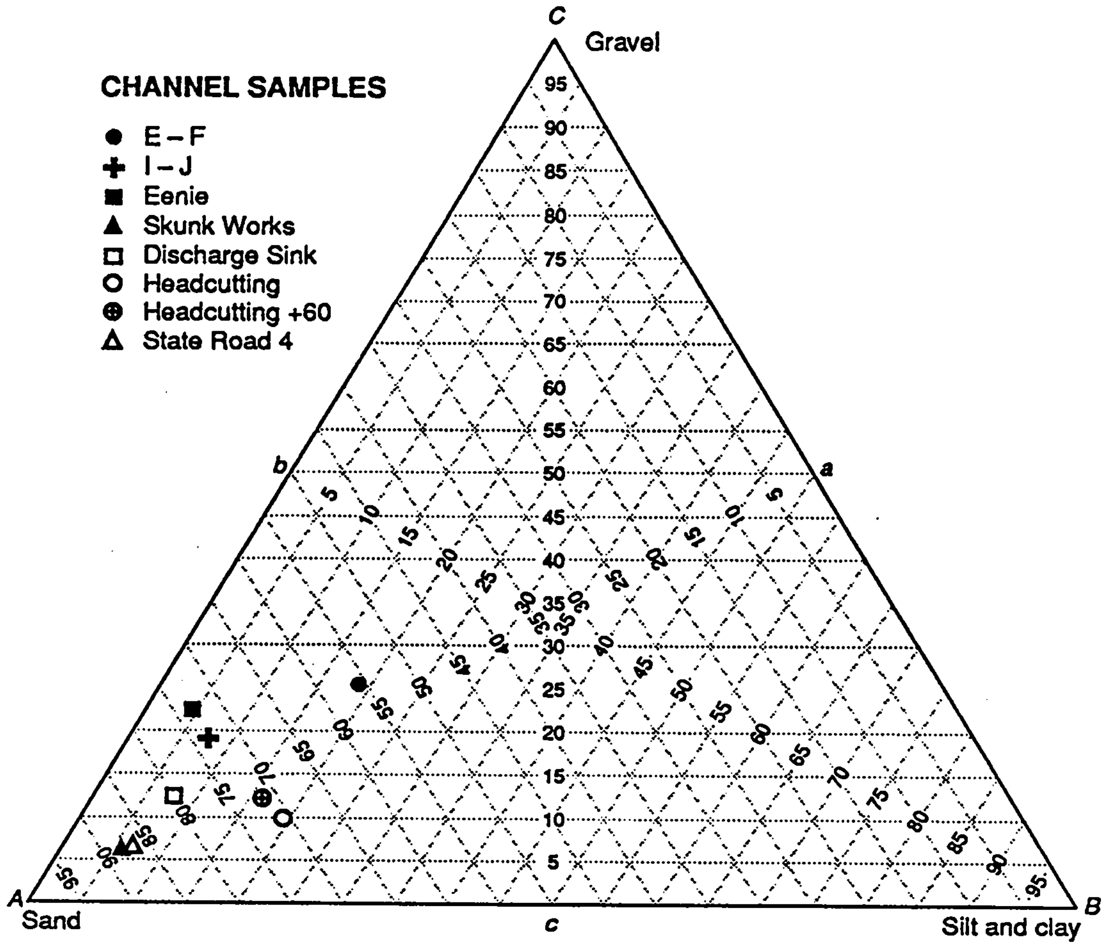



Fig 4.32. Grainsize Distribution of Channel Samples.

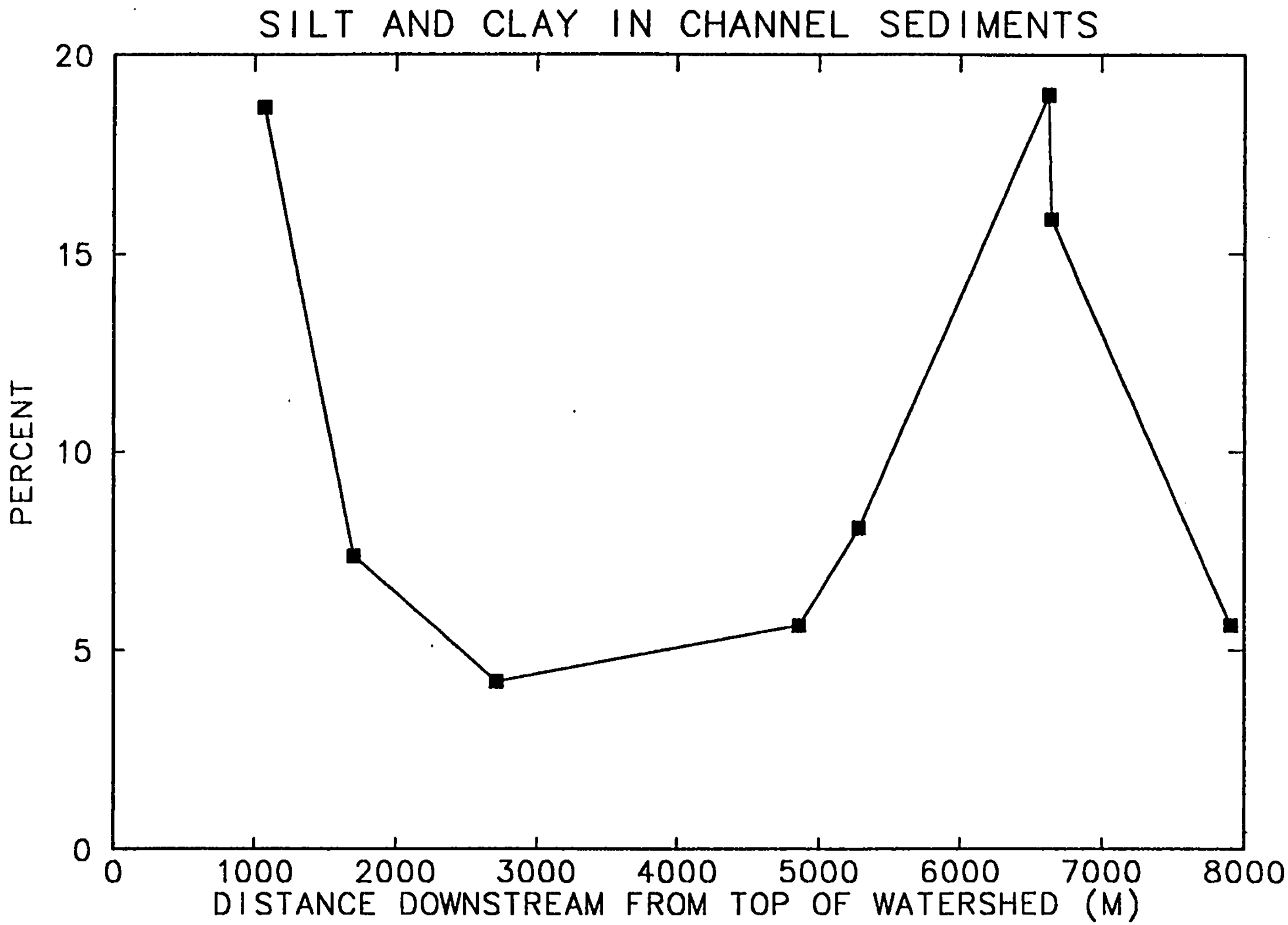



**Fig 4.33 Variation in Percent Silt and Clay with Distance Downstream from the Top of the Watershed.**

deposition is very rapid (Folk, 1968). As velocities increase, winnowing and particle sorting occur, and the percent of silt and clay decreases to under 5 percent, termed the submature and mature phases of textural maturity. The bimodality of clay content along the length of the watershed echoes the watershed flow dynamics. Clay content is relatively large near the top of the watershed, where a small contributing runoff area results in relatively low flows and velocities. The canyon there is narrow, and the channel cuts through talus; some of the clay measured could be mass wasting products. Clay content decreases in the downstream direction as the contributing area to runoff increases and the discharge and velocity increase. The silt/clay content increases to 8 percent at 5300 meters at the upstream end of the discharge sink. Silt and clay settle in the discharge sink along with the remaining sediment that is carried in suspension and as bed load. A rapid increase of silt/clay content to 19 percent at 6600 meters marks the surface flow discontinuity in this watershed. At 6600 m, at the end of the discharge sink channelized flow resumes (a second watershed within a watershed). The majority of the time there is no surface flow through the discharge sink. At the downstream end there is some headcutting which supplies sediment to the channel. Below the discharge sink, the silt/clay content decreases, until at State Road 4 (nearly 26,000 meters from the top of the watershed) the clay content is just over 5 percent. Here the textural maturity of the watershed could be described as nearly submature.

Total uranium and isotopic ratios were performed on channel sediments; results are given in Table 4.6. At E-F site, total uranium values of pebble, granule and coarse sand fractions do not exceed background concentrations. The medium

TABLE 4.6
GRAINSIZE DISTRIBUTION OF TOTAL URANIUM AND ISOTOPIC RATIOS
OF CHANNEL AND BANK SEDIMENTS IN POTRILLO CANYON DURING 1988

Total Uranium
(μg/g)

**IN THE CHANNEL**

| Sieve Size | #4 | #10 | #20 | #40 | #60 | #100 | #200 | PAN |
|---|---|---|---|---|---|---|---|---|
| E-F | 1.3 | 2.8 | 1.2 | 2.5 | 5.6 | 9.0 | 6.7 | 18.3 |
| I-J | 2.3 | 4.6 | 1.9 | 2.0 | 14.2 | 32.8 | 14.1 | 53.7 |
| Eenie | 2.1 | 0.9 | 1.5 | 1.6 | 2.4 | 3.7 | 16.3 | 20.4 |
| Skunk Wks | 1.0 | 1.9 | 0.6 | 1.3 | 1.8 | 4.8 | 4.9 | 17.1 |
| Dchge Sk | 664 | 1.6 | 0.7 | 1.3 | 2.3 | 17.4 | 8.5 | 15.1 |
| Headcut | 2.4 | 3.0 | 0.9 | 1.6 | 2.9 | 3.9 | 5.4 | 9.2 |
| Headcut+60 | 3.4 | 3.6 | 1.1 | 3.3 | 3.8 | 4.7 | 4.8 | 6.6 |
| SR4 | 3.6 | 3.2 | 0.5 | 1.5 | 2.2 | 2.3 | 2.4 | 3.1 |

Isotopic Ratio

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| E-F | 0.0076 | 0.0060 | 0.0069 | 0.0060 | 0.0060 | 0.0053 | 0.0060 | 0.0074 |
| I-J | 0.0067 | 0.0067 | 0.0059 | 0.0055 | 0.0053 | 0.0065 | 0.0054 | 0.0052 |
| Eenie | 0.0068 | 0.0069 | 0.0073 | 0.0070 | 0.0077 | 0.0066 | 0.0070 | 0.0065 |
| Skunk Wks | 0.0070 | 0.0071 | 0.0075 | 0.0058 | 0.0061 | 0.0058 | 0.0051 | 0.0051 |
| Dchge Sk | 0.0038 | 0.0050 | 0.0069 | 0.0071 | 0.0074 | 0.0071 | 0.0056 | 0.0065 |
| Headcut | 0.0074 | 0.0078 | 0.0078 | 0.0071 | 0.0078 | 0.0077 | 0.0067 | 0.0041 |
| Headcut+60 | 0.0076 | 0.0077 | 0.0075 | 0.0078 | 0.0075 | 0.0070 | 0.0070 | 0.0073 |
| SR4 | 0.0068 | 0.0064 | 0.0077 | 0.0065 | 0.0073 | 0.0079 | 0.0072 | 0.0053 |

TABLE 4.6
(con't)

Total Uranium
(μg/g)

**ON THE BANKS**

| Sieve Size | #4 | #10 | #20 | #40 | #60 | #100 | #200 | PAN |
|---|---|---|---|---|---|---|---|---|
| E-F | 3.4 | 4.6 | 1.6 | 4.8 | 16.4 | 12.7 | 21.1 | 23.0 |
| I-J | 3.8 | 3.1 | 2.4 | 3.8 | 4.8 | 8.8 | 4.9 | 10.8 |
| Eenie | 7.7 | 7.1 | 22.8 | 18.2 | 28.3 | 33.0 | 27.8 | 71.6 |
| Skunk Wks | 2.2 | 1.9 | 0.7 | 0.9 | 2.2 | 2.6 | 2.0 | 3.3 |
| Dchge Sk | 5.5 | 2.7 | 5.0 | 7.8 | 7.5 | 9.0 | 7.5 | 18.4 |
| SR4 | 2.8 | 2.9 | 1.5 | 2.2 | 3.1 | 3.4 | 2.9 | 2.7 |

Isotopic Ratio

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| E-F | 0.0037 | 0.0045 | 0.0053 | 0.0042 | 0.0057 | 0.0049 | 0.0040 | 0.0048 |
| I-J | 0.0067 | 0.0078 | 0.0068 | 0.0062 | 0.0066 | 0.0068 | 0.0068 | 0.0064 |
| Eenie | 0.0074 | 0.0067 | 0.0049 | 0.0056 | 0.0057 | 0.0060 | 0.0049 | 0.0035 |
| Skunk Wks | 0.0058 | 0.0072 | 0.0077 | 0.0079 | 0.0061 | 0.0064 | 0.0067 | 0.0070 |
| Dchge Sk | 0.0059 | 0.0072 | 0.0057 | 0.0053 | 0.0050 | 0.0047 | 0.0049 | 0.0040 |
| SR4 | 0.0077 | 0.0075 | 0.0075 | 0.0068 | 0.0076 | 0.0075 | 0.0069 | 0.0073 |

to fine sand size fraction does exceed background concentrations; concentrations increase with decreasing size fraction. The isotopic ratios indicate that all fractions except the pebble and pan contained depleted uranium. The isotopic ratio in the pebble and pan fractions indicates that the uranium in the sample is natural. The elevated total uranium value of 18.3 μg/g in the pan could be from remnants of dynamic testing with natural uranium during the late 1940's and early 1950's.

At the I-J location, channel fractions ranging from pebbles to medium sand were at background levels of total uranium, although the isotopic ratio of the coarse and medium sand indicated the presence of depleted uranium. Channel fractions smaller than medium sand were all elevated above background levels of total uranium, and the isotopic ratios were all below 0.0065 (depleted uranium). The highest concentration of 53.7 μg/g total uranium was in the pan (silt and clay) sample.

Channel samples at the Eenie location were at background levels of total uranium in the pebble through fine sand fraction. The corresponding isotopic ratios of these samples showed that the uranium in these samples was natural. Fractions of very fine sand and silt and clay (pan) were elevated in total uranium; the pan fraction may contain depleted uranium (isotopic ratio was 0.0065).

At Skunk Works, total uranium in channel samples in the fractions from pebble through fine sand were at background levels; total uranium levels of the fine and very fine sand may be above background. The pan fraction was above background levels at 17.1 μg/g. Isotopic ratios of these samples indicated depleted uranium in all samples except the pebble, granule, and coarse sand fractions.

In the discharge sink, depleted uranium was evident in the pebble, granule, and very fine sand fractions, and the pan for the channel samples. Elevated uranium values were present in the pebble, fine and very fine sand fractions, and in the pan.

Downstream of the discharge sink, at the headcutting location, elevated levels of total uranium in the channel samples were present only in the pan fraction. Isotopic ratios followed the same trend, all samples contained natural uranium except for the pan, which contained depleted uranium.

At the headcutting+60, about 20 meters downstream, the sample results were similar to the headcutting sample. The only incidence of elevated total uranium levels was in the pan fraction. The isotopic ratio of all samples was within the range of natural uranium.

At State Road 4 all channel samples were within background total uranium levels. The isotopic ratio of the pan fraction was 0.0053, indicating the only presence of depleted uranium at this location.

Bank samples from the E-F, I-J, Eenie, Skunk Works, discharge sink and State Road 4 locations were divided in grainsize fractions and analyzed for total uranium and isotopic ratio, Fig 4.34 and Table 4.6. The percent gravel in the bank samples varied from 9.7 percent at E-F site and at Skunk Works to 13.9 percent at I-J site. The percent sand present varied from 63.6 percent at Eenie to 74.8 percent at Skunk Works. The percent silt and clay varied from 15.5 percent at Skunk Works and State Road 4 to 23.4 percent at E-F site. Notice the smaller variations between

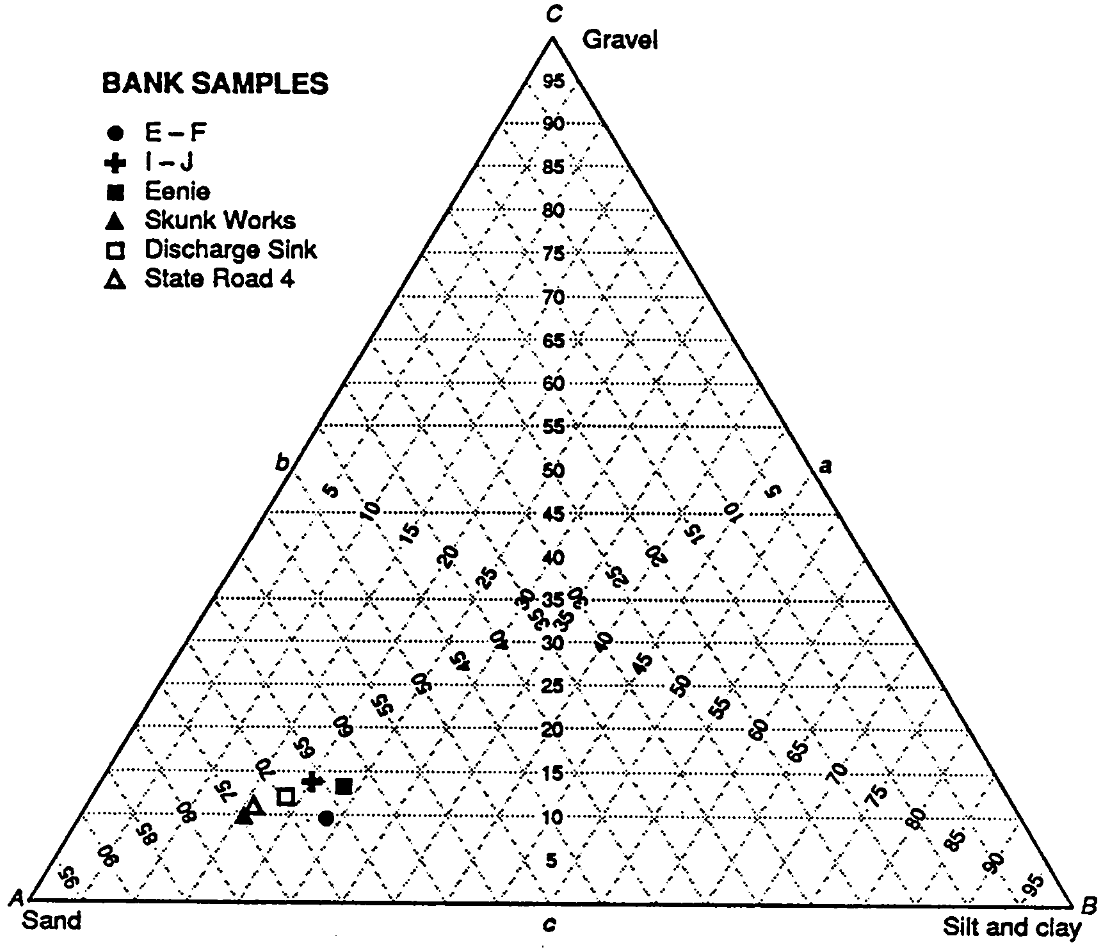



Fig 4.34. Grainsize Distribution of Bank Samples.

locations for the bank samples compared to the channel samples.

At E-F site, the fractions from pebble through medium sand were within or slightly elevated above background levels of total uranium . Fractions smaller than medium sand were consistently elevated above background, with the highest value in the pan fraction. The isotopic ratio indicated depleted uranium in all fractions. Bank samples at the I-J location showed elevated total uranium in the fine sand fraction, and the pan. Isotopic ratio analyses indicated the presence of depleted uranium in the medium sand fraction and the pan.

At Eenie location, all bank samples were elevated in total uranium levels. The isotopic ratio of these samples showed depleted uranium in the coarse sand through the pan fraction.

All bank samples at Skunk Works were within background concentrations for total uranium. The isotopic ratios showed the presence of depleted uranium in the pebble, and the medium to fine sand fractions. In the discharge sink, all bank samples except the granules displayed elevated total uranium concentrations, and had isotopic ratios indicative of depleted uranium.

Bank samples at State Road 4 contained total uranium levels within background concentration values. The isotopic ratios of these samples were all within the range of natural uranium values.

A number of comments can be made from these data. Regarding the channel samples, all the pan samples were contaminated, and with a few exceptions, the pan had the highest levels of total uranium concentration of all fractions. There was, with one exception, a preference for greater uranium concentrations with small particle size, especially sizes smaller than medium to fine sand. Another observation is that the isotopic ratio can be useful for identifying samples which contain depleted uranium contamination, but whose total uranium levels fall within the range of background values. Because natural uranium has also been used in weapons testing in this environment, the level of total uranium alone also is an indicator of contamination.

The skewness in the distribution of elevated total uranium level toward the small particle sizes range in the channel sediments can be related to the size distribution of the firing site sands. Recalling the firing site results, this skewness was also apparent. There were high levels of uranium on the sand fraction, 70 to 80 percent of the samples by weight, with highest levels of uranium on the silt and clay fraction, which made up 5 to 10 percent of the samples by weight. Therefore, 75 to 90 percent of the firing site samples by weight had concentrations greater than 100 μg/g level. In the channel samples, 75 to 93 percent of the samples by weight were the sand, silt and clay fractions. The highest total uranium concentrations by particle size lies in the medium to fine, fine, very fine sand, silt and clay fractions with concentrations greater than 10 μg/g. Large size contaminated particles were not, in general, found in channel deposits. Reduction in large-sized particles having elevated uranium concentrations between firing sites and channel deposits probably reflects mechanical weathering on the surface and in the channel, leaching into the dissolved phase, and the addition of background sediment in the channel deposits.

High concentrations were found in the greatest number of size ranges in the channel below E-F and I-J site, and discharge sink. Elevated levels at E-F and I-J sites are due to the close proximity to E-F firing site, which probably contains the greatest amounts of depleted uranium on and in the surface layer of any area or firing site in the watershed. The high concentration at the discharge sink are expected, since it is, with rare exception, the final terminus for most sediment. Downstream of the discharge sink there is little contamination. In the headcutting locale, there are elevated total uranium concentrations in the very fine sand, silt and clay fractions, and evidence of depleted uranium only in the silt and clay sizes. At headcutting+60, there are elevated concentrations of total uranium in the silt and clay sizes, and no evidence of depleted uranium. High concentrations in the very small particle sizes in these areas may be due to airborne transport, to sheetwash flow across areas which were contaminated by firing activities at the nearby Lower Slobovia firing pad, or transport across the discharge sink at some time in the past. At State Road 4, there were no elevated levels of total uranium in any of the size fractions, but there was evidence of depleted uranium in the granule, possibly medium sand, and in the silt and clay fractions. This low level of contamination may be due to transport of depleted uranium in the past, which was deposited between the Lower Slobovia firing site and State Road 4, and then became available for transport in subsequent events.

The picture is different for the bank sediments. All bank sediments at the E-F location are contaminated with depleted uranium. This is due to the presence of fine-grained material in the bank deposits combined with an observed increase in uranium concentration in small sized particles, especially in the silt and clay. This pattern is also evident at the Eenie location, where all the sizes of sediments on the banks are contaminated. At the I-J location, medium sand and smaller sizes are contaminated. At Skunk Works, there were contaminated pebble, medium to fine, and fine sand sizes, but no contamination in other particle sizes. This location apparently is a fairly active site, where moderately high velocities keep most particle sizes in motion through this area. The short duration, rapid rise and fall of the measured hydrographs through this area support this idea. Contamination was present in all particle sizes except granules in the discharge sink, which may reflect the small representation of this particle size by weight (7 percent).

There was no evidence of contamination of any size fractions at State Road 4. If there had been significant uranium movement out of the discharge sink, one would expect to see elevated levels of uranium and depleted uranium in the bank deposits, the relicts of high flow deposition. This result was not observed, Table 4.6. The levels of contamination in transported particles is negligible most of the time, as shown by the cumulative sampler water quality data.

# CHAPTER 5

# GEOMORPHOLOGIC INVESTIGATIONS

## *Uranium Occurrence in Fluvial Deposits*

Channel deposits were collected to determine uranium content. A spectrum of deposits were sampled in order to evaluate selective enrichment in the fluvial system: these deposits include the channel bed, the banks, alluvial fans, point bars, and deep pools. Locations of the sampled deposits are shown in Fig 5.1.

### Channel Deposits

Channel samples were collected in the main channel of Potrillo Canyon during years 1983, 1985, 1986, and 1989. Sample locations were: upstream from the E-F cumulative sampler; below E-F firing site; below I-J firing site; near Eenie firing site; at the Skunk Works Road Crossing; below Lower Slobovia; and at State Road 4. Locations were selected mainly to evaluate the uranium contribution to stream sediments from individual firing sites. Results are shown in Table 5-1. A dash indicates that no data was collected. The (D) indicates that the sample had an isotopic ratio below 0.0064, and therefore contained depleted uranium.

There are several interesting aspects of these data. First, although there is some contamination in the main channel above E-F firing site, the largest levels of contamination are found below E-F firing site. Further, the level of contamination declines with distance downstream from E-F. Therefore, it is probable that

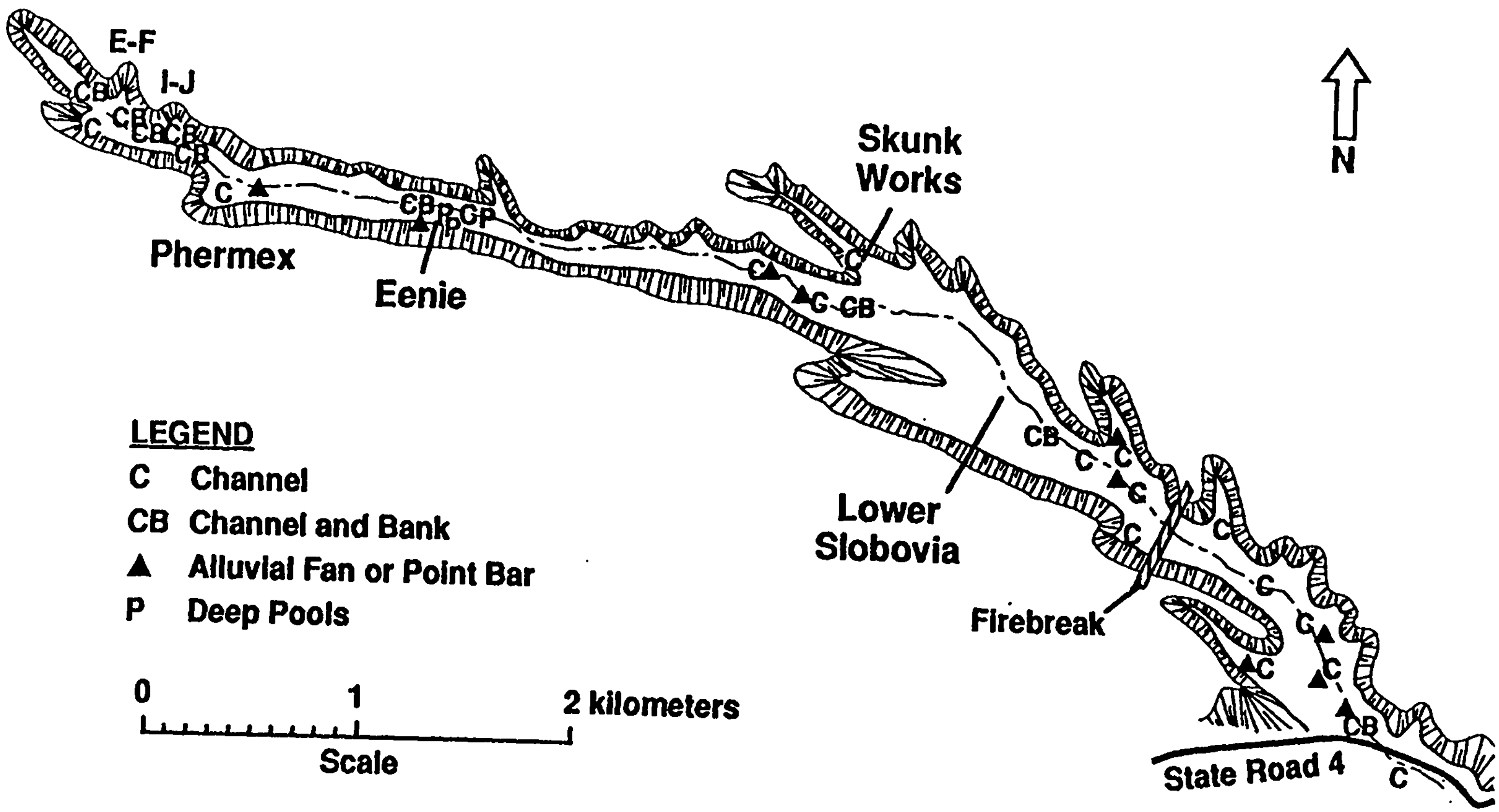



Fig 5.1 Location of Samples Collected in the Channel, On the Banks, in Alluvial Fans, Point Bars and Deep Pools.

TABLE 5.1
TOTAL URANIUM IN CHANNEL SAMPLES
(μg/g)

| Location | YEAR COLLECTED 1983 | 1985 | 1986 | 1989 |
|---|---|---|---|---|
| Upstream from E-F sampler | 7.7 (D)* | - | 2.3 (D) | 2.25 (D) |
| Below E-F Firing Site | 158.1 (D) | 14.1 (D) | 10.3 (D) | 3.92 (D) |
| Below I-J Firing Site | 7.3 (D) | 7.4 (D) | 3.5 (D) | 31.65 (D) |
| Near Eenie Firing Site | 5.0 (D) | 2.1 (D) | 6.8 (D) | 3.77 (D) |
| At Skunk Works Road | 8.3 (D) | 2.9 (D) | 3.2 (D) | 2.3 (D) |
| Below Lower Slobovia | 2.6 | - | 1.0 | 2.9 (D) |
| State Road 4 | 2.4 | <1.0 | 1.2 | 1.5 |

* (D) indicates sample contained depleted uranium; isotopic ratio < 0.0064.

the E-F firing point is the largest source of uranium available for surface water transport in Potrillo Canyon. Moreover, this same trend was evident in uranium levels in uranium traveling in the dissolved and suspended sediment phases in both snowmelt runoff and spring/summer/fall runoff events as discussed in Chapter 4.

Second, there appears to be considerable variation in uranium content in channel deposits at a particular location in time. At the location below E-F firing site, levels of uranium varied between 3.92 and 158.1 μg/g in the period 1983 to 1989. Similar variations, though reduced in magnitude, were apparent at each location. The variation in uranium concentrations at all locations were greater than twice the analytic uncertainty of 1 ppm. These variations may result from spatial variability as well as the dynamics of the system; uranium, although heavy, can be transported and redistributed during runoff events to other locations along the stream system. There was no systematic decline in uranium values with time at all locations along the channel.

Third, depleted uranium appeared uniformly in all samples located upstream of Lower Slobovia. With one exception, all samples downstream of Lower Slobovia did not contain depleted uranium and all were within background levels of total uranium. This result provides evidence that the discharge sink, located at Lower Slobovia, has been effective in trapping sediment and uranium.

Uranium concentration was measured at other locations in the main channel other than those in Table 5.1 as well as in side canyon channels, Fig 5.1 and Table 5-2. In the main channel, the first 4 locations in Table 5-2 are upstream of the

TABLE 5.2
TOTAL URANIUM IN THE MAIN CHANNEL AND IN SIDE CANYONS OF POTRILLO CANYON
(µg/g)

MAIN CHANNEL

| Location | Year Collected | Total Uranium |
|---|---|---|
| Between E-F and I-J Firing Sites | 1983 | 15.9 (D)* |
| " " | 1986 | 9.5 (D) |
| " " | 1989 | 4.1 (D) |
| Culvert at Potrillo Drive | 1989 | 2.8 (D) |
| Upstream from Firebreak | 1989 | 2.7 (D) |
| Upstream from Gate | 1989 | 1.8 (D) |
| Downstream from Gate | 1989 | 2.8 |
| Downstream from Powerline Road | 1989 | 2.4 |
| Downstream from State Road 4 | 1989 | 2.2 |

SIDE CANYONS

| Location | Year Collected | Total Uranium |
|---|---|---|
| Below Storage Magazines 241, 242, 243 | 1989 | 14.0 (D) |
| Below Phermex Firing Site | 1988 | 2.5 (D) |
| " | 1989 | 17.5 (D) |
| Below I-J Firing Site | 1983 | 7.8 (D) |
| " | 1986 | 2.9 (D) |
| In Skunk Works Canyon | 1983 | 4.5 (D) |
| " | 1986 | 2.3 |
| " | 1989 | 2.5 |
| North of Lower Slobovia Firing Site | 1989 | 3.1 |
| Upstream from Firebreak, North Side | 1989 | 1.9 |
| Upstream from Firebreak, South Side | 1989 | 2.0 |
| Downstream from Firebreak, North Side | 1989 | 1.4 |
| North of Powerline Road | 1989 | 2.2 |

* (D) indicates sample contained depleted uranium; isotopic ratio <0.0064.

discharge sink, while the last 5 locations are downstream from Lower Slobovia and the discharge sink. These results follow similar patterns as those observed and discussed above for the main channel. Elevated levels of total uranium and the presence of depleted uranium exist in locations upstream of Lower Slobovia and the discharge sink. There was one instance of a depleted uranium sample downstream of the discharge sink. All other downstream samples did not contain depleted uranium and were within background levels of total uranium.

Channel samples were collected in side canyons, Table 5-2, to assess the direct impact from firing sites. The side canyons are located directly below the firing sites and feed into the main channel. Side canyons downstream of the discharge sink were also sampled to determine if there was depleted uranium traveling away from sources in the watershed not associated with firing sites, for example, products of "midnight dumping" activities. Side canyons draining PHERMEX and I-J firing sites displayed elevated total uranium concentrations. As well, there is a source of total uranium in the drainage below Storage Magazines 242, 242, and 243 at TA-15; this could be either from early firing sites which no longer exist, or from scattered fragments associated with large test shots at E-F firing site. All these samples contained depleted uranium. In the side canyon containing the Skunk Works building, there was one instance of depleted uranium amongst the three samples collected; all samples contained background levels of total uranium. There was no presence of depleted uranium in any of the side canyons located downstream of Lower Slobovia (last 5 locations), and all samples were within background levels of total uranium. Therefore, it appears that firing sites and possibly fragments from firing sites provide the only sources for elevated total uranium and depleted uranium in Potrillo Canyon watershed.

Bank Deposits

Bank samples were collected at many of the same locations as channel samples, Fig 5.1, on the main channel. These locations were: upstream of E-F firing site; downstream of E-F firing site; upstream of I-J firing site; downstream of I-J firing site; near Eenie firing site; at the Skunk Works Road crossing; below Lower Slobovia; and at State Road 4. Additionally, there was a bank sample collected in the side canyon draining I-J firing site. Sampling occurred during 1983 and 1985, and results are presented in Table 5-3.

Similar conclusions may be drawn from the bank samples as are given above for the channel samples. Although elevated levels of uranium exist upstream from E-F firing point, the highest levels of uranium contamination were found downstream from E-F firing point, which is likely the greatest source of uranium from weapons testing experiments in the watershed. Levels of uranium decline in the downstream direction from this point. There is variation in levels of total uranium at a particular location with time, attesting to Potrillo Canyon being a dynamic fluvial system. With two exceptions, all samples upstream from Lower Slobovia and the discharge sink contained depleted uranium, as determined by an isotopic ratio less than 0.0064. Levels of total uranium below Lower Slobovia and the discharge sink were at the background levels of uranium for this area, and there was no depleted uranium was detected.

Note that the bank samples uniformly contained higher levels of total uranium than the channel samples. This result may be due to bank deposit

TABLE 5.3
URANIUM IN BANK SAMPLES
(μg/g)

| Location | Year Collected 1983 | 1985 |
|---|---|---|
| Main Channel Upstream from E-F Firing Site | 15.8 (D)* | - |
| Main Channel Downstream from E-F Firing Site | 373.0 (D) | - |
| Main Channel Upstream from I-J Firing Site | 49.5 (D) | - |
| Side Canyon below I-J Firing Site | 9.2 (D) | - |
| Main Channel Downstream from I-J Firing Site | 34.9 (D) | 14.6 |
| Main Channel near Eenie Firing Site | 9.0 | 19.5 (D) |
| Main Channel at Skunk Works Road | 6.5 (D) | 6.4 (D) |
| Main Channel below Lower Slobovia Firing Site | 4.7 | - |
| Main Channel at State Road 4 | 4.4 | 1.5 |

* (D) indicates sample contained depleted uranium; isotopic ratio <0.0064.

composition; the bank material contains more fine-grained material. As well, it was observed that uranium concentration tends to increase with decreasing particle size, with the largest uranium concentrations observed in the silt and clay fraction. Together, these factors explain why the bank deposits exhibit larger uranium concentrations.

Alluvial Fan and Point Bar Deposits

Samples of alluvial fans and point bars were collected along the watershed, Fig 5.1, to determine if these deposits were also selectively enriched in total (and depleted) uranium, Table 5-4. Elevated levels of total uranium were present in all deposits upstream of the discharge sink, except in the point bar near the Eenie firing site and the point bar upstream of the E-F cumulative sampler. Most samples contained depleted uranium, with the exception of the point bar deposit near the Eenie firing site. The point bar near the I-J cumulative sampler contained an elevated concentration of nearly 155 μg/g.

There were two samples, one from an alluvial fan and the other from a point bar in a side canyon downstream from the discharge sink which had slightly elevated levels of total uranium, 5.57 and 6.42 μg/g, respectively. Neither of these samples contained depleted uranium. All deposits downstream of the discharge sink were point bars, were within background levels, and did not contain depleted uranium.

It appears that point bar and alluvial fan deposits concentrate uranium, and occasionally in considerable amounts. Levels of total uranium exceed both bank

TABLE 5.4
URANIUM IN ALLUVIAL FAN AND POINT BAR DEPOSITS
(μG/G)

| Location | Total Uranium | Isotopic Ratio |
|---|---|---|
| Point Bar-Upstream from E-F Firing Site | 3.74 | 0.0063 |
| Alluvial Fan-Downstream from E-F Firing Site | 10.94 | 0.0059 |
| Point Bar-Upstream from I-J Cumulative Sampler | 154.51 | 0.0053 |
| Alluvial fan between Main Channel and Side Canyon draining Phermex | 10.99 | 0.0035 |
| Point Bar-Near Eenie Sampler | 2.76 | 0.0064 |
| Point Bar-Upstream from Skunk Works Road | 20.57 | 0.0065 |
| Point Bar-Upstream from Skunk Works Road | 14.81 | 0.0057 |
| Alluvial fan-Downstream from Lower Slobovia Firing Site | 5.57 | 0.0074 |
| Point Bar-Side Canyon Upstream from Firebreak, North Side | 6.42 | 0.0071 |
| Point Bar-Downstream from Gate | 2.38 | 0.0078 |
| Point Bar-Side Canyon North of Powerline Road | 4.23 | 0.0074 |
| Point Bar-Downstream from Powerline Road | 1.63 | 0.0071 |
| Point Bar-Upstream from State Road 4 | 3.48 | 0.0070 |
| Point Bar-Downstream from State Road 4 | 3.13 | 0.0080 |

Notes
1. Samples were collected during 1989.
2. Samples were collected in the main channel unless otherwise noted.

and channel deposits at the same location. However, these deposits do not contain a large volume of sediment compared to the total channel and bank sediments through the watershed and therefore do not comprise a significant amount of contamination in the watershed. One might expect that alluvial fan and point bar deposits in the lower watershed, downstream from Lower Slobovia, would concentrate total and depleted uranium if available. The absence of these concentrations gives support to the hypothesis that little depleted uranium has escaped from the discharge sink since the mid 1940's, discussed further in this chapter.

Uranium in Deep Pools

Three pools were sampled in September, 1989, to investigate whether depleted uranium in Potrillo Canyon deposited in a placer deposit fashion. In placer deposits there would be an increase in uranium concentration with depth due to its higher specific gravity than the remaining sediment. Three plunge pools were identified, Fig 5.1. Two are located upstream of Eenie firing site and are coincident with the Eenie cumulative runoff sampler location and the Eenie snowmelt collection station, and the third is located at the downstream end of a 83.8 m long culvert which runs under Potrillo Drive immediately downstream from the Eenie firing site. All three locations have distinctive plunge pools (1 m or greater drop in the channel bed) and were readily accessible.

The results from the three pools are shown in Table 5-5. Samples were collected at 7.6 cm intervals until either bedrock (tuff) was encountered, or in the case of the Eenie snowmelt location, the sampling pit collapsed. Terminal

TABLE 5-5
URANIUM DEPOSITS IN DEEP POOLS
COLLECTED SEPTEMBER 1989
(µG/G)

| Location | Total Uranium | Isotopic Ratio |
|---|---|---|
| Eenie at Stormwater Runoff Site | | |
| Surface | 7.56 | 0.0051 |
| 7.6 cm Depth | 6.96 | 0.0048 |
| 15.2 cm Depth | 4.23 | 0.0057 |
| Downstream End of Culvert Under Potrillo Drive | | |
| Surface | 16.15 | 0.0050 |
| 7.6 cm Depth | 30.31 | 0.0051 |
| 15.2 cm Depth | 24.85 | 0.0053 |
| 22.9 cm Depth | 3.59 | 0.0050 |
| 30.4 cm Depth | 2.94 | 0.0055 |
| 38.1 cm Depth | 2.87 | 0.0050 |
| Eenie at Snowmelt Runoff Site | | |
| Surface | 26.24 | 0.0046 |
| 7.6 cm Depth | 2.32 | 0.0068 |
| 15.2 cm Depth | 1.80 | 0.0057 |
| 22.9 cm Depth | 1.92 | 0.0062 |
| 30.4 cm Depth | 2.21 | 0.0062 |
| 38.1 cm Depth | 2.32 | 0.0065 |
| 45.7 cm Depth | 4.48 | 0.0061 |
| 53.3 cm Depth | 3.65 | 0.0059 |

sampling depth varied from 15.2 to 53.3 cm. At all three sites, the greatest total uranium concentration was encountered either at the surface or within the top 7.6 cm of the surface. In every case, the total uranium concentration declined with increasing depth. All samples contained depleted uranium with the exception of the sample at 7.6 cm depth in the Eenie snowmelt collection site. All samples above and below this sample were depleted. In general, sediment below 7.6 cm were close to or at background uranium concentration levels, but the isotopic ratio identifies these samples as containing depleted uranium.

These results indicate that depleted uranium is not depositing in placer fashion at these locations. Uranium is predominant in the fine-grained particles, which do no preferentially deposit with increasing depth in the channel bed.

*Transects*

In July, 1988, 3 depth transects were established within Potrillo Canyon to investigate the extent of depleted uranium transport. They were: at the upstream end of the discharge sink (Transect T-2); at the downstream end of the discharge sink (Transect T-3); and near the watershed boundary at State Road 4 (Transect T-1), Fig 5.2.

The configuration of each transect was designed to investigate the extent of depleted uranium across the canyon floor in the direction perpendicular to the stream channel, as well as the extent of depleted uranium in the vertical direction. Each transect had a unique configuration to accommodate the individual channel and canyon geometry at its location. Each transect consisted of 11 to 15 borings across the canyon floor; borings were made with a stainless steel hand auger. The spacing

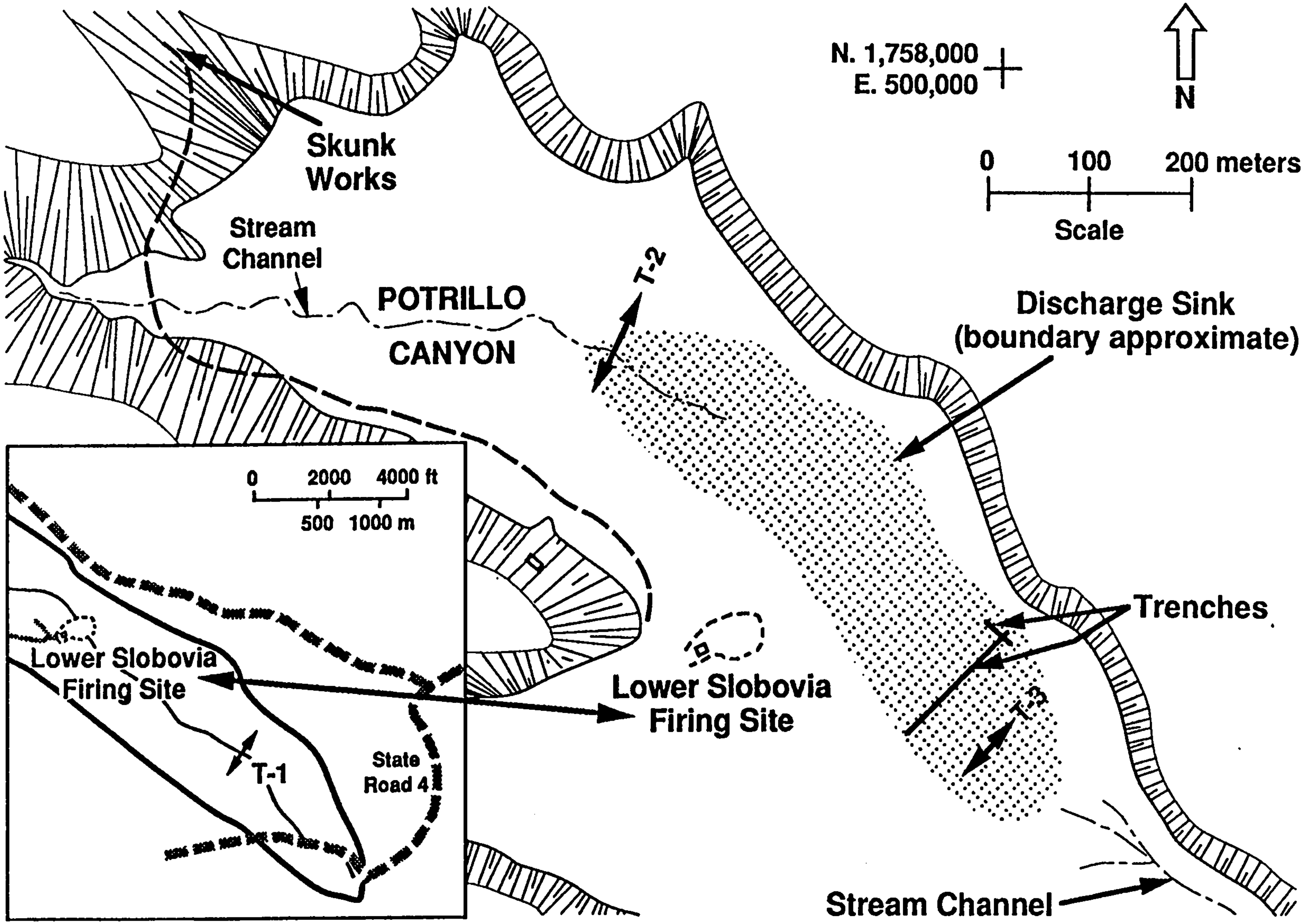



Fig 5.2 Location of the Transects.

between borings was variable; borings were spaced at 3.05 m intervals in the region of the current active channel, increasing to 6.1 m in the adjacent floodplain, and to 12.2 m spacing at greater distances from the active channel. The depth of boring was also a variable. The depth of sampling ranged from 102 to 122 cm in the active channel. Depths decreased to 30.5 cm in all other boreholes. The horizontal and vertical spacings reflected the assumption that the active channel represents the most likely location for sediment and contaminant deposition. The reason for variation in the spacing and depth sampling was to minimize the number of samples to be collected and analyzed without undue loss of information.

Samples were composited at the following depth intervals: 0-7.6 cm, 7.6-15.2 cm, 15.2-30.5 cm, 30.5-45.7 cm, 45.7-61 cm, 76.2-91.4 cm, and 106.7-121.9 cm. Each composite was analyzed for total uranium and isotopic ratio.

The results for T-2, the transect at the upstream end of the discharge sink are shown in Fig 5.3. The total length of the transect was 128 m and a total of fifteen borings were made. Elevated levels of total uranium were encountered in the 3 borings in the active channel (# 8, 9, and 10), and in the boring immediately south of the active channel (#7). Elevated uranium levels ranged from 6 to 70 μg/g, and were encountered at depths ranging from 30.5 to 76.2 cm. Fig 5.3 also shows by shading the extent of depleted uranium. Depleted uranium occurrence extended in the surface layer (0-7.6 cm) from boring 5 through boring 12 and down to 122 cm in boring 9 in the center of the active channel. This indicates that deposition of depleted uranium beyond the confines of the active channel has occurred during the past 45 years, either through floodplain inundation or through change in lateral location

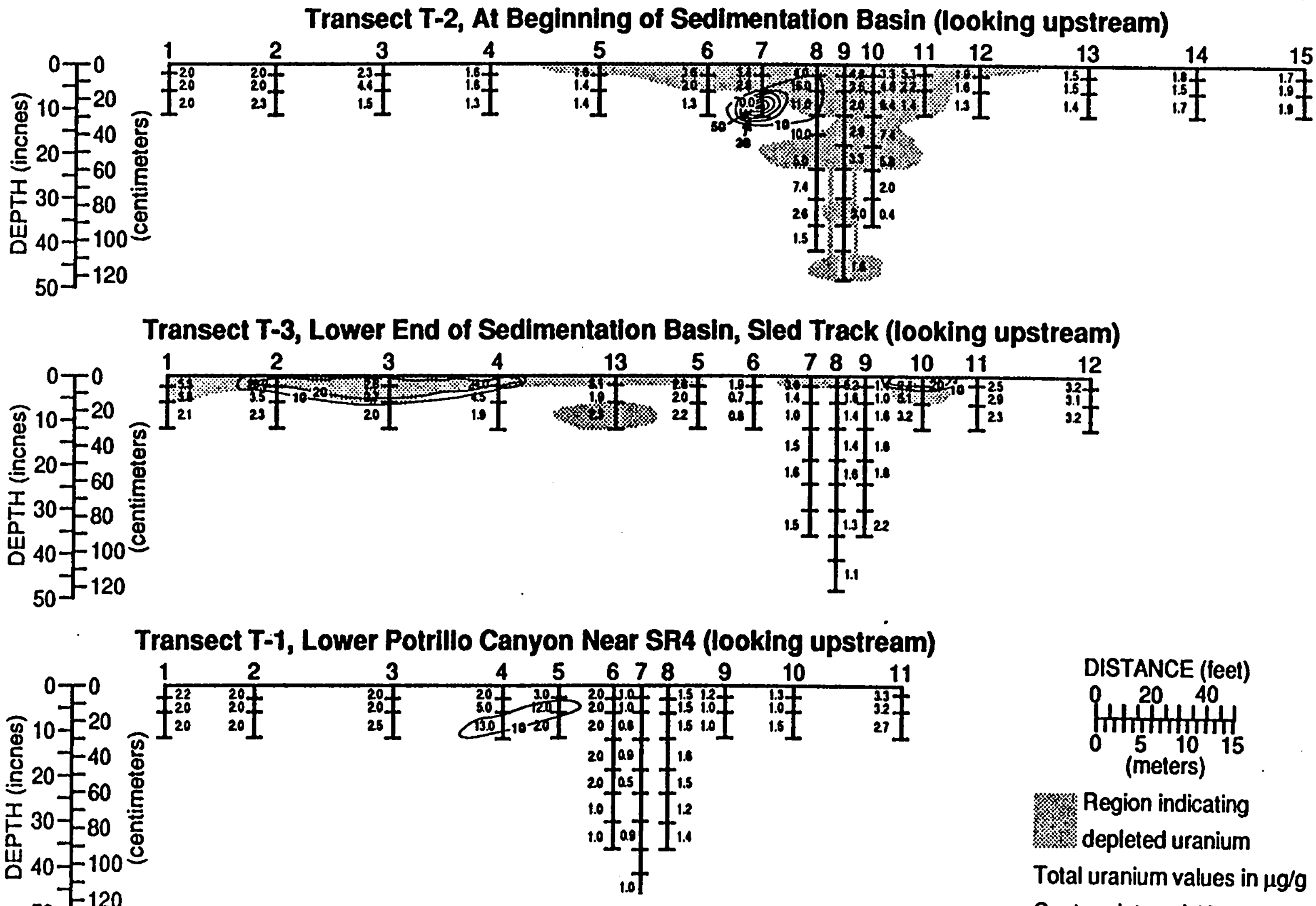



Fig 5.3 Total Uranium and the Extent of Depleted Uranium in the Transects.

of the active channel. The depth of depleted uranium deposition is a strong indication of active and aggressive sedimentation in the area, with average sedimentation rates of 2.7 cm/yr (122 cm/45 years) within the active channel.

The configuration and results for Transect T-3, located at the downstream end of the discharge sink, are shown in Fig 5.4. This transect was 100.6 m in length and contained 12 borings. Elevated levels in total uranium, ranging from 20 to 27 μg/g, were located in the surface layer, down to a depth of 15.2 cm. Elevated levels were also apparent in Borings 2, 3, 4 and 10, Fig 5.4. There were no elevated levels found in the three borings located in the present active channel (#7, 8 and 9). The presence of depleted uranium is also shown in Fig 5.4. Depleted uranium was found in the surface layers in borings 1, 2, 3, 4, 13, 5, 7, 8 and 10, to a depth of 15.2 cm in borings 1, 3, and 10, and in the deeper layer of 15.2 to 30.5 cm in boring 13. The widespread occurrence of depleted uranium across the canyon floor is indicative of movement of the active channel across the canyon floor during the last 45 years.

Transect T-1 is located about 0.6 km upstream from the watershed boundary with State Road 4. Results and configuration of the transect are shown in Fig 5.5. The transect was 81 m in length and consisted of 11 borings. Elevated levels of total uranium were found in Borings 4 and 5, both removed from the location of the present active channel. Levels of 13.0 μg/g at 15.2-30.5 cm and 12.0 μg/g at 7.6-15.2 cm were found in borings 4 and 5, respectively. There was no evidence of depleted uranium in any of the borings at any depth. These results indicate that if there had been depleted uranium transport through this area in the past, it was not widespread.

*Trenching in the Discharge Sink*

Inspection of aerial photographs suggested a lineament (a straight or gently curved length feature of the Earth's surface) trending north-south of considerable length. This lineament appeared to pass through the discharge sink about 122 m upstream of the location of Transect T-3. Because aerial lineaments are frequently associated with subsurface faulting, it seemed appropriate to conduct a ground check here for faulting. In September 1989, a trench, herein called long trench, 145 m long by 1.22 m deep trending northeast-southwest was dug across the canyon roughly perpendicular to the flow direction. A second trench 30.5 m by 1.22 m deep, called herein short trench, was dug trending northwest-southeast, intersecting the long trench about 7.6 m west of the northeast end, Fig 5.4. Trench dimensions were determined by the maximum depth allowable without shoring of the walls required by Occupational Safety and Health Act regulations (and thereby markedly increasing the costs), the canyon floor dimensions and the locations of specific structures in the canyon which could not be disturbed (e.g. the sled track). The objectives in digging the trenches were to see if faulting could be revealed through marker bed displacement, to obtain sedimentation rates through carbon-14 dating of organic material obtained at depth in the trench, to inspect geomorphologic structures exposed in the vertical cross section, and to obtain samples from geomorphologic structures for total uranium and isotopic ratio analyses.

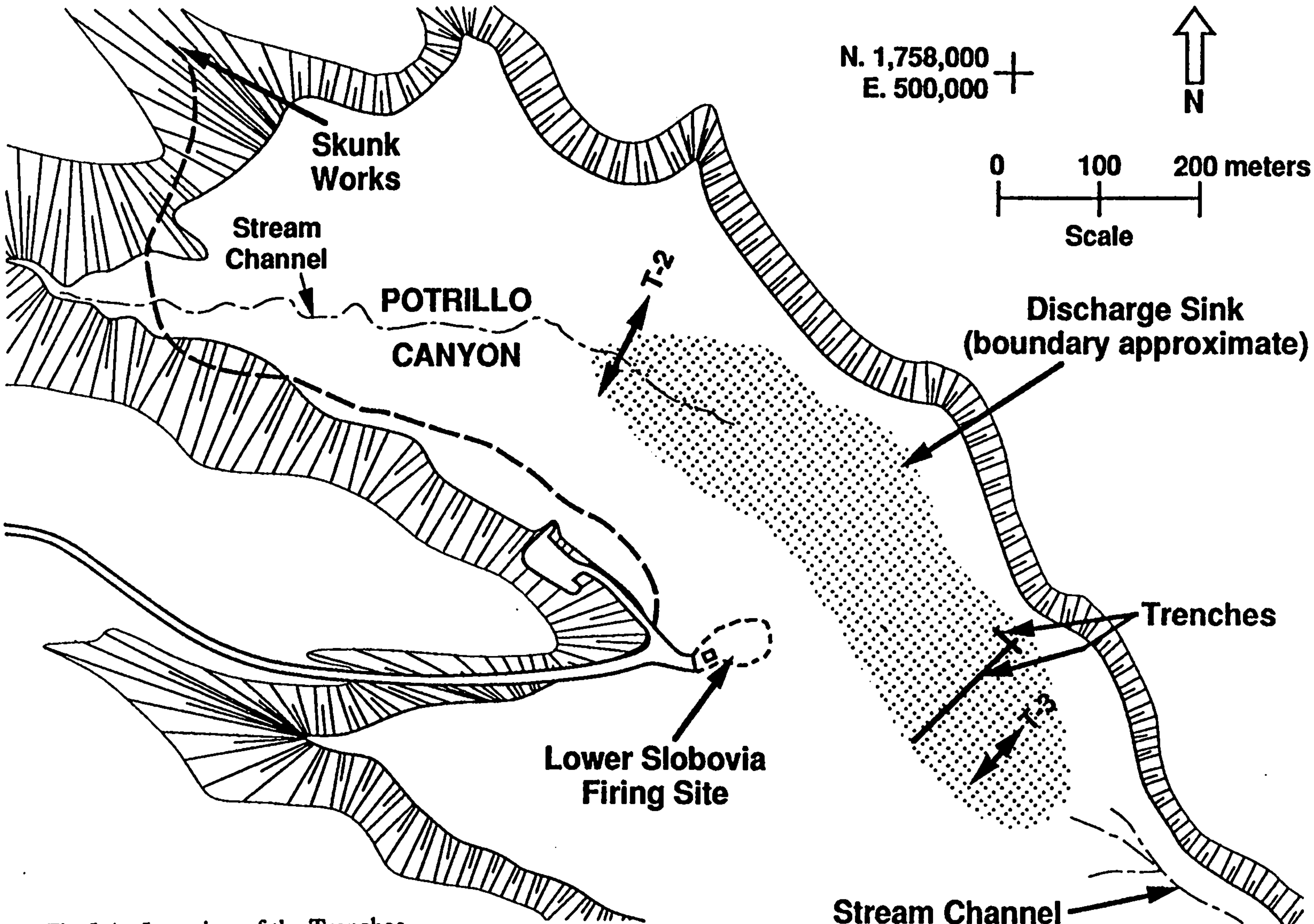



Fig 5.4 Location of the Trenches.

Vertical cross section of the long trench revealed a number of cut-and-fill structures, which are remnants of earlier channels and have been filled in by sediment. At station 80 East (all stations are referenced to the distance in ft from the northeast end) the profile consisted of fine "step" layers of sand-sized material from 0-30.5 cm, a coarse sand in a finer sand matrix from 30.5 to 83.8 cm, and fine sand in a coarse sand layering from 83.8 cm to the bottom. Beginning at station 110 and extending to station 130, there was evidence of a cut-and-fill structure beginning at about 45.7 cm depth. Crossbedding was apparent at 68.6 cm depth at station 120. Another cut-and-fill structure was visible at station 170, which extended from station 150 to station 180. It began at 45.7 cm depth and extended to 86.4 cm at the deepest point. It was characterized by layering within a more homogeneous matrix. Smaller cut-and-fill structures were also noted at stations 200 and 210, from 30.5 cm to about 91.4 cm and characterized by coarser material. Some layering was also apparent at station 230 down to 63.5 cm. At station 250, there was a tuff boulder present at 63.5 cm depth, with dimensions of 45.7 cm wide by 30.5 cm high. At station 330, a coarse layer at 91.4 cm depth was noted, while coarse sand layers increasing to small pebbles down to 63.5 cm was noted at station 340. Pebble-sized material at 91.4 cm depth was noted from stations 360 to 430.

Within the short trench, no distinct geomorphologic structures were noted. A homogeneous mix of a coarser material in a fine-grained matrix was found throughout the depth profile.

Samples were collected within geomorphologic structures, mostly within the layering or obviously coarser or finer material and analyzed for total uranium and isotopic ratio, Fig 5.5. Elevated levels of total uranium in the long trench were

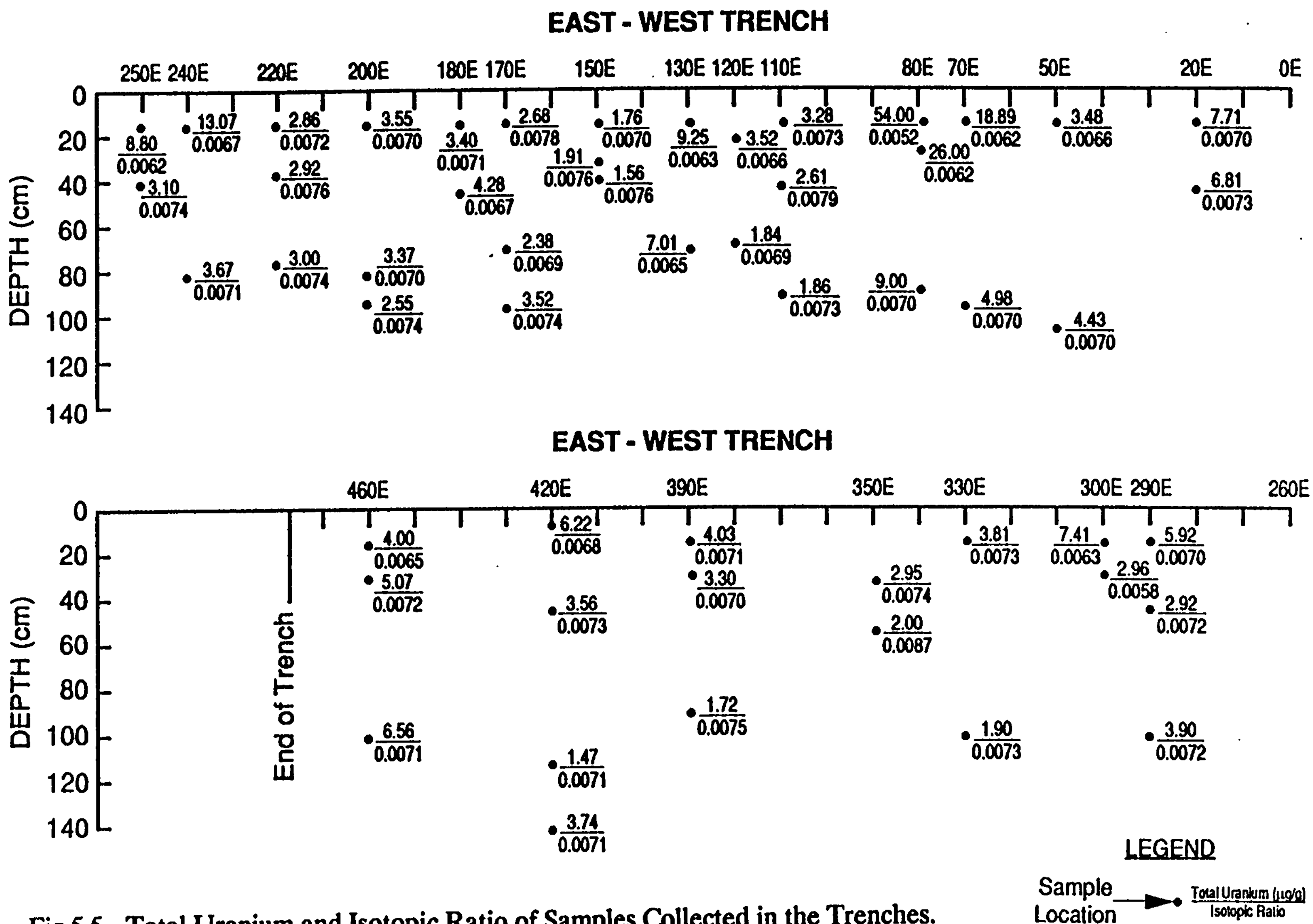



Fig 5.5 Total Uranium and Isotopic Ratio of Samples Collected in the Trenches.

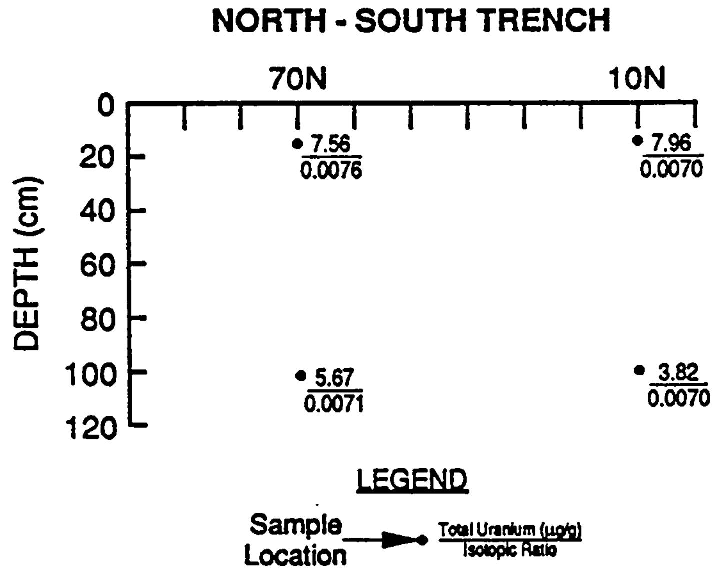



Fig 5.5 (con't) Total Uranium and Isotopic Ratio of Samples Collected in the Trenches.

measured at a number of locations. At station 20, the uranium concentration was 7.71 μg/g at 15.2 cm depth, and 6.81 μg/g at 45.7 cm. At station 70, 18.89 μg/g was measured at 15.2 cm depth. At station 80, there was 54 μg/g at 15.2 cm depth, 26.0 μg/g at 30.5 cm, and 9.0 μg/g at 88.9 cm. At station 130, there was 9.25 μg/g at 15.2 cm depth, and 7.01 μg/g at 71.1 cm. At station 240, there was 13.07 μg/g measured at 15.2 cm. At station 250 East, there was 8.8 μg/g at 15.2 cm, at station 290 there was 5.92 μg/g at 15.2 cm, at station 300 there was 7.41 μg/g at 15.2 cm, at station 420 there was 6.22 μg/g at 15.2 cm, and at station 460 there was 6.56 μg/g at 101.6 cm. Depleted uranium, determined by isotopic ratio, was apparent at the following stations: 70 at 15.2 cm, 80 at 15.2 and 30.5 cm, 130 at 15.2 and 71.1 cm, 250 at 15.2 cm, and 300 at 15.2 and 33 cm. The elevated levels of total uranium in the 15.2 and 101.6 cm samples collected in the short trench did not indicate the presence of depleted uranium from their isotopic ratios.

Nine samples of organic material were collected and submitted for carbon-14 (C-14) dating. Eight samples contained insufficient volume of material for dating. The remaining sample was dated, although the resulting age was too young (less than 400 years age) for accurate results using the C-14 technique.

There were no marker beds noted in either of the trenches. There did not appear to be any displacement of sediment; therefore, it was not possible to distinguish faulting at the depths exposed.

Cut-and-fill structures implied that channels have passed through the canyon floor in this location in the past. The location and depth of these structures indicate that these older channels did not always follow the path of the present channel. The presence of depleted uranium is helpful in dating the age of these channels. The channel structure at station 80 is contemporaneous with dynamic weapons testing, as are the structures at station 130 and station 300. Contamination within the surface layer (uppermost 15.2 cm) was found to be present at stations 70 and 250. These may also be indicative of older flow paths, but the lack of structure does not provide positive evidence of this phenomena. Results from the total uranium and isotopic ratio analyses in the trenches are similar to those found in Transect T-3. There is uranium contamination across the canyon in this region of the discharge sink. Contamination with depth is sporadic, and the locations of contamination do not necessarily coincide with the location of the present day channel.

*Historic Changes in the Channel through the Discharge Sink*

Historic changes in the appearance of the channel through the discharge sink were observed using aerial photographs. Some of the earliest aerial photography of this area was taken by the U. S. Department of Agriculture (USDA). The Soil Conservation Service of the USDA had aerial photography taken of the Upper Rio Grande Watershed in 1935 to assess soil erosion. Attempts were made to collect a photograph during each decade from the 1930's through the 1980's to document channel changes within the discharge sink. Aerial coverage during the 1940's was spotty due to the secret nature of Manhattan Project operations at Los Alamos. Aerial photography then was mostly prohibited, except for official government use, and those were classified. No negatives were located during that decade. The only aerial photographs available were taken at high elevation; enlargement to the required scale lost so much detail that they were no longer useful. For this reason, the 1940's decade will be skipped in the following discussion.

North is at the top of all photos. The cleared area near the center of the photo is the Lower Slobovia firing site. The linear feature trending southeast from the bunker barricade mound in the 1987 photo is the Sled Track. The scale of the photos from west to east is about 2800 m and from north to south, about 1000 m.

1930's

The photo in Fig 5.6 was taken in 1935. The location of the trace of the T-2 transect where it crosses the channel is shown for reference. Notice first that it appears the channel flows through the entire discharge sink. The downstream boundary of the discharge sink as seen today (1990) coincides roughly with the lower left edge of the photograph. The headcuttings at the bottom left are the beginnings of reestablishment of a well-defined channel. They result from accumulation of flow from the small side canyon west of the Lower Slobovia bunker and from contributing area on the west margin of the watershed. They are apparent in all the photos discussed, and appear not to have changed much since 1935.

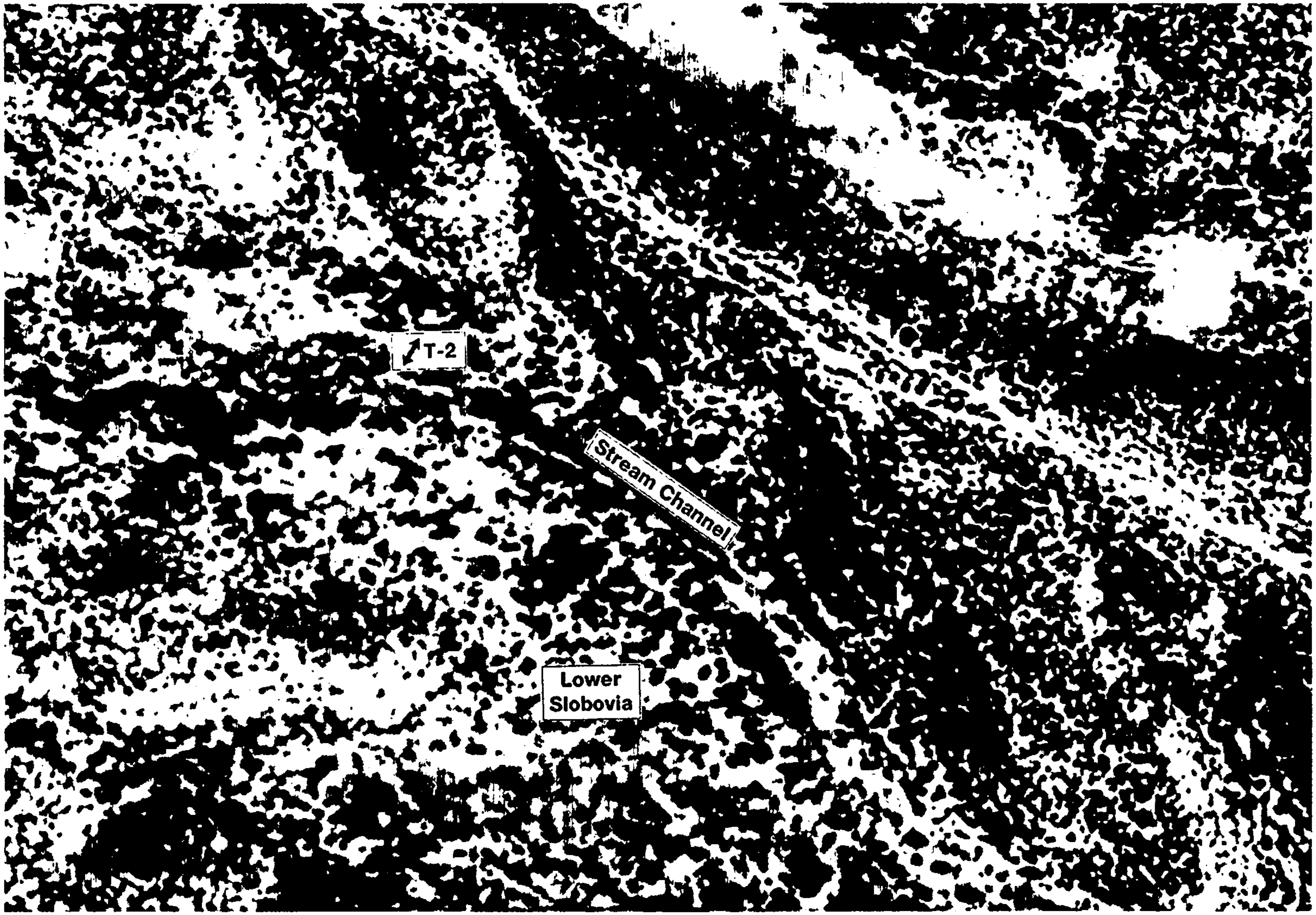



*Fig. 5.6. Discharge sink, 1935.*

1950's

This photograph shown in Fig 5.7 was taken May 27, 1954. The channel flowed past the trace of Transect T-2, southeast to a point about due east of the Lower Slobovia bunker. Southeast of this area a trace of the channel can be followed for several hundred feet downstream and then only vegetative changes suggest the active channel location. The channel appears to be rather broad, and at least one instance of a washout is evident. When comparing this photo to those taken in more recent years, notice how much more vegetation was present in this area in 1935. This is because of the pyrotechnic qualities of depleted uranium. Frequently, detonation and scattering of depleted uranium creates small brush fires and will ignite trees. Consequently, the vegetative density in the vicinity of the Lower Slobovia firing site has been reduced since the site became active in the early 1950's. Because vegetation has the ability to hold soil and reduce erosion, one would expect increased soil erosion in this area since the testing at this site began.

1960's

Fig 5.8 was taken June 28, 1965. A distinct channel can be seen flowing though the entire discharge sink. The channel flowed to the south of all four clumps of trees downstream from Transect T-2. There appears to be several washouts from the channel within the sink.


*Fig. 5.7. Discharge sink, May 27, 1954.*


*Fig. 5.8. Discharge sink, June 28, 1965.*

1970's

Fig 5.9 was taken on November 5, 1976. The channel can be observed past the T-2 transect, and lost its form about 4 tree groupings downstream. There is a secondary channel which has developed on the north side of the 3rd and 4th tree groupings. Tree 430, used in the sedimentation rate analyses (Chapter 6), is located north of the 4th grouping. This channel extends further downstream about 150 m. The channel cannot be distinguished downstream from this point, until the headcuttings at the bottom of the photo. These represent flow from the side canyon to the west of the Lower Slobovia bunker.

1980's

The date of photography in Fig 5.10 is December 6, 1987. The channel can be seen distinctly past the T-2 transect. It continued for a short distance, about 4 tree groupings downstream along the channel edge, and then becomes difficult to distinguish past the 4th grouping (fallen tree). A vague trace of the channel through the discharge sink can be delineated by vegetation changes alone. Field inspection of the area confirmed that to locate the active channel downstream of this area on the ground is very difficult. At the bottom of the photo, one can discern the resumption of an active channel, with branches flowing from the northwest. These represent the accumulation of flow from the small side canyon due west of the Lower Slobovia bunker. At the end of 1990, the discharge sink appears about the same as in this photo.


*Fig. 5.9. Discharge sink, November 5, 1976.*


*Fig. 5.10. Discharge sink, December 6, 1987.*

In summary, the channel appeared to flow continuously through the discharge sink in the 1930's. The continuity of the channel may be a relict from large rainfall/runoff events, which occurred during 1911, 1913, and 1916 (next section). There was a moderate vegetative cover over the discharge sink, which aided in retarding soil erosion. By 1954, much vegetation in the discharge sink had been incinerated as a result of dynamic testing activities. The lack of large runoff events through the reach permitted the southern half of the channel through the discharge sink to silt in. Only the difference in vegetation belies the trace of the active channel. Runoff between 1954 and 1965 reestablished the channel through the previously inactive area, which is clearly visible in the 1965 photo. Key runoff probably occurred in 1957 and 1968 (next section). Lack of runoff through the discharge sink during the 1970's and 1980's has permitted the southern two thirds of channel through the discharge sink to fill in, and again only the difference in vegetation reveals the present channel location.

*Application of Historic Changes to Prediction of Breakthrough Out of the Discharge Sink*

It is hypothesized that flow rarely leaves the discharge sink. Visible inspection of aerial photographs concluded that there has been no outflow from the discharge sink since the mid to late 1960's. Outflow has occurred in the past 45 years, as evidenced by occasional observations of depleted uranium transported in runoff past the cumulative sampler at State Road 4. When does breakthrough occur? In order to investigate the occurrence and recurrence of flow breakthrough out of the discharge sink, precipitation records were examined for candidate events or event sequences which may have created sufficient runoff. It was hypothesized that individual rain events by themselves cannot be related to runoff, but sequences of rainfall over time do appear to be related. The antecedent precipitation index (API), described in Chow (1964), is a function which describes rainfall sequences. The API is composed of the sum of an individual day's rainfall and weighted antecedent rainfall,

$$API_i = R_i + 0.9\ API_{i-1}$$

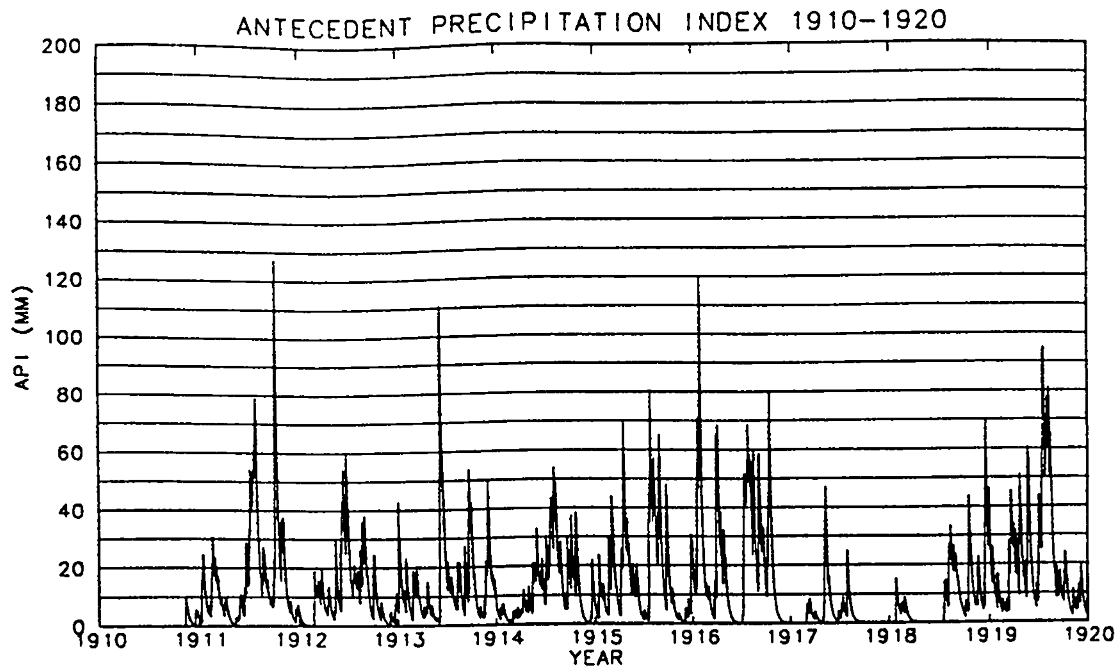
where API = Antecedent Precipitation Index

R = Daily rainfall in mm

i = day of interest

i-1 = previous day.

API was investigated to see if rainfall sequences could be distinguished which could possibly be related to occurrences of flow breakthrough out of the discharge sink. Continuous values for API were constructed for the period 1910 to 1990, Fig 5.11. Large values of API correspond to when there was significant amounts of rainfall over a period of days. Years when the value of API exceeds a value in mm of 80, 90, 100, etc. were tabulated, Table 5.6. During 1988, the API value equaled or exceeded 80, yet it was observed that there was no runoff out of the discharge sink during that year. Therefore it was hypothesized that the API must exceed at least 80 for breakthrough flow to occur, and years when API equaled or exceeded 110 or greater seemed even more likely for breakthrough runoff. Years when this occurred include 1911, 1913, 1916, 1952, 1957, and 1968, Table 7.1. Examining these candidate years indirectly using aerial photographs, it appeared possible that years 1952, 1957, and 1968 did produce sufficient flow to break



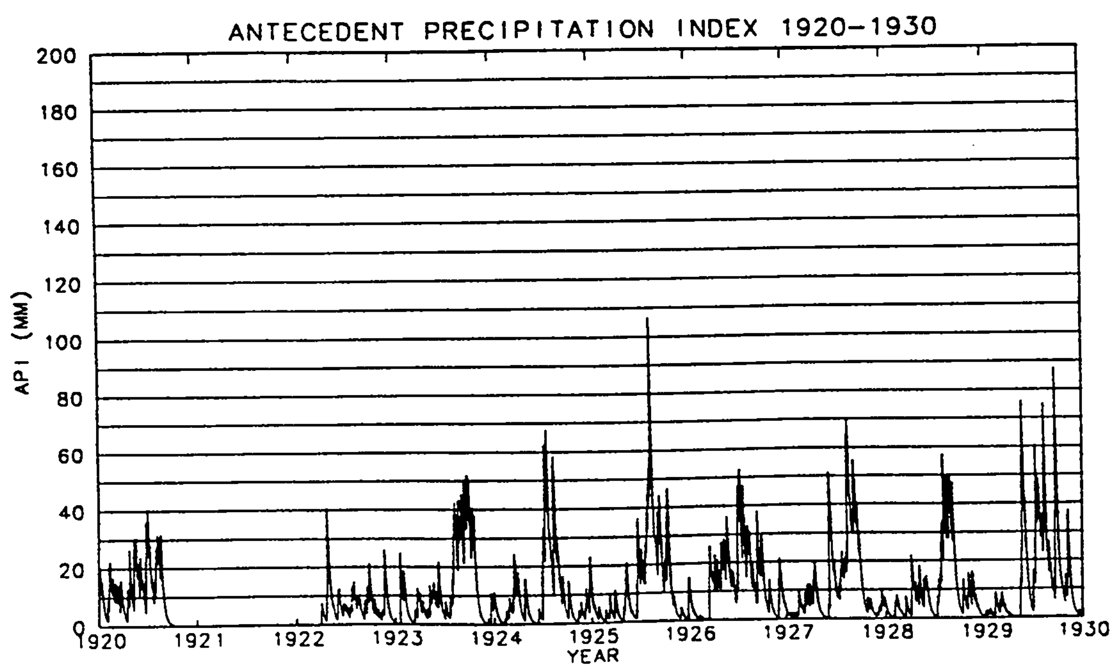
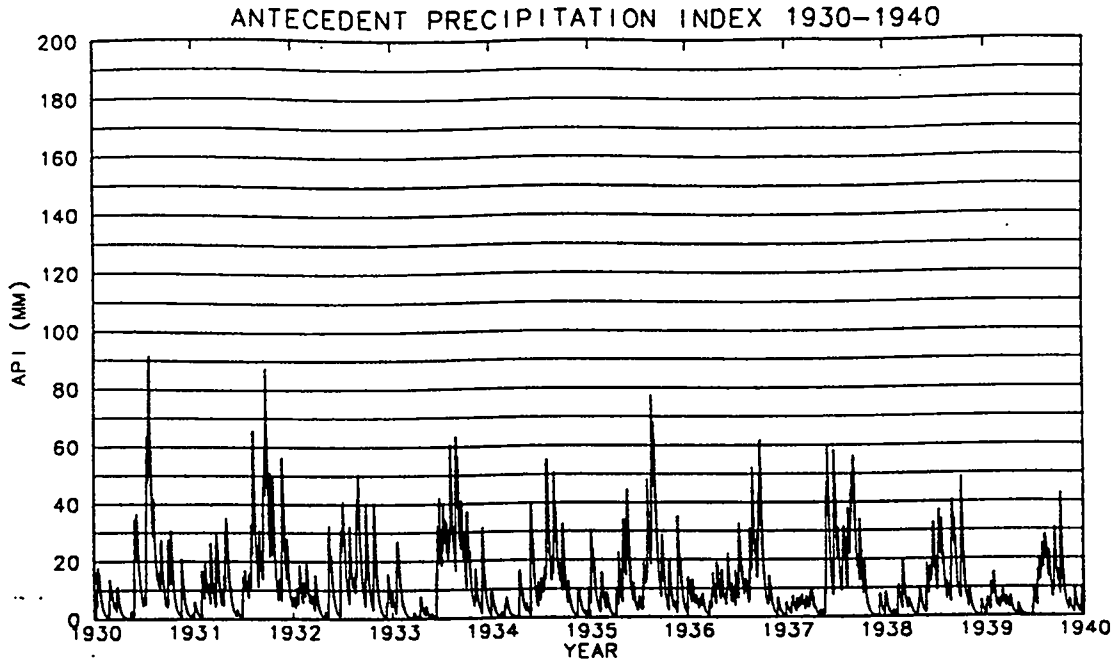




Fig 5.11 Antecedent Precipitation Index 1910-1990.



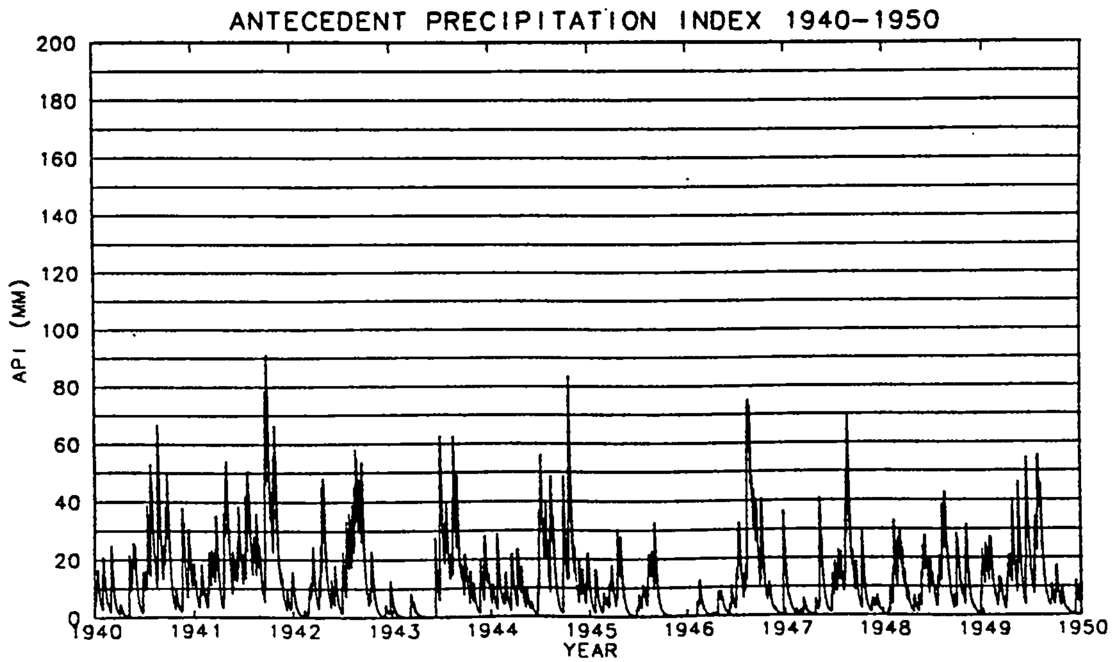
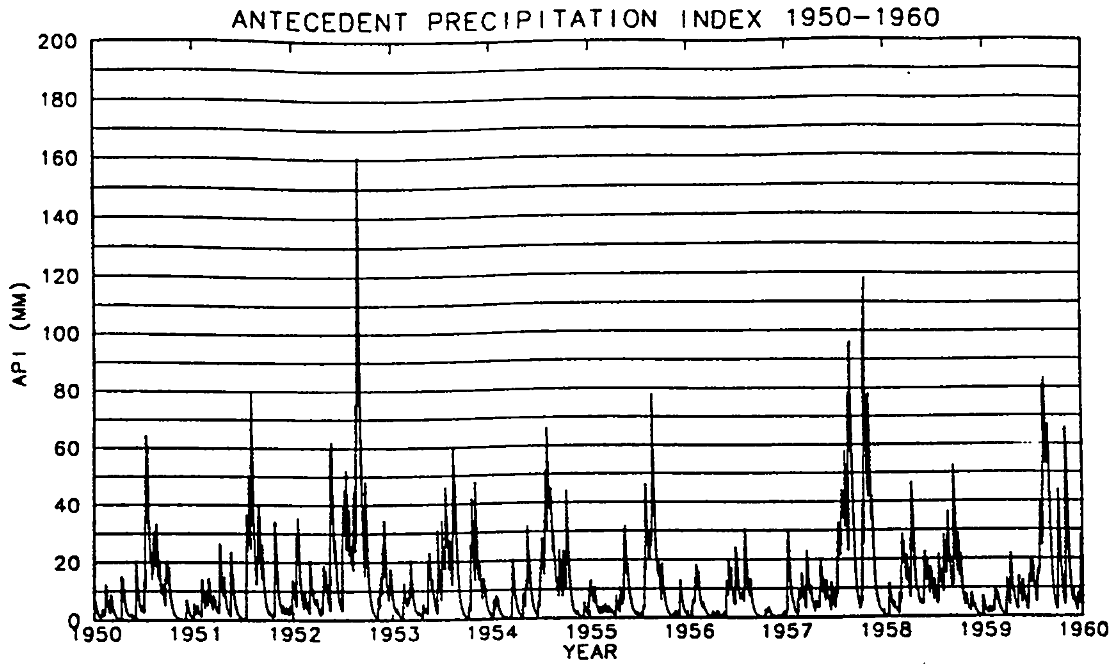




Fig 5.11 (con't) Antecedent Precipitation Index 1910-1990.



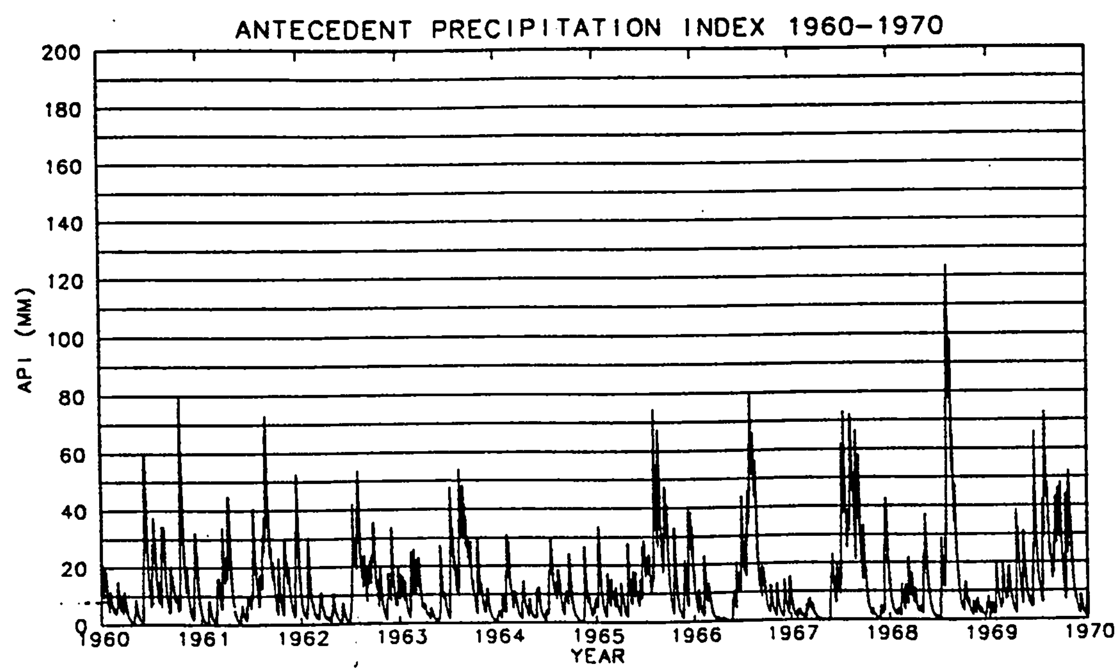
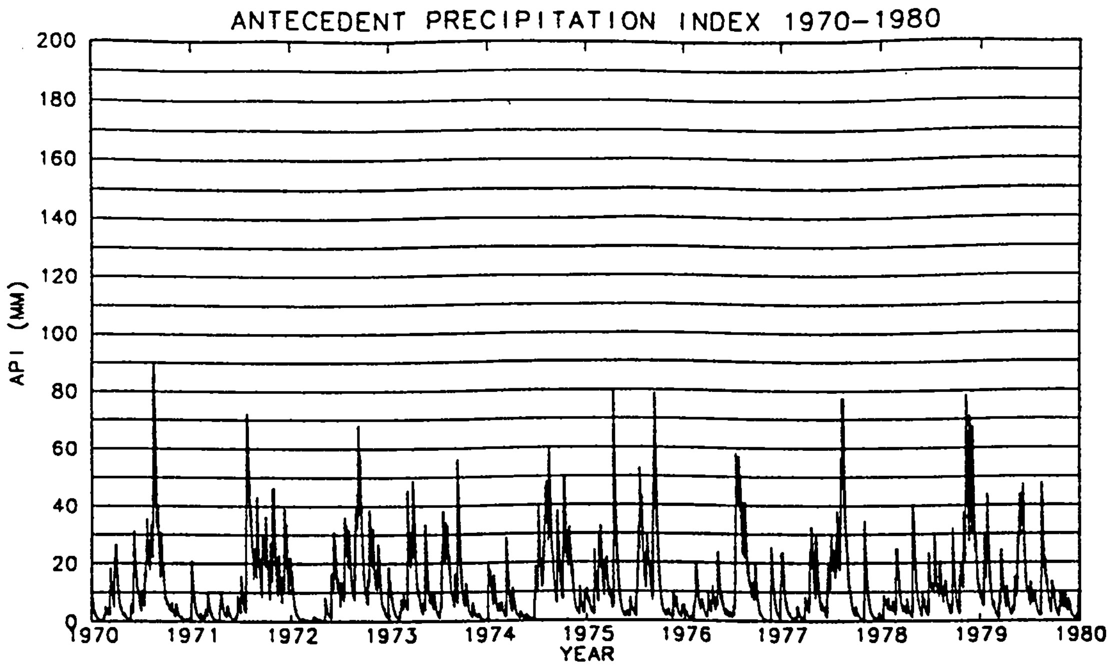




Fig 5.11 (con't) Antecedent Precipitation Index 1910-1990.



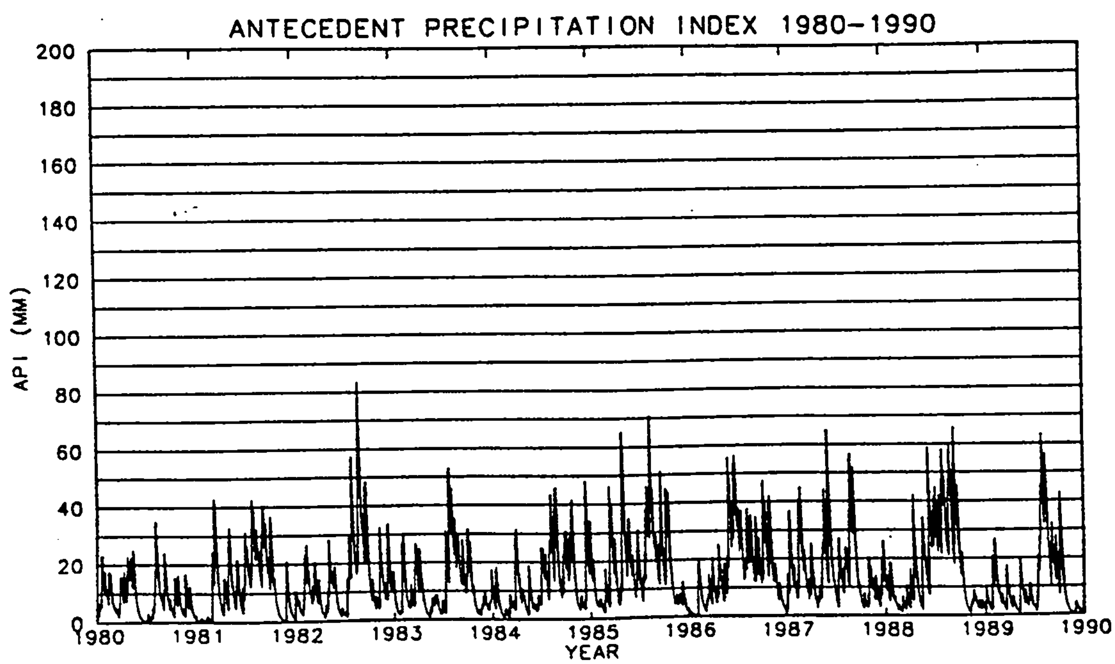




Fig 5.11 (Con't) Antecedent Precipitation Index 1910-1990.

TABLE 5.6
YEAR IN WHICH API EXCEEDS:
(mm)

| 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150+ |
|---|---|---|---|---|---|---|---|
| 1911 | 1911 | 1911 | 1911 | 1911 | 1952 | 1952 | 1952 |
| 1913 | 1913 | 1913 | 1913 | 1952 | | | |
| 1915 | 1916 | 1916 | 1916 | 1968 | | | |
| 1916 | 1919 | 1925 | 1952 | | | | |
| 1919 | 1925 | 1952 | 1957 | | | | |
| 1925 | 1930 | 1957 | 1968 | | | | |
| 1929 | 1941 | 1968 | | | | | |
| 1030 | 1952 | | | | | | |
| 1931 | 1957 | | | | | | |
| 1941 | 1968 | | | | | | |
| 1944 | | | | | | | |
| 1952 | | | | | | | |
| 1957 | | | | | | | |
| 1959 | | | | | | | |
| 1968 | | | | | | | |
| 1970 | | | | | | | |
| 1988 | | | | | | | |

out of the discharge sink and continue flow through the bottom half of the watershed. This was inferred by evidence of a distinct channel through the discharge sink on the 1954 and 1965 photos. Year 1968 was described as a year when many large runoff events traveled through other canyons through the Laboratory (Purtymun, oral communication). Weather summaries during those years were compiled and the following descriptions during high API periods were found: July/August 1952- Strong Bermuda High, strong anticyclonic vorticity in Texas with some front motion and moisture recycling; October 1957- Strong Bermuda high and on-land movement of tropical storm Bertha; July/August 1968- Series of upper level low pressure systems, accompanied by the recycling of trapped moisture. With the exception of tropical storm Bertha, series of precipitation events which might have created flow out of the discharge sink were typical summer moisture patterns. In general, it appears that flow breakthrough is not necessarily the result of catastrophic weather events. The API can be useful as a screening tool, to identify periods of significant runoff which break flow breakthrough when used with together with aerial photography. It could be inferred that 1968 was the last time that there was outflow from the discharge sink, and that 36 years elapsed between hypothesized breakthrough in 1916 and 1952.

CHAPTER 6

# ANALYSES OF SEDIMENTATION AND STRUCTURE IN POTRILLO CANYON WATERSHED

## *Sedimentation Rates*

Sedimentation rates were determined a number of ways. One method used a tracer within the transported sediment. This method was employed using depleted uranium as the tracer. By knowing that depleted uranium has been used in this watershed for the last 45 years, the maximum depth at which depleted uranium occurs places a bound on the rate of sedimentation during this period. This technique was used during the transects investigation, Chapter 5. Results will be discussed later in this chapter.

A second method of establishing sedimentation rates is to measure the amount of sediment accumulated on a tree's crown and then date the tree. Usually, the tree's crown or root is completely exposed, or buried under a slight (few centimeters) depth of soil. A substantial soil covering would be indicative of active deposition.

Using the second method, sedimentation rates were determined in and around the discharge sink. Fifteen Ponderosa pines were selected in and around the sedimentation basin, Fig 6.1. The species *Pinus ponderosa*, or Ponderosa pine was selected because this species produces an annual growth ring which can be used for dating, it exists in the discharge sink, and Ponderosa pine has been used for dating in other locations in the Southwest. Trees were selected that were healthy in

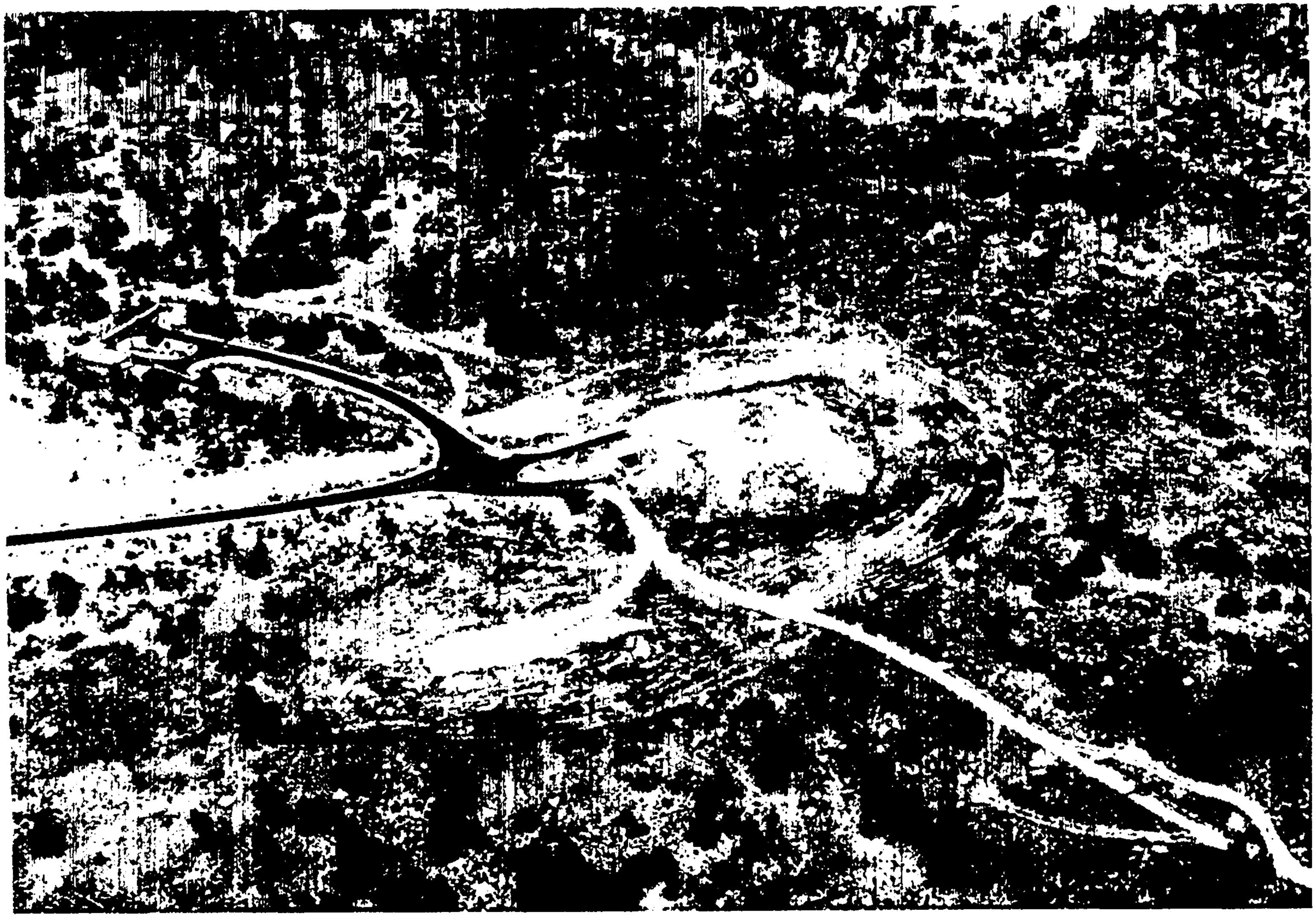


*Fig. 6.1. Locations of Ponderosa pine in the sedimentation analysis.*


*Fig. 6.1 (cont'd.). Locations of Ponderosa pine in the sedimentation analysis.*

appearance, were of considerable age (as determined by fairly large trunk diameter and height), and were located close to the present channel position along the discharge sink. Trees were tagged for identification purpose and will be referred to by their tag number.

The depth to tree crown was established by using a slim diameter soil auger to extract and measure the depth of sediment resting on the tree crown. Sediment cores were extracted at 4 ordinates around the base. The first location was selected to be closest to the upstream flow position, and the other 3 were arranged at approximately 90$^o$ around the circumference. The extracted sediment was a sandy clayey loam, mixed with organic material, usually bits of bark, and small pebbles of tuff. For those trees located in and adjacent to the channel, the greatest depth of sediment was found on the downstream side relative to the flow. This position is in a stagnation region where velocities are low and sediment is expected to settle. To calculate the sedimentation rates, the greatest soil depth was used.

Tree trunk cores were extracted from the south side of each tree at chest height using a borer. The corer was hand-drilled through the bark horizontally into the trunk until it was anticipated that the heart (center) was encountered. In this way, all growth rings would be sampled. In a few cases, cores were extracted from the north side of the tree as well. Each tree core was mounted on a wooden pallet so that the plane of the tree's tracheids was perpendicular to eyesight. A tracheid is a vertically oriented cell. Tracheids along the inner side of the tree ring are wide, have thin walls and are light in color, and are called earlywood or springwood; those along the outer side of the ring are flattened, have thick walls, are dark in color and are called latewood or summerwood. Together the earlywood and latewood comprise a growth ring (Fritts, 1976). The tree cores were prepared by sanding with a #400 grid sandpaper so that each cell was clearly visible.

Rings on each core were examined and counted using a Bannister Tree Ring Counter. False rings can be a problem in Ponderosa Pine. False rings, or interannual rings are bands of latewood within the earlywood of an annual ring. Counting false rings as annual growth rings will overestimate the age of the tree. False rings were identified when one or both of the following criteria were met: 1) the earlywood merged into latewood, and the latewood terminated abruptly in a sharp outer face against the next year's earlywood; and 2) the characteristic position of a false ring always occurred far out in the annual growth (Glock and others, 1963). Each tree core was counted for annual rings; false rings were encountered in every core. The tree ages and trunk diameters are tabulated in Table 6.1. The "m" following an age indicates that the reported age is minimum because the borer missed penetrating the heart. Dividing the depth of sediment resting on the tree's crown by the age gave the sedimentation rates.

Notice that in some instances there was in excess of 50 and at times 60 cm of sediment over the root crown. These trees, located near the channel, are literally drowning in sediment. In trees further removed from the active channel, the depth of sediment atop the crown diminishes. This effect is plotted in Fig 6.2. Trees with tag numbers 446, 445, 444, 442 and 443 lie roughly in a line perpendicular to the channel; their sedimentation rates and distances from the current active channel are shown in Fig 6.2. The sedimentation rate is greatest within 20 meters of the

TABLE 6.1
TREE AGES AND SEDIMENTATION RATES IN THE DISCHARGE SINK

| Tree Tag | Location | Tree Circumference at Core Height (cm) | Estimated Age (Yrs) | Maximum Depth to Crown (cm) | Sediment Rate (cm/yr) |
|---|---|---|---|---|---|
| 447 | Upstream of T-2, 30 m from channel edge | 218.4 | 162 | 20.32 | 0.13 |
| 440 | Downstream of T-2, <1.5 m from channel | 227.33 | 92m | 55.88 | 0.61 |
| 441 | Downstream from tree 440, at channel edge | 213.36 | 83 | 60.96 | 0.73 |
| 442 | Downstream and adjacent to tree 441, | 224.79 | 78m | 53.34 | 0.68 |
| 443 | Northeast of tree 442, 35 m from channel edge | 172.72 | 82 | 33.02 | 0.40 |
| 444 | South of tree 442, 9 m from channel edge | 158.12 | 90m | 63.50 | 0.71 |
| 445 | South of tree 444, 23 m from channel edge | 146.0 | 89 | 63.50 | 0.71 |
| 446 | Southeast of tree 445, 75 m from channel edge | 195.6 | 95 | 18.42 | 0.19 |
| 430 | Downstream and northeast of the leaning tree 50 m from channel edge | 172.7 | 89 | 43.18 | 0.49 |
| 429 | Almost due east from Lower Slobovia firing pad, by itself, 50 m from channel edge | 154.9 | 88 | 45.72 | 0.52 |
| 428 | Due east of Lower Slobovia firing pad, by itself, 6 m from channel edge | 165.1 | 96 | 39.37 | 0.41 |
| 427 | Slightly southeast of Lower Slobovia firing 30 m from channel edge | 147.3 | 89 | 49.53 | 0.56 |
| 426 | Upstream of T-3, 30 m from channel edge | 137.2 | 79 | 50.80 | 0.64 |
| 425 | Downstream from T-3, 23 m from channel edge | 208.3 | 126 | 50.80 | 0.40 |
| 424 | Downstream from T-3, west of tree 424, 46 m from channel edge | 198.1 | 93m | 22.86 | 0.25 |

m - minimum age

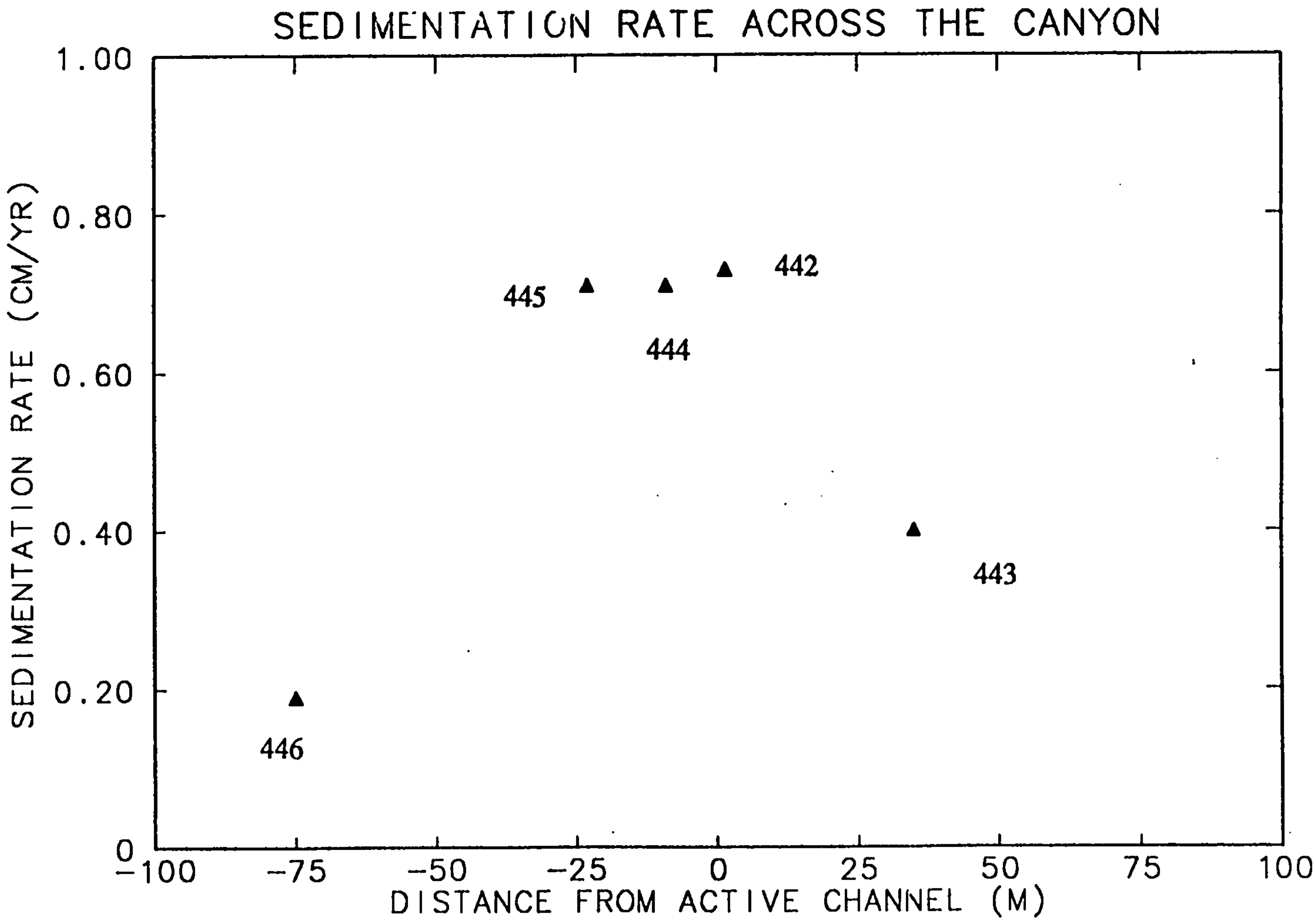



Fig 6.2 Variation in Sedimentation Rate Across the Canyon Near T-2.

active channel and then declines with increasing distance from the channel. Thus, the most active deposition is occurring within 20 meters of the active channel. A second effect can be seen in Fig 6.3. Here sedimentation rate is plotted as function of the distance downstream of the current incipience of the discharge sink. Removing the effect of tree # 426 at 5485 meters, there is a pronounced decline in sedimentation rate along the discharge sink. This may be interpreted to mean that sedimentation processes are more active recently at the upstream end of the discharge sink, and that deposition of sediments occur less frequently in the vicinity of trees # 424 and 425 during the lifespan of the trees sampled, which are 93 (conservatively) and 126 years old, respectively.

These sedimentation rates may be compared to published values. Using depth of sediments reported for canyons in Los Alamos County by Keller (1968) and Purtymun and Kennedy (1971), and using a time of accumulation of 1.1 million years from the eruption of the Bandelier tuff, sedimentation rates were computed to range from $8.4 \times 10^{-5}$ to $1.1 \times 10^{-4}$ cm/yr. Other values ranged from -27.4 (erosion) to +16.8 cm/yr in the Gila River in Safford Valley, Arizona, reported by Burkham (1972). Leopold and others (1964) describe rapid sedimentation rates of 4.6 cm/yr along the Cheyenne River Basin in Wyoming as determined from fence posts as well as lesser rates of 0.9 cm/yr along the Nile River in Egypt near Karnak and Memphis. The sedimentation rates in the discharge sink are large compared to many areas, but do not exceed observed values elsewhere.

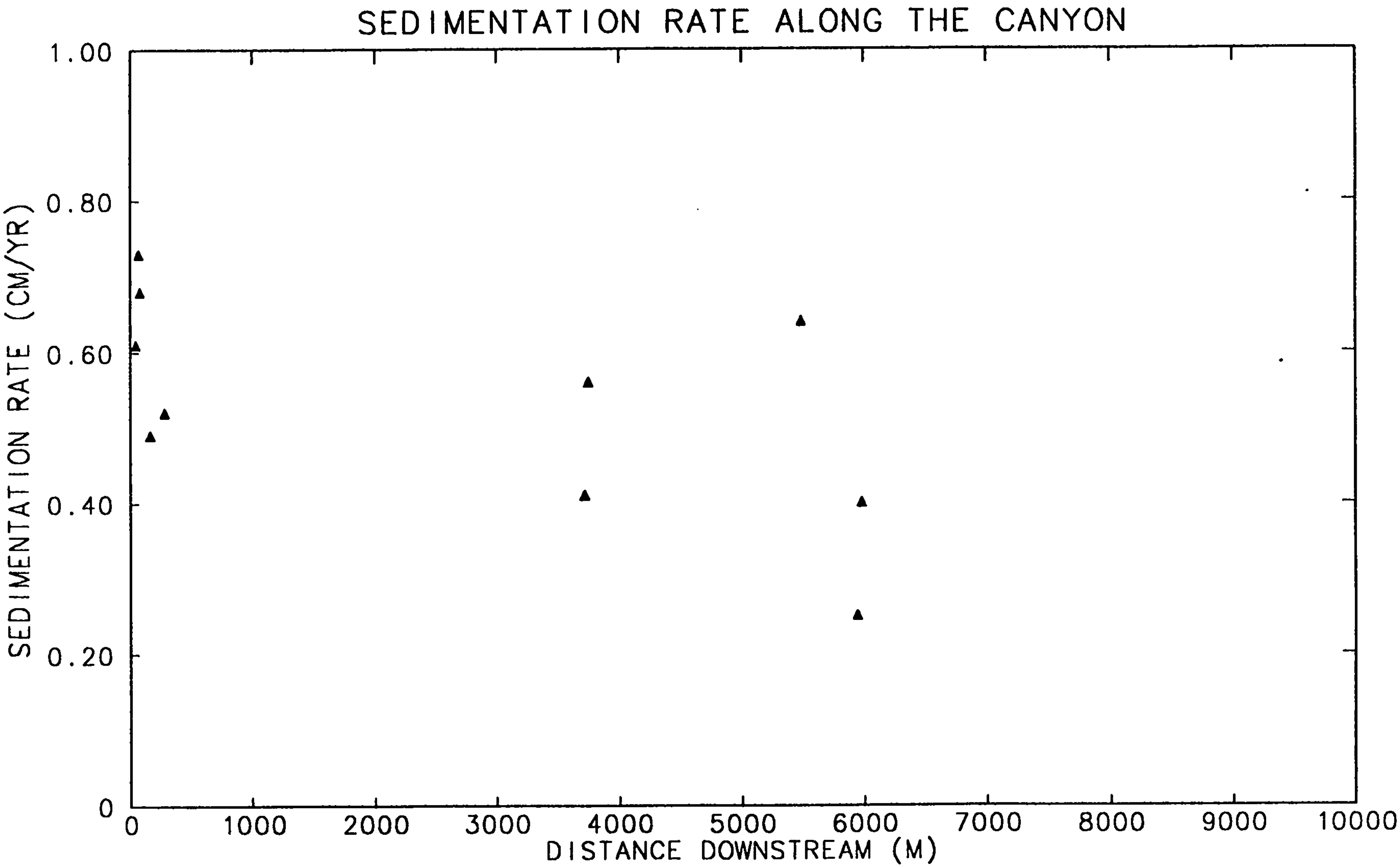



Fig 6.3 Variation in Sedimentation Rate Along the Canyon from Upstream of T-2 to Downstream of T-3.

*Land Slope Analyses*

Wachs and others (1988) reported discontinuities in stream gradients on the Pajarito Plateau where stream channels cross fault traces. In analyses of six canyons known to cross fault traces, they described that the stream gradient steepened as the fault trace was approached, became flatter at the fault crossing, and finally resumed the original gradient below the fault trace that was present above the fault. Wachs and others explained these gradient changes as resulting from lithologic changes across the fault. For canyons exclusively cut into Bandelier Tuff, the changes in stream gradient "by fault motion seem far more likely than changes from lithologic causes" (Wachs and others, 1988).

Wachs and others (1988) also reported results from seismic refraction profiles across known faults in northern Los Alamos County. Vertical faults which were downthrown to the west were believed to have created partial dams to eastern-flowing streams and permitted sizeable sediment accumulations. The largest accumulation, located in Rendija Canyon, was measured to be more than 12 m. The lack of stream-gradient discontinuities in these areas were attributed to streamflow on alluvial fill rather than in a bedrock channel.

Slopes along the channel axis through Potrillo Canyon watershed were plotted to determine if there was a possibility of faulting within the watershed which would affect the stream's gradient and depositional characteristics, Fig 6.4. There exists two locations along the watercourse where there appears a steepening of the gradient, one of Wach's criteria for the incipience of faulting. One position was upstream of the E-F cumulative sampler, and the other was downstream from the Eenie cumulative sampler. The channel is cut into Bandelier Tuff in both locations.

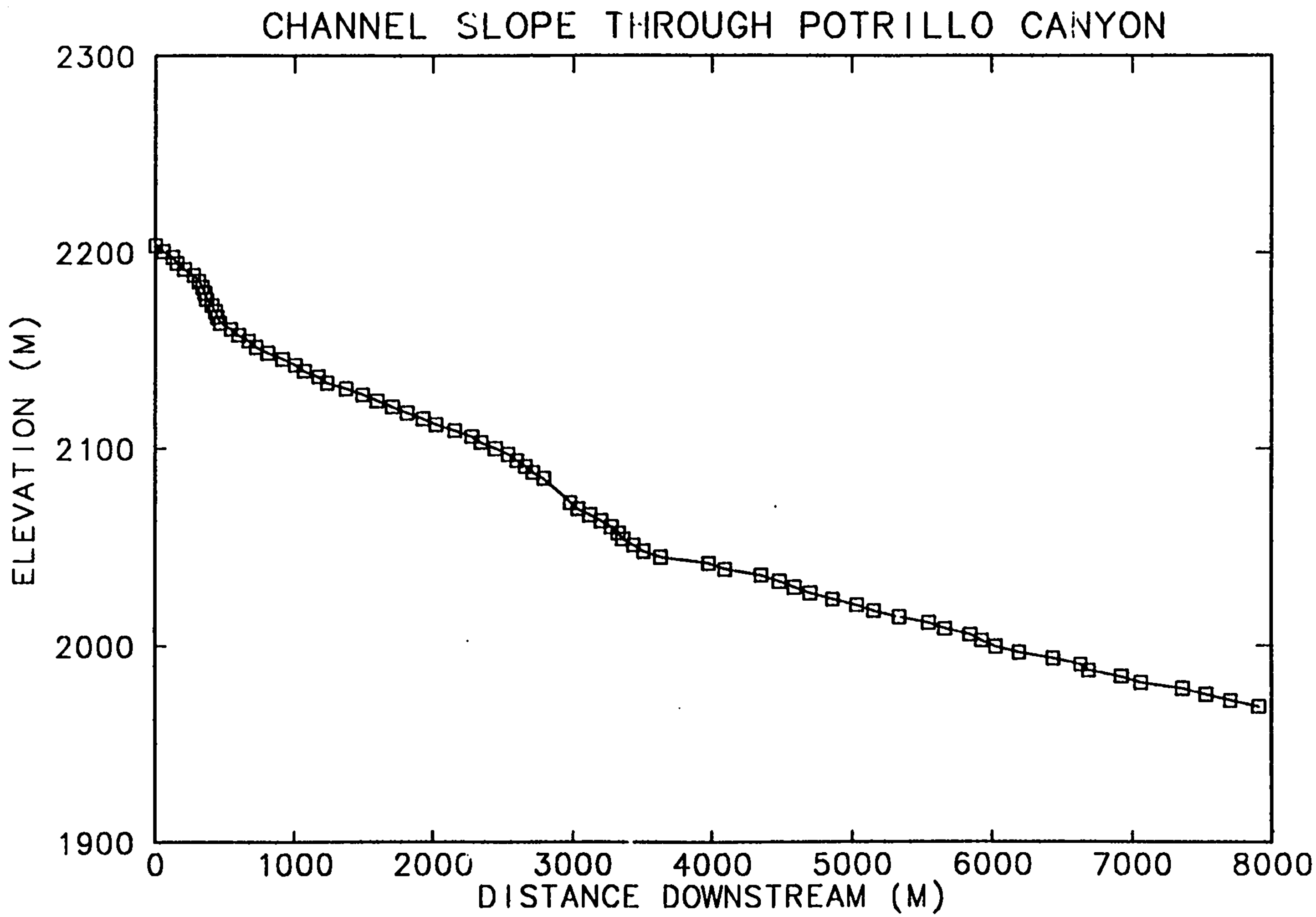



Fig 6.4 Channel Slope Along Potrillo Canyon Watershed.

Two known or inferred faults mapped in Gardner and House (1987) were shown as crossing Potrillo Canyon from north to south at the same approximate positions. Neither of these faults appear to be related to sediment accumulation in the discharge sink.

The channel slope through the discharge sink was determined using a transit and electronic distance measurement (EDM) devise. Slopes along continuous channel segments were determined, Fig 6.5. There were 2 short segments (<7m) where dense vegetation on the edge of the channel or in the channel itself precluded use of the transit and EDM. The average slope spanning 1500 m upstream of transect T-2 was 0.016, the average slope between transects T-2 and T-3 through the discharge sink was 0.017. The increase in slope at the headcutting reflects a drop in the channel at this position. The lack of gradient discontinuity does not provide proof that faulting does not exist under the discharge sink. No lithologic changes through the length or width of the watershed were found. In the area of the discharge sink, it is known that the stream channel lies in alluvial fill, and the thickness of the fill is the topic of discussion in the following section.

*Results of Shallow Seismic Refraction Surveys*

Results of the 1988 Seismic Survey

A small seismic refraction survey was conducted in the lower portion of Potrillo Canyon watershed by students and instructors in the SAGE (Summer of Applied Geophysical Experience) program, a summer program at the Laboratory designed to provide in-field geophysical experience to primarily graduate students

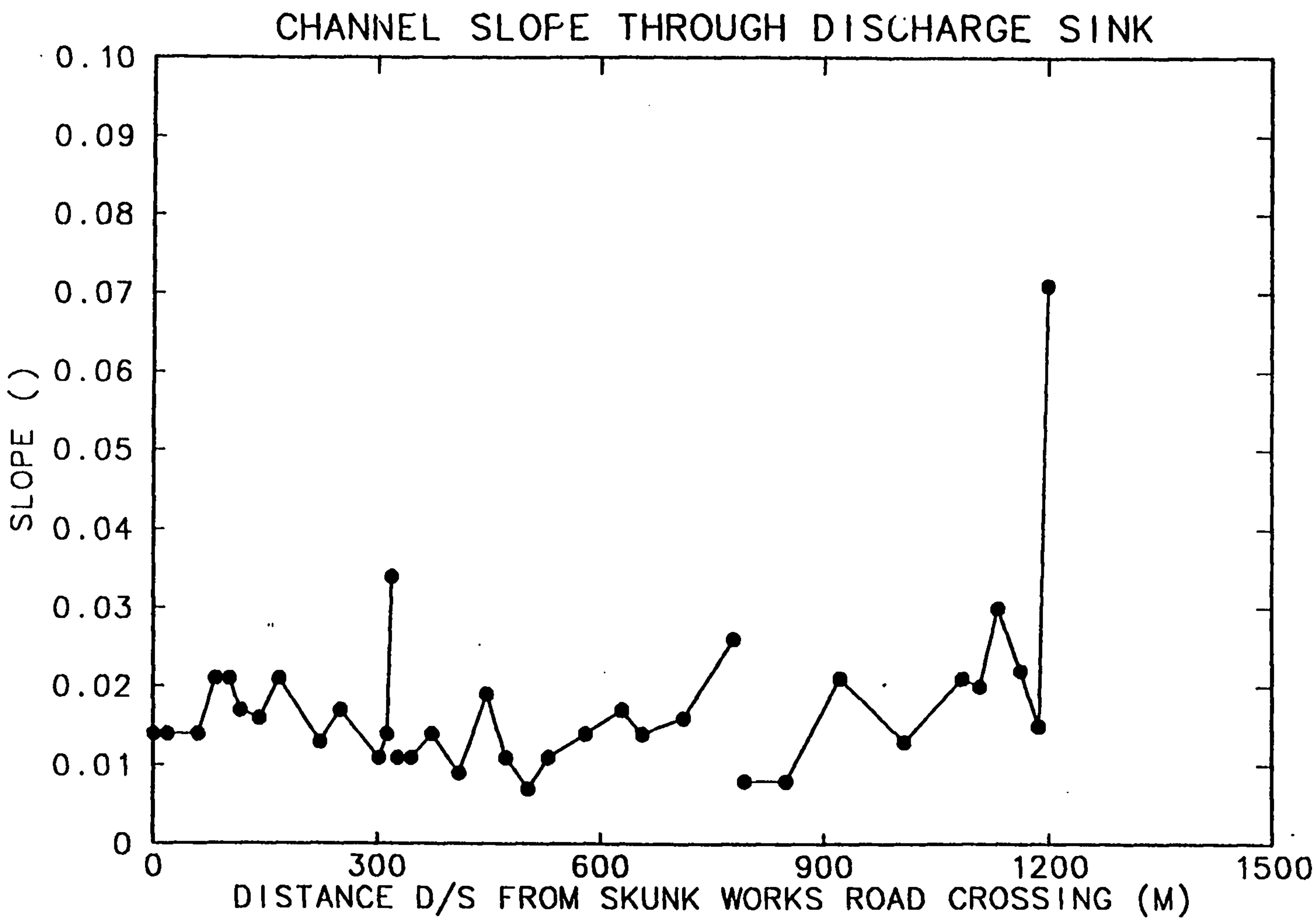



Fig 6.5 Channel Slope Through Discharge Sink.

from a number of universities. The objective of the seismic survey was to estimate the thickness of alluvium filling the canyon at that location.

Two seismic lines were investigated. Their location is shown in Fig 6.6. This particular location within the canyon was selected because of its close proximity to transect T-1 and because the area has uncleared personnel access (security clearance and escorts are not required). This location is about 1400 m downstream from T-3.

The equipment used for the survey consisted of a 24-channel digital recorder with a dynamic range of approximately 84 dB, 4.5 Hz geophones, and a relatively low-energy surface seismic source known as a Dinoseis. The Dinoseis is configured as a heavy, flat chamber, which is filled with a propane mixture and exploded to provide an energy source. It is mounted on a trailer, which constricts its use to areas accessible from roads or dirt tracks.

The two refraction lines were laid out roughly parallel and perpendicular to the canyon axis, Fig 6.6. The orientation of the canyon axis in the survey area is approximately N65W, therefore the line parallel to the axis is referred to the East-West line and the line perpendicular to the axis, the North-South line. Refraction lines were laid out with geophone group spacings of 4.57 m. Each group was arranged as a huddle of six geophones rather than a linear array. The elevation of each group was determined by leveling after the survey was completed.

The North-South line consisted of 37 geophone groups and was 165 m in length. The line crossed a dirt road which provided vehicular access. There were

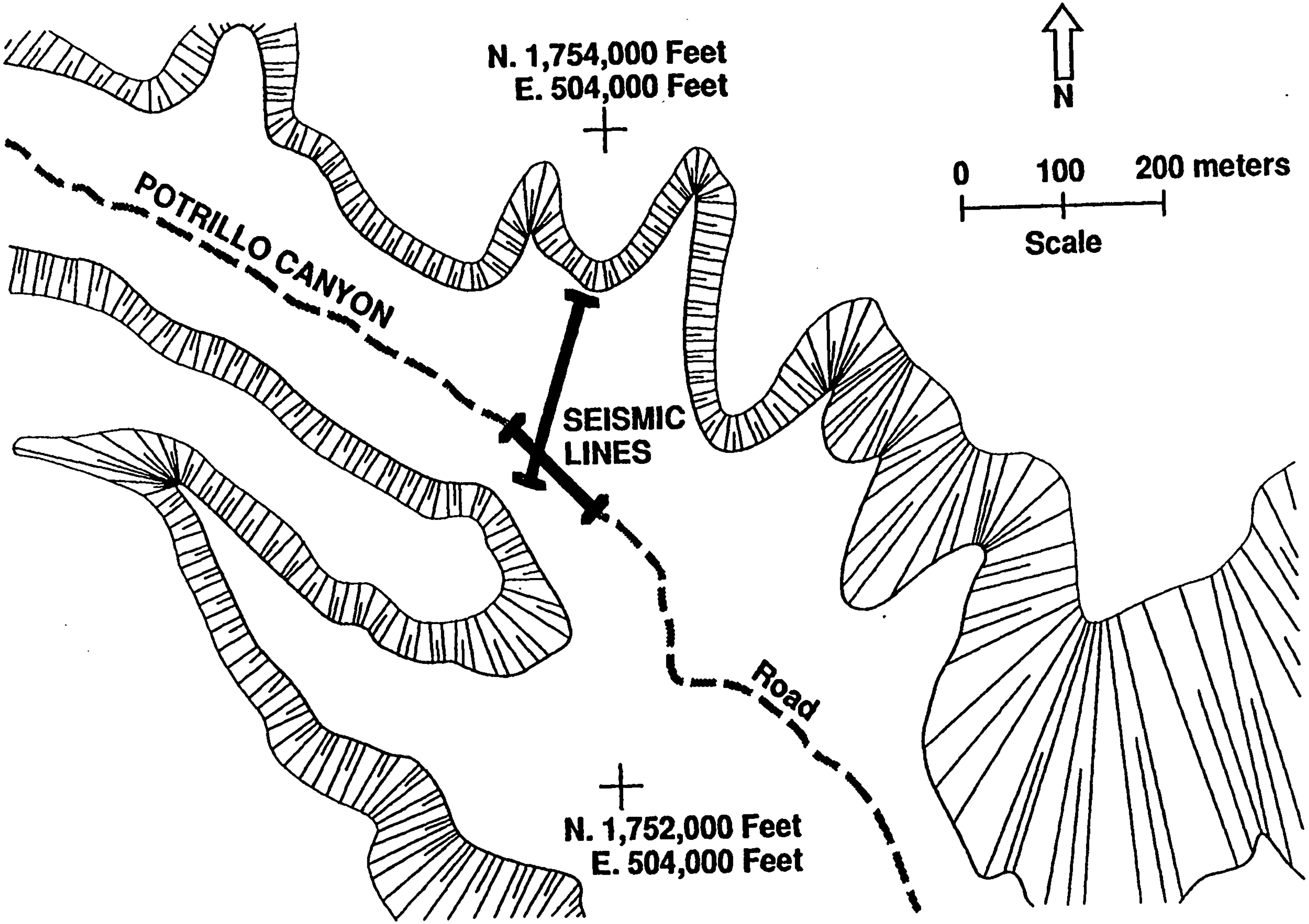



Fig 6.6 Location of Seismic Lines in Lower Potrillo Canyon.

two shot point locations along the line although the roughness of the terrain made it impossible to locate either shot at the end of the lines. Two shots were recorded at each shot point.

The East-West line consisted of 24 geophone groups and was 105 m in length. It was located along a dirt road that runs up the canyon. The road parallels the stream channel, and is located closer to the canyon's south wall than to the axis. Three shot point locations were established on the line, one on each end and one in the middle. Four shots total were recorded, two at the westernmost end, and one at each of the other locations.

Data interpretations were based on the first arrival time data using classical refraction methods. This interpretation was documented in an informal report by Cogbill (1989). A summary of the interpretation follows.

The interpretation of the East-West line corresponded to a simple model of two constant-velocity layers, one with a seismic velocity of 350 m/s, overlying a higher-velocity layer of 810 m/s. A visual interpretation of this model is presented in Fig 6.7. The thickness of alluvium was about 2.6 m at the west end, increasing to a thickness of about 9.4 m at the east end. The mean dip of the contact between the layers was 3.7$^{o}$. Below the alluvium was a layer interpreted to be unweathered tuff. About 90 m from the west end of the line there was an abrupt decrease in the observed travel time, indicating a special feature. This feature could correspond to a fault which is upthrown on the west, or, more likely, an erosional feature which was later covered by sediment. The magnitude of the seismic velocity of the lower layer

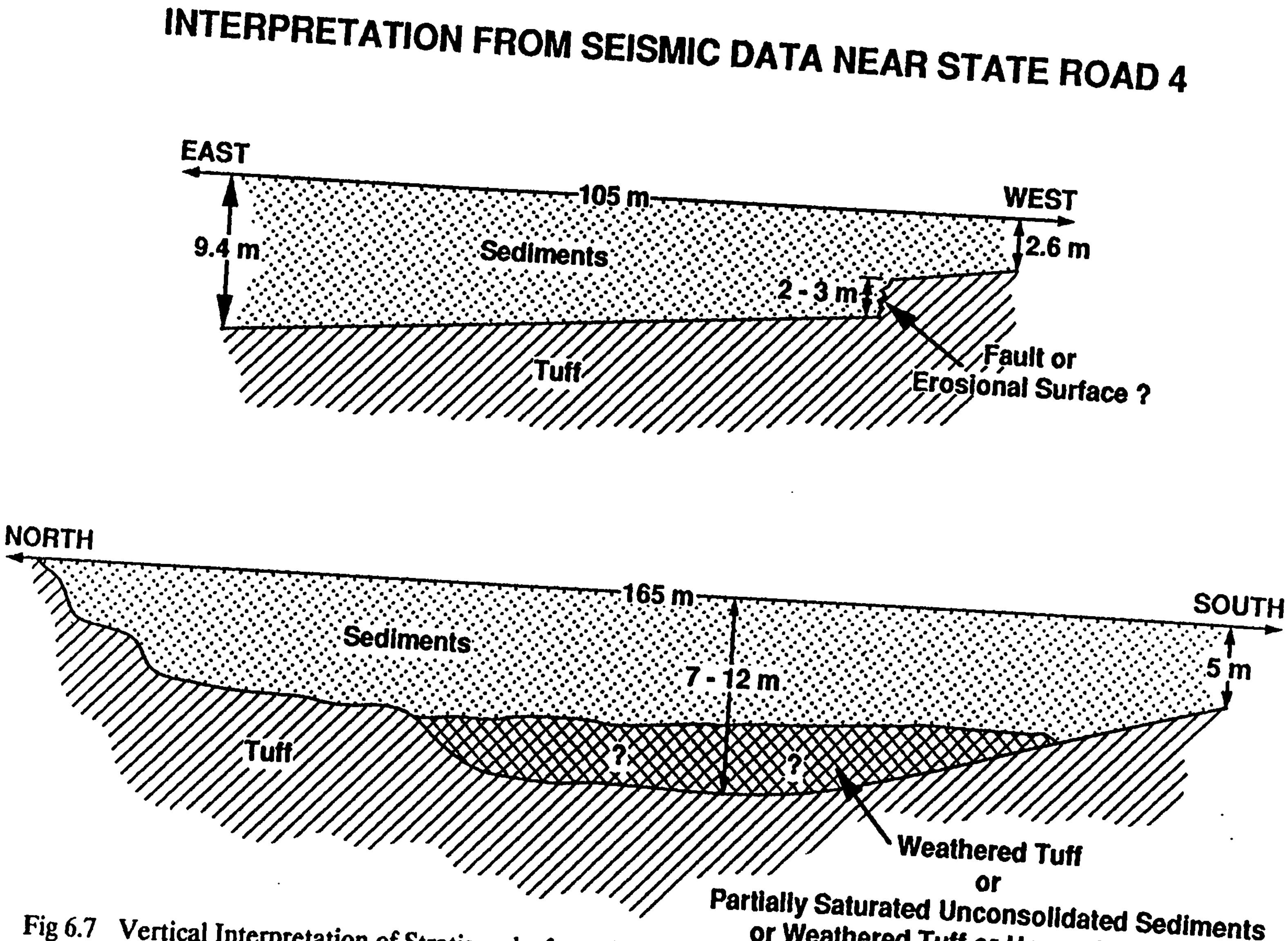



Fig 6.7 Vertical Interpretation of Stratigraphy from the Seismic Refraction Survey in Lower Potrillo Canyon.

was appropriate for an unweathered tuff. There was no evidence of a perched water table or a faster seismic layer, such as a basalt.

Data interpretation of the North-South line was less reliable because none of the shot points were located beyond the ends of the seismic line, implying inadequate reversal of subsurface coverage. The travel time curves from shots on this line were complicated compared to the East-West line, although this was not unexpected since the line crosses the canyon and lateral variation in stratigraphy was expected. North of the canyon access road, unconsolidated material overlies unweathered tuff having an apparent velocity of 700 m/s which corresponds to the simple two-layer model proposed for the East-West line. Between 60 and 65 m on the line, the apparent velocity increased abruptly to about 1200 m/s; this result is indicative of an erosional feature. From 70 m to 135 m along the line, there was a continuous increase in velocity with depth. Because shots were not located beyond the ends of the lines, only apparent velocities could be calculated. The magnitude of the apparent velocities in this portion of the line alluded to two possible explanations. Either there is a zone of weathered tuff overlying unweathered tuff, or there is a zone of partially saturated material which could be unconsolidated sediment, weathered tuff, unweathered tuff, or a combination of weathered and unweathered tuff. The magnitude of the apparent velocity makes the likelihood small of the layer being a scoriaceous basalt. A geologic log compiled while drilling a shallow observation well in this area in September and October 1989 confirmed that there was no saturated zone. Basalt was not encountered either. The uncertainty in interpreting these results is due to the possibility of error in the measured travel times and the lack of shots beyond the ends of the lines. In addition, the thickness of this layer could not be determined with certainty. South of the access road, this feature was not present. A schematic of the interpretation of this line is presented in Fig 6.7.

There were a number of preliminary conclusions from this survey. First, the results indicated that shallow seismic refraction surveys can be performed in this particular geologic locale which can successfully identify alluvial thicknesses in canyon bottoms. Second, the results of the survey indicated appropriate spacings for geophones and source term requirements for future survey work with this type of objective. Third, shallow refraction surveys of this type can also reveal information about possible geologic structure in the vicinity of the survey and information on buried saturated strata, which is of particular interest in arid basin watersheds.

Results of the 1989 Seismic Survey

A second seismic survey was performed in Potrillo Canyon during August and September, 1989 by Charles B. Reynolds & Associates, a geophysical contractor. The survey consisted of one 1050 m long line down the canyon axis, from the road to Skunk Works to past transect T-3, and 2 cross-canyon lines, one 180 m long at T-2 and the second 150 m long at T-3. The long line is referred to as LS-1, the two shorter lines LS-2 and LS-3, respectively, Fig 6.8. The purposes of this shallow seismic refraction survey were to determine the depth of alluvium and form of the surface of the top of the weathered tuff and to obtain any information on faulting along the survey lines.

The seismic energy source used was a leather bag containing 250 kg of lead bird shot, dropped from a height of 2 m to the ground from the back of a pickup

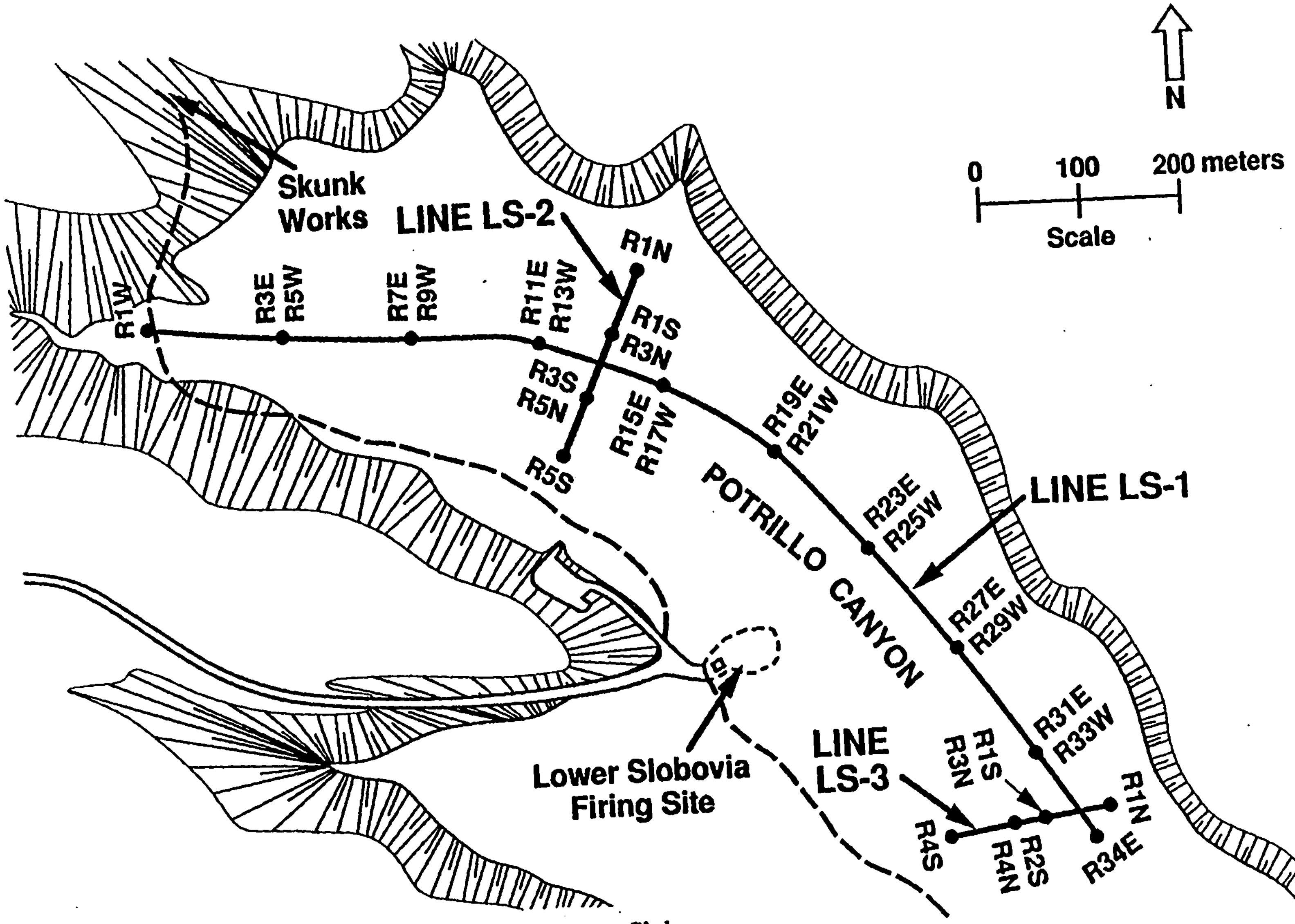



Fig 6.8 Location of Seismic Lines in the Discharge Sink.

truck. A double-ended seismic cable was used. It has 13 takeouts spaced at 5 m intervals, for a total effective spread length of 60 m. A single 8 Hz geophone was placed at each of 12 takeouts, and the bag weight dropped at one end from one to eight times, depending on the soil and energy transmission. A geophone from the far end of the line was moved to the weight drop end, and the weight moved to the other end of the spread and dropped where the geophone had been. In this way reversed or reciprocal times were obtained, providing a quality check on the data and aiding in interpretation of the refraction profiles. After the reversed profile was recorded, the geophones were detached and the cable moved forward 30 m or one half cable length. The process was repeated. The 50 percent overlap was intended to provide nearly continuous coverage on the deepest refractor.

Data was recorded using both analog and digital methods. Digital data was reduced by picking first breaks and fitting inverse velocity lines by a least squares method; and refractor thicknesses and depths were calculated by the zero-distance time intercept method (Reynolds, 1986). A wave reconstruction method was used to analyze the deepest refraction results, indicated by the reversed or reciprocal data. This method assumes that only the overburden velocity is known.

Reynolds (1989) interpreted the presence of three to five velocity layers from the collected data, with the most common number of layers being four. The layers were described as follows:

The shallowest or surface layer had a calculated mean velocity of about 270 m/sec and a mean calculated thickness of about 3.3 meters. This slow velocity is typical of a very soft, very dry, completely unconsolidated and highly compacting soil.

The second layer was described as a set of lenticular, overlapping, probably stream-laid velocity units. Measured velocities varied from 287 to 490 m/sec, with a mean velocity of about 340 m/sec. The velocity suggested that these layers were also unconsolidated, but may contain somewhat coarser (sandier?) material. This layer was not always present, but averages 3 meters in thickness when present.

The third velocity layer had a mean thickness of 8.4 meters but appeared to be locally absent along part of the long line. The calculated mean velocity was about 470 m/sec, which suggested that this layer may also represent an alluvial unit.

The fourth velocity layer had a mean measured velocity of about 610 m/sec, which is reasonably typical of weathered Bandelier tuff. The calculated mean thickness of this layer was about 8 meters.

The deepest layer detected was observed only locally on the long line, but under the full length of both short lines. It had a mean measured velocity of about 850 m/sec, which suggests that it is probably unweathered Bandelier tuff.

Mis-ties between adjacent wavefront reconstruction solutions which were greater than 5 meters were interpreted as possible faults, although they could also be erosional features, as pointed out by Cogbill (1989). Mis-ties of lesser magnitude were not shown on the interpretation cross-sections. The faults delineated by this study do not appear on maps of previous faulting investigations (Gardner and House, 1987, Dransfield and Gardner, 1985).

Two possible fault zones of interest were noted along the long line LS-1. One is located near the northwest end (near the Skunk Works road) and shows substantial deepening southeastward of the top of the weathered tuff along with steep dips. A second fault zone is located east of the intersection with line LS-2, which coincides with transect T-2. Reynolds has interpreted this feature as a fault downthrown to the west (Fig 6.9).

There was another interesting geologic feature about 125 meters southeast of the LS-1 - LS-2 line intersection. Here an unusually great thickness of the surface layer (270 m/sec) overlies a ridge of the fourth or weathered tuff layer. The third or 470 m/sec layer appears to pinch out against this apparent ridge. The deepest layer (850 m/sec) presumably also comes to shallow depth under this high (Fig 6.9).

A velocity which was high enough to represent saturated rock was measured in only one location, at the east-northeast end of line LS-3. The velocity of 1796 m/sec could indicate either locally perched water or a locally better indurated bed within the tuff. A borehole placed in this location prior to the seismic survey for neutron moisture probe measurements down to about 16 meters did not encounter any perched water.

Canyon alluvium thicknesses derived from these data were plotted for the three lines, Fig. 6.10, 6.11, and 6.12. Open circles indicate the depth to the top of the weathered tuff, and closed circles the depth or thickness of the top two layers, namely dry soil plus stream-lain deposits. The bars on the bottom indicate where fault traces intersect the lines. The closed circles are probably more indicative of recent stream-lain deposits.

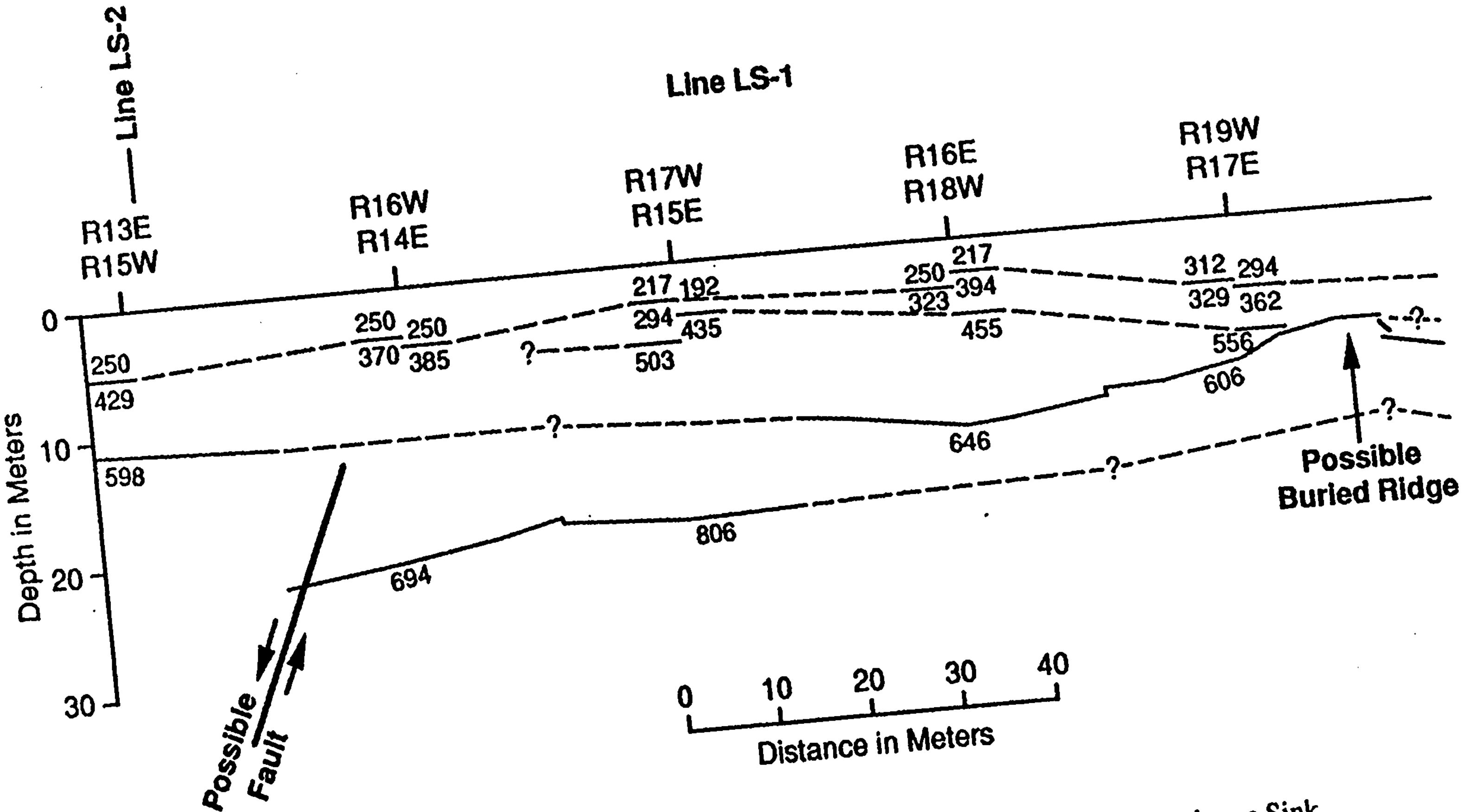



Fig 6.9 Vertical Interpretation of Stratigraphy from the Seismic Refraction Survey in the Discharge Sink.

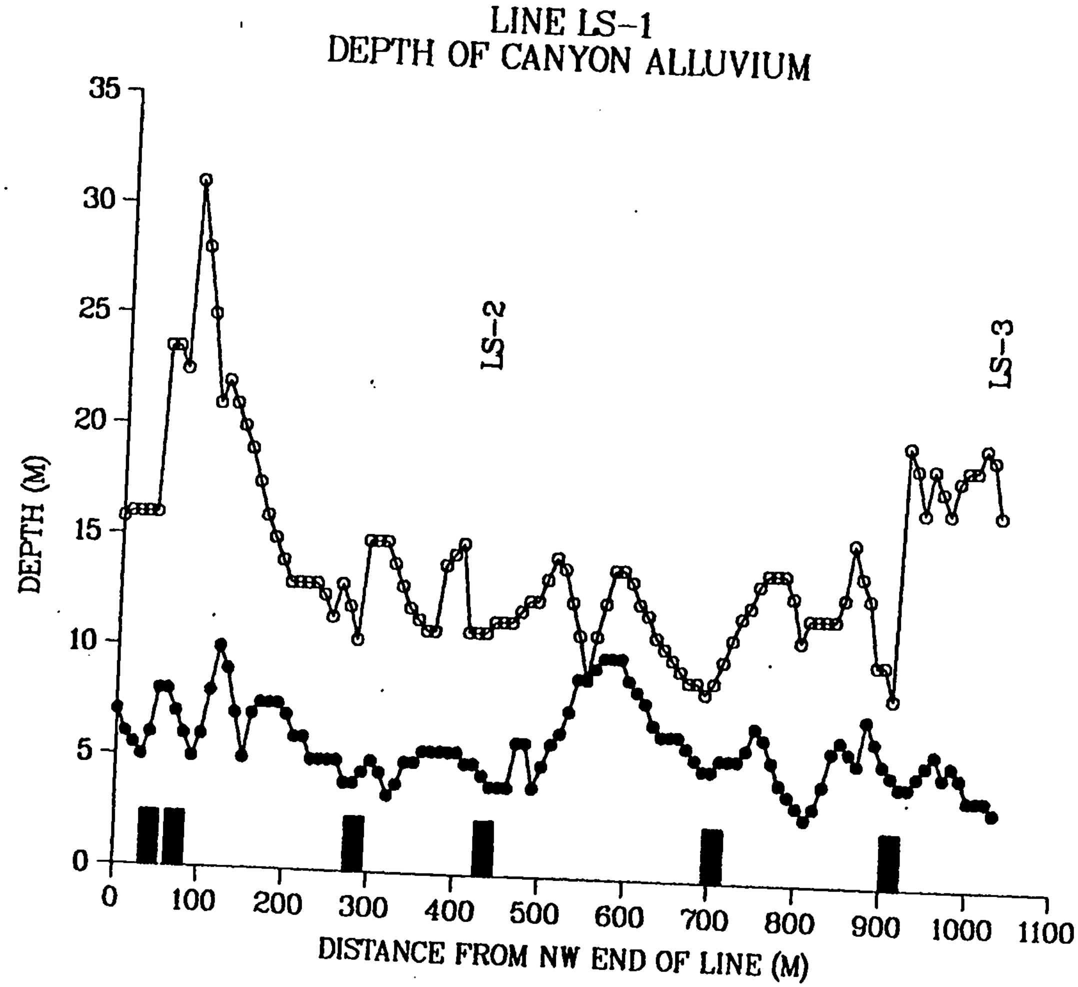



Fig 6.10 Depth to Alluvium (Closed Circles), Top of Weathered Tuff (Open Circles) and Faults (Bars) Along Line LS-1.

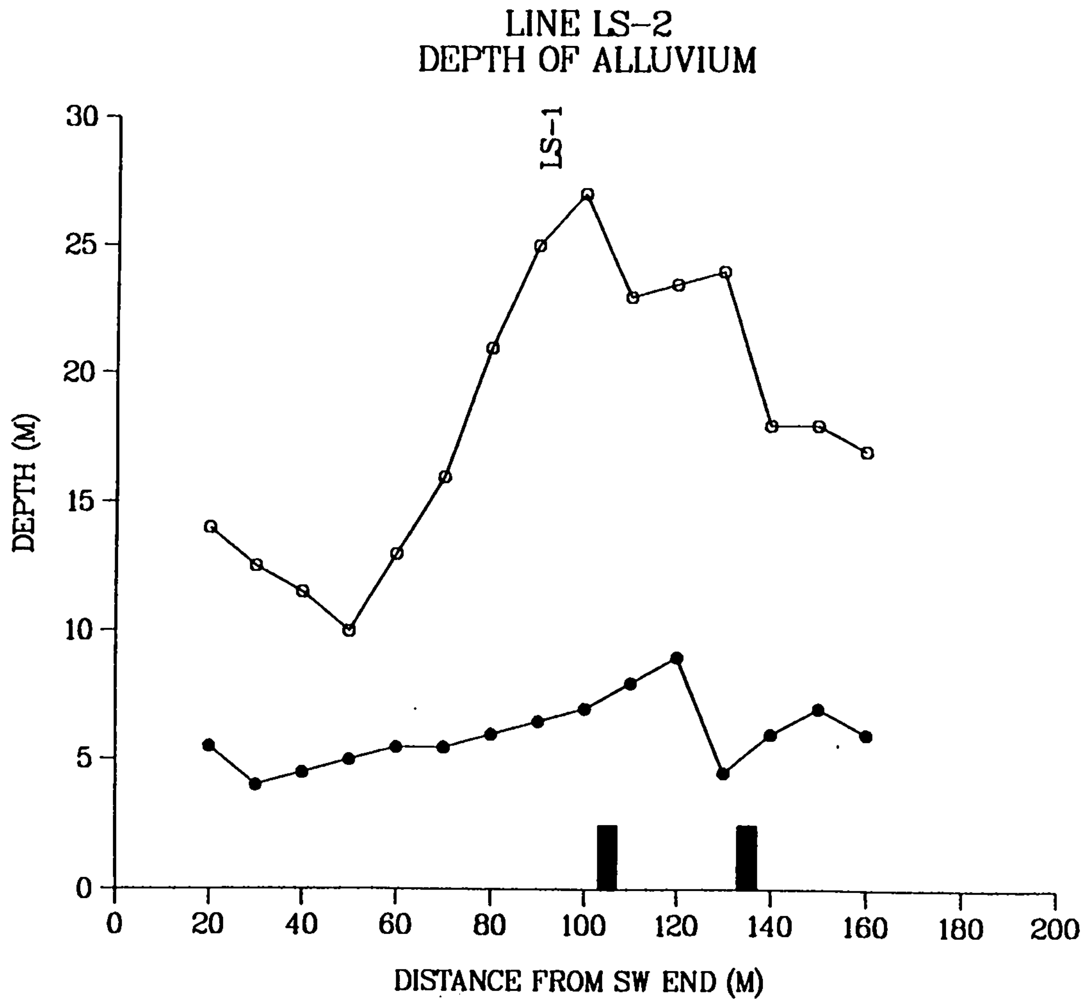



Fig 6.11 Depth to Alluvium (Closed Circles), Top of Weathered Tuff (Open Circles) and Faults (Bars) Along Line LS-2.

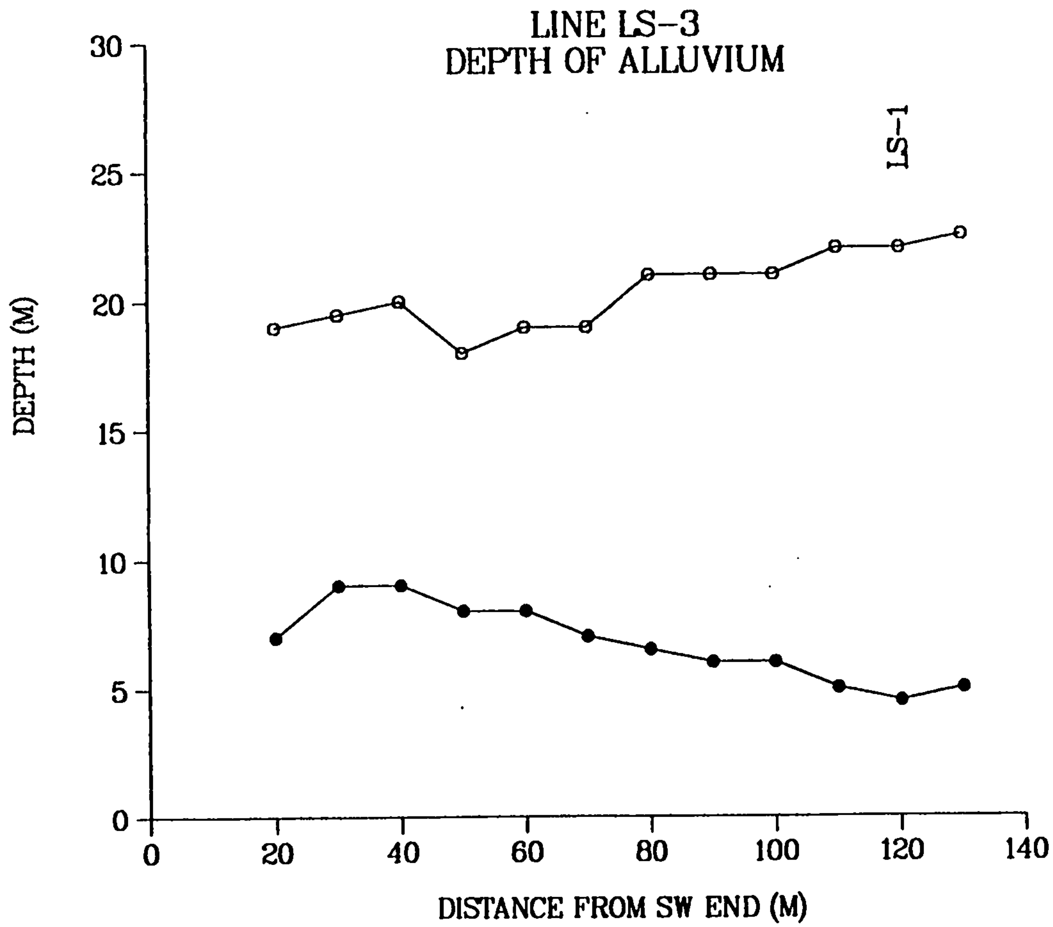



Fig 6.12 Depth to Alluvium (Closed Circles), Top of Weathered Tuff (Open Circles) and Faults (Bars) Along Line LS-3.

The average thickness of stream-derived deposits along the canyon axis is about 5.9 meters, Fig 6.10. Although the thickness varied along the canyon length, there is a pronounced thickening to greater than 10 meters south or downstream of the intersection of LS-2, beginning at about distance marker 470. This subsurface thickening of sediments coincides with the current upstream end of the discharge sink. The location of this thickening also is in close proximity with two pronounced geologic features elucidated by the seismic survey; a fault and a buried ridge, Fig 6.10.

The fault, located at 436 meters distance from the northwest end of the line LS-1, had a displacement of 11 meters. Comparing the alluvial thickness of both the sediments to the top of the weathered tuff (open circles) and of the soil plus stream-lain deposits (closed circles) on Fig 6.10 and 6.11 where Lines LS-1 and LS-2 cross indicated a discrepancy. On Line LS-1, the thickness of the alluvium on top of the weathered tuff is about 15 meters, whereas the same location on Line LS-2 is about 25 meters. On Line LS-1, the thickness of the alluvial deposits at the intersection with Line LS-2 is about 6 meters, about the same as on Line LS-2. That there is a disagreement on total alluvium thickness between the two lines indicates that there is probably a three-dimensional feature, in all likelihood a fault, at or near the intersection between these two lines, but the orientation of both lines and the shot drop locations were inadequate to properly define its correct orientation and offset.

A buried ridge located at 540 or 550 meters from the northwest end, about 100 meters downstream from the LS-1 - LS-2 intersection, appeared to post-date the third alluvial layer. This layer is absent over the ridge. Reynolds (1989) described this ridge as being possibly a small horst block, a mineralized fault zone, a small dike or simply a residual erosional hill. These two features, the fault at the LS-1 - LS-2 intersection and this buried ridge, may together control the location of sediment deposition in this watershed. Gentle faulting of the underlying geologic structure and gentle warping of the pre-alluvium topography may together be controlling present stream dynamics, manifesting in an area of lower flow velocities and thereby locally enhancing stream deposition.

There was less information concerning sedimentation patterning along lines LS-2 and LS-3. There appeared to be faulting on LS-2 near the intersection with LS-1, together with increased alluvial thickness in the subsurface, Fig 6.11, although the exact form and locus was not determined by the seismic survey. The fault shown on Line LS-1 and LS-2 could in fact be the same fault. However, great lateral variation of sedimentary deposits along these lines makes the interpretation of these collected data less certain. There were no interesting subsurface features at the intersection of LS-1 and LS-3.

## CHAPTER 7

## A CONCEPTUAL WATERSHED MODEL

Uranium transport in Potrillo Canyon is subject to the particular hydrologic, geologic, and geomorphologic conditions present in the watershed. Before the conceptual transport processes which control the movement of uranium in Potrillo Canyon are presented, the hydrologic behavior of the watershed will be reviewed.

### *Hydrology*

Precipitation falls on the watershed as snow and as rain. Snowmelt, when it occurs, produces low discharge over several months during the spring. Much of the snow sublimates, or melts and evaporates and infiltrates into the soil profile before reaching the channel. Infiltration losses occur into the channel bed as well. Forty percent of the annual precipitation falls as rain, primarily during the summer months. For runoff to be produced in the channel, there needs to be rain over a number of consecutive days. This is because of the soil's requirements for moisture replenishment before overland flow can occur. Streamflow was inferred to flow continuously down the channel past E-F, I-J, and Eenie firing sites, past the road to Skunk Works into the discharge sink.

Once into the discharge sink, the flow spreads out into a braiding channel. Here, for most of the streamflow events in this region, all discharge infiltrates into the subsurface and all sediment load is deposited. It was observed that debris carried with the larger runoff events has the capability to alter the direction of flow within the discharge sink. This debris is composed of pine cones, pine needles, bark and twigs, small pebbles and silt, and other forest litter and animal droppings. Together it compacts to form a thick mat or side wall and can confine the flow by forming lateral dams or terminal dams, Fig 7.1. Existing shrubs provide foundation support. These structures can serve to diminish the velocity and facilitate infiltration. They can contain a significant volume of material; the largest debris dam observed contained an estimated 4.25 cubic meters of material, in the dimensions 4.6 meters by 4.6 meters by 0.2 meters high.

There is evidence that flow has traveled through the discharge sink, which covers an estimated 142,000 $m^2$. As delineated in Fig 5.3 by elevated total uranium concentrations and the presence of depleted uranium, there must have been considerable flow into the discharge sink at T-2 to leave behind remnant traces of a channel in excess of 1.2 m deep. The 1965 aerial photo of the discharge sink (Fig 5.8) shows clearly an active channel through the entire length of the discharge sink. The channel remnants which are prominent at T-2 are presumed to also exist at T-3. The transect sampling was conducted before the aerials were available. The boring spacing in the vicinity of the 1965 channel is 15 m, the channel is estimated to be about 6 m wide; the absence in the T-3 crosssection in Fig 5.3 only means that this channel was not intersected.

Fig 7.1 Schematic of Debris Dams.

Between 1965 and 1976 (Fig 5.9), the channel has filled in. The infilling of the channel is postulated to have occurred as the result of a sequence of runoff events. Average event sequences (which were probably smaller in magnitude that event sequences in 1952, 1957, or 1968) had the capacity to move debris and sediment downstream, but were insufficient to flow continuously over the sink. Sequences of these events eventually filled in the channel. Because channel cutting was observed to have occurred in the past, and land use changes in the watershed have been relatively minimal, there are no anthropogenic causes for channel cutting. Climatic events and possibly active tectonism are expected which will cut a channel through the discharge sink in the future. Channel cut and fill in this watershed are assumed to be natural processes.

Downstream from the discharge sink flow resumes by coalescing overland flow in multiple channels, to a single, well-defined channel. Flow in this channel is observed to reach the watershed boundary at State Road 4 several times a year. Hence, the discharge sink serves to separate the watershed into two sub-watersheds for the majority of the time and has provided the detention location of sediment sorbed uranium during the last 23 years.

Potrillo Canyon watershed is not unique with respect to the presence of a discharge sink. It is speculated that Mortandad Canyon, a small canyon which heads on the Pajarito Plateau also contains such an area as well as Cañada del Buey, Fig 1.2. In Rendija Canyon, alluvial thicknesses in excess of 12 m were recorded on the downthrown side of a fault (or almost 6 m greater than the downstream side) (Wachs and others, 1988). In areas of active tectonism and faulting, discharge sinks may be expected, even in watersheds enclosing small areas, on the order of tens of square kilometers or less.

*Uranium*

With the hydrologic foundation thus established, conceptual models of uranium transport can now be examined. Consider the following simple mass balance. After a shot has been fired, there is a practice of picking up the largest pieces of depleted uranium left on or near the firing pad. This has been a careful practice for the past 2 to 4 years. In the past, large fragments of depleted uranium were removed from the firing pad but not from the surrounding area (Collected fragments are sent to the radioactive waste disposal site at the Laboratory). Due to numerous variables which change with each shot (e.g., configuration, size, purpose, amount of high explosive used, etc.) which affect the fragment size and distribution, it is not possible to estimate the percent of depleted uranium removed by this practice.

During a shot, there are extremely short periods when the temperatures and pressures are sufficiently great to volatilize uranium. Uranium is, however, a very reactive metal, and will react nearly instantaneously with oxygen present in the air to form uranium oxides. These oxides form particles, which (together with uranium metal fragments) drop to the ground as fallout. Therefore it was assumed that the uranium loss by gaseous transfer and dispersal was negligible.

A rough calculation was made to determine the amount of uranium which is currently co-existing on or attached to fluvial sediment in the watershed today. Using average concentration values of uranium in fluvial deposits presented in Chapter 5, *Uranium Occurrence in Fluvial Deposits*, and subtracting off background levels of uranium, estimates were made of the uranium inventory in the channel and on the banks, in point bars and alluvial fans, and within the discharge sink. Calculations were made considering uranium concentrations above background of: (1) 3 ppm along the entire channel length and width to a depth of 0.1 m in the channel bed; (2) 3.5 ppm above background along the entire channel length on both banks extending 1 m from the bank edge and 0.1 m depth; (3) 7 ppm in an estimated 30 point bar deposits upstream from the discharge sink; (4) 9 ppm in 2 major alluvial fans; and (5) 1 ppm above background in a 0.2 m depth profile within the discharge sink. For each of these 5 regions, soil masses were multiplied by soil concentrations to obtain uranium volumes. For the channel and bank segments, point bar deposits and major alluvial fans upstream of the discharge sink, it was estimated that between 100 and 300 kg of uranium are present. This quantity represents less than 1 percent of the estimated total uranium expenditure (35,000 kg).

Thus, it may be concluded that most of the uranium mass 1) is not tied up in the channel sediments, 2) has already left the watershed, or 3) remains on the firing sites. Flow and uranium loss can occur by vertical flow (infiltration) towards groundwater in the discharge sink or through horizontal flow (surface water) past State Road 4. Infiltration and surface water losses are considered separately.

Examining the volume of uranium which enters the discharge sink, there are dissolved and suspended uranium components. Assuming an annual total inflow of 5200 $m^3$ (Table 2.3) and an average, dissolved uranium concentration in the Skunk Works cumulative sampler of 1.86 ppb (Chapter 4, *Summer Runoff*), then 9.5 g of uranium annually are carried in the dissolved phase (product of uranium concentration and runoff volume). Over 45 years, this would amount to an influx of about 0.5 kg of dissolved uranium transported into the discharge sink, or less than 1 percent of the estimated 35,000 kg source term. The average, annual suspended sediment load was calculated by assuming the suspended load to be 5 percent of the average discharge. The 5 percent was based upon visual observations of the volume of suspended sediment collected in the cumulative samplers. The average sediment load was then computed from

$$\text{Load} = 0.05\,(\text{Qav})(\text{Event Duration})(6\ \text{Events/Yr})(\gamma\ \text{tuff})/\ \text{Watershed Area}$$
$$= 2{,}350{,}000\ \text{kg/km}^2/\text{yr}\quad (6700\ \text{tons/mi}^2/\text{yr}),$$

where Qav is the average discharge (assumed to be half the peak discharge), event duration was assumed to be 4 hours (Table 2.3), $\gamma$ tuff was the specific weight of Bandelier Tuff (assumed to be 1.5 g/cm$^3$), and the upstream watershed area measured 3.25 km$^2$. This predicted sediment load of 2,350,000 kg/km$^2$/yr (6700 tons/mi$^2$/yr) exceeds published values. Leopold and others (1966) reported values of 35,000 kg/km$^2$/yr (98 tons/mi$^2$/yr) in a small 9.7 km$^2$ (3.75 mi$^2$) watershed near Santa Fe, New Mexico, and reviewed other published sediment load values which ranged from 1,050,000 to 1,400,000 kg/km$^2$/yr (3000 to 4000 tons/mi$^2$/yr). Using a range of 35,000 to 1,400,000 kg/km$^2$/yr (100 to 4000 tons/mi$^2$/yr) and multiplying by an average suspended sediment uranium concentration of 8.01 ppm (Chapter 4, *Summer Runoff*), the average annual uranium influx into the discharge sink ranged from 1 to 36.5 kg/yr. This range of sediment load was compared to observed sedimentation rates in the discharge sink, which ranged from 0.75 cm/yr to nearly 3 cm/yr in the center of the active channel. The sediment load producing these rates was computed from

Sediment Load = Sedimentation Rate in the Discharge Sink ($\gamma$ tuff)/Watershed Area

$\cong$ 650,000 kg/km$^2$/yr (1866 tons/mi$^2$/yr) for a rate of 1 cm/yr

$\cong$ 2,000,000 kg/km$^2$/yr (5600 tons/mi$^2$/yr) for a rate of 3 cm/yr,

where the area of the discharge sink is estimated to be about 142,000 m$^2$. Thus the range of 35,000 to 1,400,000 kg/km$^2$/yr (100 to 4000 tons/mi$^2$/yr) is the correct order of magnitude estimate. Hence, the combined dissolved and suspended sediment influx to the discharge sink over a 45 year period constitutes 0.13 to 4.72 percent of the 35,000 kg uranium source term.

Addressing the surface water losses past State Road 4, if large volumes of depleted uranium had exited the watershed by surface water transport past State Road 4, a depleted uranium signature would remain in the sediments in the lower half of the watershed. Because there is little depleted uranium observed in sediments in the channel, banks, and floodplain downstream of the discharge sink and inferred little to no movement out of the discharge sink over the last 23 years, it is assumed that most of the uranium must remain in the watershed.

Considering the dissolved uranium transport by surface water, a second calculation was made to determine what the concentration of uranium in runoff water would be if all the uranium expended were uniformly dissolved in precipitation on an annual basis. Considering 0.5 m of precipitation annually, and assuming that 80 percent of the precipitation is lost to evaporation, transpiration, and infiltration, then,

Dissolved Concentration= 35,000 kg/(0.2)(50 cm)(7.8 $km^2$)(45 yrs)≅1 ppm.

A dissolved concentration of one ppm is an underestimate because not all precipitation contacts the uranium; expected concentrations would be even higher. This dissolved concentration of 1 ppm exceeds observed dissolved uranium concentrations in runoff water by 2 to 3 orders of magnitude. Clearly, high dissolved uranium concentrations in surface water are not observed and dissolved transport in surface water is not a main uranium transport mechanism.

Using these calculations, the argument that most of the uranium mass has left the watershed either by movement into the discharge sink or by flowing out the watershed at State Road 4 is rejected. Calculations also showed that the fluvial sediments in the watershed contain a small percent (less than 5) of the expended mass. The only plausible location for the remaining uranium is at or near firing sites.

Returning to the EG&G radiological flyover results, it was estimated that between 4 and 23 Curies of Pa-234m remained at E-F, I-J, and PHERMEX firing sites, depending on the vertical distribution (EG&G, 1986). The assumption of equilibrium between Pa-234m and uranium-238 is reasonable because the half-life decay from uranium-238 to Protactinium is short, on the order of about a half year, whereas the half-life of uranium-238 is long, on the order of 4.5 X $10^9$ years. Equilibrium means the activities of Pa-234m and uranium-238 are equal; then an estimated 4-23 Curies of uranium remain at these 3 firing sites. Multiplying Curies by 3.003 X $10^6$ to convert to kilograms, the amount of uranium still remaining at these three firing sites is calculated to range from 12,000 to 69,000 kg which brackets the estimated 35,000 kg uranium expended in Potrillo Canyon. Uranium was shown to be transported by surface water in Potrillo Canyon watershed, but most of the expended mass (source term) is believed to still reside at or near firing sites, with the most uranium mass at E-F firing site.

Consider this hypothesis from another viewpoint. If all the 35,000 kg of uranium were situated at E-F, I-J, and PHERMEX firing sites, then what magnitude of soil concentration would be expected? If it is assumed that the contaminated area at E-F firing site is 17,000 $m^3$, at I-J firing site is 4250 $m^3$, and at PHERMEX is 4530 $m^3$, with a uniform contamination to 0.6 m depth at the three sites, the contaminated soil volume would be about 26,000 $m^3$. Hence,

$$\text{Soil Concentration} = 35{,}000 \text{ kg} / (26{,}000 \text{ m}^3 * 19 \text{g/cm}^3) \cong 72 \text{ ppm},$$

and 19 $g/cm^3$ is the approximate specific weight of uranium. Unpublished surface soil (top 5 cm?) studies, conducted at the Laboratory by the Environmental Sciences Group in February 1985, gave concentrations of uranium ranging from 408 to 3359 ppm by weight at E-F firing site. Unpublished surface soil and core data, collected at PHERMEX firing site by the Laboratory's Environmental Surveillance Group during 1987, gave uranium concentrations ranging from 560 to 4580 ppm uranium by weight. Concentrations in depth samples ranged from 2 to 75 ppm by weight down to 3.7 m; the largest concentrations were in the uppermost 0.6 m. Therefore, an average soil concentration of 72 ppm is consistent with measured concentrations at firing sites. A second conclusion from this comparison is that the original estimated source term of 35,000 kg may even be slightly low.

Returning to the issue of uranium transport, it was demonstrated that dissolved uranium concentrations in surface water are low and represent a very small percentage of the expended uranium mass. A corollary could be posed. What is the potential for dissolved uranium transport vertically into the soil profile? Leaching investigations, Chapter 4, simulate the movement of uranium from the particulate phase into the dissolved phase when the available water, rainwater or streamflow, is undersaturated with respect to uranium. Levels of uranium in soil on the order of 1 to 10 ppm by weight were observed to produce uranium concentrations in the dissolved phase on the order of 1 to 10 ppb. The the ratio of the activity in the solid phase per unit mass of solid to the activity in solution per unit volume of solution is known as the partition coefficient. The leaching investigation determined a partition coefficient of 750 for channel material composed of weathered Bandelier Tuff. This result compares to published values ranging from about 1 to 20 for Yucca Mountain Nevada tuff core samples (Thomas, 1987). The determined partition coefficient may be high due to uranium sorbed onto the container walls (not measured), and due to the fact that the activity in the solid phase was determined by mass balance rather than analytically. Equilibrium, defined to be the state when uranium ceases to leach from the particulate into the dissolved phase or vice versa, was seen to be attained in about 24 to 48 hours time for both high and low initial uranium levels in soil.

How can this result be applied to uranium movement in the watershed? At firing sites, high uranium concentrations are believed to be present in the surface soil layers and at shallow depths. When rain or snowmelt infiltrates into the soil, uranium can leach from the particulate phase into the dissolved phase. The leaching studies showed that equilibrium between the solid and dissolved phases required 24 to 48 hours. This time restraint for dissolution is met under field conditions when moisture is retained in the soil profile following a rainfall event and certainly during snowmelt conditions. However, the volume of rainfall at firing sites is limited due to the small overland areas which drain onto firing sites. E-F, I-J, PHERMEX, and Eenie firing sites are all located on mesa tops near the edge of the canyon, and the mesas are narrow; therefore the contributing area is limited. As a result, the volume of water from rainfall available to infiltrate at these firing sites is relatively small. Even dense snowpack is believed not to infiltrate to great depths on the mesa tops. Moisture studies on other mesa tops at the Laboratory showed that the downward movement of moisture from rainfall was impeded or stopped at the soil-tuff transition zone. In this study the equivalent of almost 50 years of precipitation was applied over 99 days into an infiltration pit on a mesa top. Moisture penetration through a 1.8 m soil profile and into 0.6 m of the underlying tuff were observed (Abrahams and others, 1961). Hence, it is hypothesized that moisture infiltrates into the soil at firing sites and dissolves a great deal of uranium, but uranium movement in the dissolved phases is probably limited to the upper 2-3 m of the soil profile because of the competing evaporation gradient. Depth sampling at E-F firing site would aid in testing this hypothesis.

The hypothesized picture of uranium transport in the vertical direction in the discharge sink differs from the firing sites due to the difference in applied water volume. The discharge sink is the locus for nearly all runoff from the entire upper portion of the watershed. It was shown that annual water volumes into this region can be thousands of cubic meters (Table 2.3). Data from the infiltration studies (Chapter 2) support the hypothesis of rapid vertical movement of water through the discharge sink to deeper levels. Neutron moisture measurements were taken in a well at the upstream end of the discharge sink the day after a runoff/infiltration event, but still couldn't record moisture front movement vertically due to large downward Darcy velocities. Published saturated hydraulic conductivities at nearby locations support a rapid vertical movement (e.g., measured saturated hydraulic conductivity in upper, middle, and lower Mortandad Canyon alluvium ranged from 7.6 to 141 m/day (Purtymun, 1974)). Informal infiltration studies made in the main channel near Skunk Works gave infiltration rates over 280 m/day. All these data, both direct and indirect, support the theory of very rapid vertical moisture movement in the canyon alluvium.

The discharge sink is a region of significant uranium detention. Although most uranium concentrations in soil there are slightly above background, there are small pockets of high uranium concentrations, and each runoff event adds more uranium. Vertical movement of large volumes of surface water through the contaminated sediment deposit can potentially dissolve significant quantities of uranium, which percolate downward to the water table or to deep (buried) layers and adsorb. This process could provide the key mechanism for uranium transport out of the watershed.

A final calculation was performed to estimate the annual quantity of uranium dissolved by runoff into the discharge sink and transported out of the watershed through infiltration and vertical movement. The uranium concentrations in the individual size fractions of discharge sediments (Table 4.6) were used together with a partition coefficient ($K_D$) to compute the uranium concentration in the dissolved phase for individual particle sizes. The individual dissolved phase concentrations were summed and multiplied by the measured total inflow of 5300 $m^3$ (Table 2.3). The annual uranium dissolved in the discharge sink was computed to be:

$$\text{Dissolved Uranium} = (12.68\ \mu g/ml)\ (5300\ m^3) = 67.2\ kg.$$

This value exceeds the annual uranium influx, estimated to range from 1 to 36.5 kg/yr. This calculation made the following assumptions: 1) an annual inflow of 5300 $m^3$, whereas the annual inflow may be greater or less, depending on the individual year; 2) instantaneous equilibrium between the liquid and solid phases which has not been proven for this solute and material and which (based upon the time to equilibrium of 1-2 days in the leaching studies) is inaccurate for an individual runoff event but may be reasonable over the timespan of a year; and 3) a uranium $K_D$ value of 5 ml/$g_{soil}$ was used in the calculation, which is an average value in Thomas' data (1987). The leaching studies in this investigation suggested a $K_D$ value ranging from 750 to nearly 5000 (dependent on the grainsize); there is concern about using this value since the uranium adsorbed onto the container walls and final uranium concentration in the soil fraction were not analytically evaluated. $K_D$ is expected to be sensitive to factors such as grainsize and surface area, agitation rate in the batch experiment, pH and $E_H$, initial soil concentration, temperature and pressure. The dissolved uranium concentration computed varies inversely with $K_D$. Without further evaluation of the appropriate $K_D$ in this particular sediment and setting, the estimate of dissolved uranium moving vertically out of the discharge sink should be used carefully and cautiously. As the influx and efflux computed are of the same order of magnitude, there appears to be no net uranium accumulation in the discharge sink, and perhaps even a net decrease in uranium with time.

## CHAPTER 8

## SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

### *Summary*

This investigation initially focused on an evaluation of the amount of uranium transported in the dissolved and suspended sediment phases of runoff during the spring, summer and fall seasons in order to assess the transport and fate of uranium associated with dynamic weapons testing. Evaluation of uranium movement required consideration of three topics: the location of the uranium source term, the watershed response to precipitation, and the dynamics of sediment and contaminant transport.

#### Location of the Uranium

Uranium usage in the watershed was compiled from historic data. Uranium had been used at E-F firing site since the mid 1940's. Operations using depleted uranium began at I-J firing site in 1949, at Eenie and Lower Slobovia in the early 1950's, and at PHERMEX in the early 1960's. When field investigations began 7 years ago, it was unknown exactly how much uranium had been expended, how much natural uranium and depleted uranium was still resting in close proximity to the firing pads, the amount trapped in the canyon sediments, and the amount released out of the watershed into the Rio Grande. Uranium expenditure by firing site has not been compiled; therefore the exact magnitude of the source term is still unknown.

An aerial radiological survey flown in 1982 by EG&G over the upper third of the watershed indicated that considerable Uranium-238 remained in the soil profile surrounding E-F, I-J and PHERMEX firing sites, as inferred by the calculated concentrations of Pa-234m, a metastable daughter product of Uranium-238. The surface soil inventory in Potrillo Canyon watershed and the sampling of channel and bank deposits, point bars and alluvial fans in this study indicated that elevated levels (above background) of depleted and natural uranium exist in these fluvial deposits, though generally at relatively low levels compared to those in the vicinity of the firing sites. Further, significant amounts of uranium do not appear to have left the watershed as the quantities of depleted uranium present in the lower half of the watershed are small compared to the quantities in the upper half. Calculations strongly suggest that significant quantities of uranium still remain in close proximity to the firing sites, or have been transported in the liquid or solid phase to the discharge sink and have infiltrated, having leached from the sediments, and percolated downward to the water table or to deep (buried) layers and adsorbed. Existing records indicate that a large quantity of uranium, up to 45,000 kg, was expended in the watersheds of Potrillo, Pajarito and Water Canyons between 1943 and 1953. This represents one-third to one-half the total estimated expenditure at the Laboratory. In the opinion of employees who worked at the firing sites during that period, the majority of shots involving large quantities of uranium were fired at E-F site. Based upon this opinion, the results from the EG&G radiological flyover, calculations and comparisons with limited sampling at E-F firing site, it appears that the largest expenditure of natural and depleted uranium was made at E-F firing point and that there is still a considerable quantity of uranium remaining in the vicinity of E-F firing site today.

Watershed Response to Precipitation

Watershed response to precipitation and snowmelt was determined from observations at locations throughout the watershed and by direct rainfall and streamflow gaging in the canyon below I-J Firing Site and near the road crossing to Skunk Works.

Snowmelt runoff did not occur each year. The following conditions appear to determine the occurrence of snowmelt runoff: 1) normal to heavy snowfall during the winter, greater than or equal 130 cm (Bowen, 1990); and 2) normal to heavy snowfall relatively early in the winter, during the months of December, January, and early February. Both criteria incorporate the effects of snowmelt losses due to evaporation, sublimation, and infiltration. When snowfall is relatively light, the snow can melt and evaporate, or sublimate, or melt and infiltrate into the soil surface without producing sufficient overland flow or interflow to create flow in the main channel. When snowfall occurs relatively late in the winter season, during late February, March, and April, warm daytime temperatures enable the snow to melt and evaporate, or melt and infiltrate into the soil and not produce sufficient overland flow or interflow to create flow in the main channel. When flow does reach the channel, it may infiltrate into the channel bed locally without producing widespread channel flow. Sufficient and early snowfall which did produce stream runoff was observed to create very low discharge with depths on the order of centimeters. Runoff was observed to begin in March and continue into April and May.

Precipitation during the spring, summer, and fall seasons results in a very different runoff pattern. During the monsoon season (summer), rainfall occurs nearly every day. The cumulative runoff samples and the continuous rainfall and discharge monitoring showed that every rainfall event in the watershed does not produce runoff. For example, during 1990 there was three weeks of nearly daily rainfall before the first runoff event occurred. Soil moisture requirements appear to be very important in controlling the occurrence of runoff. Only after soil moisture requirements are satisfied will overland and channel flow begin.

Once soil moisture requirements are met, there often does not have to be an abundance of rain to create runoff. In 1990, rainfall amounts between 10 and 21 mm produced runoff events at the I-J gage, and amounts between 8 and 25 mm produced runoff at the Skunk Works gage. The Skunk Works gage recorded 18.29 mm of rain on September 6, 1990, and 17.78 mm of rain on September 28, 1990, but neither event created measurable runoff in the channel. Corresponding to those dates, the I-J gage recorded 10.67 and 20.32 mm of rainfall, and runoff was produced both days. This difference appears to reflect slightly more rain at the I-J gage during the month of August and more days of rainfall at I-J gage preceding those rainfall events (i.e., higher soil moisture).

Response to rainfall in the form of runoff, when it occurs, can be very rapid. The time to hydrograph peak at I-J gage ranged from 7 to 66 minutes and from 14 to 31 minutes at Skunk Works. At Skunk Works on July 22, 1990, the 31 minute time to peak occurred 41 minutes after it began raining. The hydrograph duration was short, just under 4 hours, with a hydrograph volume of nearly 3800 $m^3$. Other hydrographs measured during 1990 were not as dramatic in shape and duration. Nevertheless, hydrographs in this watershed have been seen to peak rapidly and have relatively short time bases. By comparing this hydrograph with the one produced at the I-J gage for the same event, it was estimated that channel infiltration losses between the two gages was large (about 60 percent of the runoff volume measured at I-J site was lost before reaching Skunk Works, a distance of little more than 3 km).

Dynamics of Sediment and Contaminant Transport

Investigations were undertaken to understand the main modes of uranium transport in Potrillo Canyon watershed. Fallout studies during 1984 and 1985 showed that airborne transport and wind redistribution were not significant uranium transport mechanisms. Had airborne transport been significant, one would expect to see uranium in elevated concentrations in fallout samples. Instead, in nearly every instance the concentration of uranium in fallout samples was within the levels of uranium observed in particulate samples collected within regional northern New Mexico. Airborne transport would result in a widespread contamination of surface soils in the prevailing wind direction away from firing sites. This was not observed in the surface soil collection data. Instead, elevated levels of uranium and the presence of depleted uranium were observed in surface soils in surface water runoff pathways away from firing sites. Elevated uranium levels were continuously observed in the dissolved and suspended sediment components of runoff waters resulting from precipitation and snowmelt events from 1983 through 1990 in channel runoff collection samplers downstream from firing sites. These investigations have shown surface water runoff to be the predominant mechanism for the transport of total and depleted uranium in Potrillo Canyon watershed. Airborne transport and redistribution is not important as a transport mechanism.

Hydrologic investigations began in 1983 with the installation of 5 cumulative runoff samplers in the channel along the length of the watershed. After each rainfall event, each sampler was checked, removed if it contained water, and replaced.

Runoff samples were analyzed for total uranium in the dissolved phase and for total uranium and the uranium isotopic ratio of U-235 to U-238 in the suspended sediment phase. Analyses of runoff samples over an 8 year period showed a systematic decline in uranium in both the dissolved and suspended sediment components of runoff with distance downstream from the top of the watershed.

After nearly 5 years of collection during the spring, summer and fall, there were a sufficient number of runoff events to distinguish a pattern. For the majority of rainfall events, a runoff sample was collected in the upper half of the watershed: at E-F, I-J (after it was moved into the main channel), Eenie, and at Skunk Works. Most of the time, the sampler at State Road 4 was dry. Sometimes, there was water at State Road 4 but in none of the other samplers. There were a few instances when there was a runoff sample in each of the cumulative samplers implying that there were occasional runoff events that traversed the entire length of the watershed. Closer examination of the records of cumulative sampler filling frequency suggested a discontinuity in streamflow between Skunks Works and State Road 4 cumulative samplers. Consequently, the sampling scheme was modified to test this condition. Discontinuity of flow over the length of a watershed is not unusual in semi-arid and arid basins; however, it was not expected to be present on a small scale (watershed area less than 8 square kilometers with an average (steep) gradient of about 3 percent).

The channel from the Skunk Works road toward Lower Slobovia revealed a reason for a flow discontinuity. The channel transformed from a well-defined, sand-bottomed channel bed with relatively stable banks into a braided channel sequence, which subsequently diffused into a landscape of shrubs, trees, and grasses. Here it was impossible to delineate a constant flow path. This section continued for another 0.5 km downstream, where there was a transition to several well-defined subparallel channels which coalesced into a single channel within a short distance. These channels, which began at the canyon floor and abruptly dropped into the single channel bed, at first appeared to be headword erosion products (headcuttings); later it became apparent that they were manifestation of the beginning of channelized flow at the headwater of the downstream subwatershed. Based upon these observations, the following conceptual watershed model is hypothesized: the reach where the flow path could no longer be distinguished is a region where streamflow spreads out and infiltrates into the substrata, is an area of increased sedimentation and infiltration, and therefore is a region of significant uranium detention. This region is called a discharge sink, as flow infiltrates and sediment deposits. The discharge sink would perform as an interface between the two sub-watersheds within Potrillo Canyon watershed. Upstream from the discharge sink (upstream subwatershed), precipitation events would create runoff and flow which travel down the main channel into the discharge sink. There the flow would seep into the canyon alluvium, and drop its sediment (and contaminant) load. Flow out of the discharge sink would occur in response to infrequent precipitation event sequences. Downstream from the discharge sink, contributing area overland flow would collect and grow until channelized flow could be sustained. This flow from runoff in the downstream subwatershed would continue downstream, collecting in the sampler at State Road 4. Flow in the downstream sub-watershed is usually not produced from daily, summer, orographic precipitation events which move from west to east across the watershed, while dropping rain which causes runoff at the E-F, I-J, and Eenie samplers. Flow would most likely occur in response to the large-scale storms whose sizes are on the order of several hundred kilometers, or from storms which come into the area from an eastward direction when, for example, it will rain in White Rock, but not Los Alamos (Fig 1.1). Consequences of this conceptual watershed model are: 1) the discharge sink is an area of increased sedimentation; 2) the discharge sink contains significant amounts of uranium absorbed on the surface soils and with depth; 3) there are rare instances of surface outflow from the discharge sink; 4) leaching and deep percolation transport uranium (dissolved phase) to the groundwater or to adsorption by deeper strata; and 5) only small amounts of uranium are associated with the fluvial sediments downstream.

The sedimentation history in the discharge sink over the last 45 years was relatively easy to distinguish because depleted uranium creates a unique signature. Transect data from T-2 near the upstream end showed very rapid sedimentation. The measured rate of nearly 3 cm/yr in the center of the channel compares to some of the most rapid sedimentation rates documented in the literature. At a depth of 127 cm the bottom of the depleted uranium deposits was not reached. Depleted uranium was widely distributed across the canyon floor at T-2. Sedimentation rates, ranging from 0.2 to 0.74 cm/yr, were obtained across the canyon using data from tree cores and sediment-accumulation atop tree-crowns.

Transect T-3, near the downstream end of the discharge sink, showed depleted uranium deposits across the canyon floor but at much shallower depths compared to T-2. This result implies that few flows had traveled downstream to T-3. The levels of total uranium at T-3 were less than at T-2. There was evidence that the channel had traveled across the canyon floor spatially. It was clear that in the past there had been flow through this area, but it appeared to be of smaller magnitude, carrying smaller concentrations of uranium, and occurring less frequently.

The trench located upstream from T-3 transect provided a similar picture to T-3. Cut-and-fill structures across the canyon floor and the presence of depleted uranium in some of these structures implied that the channel had been active spatially across the discharge sink during the last 45 years. The relatively low levels of uranium and limited vertical extent provided further evidence that the magnitude of the flows which created those former channels have been small during that timeframe. That all the channels were buried, and the lack of any present channel indicates that this section of the reach has not been active for some period of time. The inferences from the aerial photography corroborates that breakthrough out of the discharge sink has not occurred in the last 23 years.

Transect T-1 at State Road 4 showed no depleted uranium in any of the borings. Uranium analyses of the bank samples and the grain size analyses of bank samples both confirmed that there was no depleted uranium down near State Road 4. Channel sediments displayed the same result except in the silts and clays. These results support the hypothesis that uranium and water movement out of the discharge sink was not occurring during every runoff event, or even annually.

The textural maturity of the sediments through the length of the watershed provided indirect evidence that the discharge sink was an area of sediment accumulation. Textural maturity for a deposit was defined by a percentage of silt/clay less than 5 percent; a texturally immature deposit can indicate proximity to the parent rock source and implies low flow velocities (Folk, 1968). The percentage of silt and clay was bimodal in samples collected along the watershed length: there were peaks near the top of the watershed and at the downstream end of the discharge sink. If there were active, relatively frequent flow through and out of the discharge sink, one would expect the percentage of silt and clay to decline uniformly through the length of the watershed. The rapid rise in texturally immature sediments downstream of the discharge sink is characteristic of close proximity to a watershed divide, indicating the presence of a second or subwatershed.

The information obtained from the crest stage recorders provided further evidence that there was not regular outflow from the discharge sink. The recorder downstream of the discharge sink did not indicate flow until the end of 1990 (which was determined to come from a new construction site adjacent to the discharge sink), suggesting there was no flow out of the discharge sink during 1988, 1989, and 1990. Whereas 1990 was a year of average total precipitation (475 mm), 1988 recorded 30 percent greater precipitation that the mean (618 mm). During each year, there were large-sized flows which entered the discharge sink. There was no record of outflow or underflow through the discharge sink at this downstream crest stage recorder.

Historic precipitation records were examined to locate rainfall sequences which may have created sufficient flow to break through the discharge sink. The Antecedent Precipitation Index was employed for the period of record 1910-1990. Years 1952, 1957 and 1968 were identified as possible candidate years post World War II during which there may have been streamflow through and out of the discharge sink. Aerial photography supported this hypothesis.

Investigations were performed to determine the cause and location of the discharge sink. A number of methods were tried. A shallow seismic refraction survey proved successful. A fault with 9 m of vertical offset at the upstream end of the discharge sink combined with a nearby buried ridge were delineated. It is believed that together these features preferentially enhance deposition and infiltration in this region of the watershed.

The discharge sink in Potrillo Canyon is postulated to be a prime region of recharge to deep groundwater on the Pajarito Plateau. The analyses of the 1990 hydrographs along with visual observations was interpreted that an estimated 5200 $m^3$ infiltrated into an area less than 70,000 $m^2$ (infiltration occurred in less than one-half of the total discharge sink) in a period of hours. The rapidity of infiltration permitted the assumption of small losses to evaporation and transpiration. Moisture measurements in wells in the discharge sink did not record significant increases in moisture content in the alluvium to 15 m depth. Therefore, it is hypothesized that discharge which enters the discharge sink percolates downward towards deep groundwater.

Simple mass balance calculations were performed to account for where the uranium is located. Concentrations in the surface and depth profiles and the aerial radiological survey of soils at E-F, I-J and PHERMEX firing sites can account for the entire estimated uranium mass of 35,000 kg. The amount of uranium present in fluvial sediments in Potrillo canyon is estimated to represent between about 1 and 5 percent of the 35,000 kg. Surface water has been shown to transport relatively low concentrations of uranium with final detention in the discharge sink for the past 23 years. Uranium movement out of the discharge sink into the lower half of the watershed was shown to be small. Uranium transport in the dissolved phase is probably occurring by infiltration through contaminated sediments at the firing sites and the discharge sink. This mechanism has the potential to transport uranium in the dissolved phase towards groundwater, or transfer uranium to deeper strata, where it is absorbed. The vertical movement of dissolved uranium provides the key transport mechanism to remove total and depleted uranium out of the watershed.

*Conclusions*

1. Airborne transport and wind redistribution of uranium is not an important transport mechanism in Potrillo Canyon watershed.
2. Surface water transports uranium in the dissolved and suspended sediment phases. Uranium concentrations in both phases decline with distance downstream from the top of the watershed.
3. An estimated 35,000 kg of uranium was expended in dynamic tests in Potrillo Canyon watershed from 1943 to the present. Over half of the expended mass is believed to have been fired during the period 1943 to 1953.
4. Nearly all the expended uranium inventory is thought to remain in surface soils and in the depth profile near three firing sites: they are E-F firing site, I-J firing site, and PHERMEX firing site.
5. Surface water flows discontinuously in Potrillo Canyon watershed. There exists a 142,000 $m^2$ area near the Lower Slobovia firing site called a discharge sink. Here all flow infiltrates and the sediment and contaminant load drops out. The discharge sink serves to detain uranium and separate the watershed into two subwatersheds.
6. Consequences of the discharge sink are 1) the discharge sink is an area of increased sedimentation; 2) it contains significant amounts of uranium adsorbed on the surface soils and with depth; 3) there are rare instances of

surface outflow from the discharge sink; 4) leaching and deep infiltration transport uranium (dissolved phase) to groundwater or to adsorption by deeper strata; and 5) only small amounts of uranium are associated with the fluvial sediments downstream.

7. Sedimentation rates were determined in the discharge sink to range from 0.2 cm/yr on the margins to nearly 3 cm/yr in the active channel at the upstream end.

8. Using a running antecedent precipitation index on daily precipitation records from 1910 to 1990, in concert with aerial photography, it is hypothesized that there has been no outflow from the discharge sink since 1968.

9. The probable feature which creates the discharge sink is an underlying fault, below the alluvium at the upstream end of the discharge sink, having a 9 m offset. A nearby buried ridge, also below the alluvium, may also be contributing to the location and dynamics.

10. Leaching studies of uranium attached to channel sediments showed that uranium readily leached into the dissolved phase. A partition coefficient of 750 was determined. Equilibrium between the dissolved and sediment phases was determined to range between 24 and 48 hours.

11. The key mechanism for transporting uranium out of the watershed is by vertical transport in the dissolved phase. Water infiltrating through contaminated deposits can percolate downward and transport uranium to groundwater or to be adsorbed onto deeper strata. Prime locations in the watershed for this to occur is at firing sites and in the discharge sink.

12. The discharge sink in Potrillo Canyon is a prime location of recharge of deep groundwater on the Pajarito Plateau.

*Recommendations*

Future studies which would enhance this work, and provide closure on the transport and fate of uranium in Potrillo Canyon would include the following:

1. Conduct spatial and depth sampling for uranium at firing sites in the watershed to aid in quantifying actual amounts of uranium remaining at firing sites and improve estimates of the total mass of uranium expended.
2. Install vertical monitoring equipment in the discharge sink to evaluate the uranium concentration associated with infiltrating moisture fronts and to provide a better estimate of the volume of moisture moving vertically. Equipment might include piezometers, tensiometers, or gypsum blocks, and be configured to collect and store data independently. Determine field values of unsaturated and saturated hydraulic conductivity in the discharge sink to provide quantitative values to aid in flux estimates and vertical moisture modelling.
3. Continue streamflow and rainfall gaging at the Skunk Works location. These records are extremely useful in reconstructing the hydrologic budget.
4. Continue cumulative sampler collection of runoff at State Road 4 to provide a continuous record of surface water quality (uranium concentration) at the Laboratory boundary, and identify and document contaminant movement should it occur.

5. Stabilize the downstream end of the discharge sink to prevent future escape of uranium. Construction of on-stream sedimentation ponds downstream from the sink would be one method. The new construction of Pixie at Lower Slobovia has created a bypass channel which parallels the discharge sink axis and enters the main channel downstream of the discharge sink. The flow from this bypass channel should be sampled and evaluated for uranium contamination. In addition, this bypass channel should be evaluated in terms of its potential for destabilizing the downstream end of the discharge sink. If this potential exists, then the bypass drainage should be modified to prevent destabilization.

6. Conduct further investigations on the partitioning of uranium between the solid and dissolved phases including equilibrium and kinetics modelling, and additional experiments to estimate the quantity and rates of exchange between the solid and dissolved phases.

7. Conduct modelling investigations on the flow and sediment transport through the watershed to obtain a better understanding of the discharge sink and its stability.

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## ACKNOWLEDGMENTS

This dissertation would not have been possible without the assistance of many people. I gratefully acknowledge the untiring support of my major professor John Hoopes and dissertation committee member Ken Potter. I thank them for their input, suggestions, and unfailing encouragement during the duration of these studies.

I also gratefully acknowledge my supporters at Los Alamos, Lud Gritzo, Dennis Erickson, Frank Jackson, and Tim Neal, whose assistance and patience enabled me to complete these investigations. These members of the Dynamic Testing Division, as well as Tom Gunderson and Ken Hargis of the Health, Safety, and Environment Division at Los Alamos National Laboratory, were instrumental in providing financial and technician support for data collection and interpretation.

It would be difficult to name all those others who made the completion of this work possible. However, the following provided assistance beyond the call of duty. Rudy Archuleta, Steve DePaula, Adrian Archuleta, Max Maes, Bill Purtymun and Mike Trujillo all assisted in field data collection and instrumentation. Analytical chemistry support was provided by Ernie Gladney, Mike Bell, Richard Peters, and Richard Robinson. Aaron Honey, Gary Warren and Jim Lewis photographed and printed the photos here, as well as many others which document the temporal hydrologic changes in the watershed. Al Swain devoted his spare time to teach tree ring deciphering and identification of false rings. To all of them I give my sincere thanks.

Finally, I would like to thank Allen Cogbill. His endless support, encouragement, and patience enabled me to persist and see this dissertation to completion.

The photograph in Fig 6.1 courtesy of Los Alamos National Laboratory.