Title
Sediment Routing in Channels Draining Disturbed Lands

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COMPLETION REPORT

SEDIMENT ROUTING IN CHANNELS DRAINING DISTURBED LANDS

PROJECT W-734
Water Resources Center

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Problem and Research Objectives

The poorly understood relationship between specific land uses, consequent altered sediment loads and runoff, and the downstream river channel response to these altered patterns lies at the heart of the problem of management decisions regarding cumulative watershed effects. Most rivers in California have experienced altered sediment supply due to land use. The pristine state of these channels is unknown, and because channels do not respond immediately to inputs of sediment, it can not be assumed that current channel conditions reflect current sediment loads. This makes stream rehabilitation projects, which are becoming increasingly commonplace, subject to considerable uncertainty as to their outcome. There are many aspects to this relationship between land use, sediment loads, runoff, and channel response that are challenging, including: 1) the prediction of the rate and grain size of altered sediment yield caused by a particular disturbance; 2) the prediction of the changes in runoff amounts, including how these effects influence hillslope erosion rates; and 3) the prediction of stream channel changes that include effects on surface grain size distributions, sediment storage, channel geometry, bank instability, sediment loads, and sediment concentrations. The pressure now to make decisions in advance of complete understanding of this relationship suggests that the problem be turned around: is it possible to examine a channel reach of interest and with some relatively simple observations anticipate how it will respond to altered sediment yields?

The work accomplished here was oriented toward devising methodologies to predict probable channel response to altered runoff and sediment supply due to land use by "reading" rivers. Our approach was based on our recent experimental results that demonstrated a quantitative relationship between sediment supply and the degree and spatial extent of surface armoring in gravel bedded rivers (Dietrich, et al., 1989). The theory we proposed (see Appendix A for complete paper) argues that under an imposed boundary shear stress, such as that which occurs at bankfull discharge, grain size adjustments modify critical boundary shear stress and, consequently, the excess stress that controls bedload transport rates. When sediment supply is high for the imposed shear stress, the grain size of the bed will be close to that of the load. In contrast, if the supply is reduced, the surface will coarsen, thereby causing reduction in transport rate in concert with the reduced load. Hence the degree of stream surface armoring may be used to define a stream's state of adjustment relative to sediment supply.

Three specific research objectives were proposed in Project W-734. The first was to test in a natural river the validity of recent theories for initial motion of heterogeneous mixtures of gravels and sand size sediment. This objective was accomplished through a combination of tracer studies and direct measurement of friction angles of individual particles. The second objective was to test our theory regarding grain size adjustments (Dietrich, et al., 1989) by measuring vertical and lateral sorting variation in relation to sediment supply.

(The theory assumes that the median grain size of the bed is the scale for critical shear stress of the bed and that selective entrainment can occur, causing grain size adjustments to develop from supply variations.) This work was done in conjunction with another project which examined several rivers. The work funded here focussed primarily on one study site and examined it in greater detail. The third objective was to examine whether alternating zones of high and low rates of sediment movement along a particular creek could be identified. This was done through a combination of mapping and tracer studies.

As proposed, this work was accomplished in close collaboration with Laurel Collins, geologist for the East Bay Regional Park District.

Field Site and Methodology

This study was carried out in Wildcat Creek, a sandy, gravel bedded river that drains northward along the eastern base of the Berkeley hills in East Bay Park District lands and then turns west across the hills and empties into San Francisco Bay (Figure 1). Near the headwaters there are two small lakes, Lake Anza and, just below Anza, Jewell Lake. The study reach of interest extended from just below Jewell Lake to the downstream end of Park District land as the Creek crosses the hills.

Much of the study reach was mapped using methods developed by Laurel Collins. These methods produce a detailed planimetric view of channel configuration, surface grain size distributions, and channel bank conditions (such as adjacent landsliding), as well as detailed topographic data on cross-sections and the longitudinal profile of the channel. Two study reaches were initially selected for tracer studies and are referred to here as the "dam site" (below Jewell Lake) and the "117 site" (an easily accessible reach where class exercises are held each year) (see Figure 1 for locations). A third reach, at the most downstream end of the river in the Park, was added in the second year.

Tracer studies were conducted in two ways. At the two upstream reaches a total of five sites were selected where paint was applied to the exposed dry creek bed over a square meter. This square was chosen to represent one of the mapping units used to describe surface grain size patterns or "facies" on the stream bed. After each flow event, grain size and distance travelled were noted on all painted grains downstream of the square. In addition, the size and presence of paint were recorded on the grains remaining in the square. In the second year of the project we painted and placed three narrow classes of grain sizes (76, 20, and 5 millimeters) at three locations on the bed at three reaches of the river. We then recorded the size and distance travelled at all locations of these painted rocks.

Measurement of friction angle (also referred to as pivot angle by some authors, e.g., Komar and Li, 1986, 1988) was accomplished by collecting large (0.5 meters by 0.5 meters) undisturbed samples of the bed surface by applying epoxy resin to the dry creek bed at the 117 site. Carefully selected grains in narrow size class ranges were then dropped from a small distance on these fixed surfaces. Five surfaces were used and in most cases five different size classes (4, 8, 16, 32, and 64 millimeters) were placed on these surfaces. Friction angles were measured by slowly raising the surfaces which had been placed on a tilt-table and recording the grains that moved at the end of each successive 5 degree inclination, up to 100 degrees. For a given test size on each surface, the movement of 200 to 300 grains was recorded. From these friction angle measurements the critical shear stress probability distributions were calculated from the procedure proposed by Kirchner, et al., (in press) which relies on the theoretical formulation proposed by Wiberg and Smith (1987).

As part of a Master's Thesis study involving several other rivers, Kinerson (1990) chose several reaches on Wildcat Creek, mostly near the 117 site, and quantified the size distribution of the surface and the subsurface sediment to examine the relationship between sediment supply and surface armoring. Wildcat Creek receives a very high sediment load due to massive landsliding immediately adjacent to the river. Much of the bed surface is clearly unarmored, so Kinerson selected local reaches where debris dams and other local effects would be expected to alter the local sediment supply and induce armoring. Surface texture was determined through pebble counting. The surface was then removed to the largest rock exposed and a large sample of the subsurface was removed and sieved on site using rocker sieves and portable scales. Details were reported in Kinerson (1990).

The tracer studies and channel mapping were used to infer spatial patterns of sediment movement. In addition, we used the flow model, HEC-2, to estimate spatial variation in boundary shear stress due to channel topography and roughness. Unfortunately, much of the channel was too steep for reliable application of HEC-2.

Results and Discussion

Tracer studies

Tracer experiments in the 1988-1989 winter were performed in two reaches separated by several kilometers. The upstream site, or "dam site," (see Figure 1 for location) is in a reach where surface grain size variation is primarily in the downstream direction rather than across the channel (Figure 2) and is controlled by local debris jams and channel width variations. Narrow, coarse-bedded reaches are separated by wide, fine-bedded ones. An area of one square meter was selected in each of the dominant grain surface textures found on the creek bed and a pebble count was performed to determine surface grain size and distribution of grains. All grains exposed at the surface were painted in place. The two size textures studied were: 1) sand and gravel (painted blue); and 2) sand, gravel, and cobble (painted green). After each rain storm, when the river became clear enough so that the bed was visible, the distance and the size of each particle that moved from the square was recorded.

Although the 1988-1989 winter was quite dry, we were able to map the displacement caused by each of 4 runoff events at the "dam site"; the events ranged from less than 10% of bankfull discharge to a discharge close to bankfull. As a consequence of the dry initial conditions, each runoff event was progressively greater than the previous one. Figure 3 illustrates the total displacement from the upstream sand and gravel surface caused by the end of the second runoff event on March 7, 1989. All points are shown in Figure 3A, whereas the mean and total variation in distance moved by those grains that left the initial square are shown in Figure 3B. Figure 3C shows the number of grains counted in each size class. Figures 4A, B, and C show the same sequence of graphs for the last runoff event of the season and indicates the decline in recovery rate due to particle breakdown, loss of paint, and burial. Figures 5A and B summarize the displacement curves for those two square patches at the dam site.

Despite the large difference in surface grain sizes, (upstream median and 84th percentile are, respectively, 8 and 24 millimeters, whereas downstream median and 84th percentile are 20 and 64 millimeters, respectively), the displacement histories of the two sites are similar. The first very low flow event caused grains of all sizes on the fine bed and grains smaller than about K90 on the coarser bed to move. This strongly supports the theoretical analyses described in the next section.

Initial data, where recovery was high because of the short distances travelled by the grains and the minor disturbances to the bed, show that grains with an approximately 8 millimeter diameter travelled the greatest distance from both the fine and coarse bed patches. Few large grains moved; those that did travelled only a short distance. Here we see the distinction, then, between the similarity of minimum critical shear stress and the dissimilarity of number of grains, which must be higher for smaller grains with the same percent weight contribution, and distance moved. These data suggest that selective sorting, when it contributes to downstream changes in grain size and the development of armor under sediment supply limitations, is perhaps accomplished more through differential transport per event and less through significant differences in minimum critical shear stresses.

The later, larger runoff events not only caused the smaller grains to travel farther, but also caused a greater proportion of the median and coarser grains to move. Note that in Figure 5 the downstream termination of the painted grains, measured in absolute distance along the river, was the same, although the two patches of painted grains were separated by approximately 15 meters. A debris jam is located on the creek at this termination point, as indicated by Figure 4, and the resultant backwater effect reduced the water surface slope and boundary shear stress, thereby causing deposition of the painted rocks at the site.

Figures 6A and B summarize the changes in the number of painted rocks in the two patches (in which initially all rocks were painted), the median and 84th percentile of all rocks painted and unpainted in the square, the size range of painted rocks in the square, and the size range of the unpainted rocks in the square. There are several important points to make here. First, the fine surface quickly lost all painted rocks, whereas the coarser bed still had a few painted grains that had not moved at the end of the season. This clearly demonstrates the much greater mobility of the finer bed, an important observation for interpretation of the channel maps of the kind shown in Figures 2, 7, and 10. Second, despite the large exchange of unpainted rocks with painted ones and, in some cases, burial of painted grains in situ, both median grain size and grain size distribution were remarkably stable. In the last storm event of 1989, the surface of the upstream patch fined considerably, but only after all painted rocks were gone and the debris jam had caused local upstream changes in flow. In 1990, this site underwent significant change, specifically a coarsening of the bed due to bar migration. However, the downstream patch remained essentially the same. Finally, Figure 6 also shows that the coarse particles were the last to travel out of the square.

The tracer experiments at the downstream study reach, referred to as the "117 site," revealed a similar pattern. Figure 7 shows the location of the three sites on sand and gravel, on sand, gravel, and cobble, and on gravel and cobble. At this location lateral variations in surface texture occur through bends, across bars, and in reaches influenced by bank irregularities. Figure 8 summarizes the transport history from the sand, gravel and cobble class, which is the same class as the lower patch at the "dam site." Figures 9A, B, and C summarize the grain size history of the three patches. Note that the data in Figure 9 extend to 1987, the year when we first began to explore the use of tracers on Wildcat Creek.

Early in the wet season of 1988-1989, a large poison oak vine fell directly between the sand, gravel, and cobble patch and the sand and gravel patch, causing a local backwater which not only reduced the boundary shear stress and grain travel distances upstream of the obstruction, but also focussed flow directly on the finer patch downstream of the vine, causing scouring of the fine patch and formation of a pool of gravel and cobble. As a result, no data were collected. However, later high flows carried the vine away and the fine patch reformed with a texture nearly identical to its previous one. In contrast, during the two years of record, the coarser bed remained unchanged, despite large numbers of painted rock departures and unpainted rock arrivals. Therefore, as found upstream, the dynamic fine patches retain remarkably similar sorting patterns despite episodes of significant bedload transport. Moreover, although the case is not as clear because of local disturbances, the finer gravel moved most frequently and travelled the greatest distance of those grains located in the sand, gravel, and cobble square. The coarsest patch, of gravel and cobble, was located on a bar top and did not experience significant flows due to the drought. During the 1987-1988 season, it became partially covered with sand and vegetation, so that during the highest flow of 1989, which was still below bankfull, a few rocks were mobilized but the finer material was not swept away.

In the winter of 1989-1990 we designed a tracer experiment to examine more completely the observations made in the previous year regarding relative mobility of the fine gravel on different surface textures. As mentioned in the methodology section, a third reach, where the creek crosses the hills and leaves East Bay Regional Park District land, was added. At each of the reaches three surface texture types were selected. "Dam site" median grain sizes were 29, 14, and less than 1 millimeter; "117 site" median grain sizes were 46, 29, and 5.5 millimeters; and the lowest reach had median grain sizes of 21, 6.8, and less than 2 millimeters. On each site a mixture of 76, 20, and 5 millimeter painted rocks were added to an area of one square meter. Only about five of the largest rocks were added in order to avoid significantly altering the finer beds.

Only relatively small discharge events occurred during the monitoring period as the second year was also a drought year, but these low discharges gave a consistent result that was easily quantified because of the minor sediment transport amounts. At all nine patches the 5 millimeter grains moved the greatest distance and the greatest proportion of placed particles that moved were also the 5 millimeter size grains, a similar result to what we found in the previous year when the bed surface was painted in place. At the lowest reach, which was the least affected by debris jams, the 5 millimeter particles travelled farther on finer beds than on coarser ones. For example, the grains moved 50 meters on a 21 millimeter bed, 72 meters on a 6.8 millimeter bed, and 80 meters on the less than 2 millimeter bed. Fewer of the 20 millimeter grains moved, and those that did travelled only a short distance. On the two sand bed sites, however, neither the 20 millimeter nor the 76 millimeter grains moved. On only one-half of the remaining 7 patches did the 76 millimeter particles move, and then only a short distance.

This tracer experiment confirms and extends previous conclusions: 1) that the critical shear stress is similar for a broad range of grain sizes resting on a bed, although at the extreme end (i.e., 76 millimeter grains on sand and fine gravel beds) large grains have higher shear stresses than the average bed surface; 2) that the fine gravel patches, mapped as sand and gravel, experience the greatest movement for a given discharge event and particles travel the farthest on these surfaces; and 3) that fine gravel moves most frequently and travels longer distances on all surface types.

Friction angle measurements and critical shear stress

A manuscript on this work has been completed and will be submitted to a peer reviewed journal in the Fall 1990. It is authored by a former undergraduate at Berkeley who now works for the U.S. Forest Service in Alaska (John Buffington), a former graduate student at Berkeley and now assistant professor here (Jim Kirchner), and myself. Below I summarize briefly our findings; a reprint, which will provide the details, will be sent to the Center after publication of the manuscript.

Figures 10A and B show the sample locations for the undisturbed bed surfaces that were collected. These maps use symbols that correspond with bed surface sizes and the three most common and mobile bed surface types were selected for measurement. One sample split in half, resulting in a total of five surfaces on which tipping experiments were performed. Figure 11 gives the size distribution and the median grain size (K50) for each surface and

Figure 12 shows photographs of each bed. These beds provided a large range of median grain sizes (4 to 45 millimeters) and sorting patterns.

Our studies of surfaces generated in laboratory flumes (Kirchner, et al., in press) have revealed that friction angle, projection, and exposure of single grain sizes vary widely from point to point within a given bed surface; the variability within a single surface often exceeds the difference between mean values of disparate surfaces. Consequently, the critical shear stress for a given grain size on a sediment surface is characterized by a probability distribution, rather than a single value.

Figure 13 gives the frequency distribution of friction angles found in the tipping experiments. These represent the first data to be collected on friction angles of bed surfaces formed in the field. All the data can be plotted in a single graph (Figure 14) using the ratio of the grain size of the tipping experiment (D) over the median size of the bed surface (K50) and the following expression accurately represents the relationships shown in Figure 6:

$$\phi_n = (25 + 0.54n)[(D/K50)^{-(0.146 + 0.0013n)}]$$

where ϕ_n is the fiction angle for a given percentile n (percent smaller). This expression can then be used in a theory for initial motion proposed by Wiberg and Smith (1987) and modified by Kirchner, et al. (in press) to include the probability distribution functions of friction angle, grain exposure, and projection into the flow.

Figure 15 shows the probability distributions for critical shear stress for each grain size and bed surface tested. The small panel shows the full range of critical shear stress values whereas the large graph is expanded to show the first 10% of this distribution. All graphs show the same trend, which is summarized by using non-dimensional critical boundary shear stress (critical shear stress normalized by median grain weight of the bed) in Figure 16. The minimum critical shear stress, as controlled by friction angle and the height a grain protrudes into a flow, is found to be approximately the same for all sizes on a bed composed of a range of grain sizes that do not exceed ±4 times the median grain diameter. This is the same finding reported on laboratory beds by Kirchner, et al. (in press) and strongly supports Parker's contention (e.g. Parker and Klingeman, 1982) that, as a first approximation, it is much more accurate to assume that grains on a natural river bed of sediment mixtures have the same critical shear stress rather than to argue, as has been done for the last 50 years, that critical shear stress is proportional to grain size. This approximation is known as the "equal mobility" hypothesis.

In Figure 17, the "equal mobility" line has a slope of -1. Note that the tendency toward equal mobility depends on what probability value is chosen as the minimum. In our data, if the very low probability of 0.1% is chosen then small grains will tend to be entrained relative to large ones, whereas the high values of 10% on the percentile shear stress distribution indicate that the smaller grains are much less mobile. This latter surprising result can be understood by inspection of Figures 13, 15, and 16. Although small grains have similar minimum friction angles, many of the grains settle between the larger ones and will not move out unless the bigger one moves first. The larger grains tend to trap the smaller ones (see Whiting, et al., 1988 for a discussion of the importance of this tendency in bedform development).

These distribution functions of critical shear stress also suggest that as shear stress progressively exceeds "critical," (i.e., a very low probability resting position), more grains resting in more resistant positions, including deeper in pockets and on the lee side of larger upstream grains, will be mobilized. This would explain the long recognized relationship between bedload transport rate and excess shear stress that forms the basis of many bedload transport theories. This suggestion was made by us (Kirchner, et al., in press) based on laboratory data, and these field data, the first of their kind, support this hypothesis. However, the field data raise a serious problem as well. One interpretation of the curves in Figures 15 and 16 would be that at shear stresses above minimum values, the larger grains are more mobile than the smaller grains. This seems unlikely and is inconsistent with the limited published data on grain motion. In particular, the results of the tracer experiments described above stand in contrast to this interpretation. The tracer experiments instead indicate that the coarse fraction does not have a higher mobility than the fine material. One explanation for this apparent contradiction is that when larger grains move they release smaller ones, so the probability distribution changes as the bed becomes active. Another effect, not accounted for by either the tipping experiments or in theoretical analyses, is that larger grains tend to become partially buried in the bed. Preliminary efforts to examine this effect in natural stream beds remain fairly subjective, but suggest to us that about 50% of the grains exposed at the surface are partially buried by others, making them immobile until the burying grains move. Importantly, it appears that most larger grains tend to be partly buried.

Bed surface texture and sediment supply

A separate project was undertaken by a student working with me, Dean Kinerson, to test the theory described in Appendix A. Kinerson (1990) gathered data on the degree of surface armoring in 6 rivers where sediment supply was either approximately or well known. Two of these rivers, Wildcat Creek and Lagunitas Creek, were proposed for study in this Water Resources Center grant and some of the cost of his fieldwork was covered by this grant. Kinerson has completed his Master's Thesis.

In essence, the theory described in Appendix A states that the ratio, q^*, of bedload transport to that bedload transport occurring if the surface texture is considered to be the same as the subsurface, (i.e., no armoring), varies with the degree of surface armoring and excess boundary shear stress (see Appendix A, equation 2). The theory predicts that rivers with high sediment supply will have a q* close to 1.0 whereas rivers with relatively low sediment supply will have q* values closer to 0.0. In Figures 18 and 19 the variation of q* with surface armoring is detailed for the two creeks mentioned above. As hypothesized, on Lagunitas Creek, at a site immediately downstream from a dam where sediment supply is essentially zero, the surface coarsening is very high and q* is essentially zero. In contrast, downstream of a major tributary on Lagunitas Creek, in an area where sediment supply is not affected by the dam, q* increases. On Wildcat Creek, which has a high sediment supply, the sand and gravel mapping category is mostly lacking in armor and has a q* of 1.0. Even in patches with fairly strong armoring, the q* remains high because the excess boundary shear stress at bankfull discharge is high. Figure 20, which summarizes the results from the other studies, shows that Lagunitas and Wildcat Creek data are consistent with other channel data and provides strong support for the sediment supply hypothesis.

Alternating zones of high and low sediment transport

In Wildcat Creek, effects of debris jams strongly influence local sediment transport patterns. Backwater reaches tend to aggrade with the abundant, highly mobile fine sand and gravel, while downstream of the debris jams the bed tends to scour and coarsen. Flood destruction of these debris jams can lead to formation of both a local terrace in the backwater sediments and a reach of very mobile fine sediment. The painted rock experiments show that where a sand and gravel patch occurs, the bed will display much mobility and sediment transport, but that coarser reaches can still receive and transport this finer sediment without either significant textural changes or significant movement of the coarse sediment. Hence a coarse reach is not equivalent to a reach with low total bedload transport rate, but rather, it is in general a reach in which the bed surface experiences infrequent significant grain movement of the coarse fraction.

Conclusions and Implications of Findings

Taken together, the set of field observations and theoretical calculations suggests the elements of a quantitative methodology for predicting stream channel response to altered sediment loads. The methodology is fairly simple and inexpensive, although more work is needed to evaluate site selection and sampling procedures. (Tom Lisle of the U.S. Forest Service, Arcata, is currently pursuing aspects of this problem.)

It is proposed that a combination of quantitative mapping, local grain size analyses, and calculations based on the theory presented in Appendix A can be the major elements of this methodology. Maps of the kind shown here (using procedures developed by Laurel Collins) can define the spatial pattern of surface textures. The associated cross-sections and longitudinal profiles can be used to calculate local boundary shear stresses at some index flow such as bankfull stage. Grain surface armoring can be quantified by field sieving, although from experience gained by Kinerson (1990), it may be possible to categorize armored and not armored surfaces based on visual inspection. Calculated and assigned q* values can then be multiplied by percent of bed area occupied by that surface type in order to obtain a single value of q* for the reach of interest.

Reaches with well-developed armoring and few areas with finer mobile patches will generally have low q* values. We would infer that such a reach could experience a significant increase in bedload material without significant aggradation or morphologic change. On the other hand, a river with extensive zones of high mobility and consequent high average q* would respond to increased sediment supply by filling of pools and otherwise aggrading. Rivers with already extensive zones of high bed mobility may be most sensitive morphologically to altered sediment yields. Further work testing this methodology and interpretation in a practical application is now needed.

References

Dietrich, W. E., Kirchner, J. W., Ikeda, H., and Iseya, F., 1989, Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature, v. 340, p. 215-217.

Kinerson, D., 1990, Bed surface response to sediment supply. Unpublished M.S. Thesis, Department of Geology and Geophysics, University of California, Berkeley, California.

Kirchner, J. W., Dietrich, W. E., Iseya, F., and Ikeda, H., in press, The variability of critical shear stress, friction angle, and grain protrusion in water-worked sediments. Sedimentology.

Komar, P. D. and Li, Z., 1986, Pivoting analyses of the selective entrainment of sediments by shape and size with application of gravel threshold. Sedimentology, v. 33, p. 425-436.

Komar, P. D. and Li, Z., 1988, Applications of grain-pivoting and sliding analyses to selective entrainment of gravel and to flow-competence evaluations. Sedimentology, v. 35, p. 681-695.

Parker, G. and Klingeman, P. C., 1982, On why gravel bed streams are paved. Water Resources Research, v. 18, p. 1409-1423.

Whiting, P. J., Dietrich, W. E., Leopold, L. B., Shreve, R. L., and Drake, T., 1988, Bedload sheets in heterogeneous sediment. Geology, v. 16, p. 105-108.

Wiberg, P. L. and Smith, J. D., 1987, Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. Water Resources Research, v. 23, p. 1471-1480.

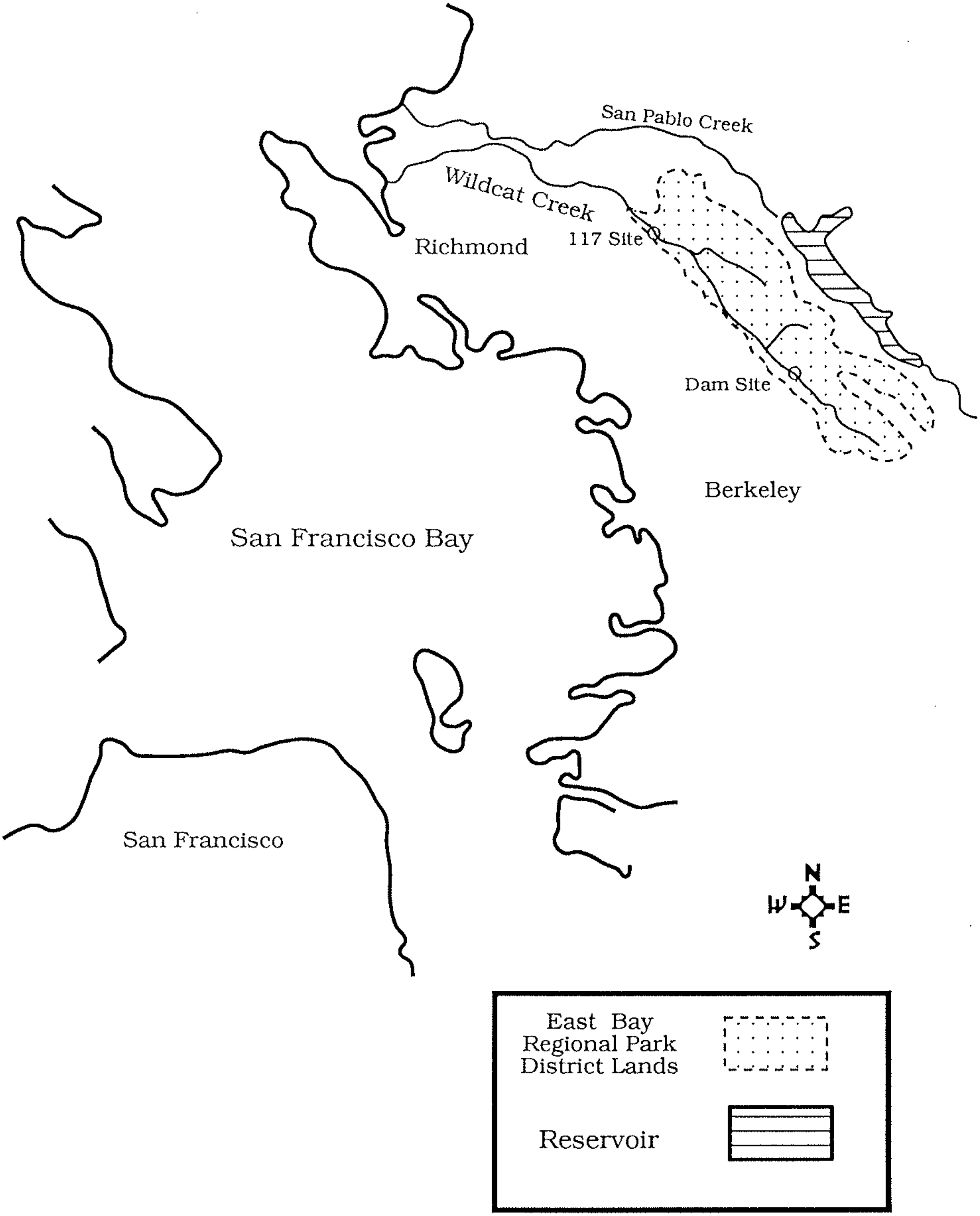
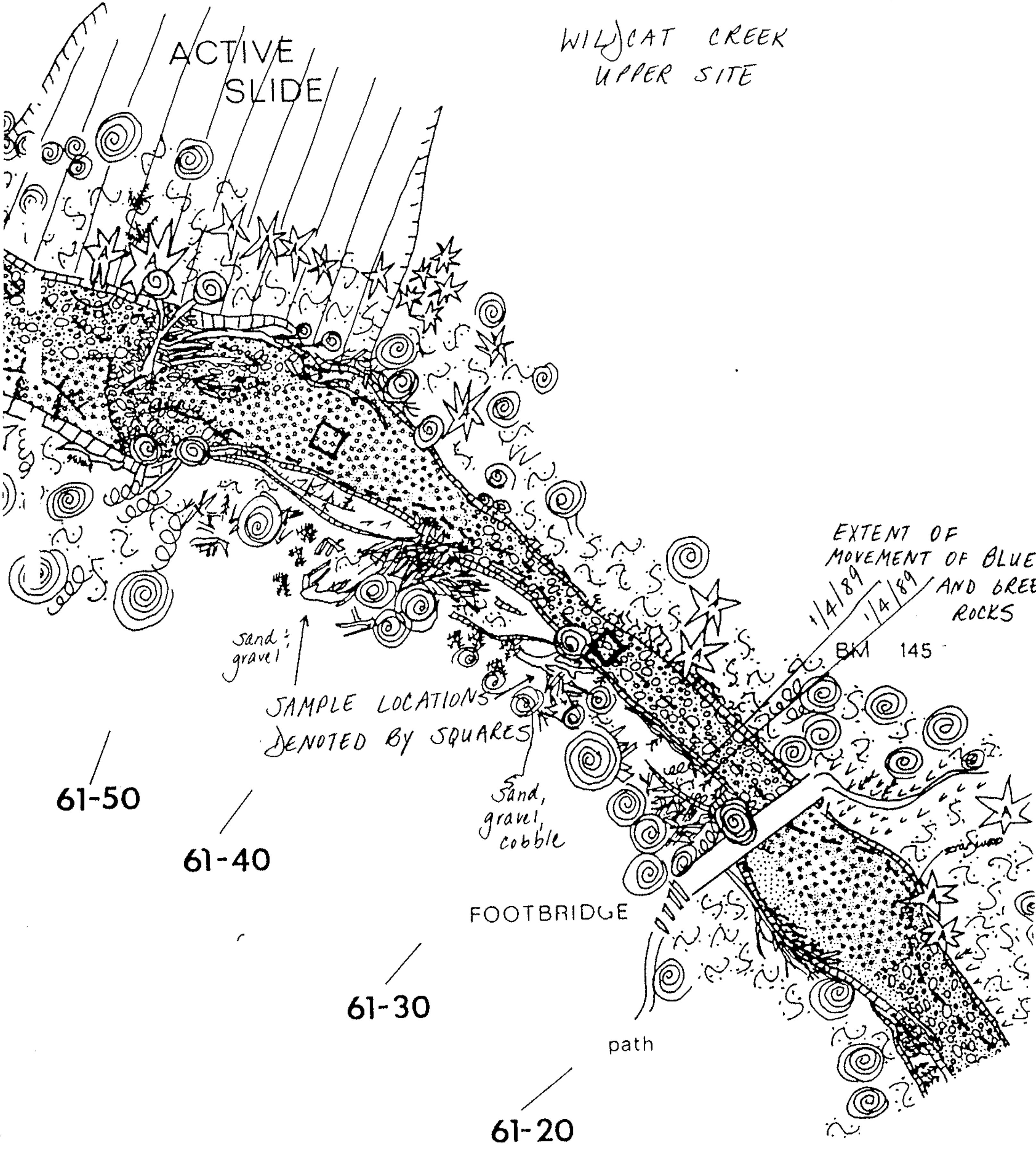

San Pablo Creek
Wildcat Creek
Richmond
117 Site
Dam Site
Berkeley
San Francisco Bay
San Francisco
N
W
E
S
East Bay Regional Park District Lands
Reservoir

Figure 1


WILDCAT CREEK
UPPER SITE
ACTIVE
SLIDE
EXTENT OF
MOVEMENT OF BLUE
AND GREE
ROCKS
1/4/89
1/4/89
BM 145
Sand & gravel
SAMPLE LOCATIONS
DENOTED BY SQUARES
Sand,
gravel,
cobble
FOOTBRIDGE
path
61-50
61-40
61-30
61-20

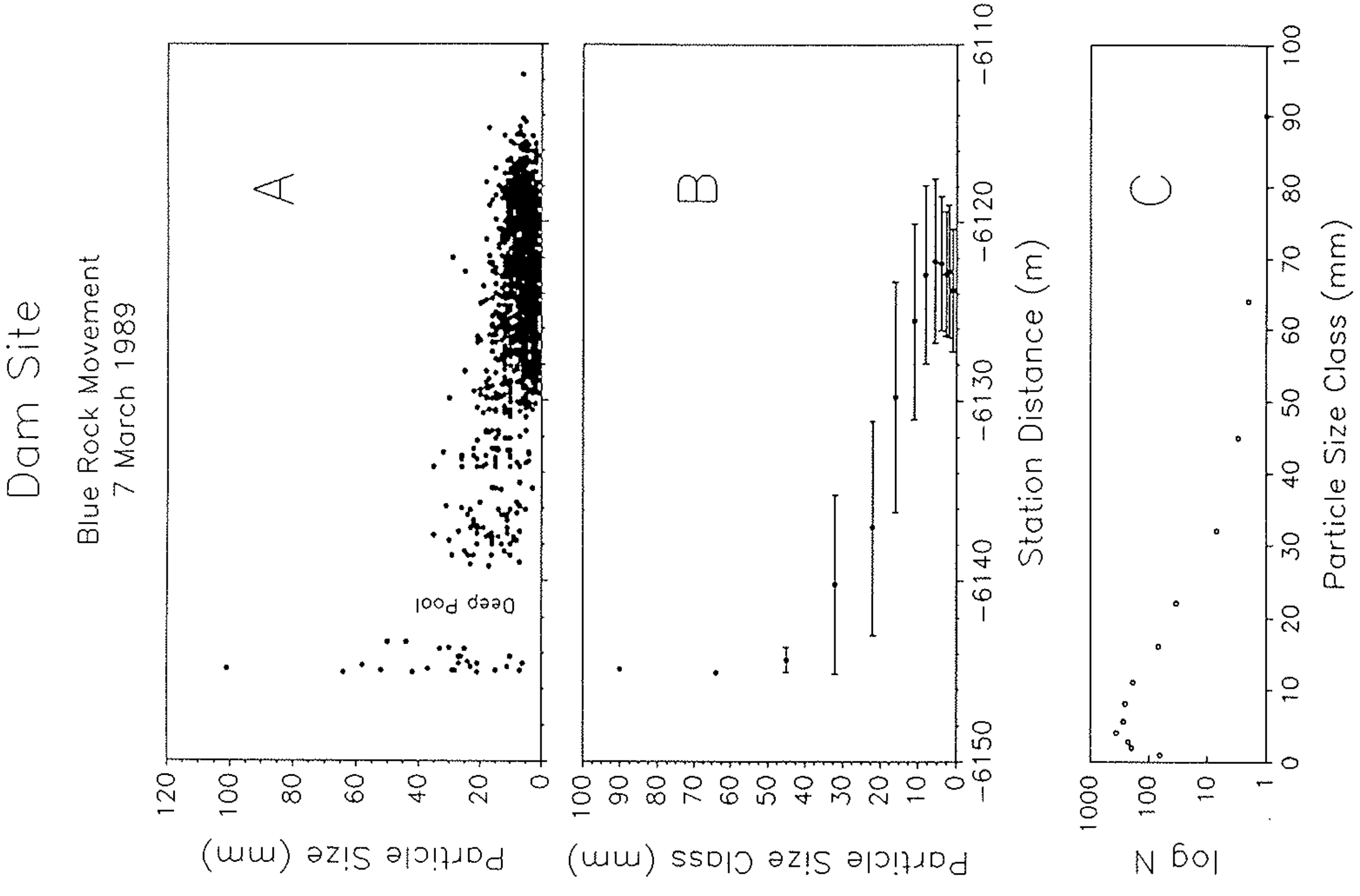

Dam Site
Blue Rock Movement
7 March 1989
A
B
C
Deep Pool
Particle Size (mm)
120
100
80
60
40
20
0
Particle Size Class (mm)
100
90
80
70
60
50
40
30
20
10
0
-6150
-6140
-6130
-6120
-6110
Station Distance (m)
log N
1000
100
10
1
0
10
20
30
40
50
60
70
80
90
100
Particle Size Class (mm)

Figure 3

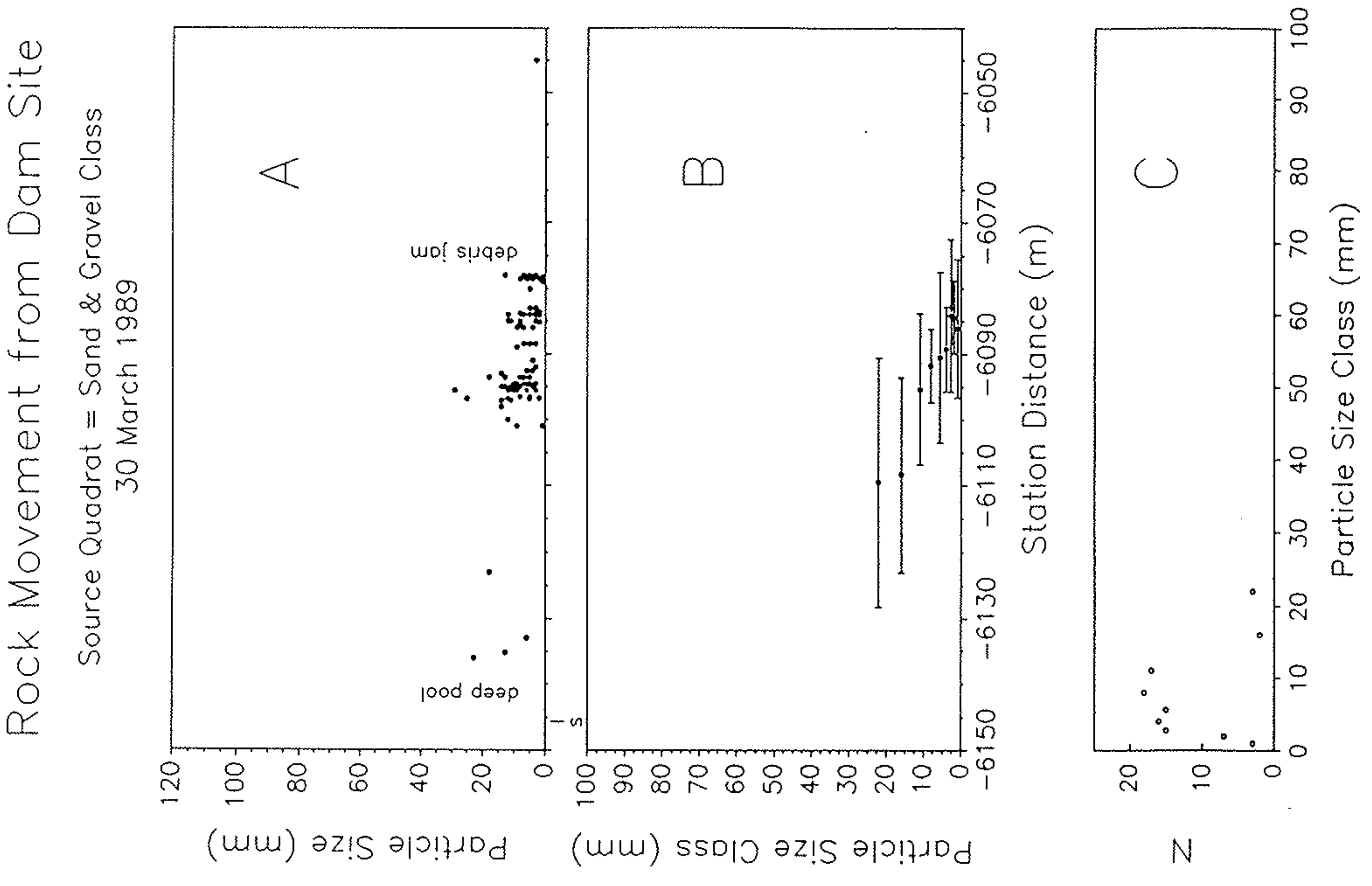

Rock Movement from Dam Site
Source Quadrat = Sand & Gravel Class
30 March 1989
A
B
C
deep pool
debris jam
s
Particle Size (mm)
120
100
80
60
40
20
0
Particle Size Class (mm)
100
90
80
70
60
50
40
30
20
10
0
Station Distance (m)
-6150
-6130
-6110
-6090
-6070
-6050
N
20
10
0
Particle Size Class (mm)
0
10
20
30
40
50
60
70
80
90
100

Figure 4

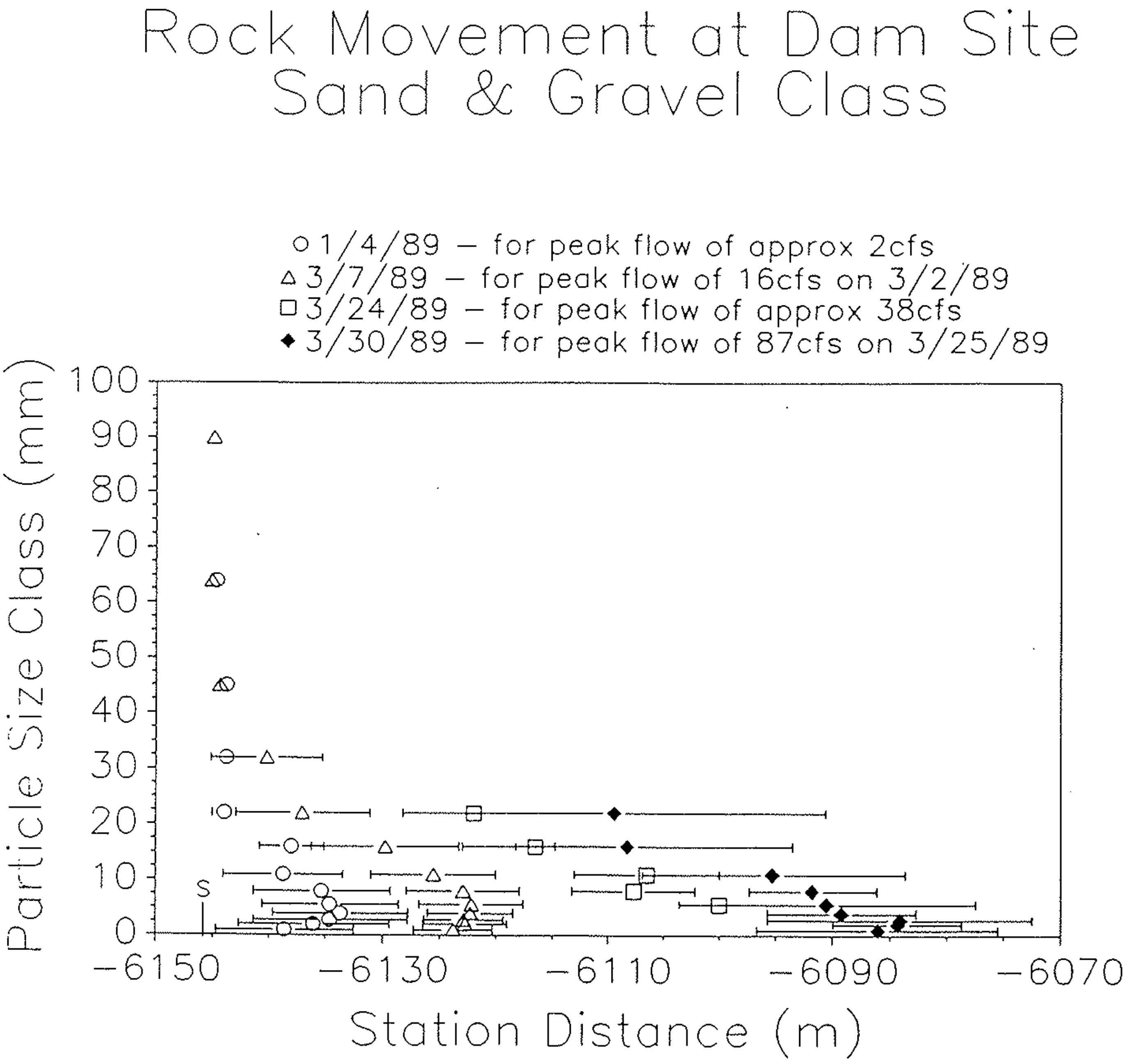

Rock Movement at Dam Site
Sand & Gravel Class
○ 1/4/89 – for peak flow of approx 2cfs
△ 3/7/89 – for peak flow of 16cfs on 3/2/89
□ 3/24/89 – for peak flow of approx 38cfs
◆ 3/30/89 – for peak flow of 87cfs on 3/25/89
Particle Size Class (mm)
100
90
80
70
60
50
40
30
20
10
0
S
−6150
−6130
−6110
−6090
−6070
Station Distance (m)

Figure 5A

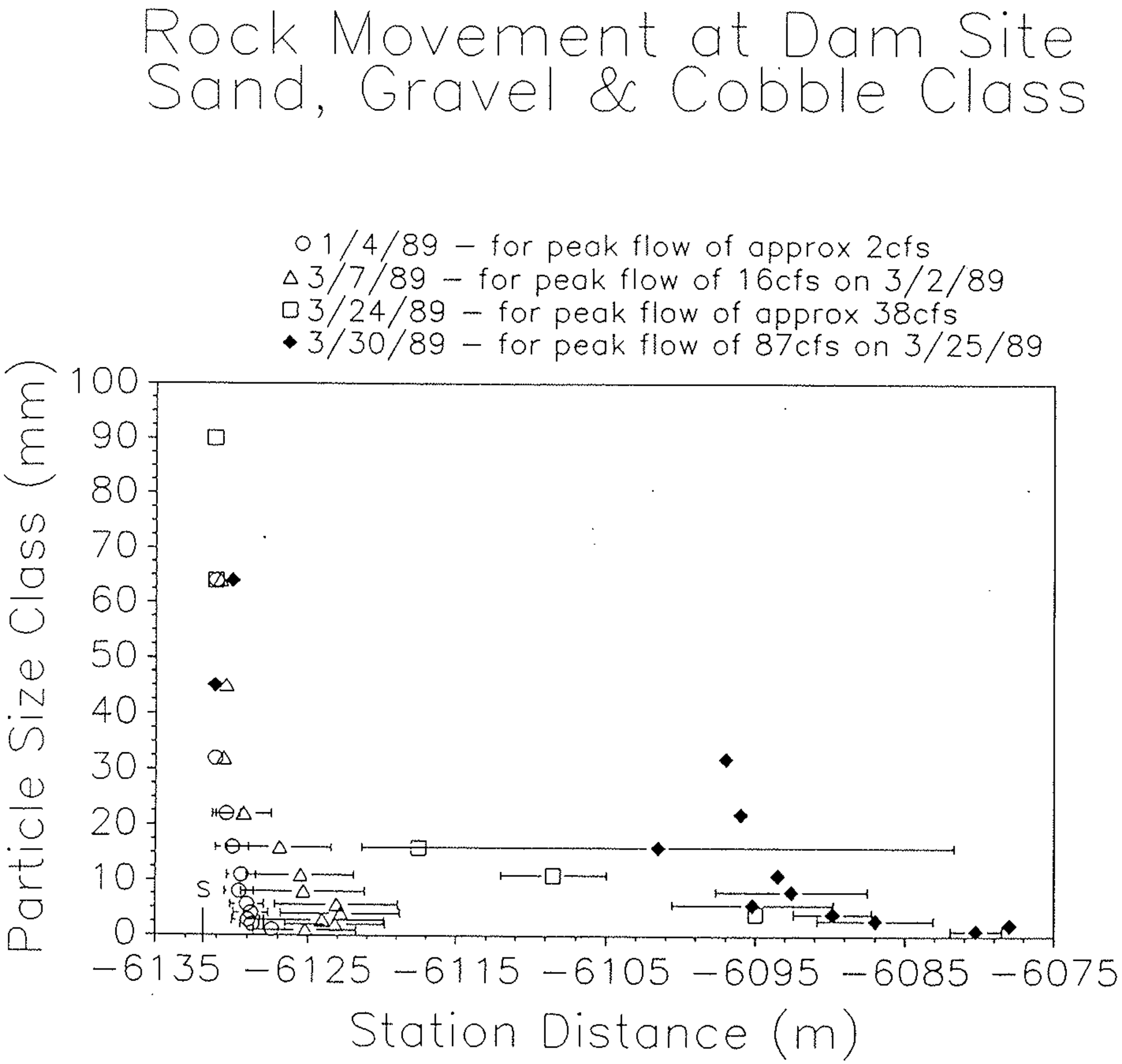

Rock Movement at Dam Site
Sand, Gravel & Cobble Class
○ 1/4/89 – for peak flow of approx 2cfs
△ 3/7/89 – for peak flow of 16cfs on 3/2/89
□ 3/24/89 – for peak flow of approx 38cfs
◆ 3/30/89 – for peak flow of 87cfs on 3/25/89
Particle Size Class (mm)
100
90
80
70
60
50
40
30
20
10
0
S
−6135
−6125
−6115
−6105
−6095
−6085
−6075
Station Distance (m)

Figure 5B

Changes within Painted Rock Quadrats at Dam Site

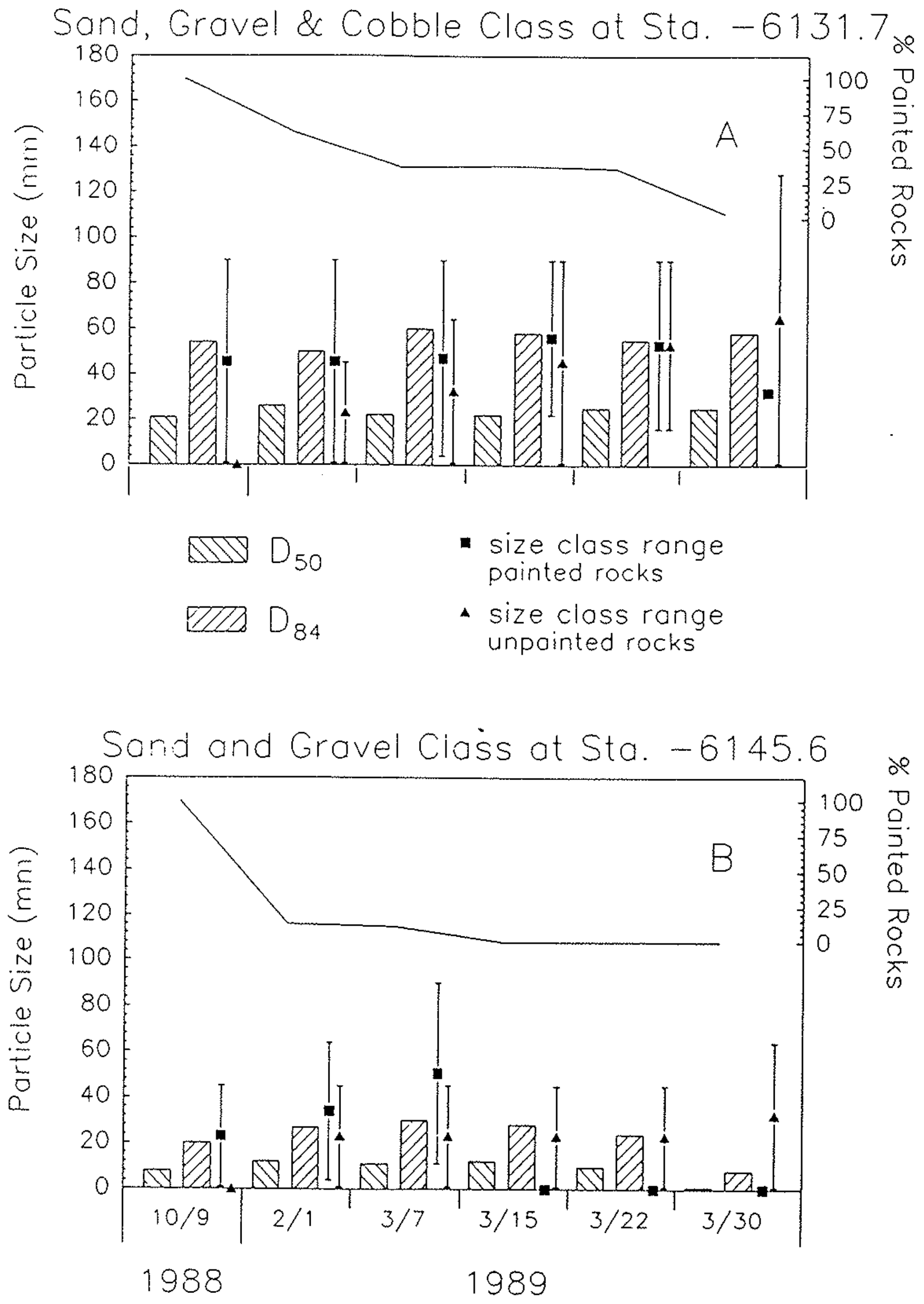


Figure 6

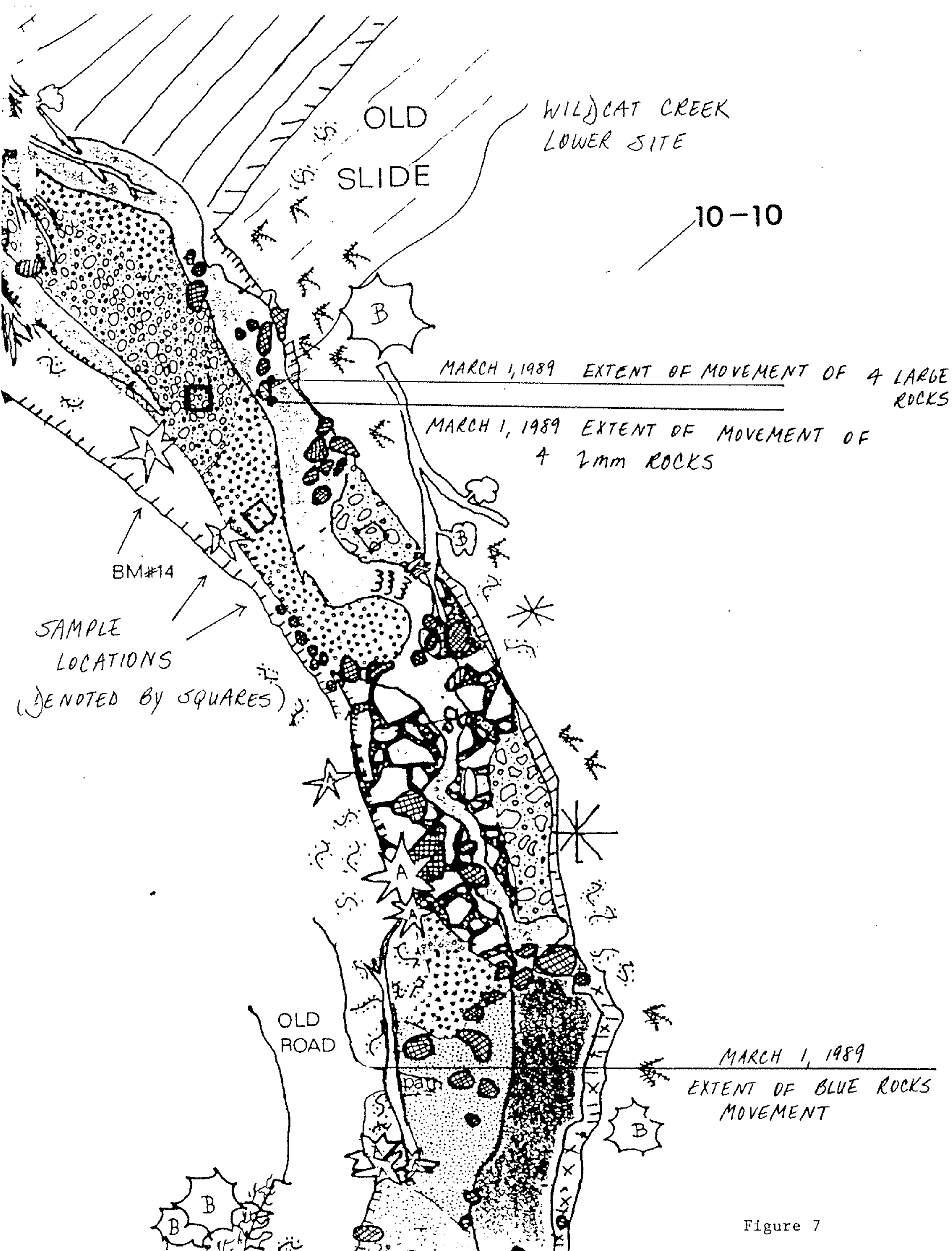

OLD
SLIDE
WILDCAT CREEK
LOWER SITE
10-10
B
MARCH 1, 1989 EXTENT OF MOVEMENT OF 4 LARGE ROCKS
MARCH 1, 1989 EXTENT OF MOVEMENT OF 4 2mm ROCKS
B
BM#14
SAMPLE
LOCATIONS
(DENOTED BY SQUARES)
A
A
A
A
OLD
ROAD
path
MARCH 1, 1989
EXTENT OF BLUE ROCKS
MOVEMENT
B
A
B
B

Figure 7

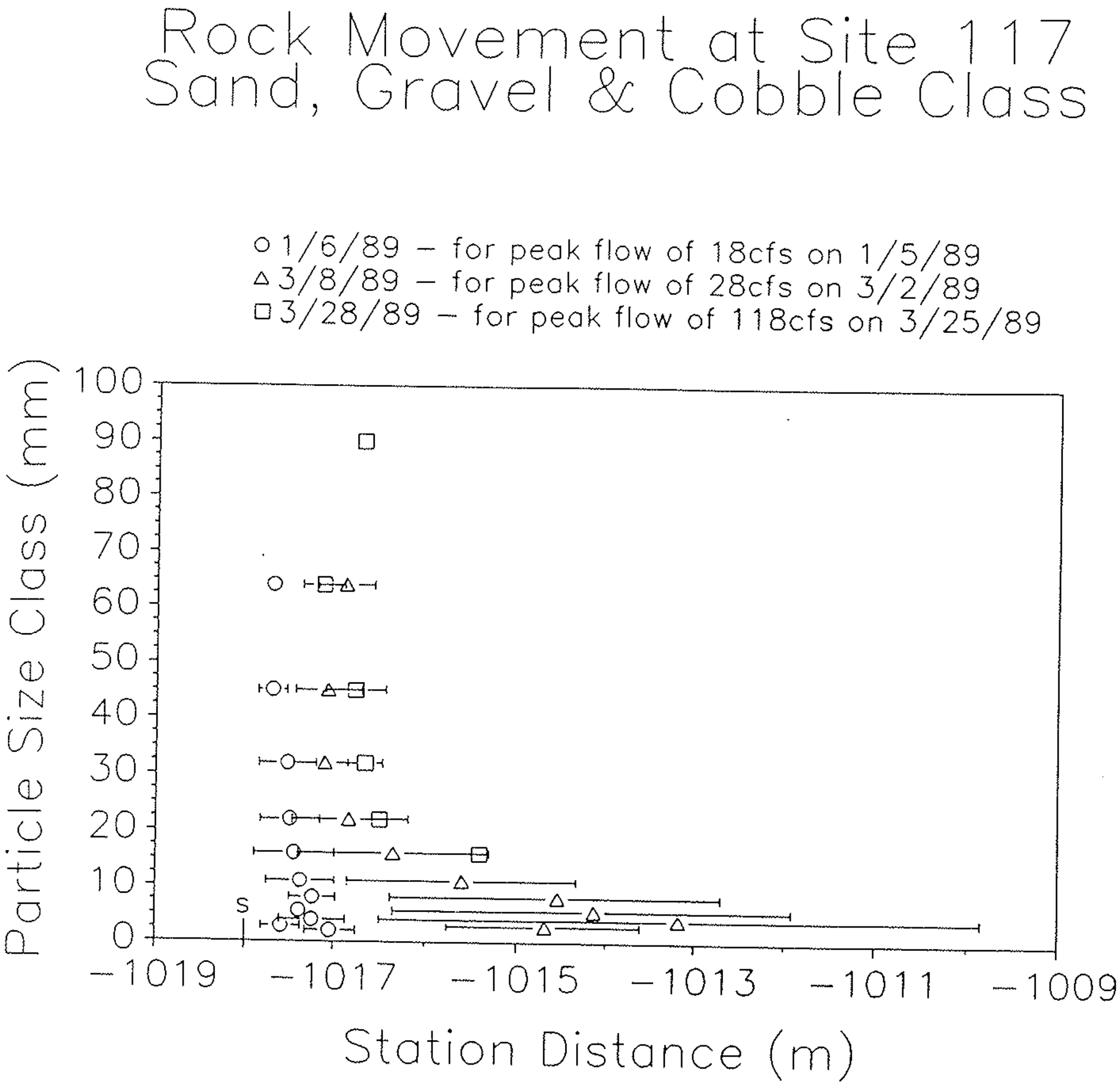
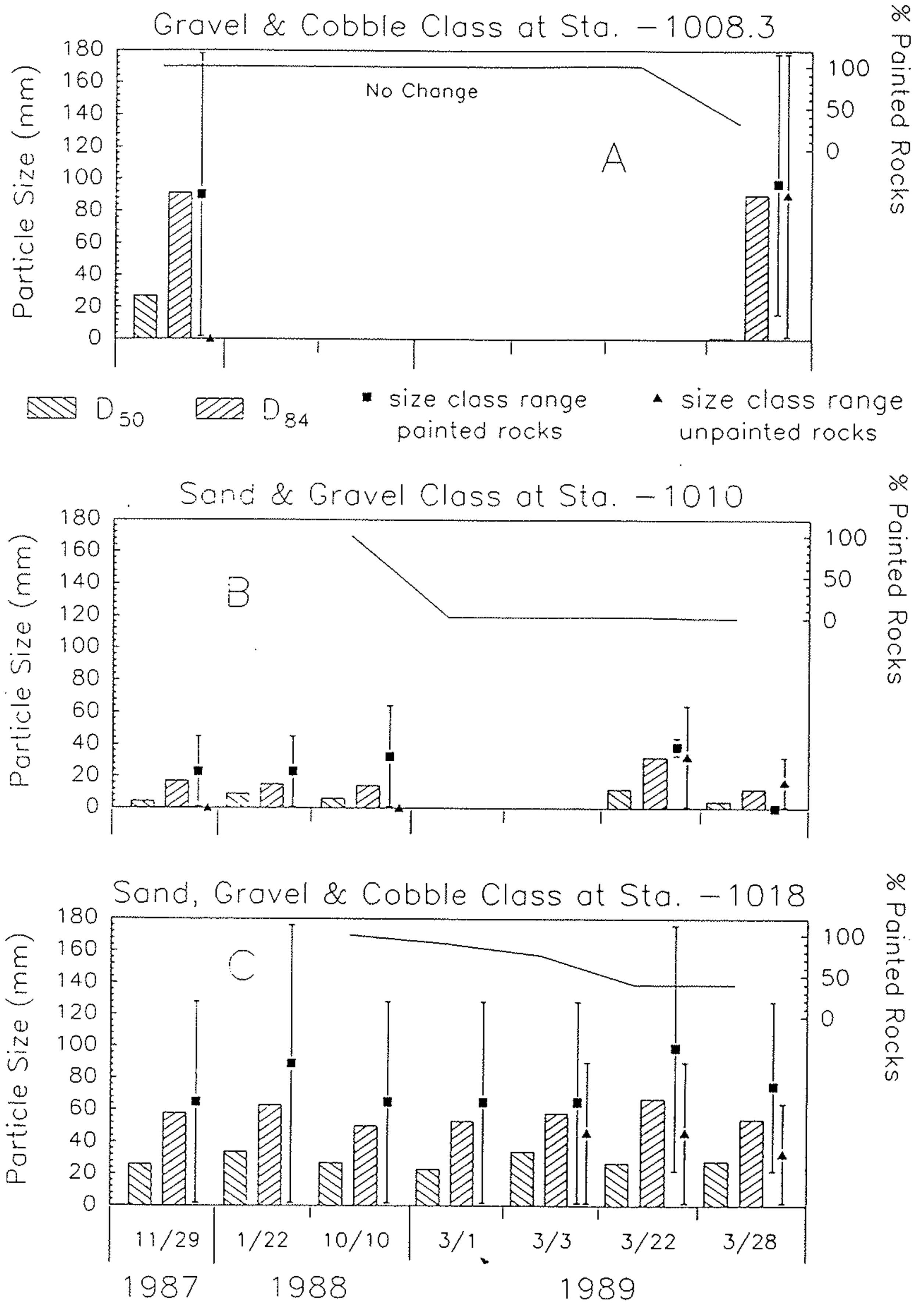

Rock Movement at Site 117
Sand, Gravel & Cobble Class
○ 1/6/89 – for peak flow of 18cfs on 1/5/89
△ 3/8/89 – for peak flow of 28cfs on 3/2/89
□ 3/28/89 – for peak flow of 118cfs on 3/25/89
Particle Size Class (mm)
100
90
80
70
60
50
40
30
20
10
0
S
–1019
–1017
–1015
–1013
–1011
–1009
Station Distance (m)

Figure 8

Changes within Painted Rock Quadrats at Site 117



Gravel & Cobble Class at Sta. −1008.3

Sand & Gravel Class at Sta. −1010

Sand, Gravel & Cobble Class at Sta. −1018

Figure

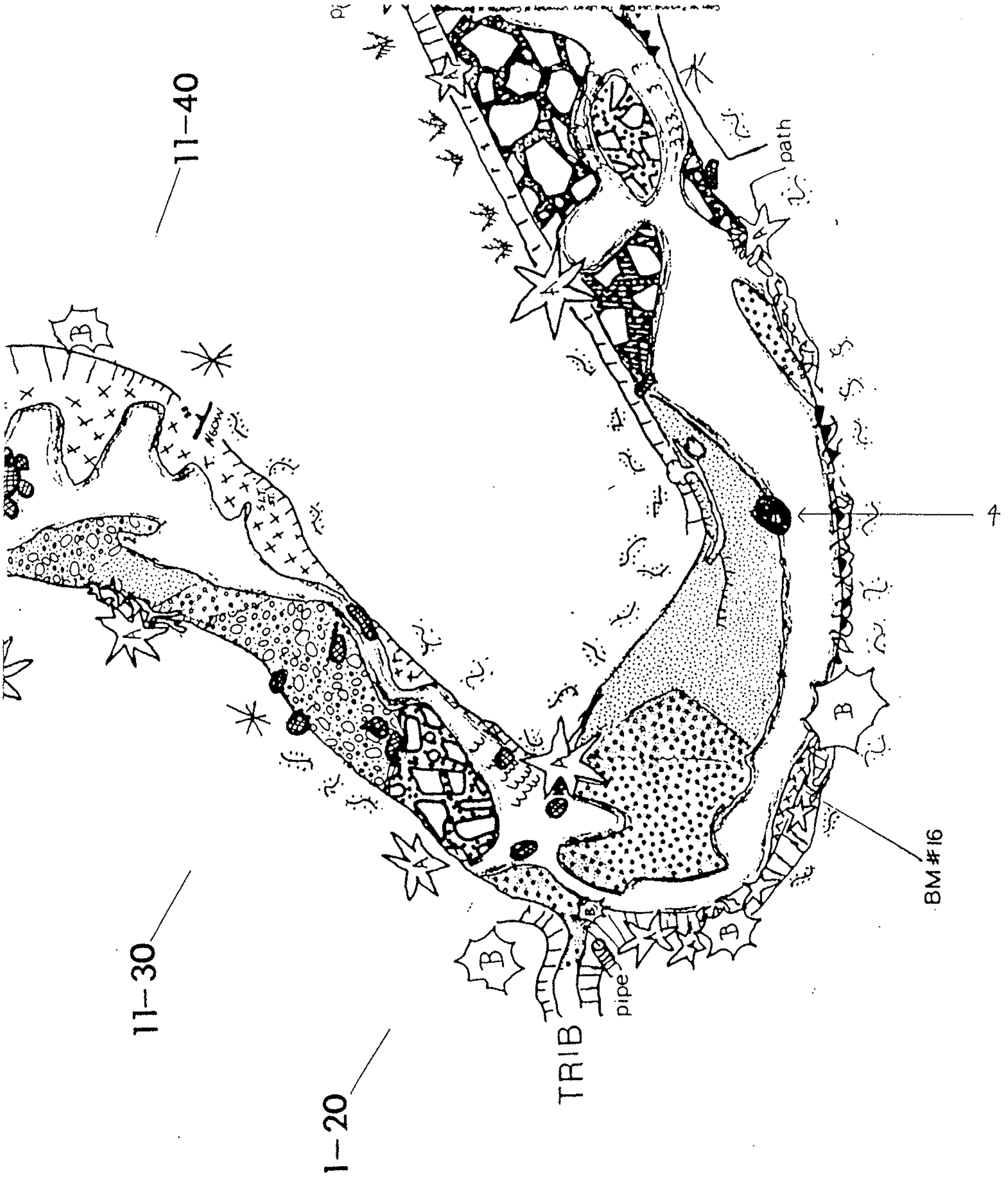


Figure 10A (Arrow and dark circle denote sample location)

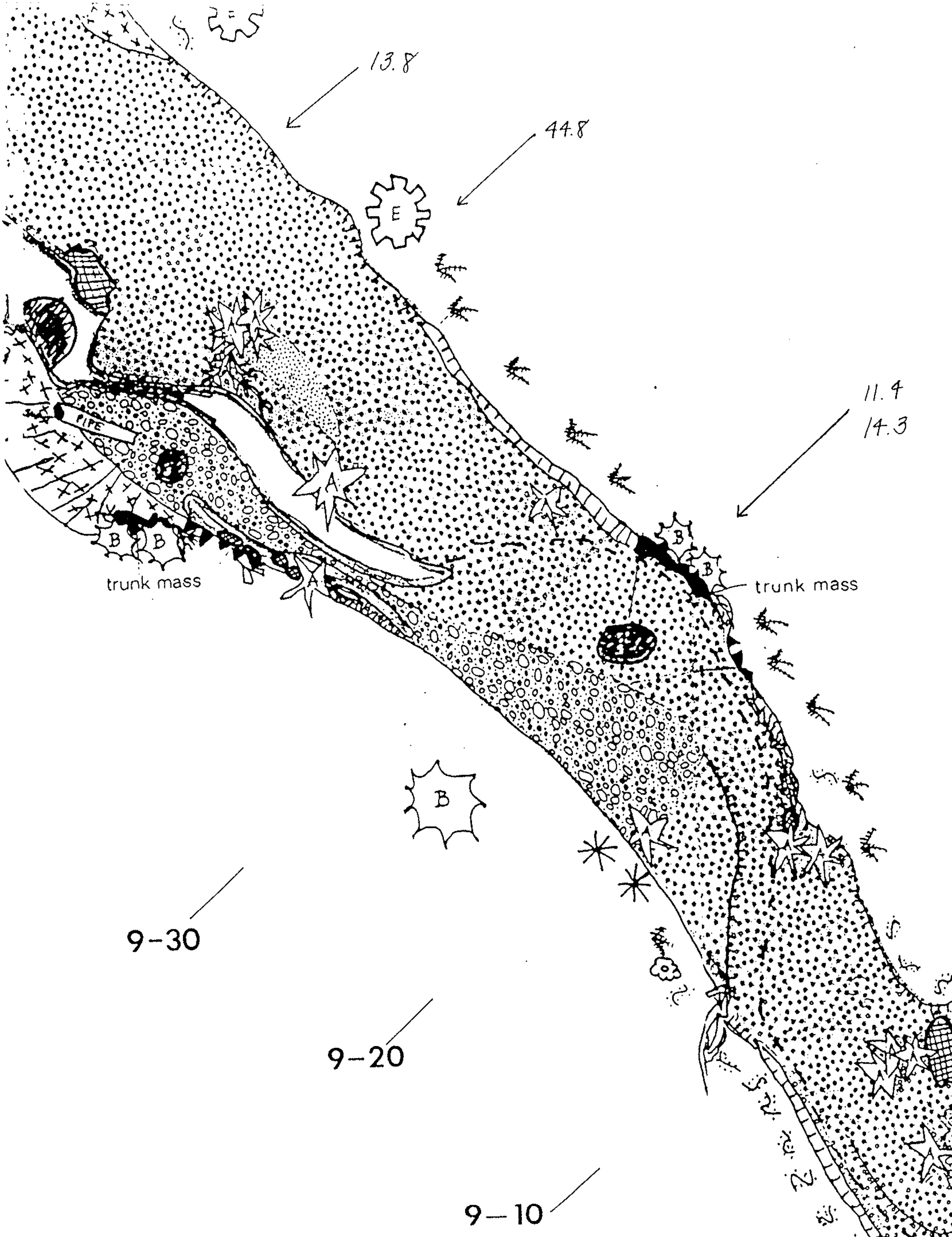


Figure 10B (Arrows and dark circles denote sample

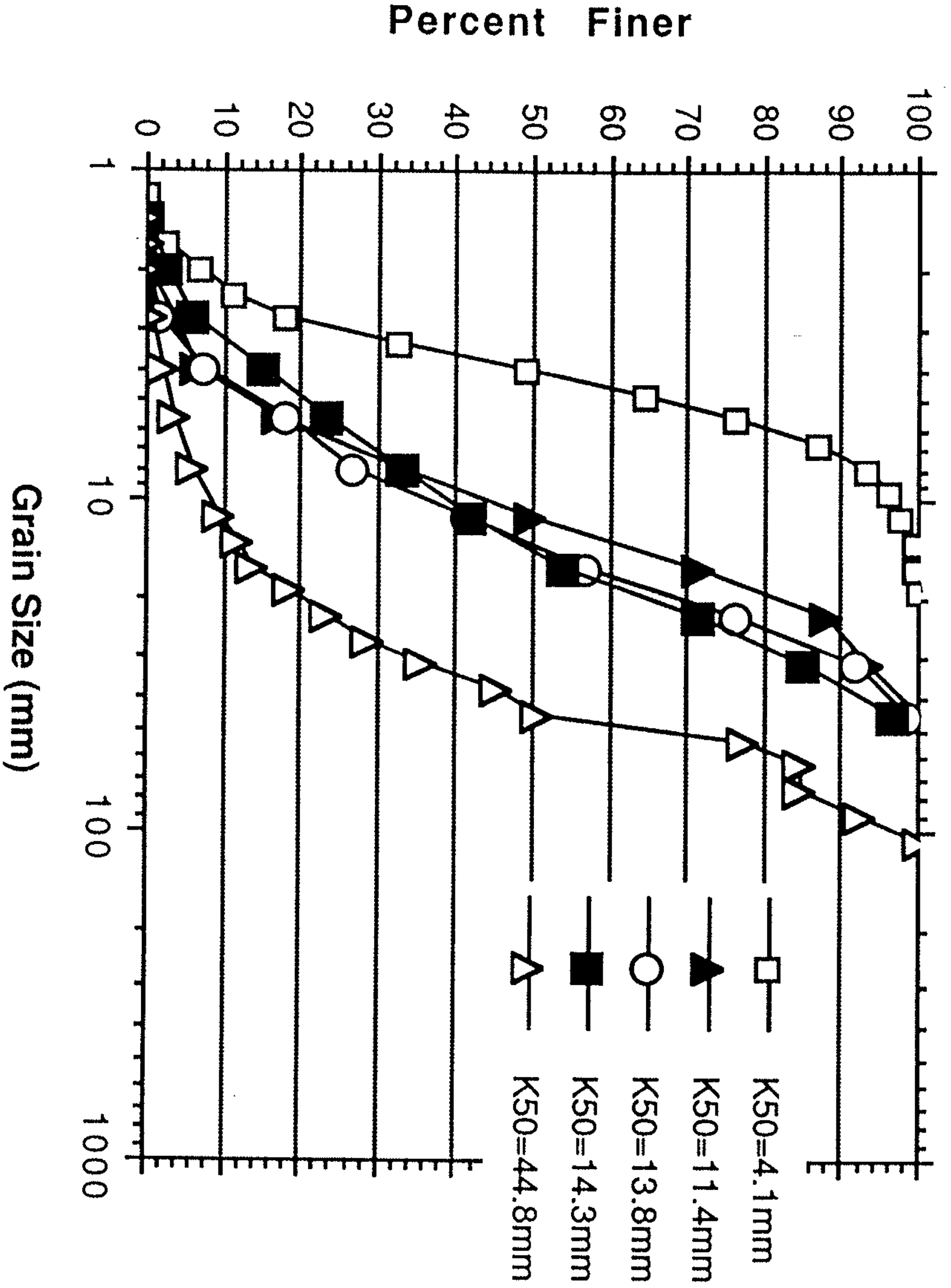
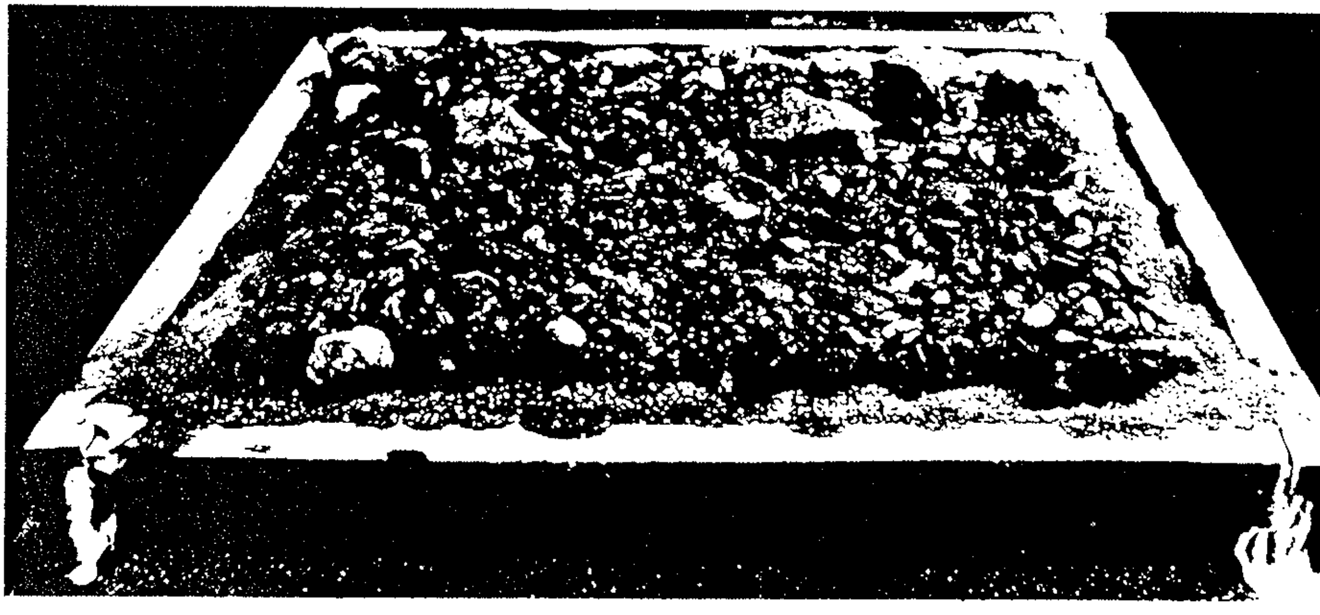

Percent Finer
0
10
20
30
40
50
60
70
80
90
100
Grain Size (mm)
1
10
100
1000
K50=4.1mm
K50=11.4mm
K50=13.8mm
K50=14.3mm
K50=44.8mm

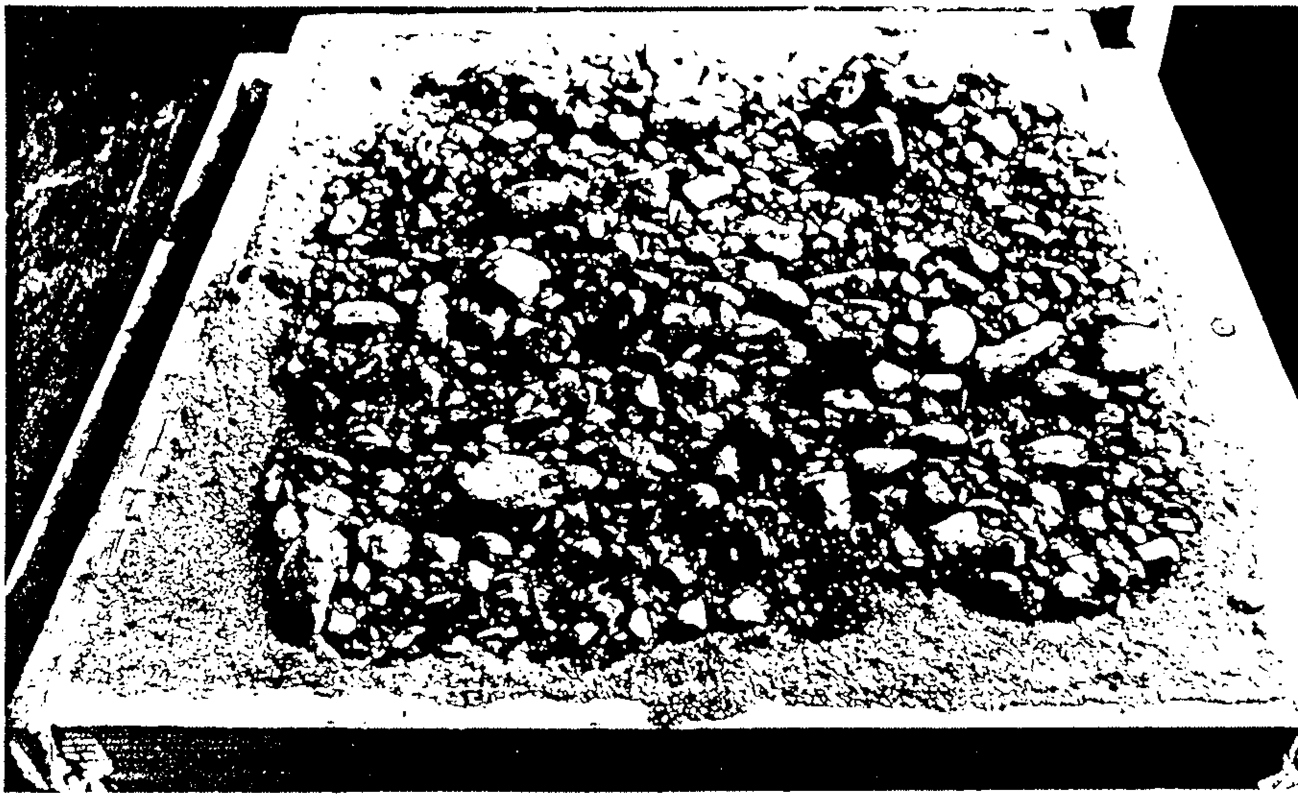
Figure 11

4



11.4

Figure 12



13.8

14.3

Figure 12 (Continued)

44.8

Figure 12 (Continued)

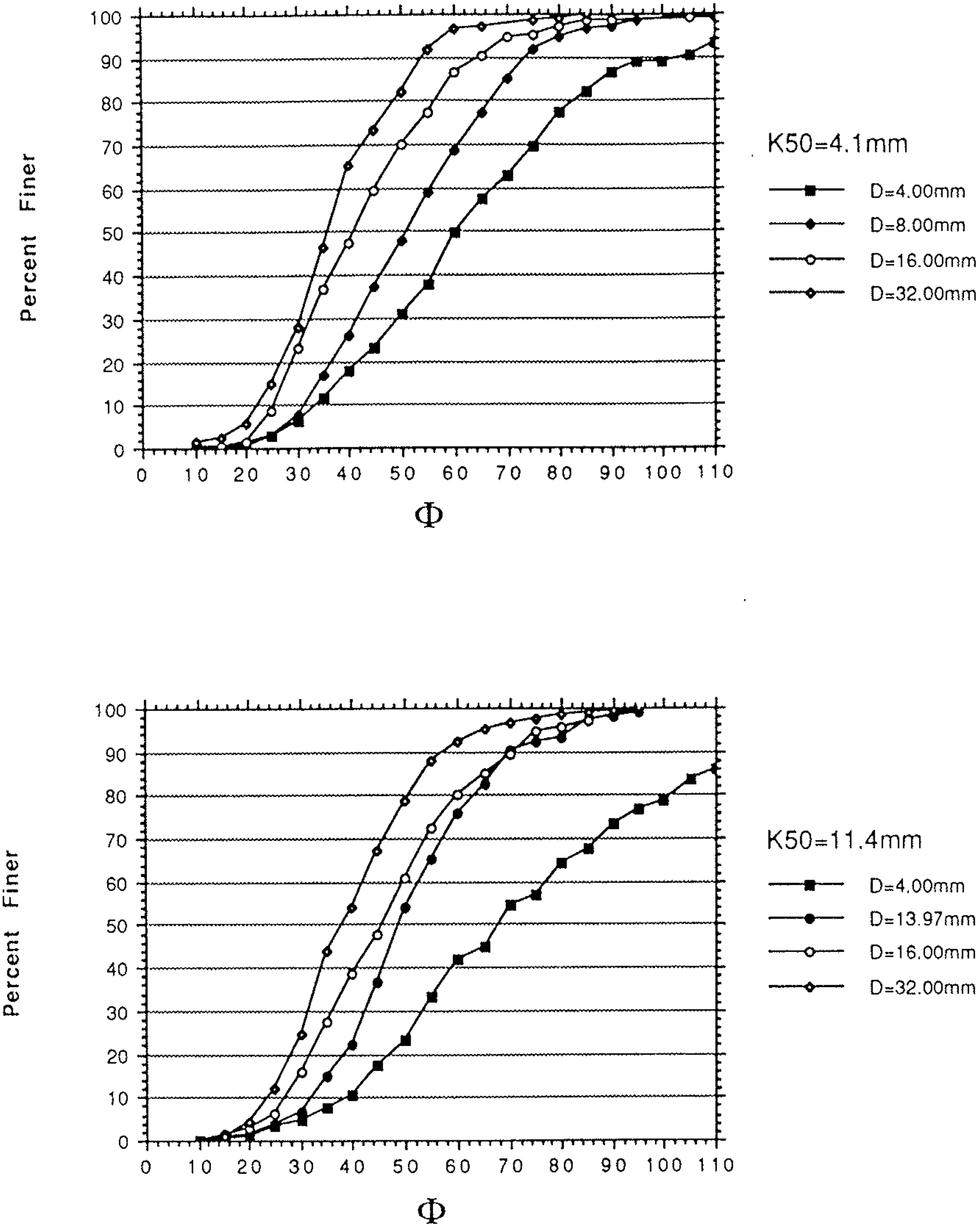
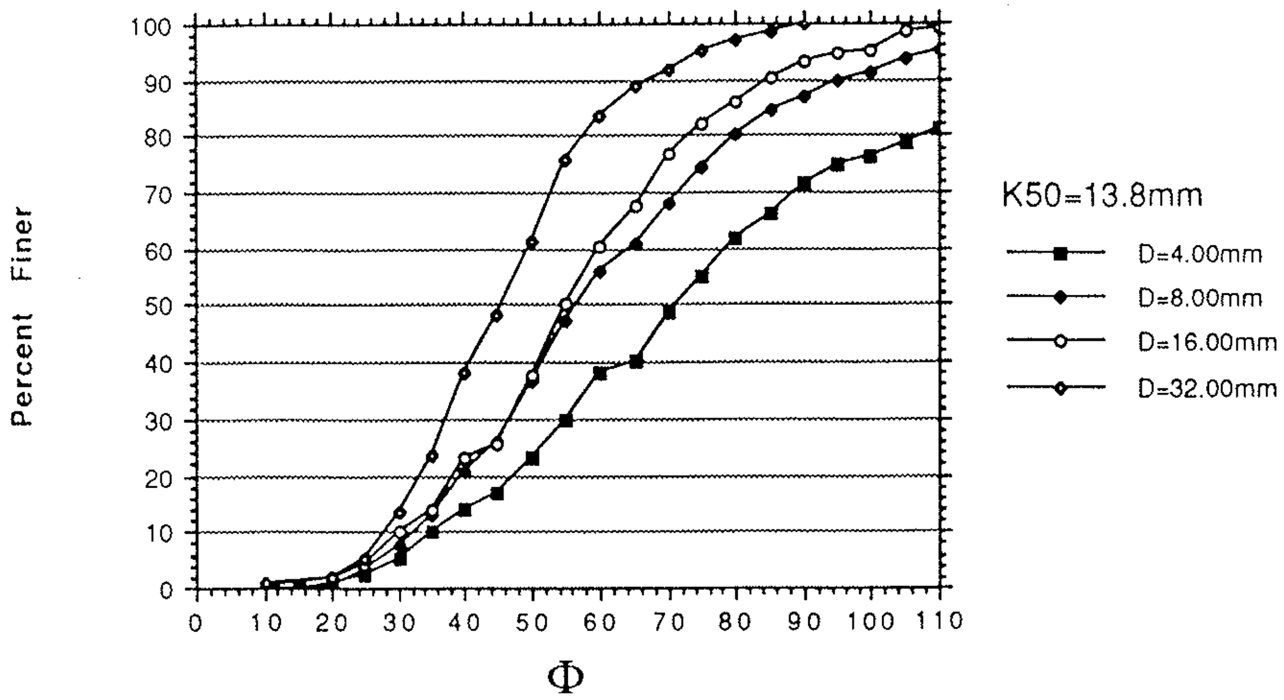

Percent Finer
0
10
20
30
40
50
60
70
80
90
100
0 10 20 30 40 50 60 70 80 90 100 110
Φ
K50=4.1mm
D=4.00mm
D=8.00mm
D=16.00mm
D=32.00mm
Percent Finer
0 10 20 30 40 50 60 70 80 90 100 110
Φ
K50=11.4mm
D=4.00mm
D=13.97mm
D=16.00mm
D=32.00mm

Figure 13



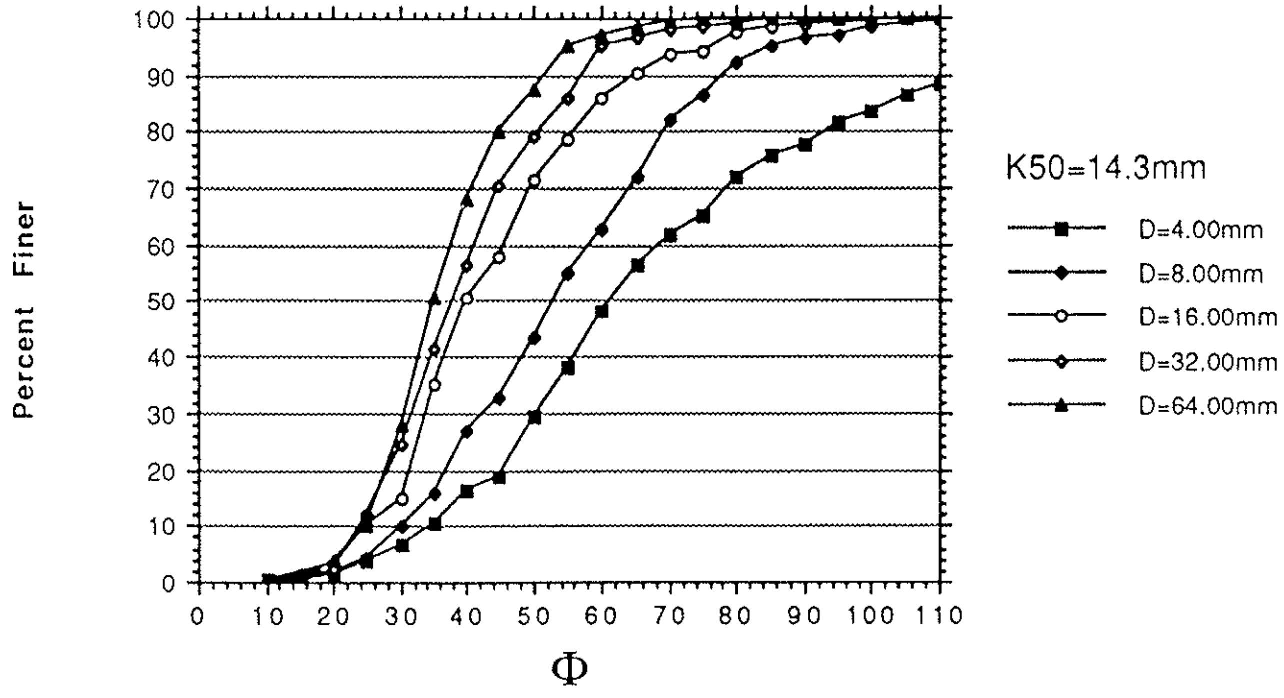


Figure 13 (Continued)

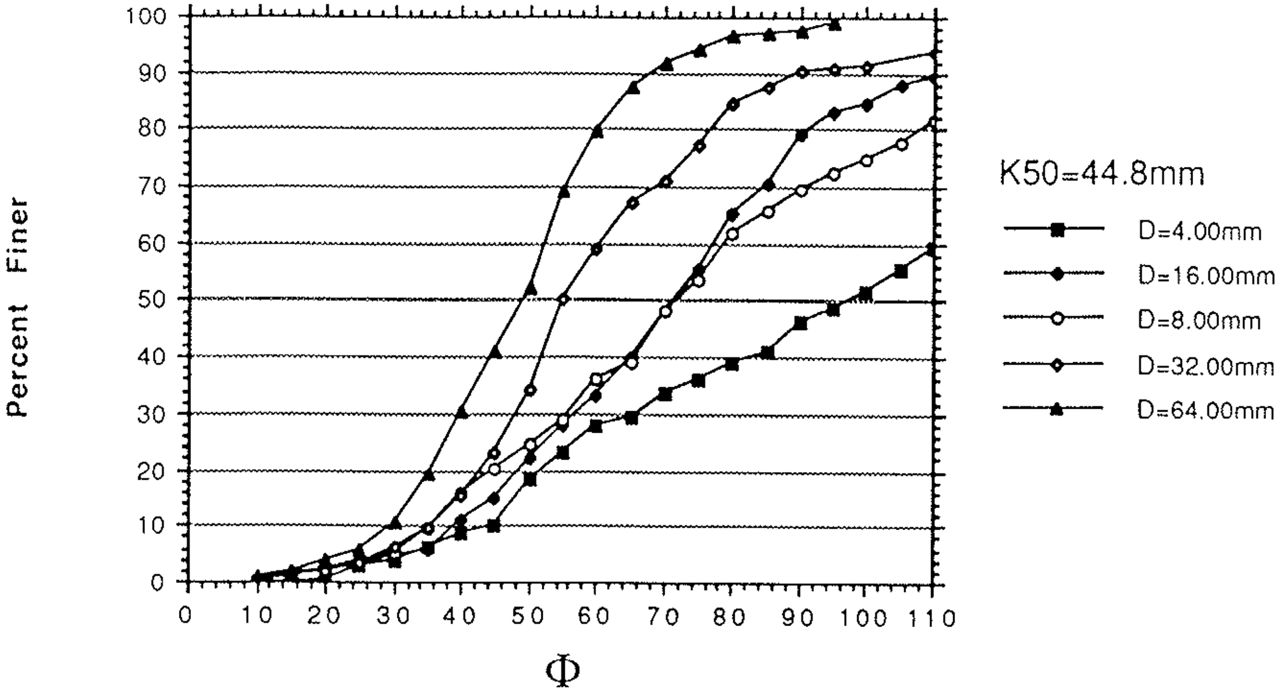


Figure 13 (Continued)

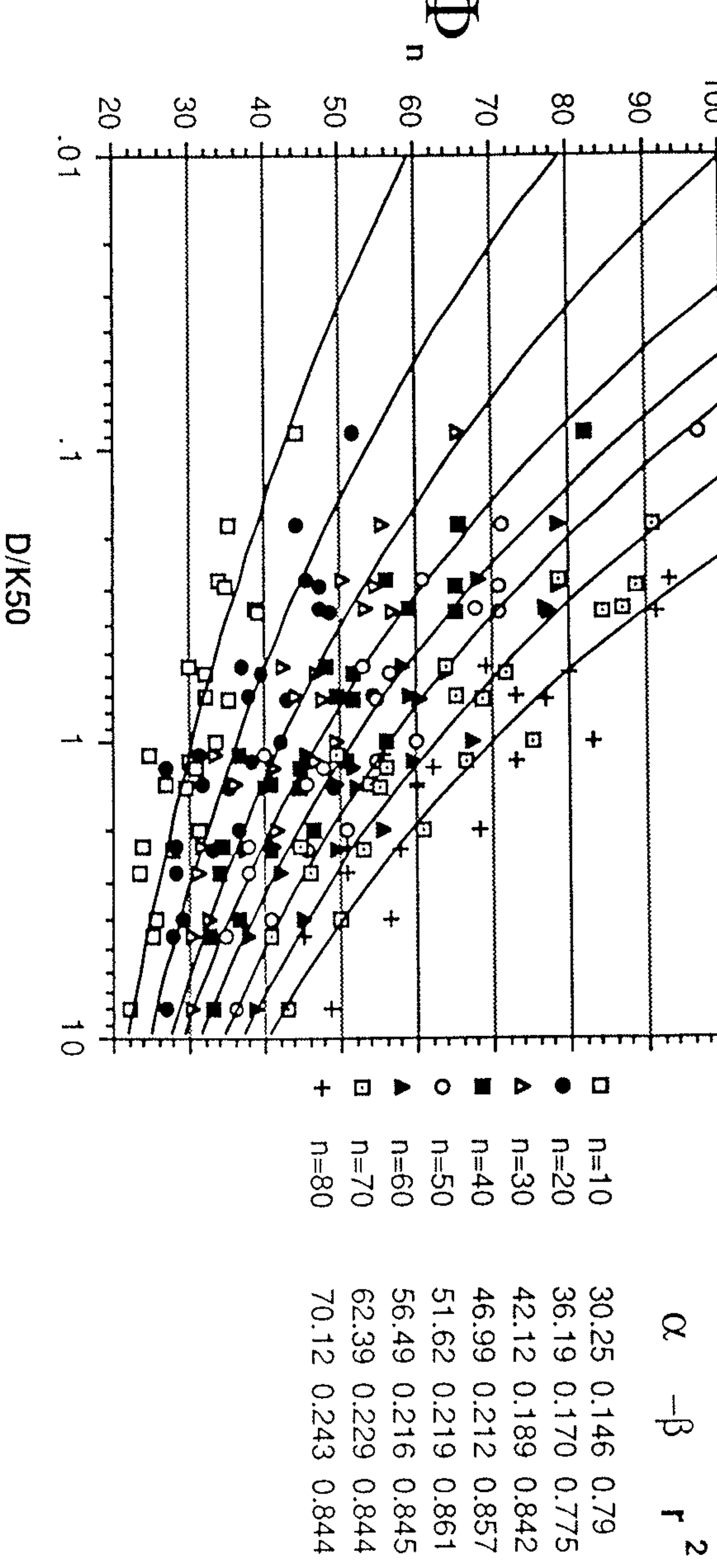
Φ n
110
100
90
80
70
60
50
40
30
20
.01
.1
1
10
D/K50
α −β r 2
□ n=10 30.25 0.146 0.79
● n=20 36.19 0.170 0.775
▷ n=30 42.12 0.189 0.842
■ n=40 46.99 0.212 0.857
○ n=50 51.62 0.219 0.861
▲ n=60 56.49 0.216 0.845
⊡ n=70 62.39 0.229 0.844
+ n=80 70.12 0.243 0.844

Figure 14

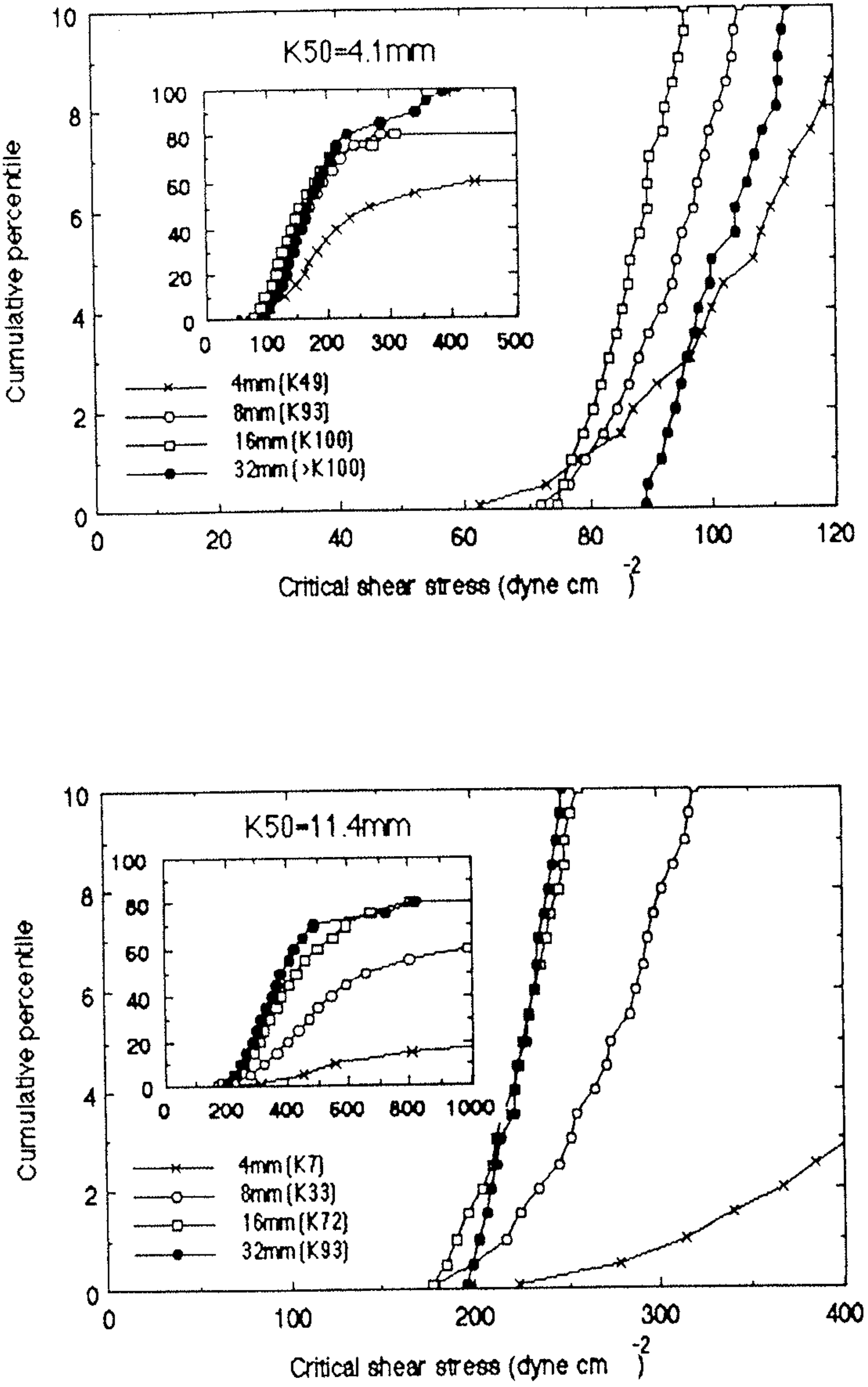

K50=4.1mm
Cumulative percentile
Critical shear stress (dyne cm $^{-2}$)
0
2
4
6
8
10
0
20
40
60
80
100
120
100
80
60
40
20
0
0
100
200
300
400
500
4mm (K49)
8mm (K93)
16mm (K100)
32mm (>K100)
K50=11.4mm
Cumulative percentile
Critical shear stress (dyne cm $^{-2}$)
0
2
4
6
8
10
0
100
200
300
400
100
80
60
40
20
0
0
200
400
600
800
1000
4mm (K7)
8mm (K33)
16mm (K72)
32mm (K93)

Figure 15

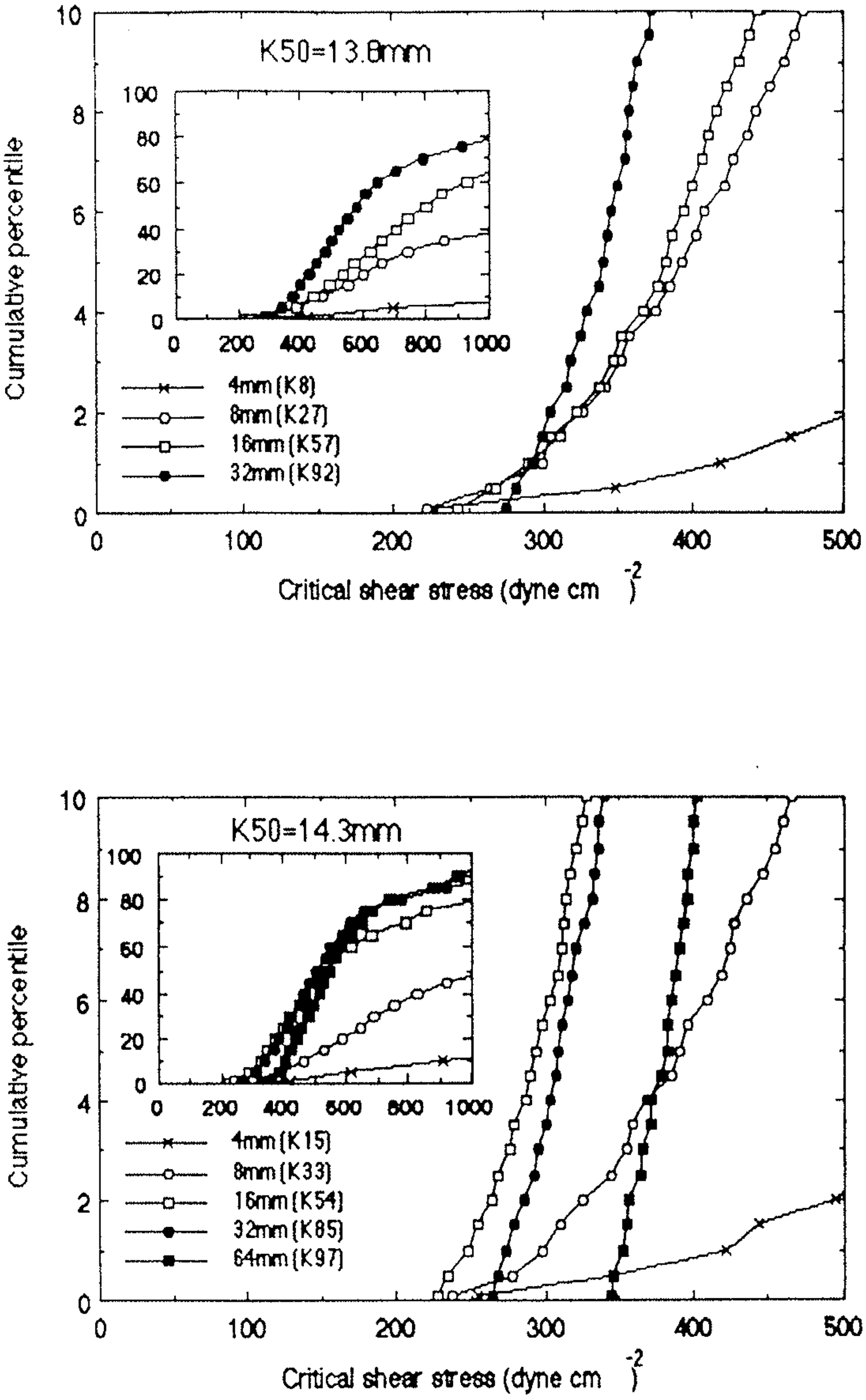


Figure 15 (Continued)

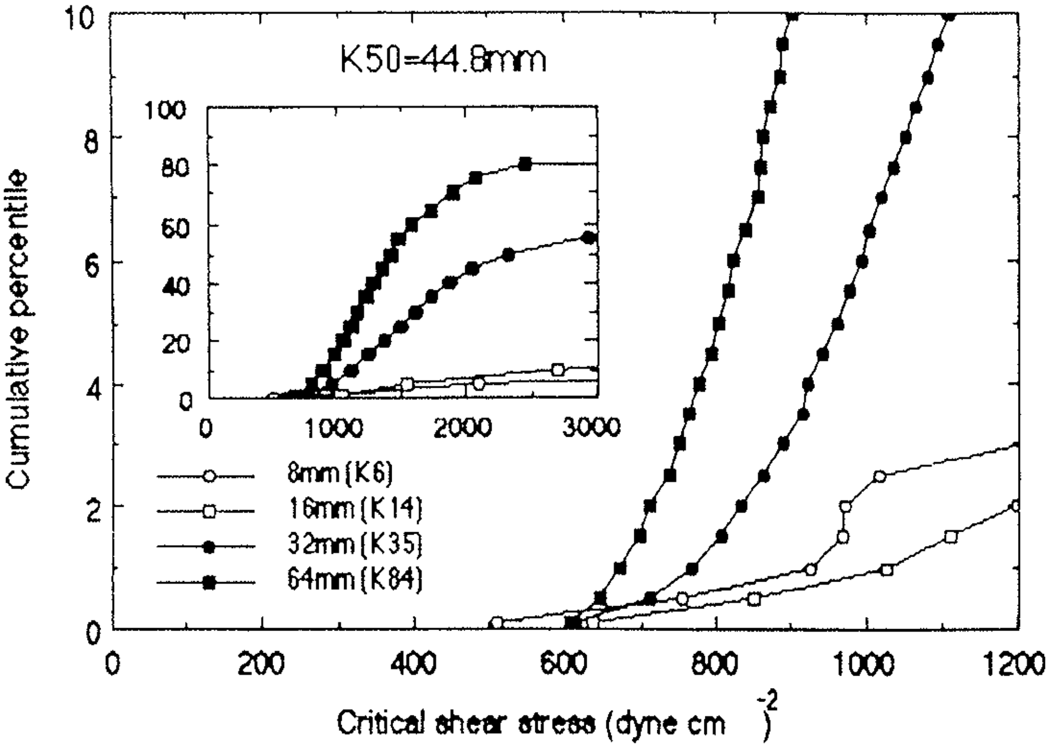


Figure 15 (Continued)

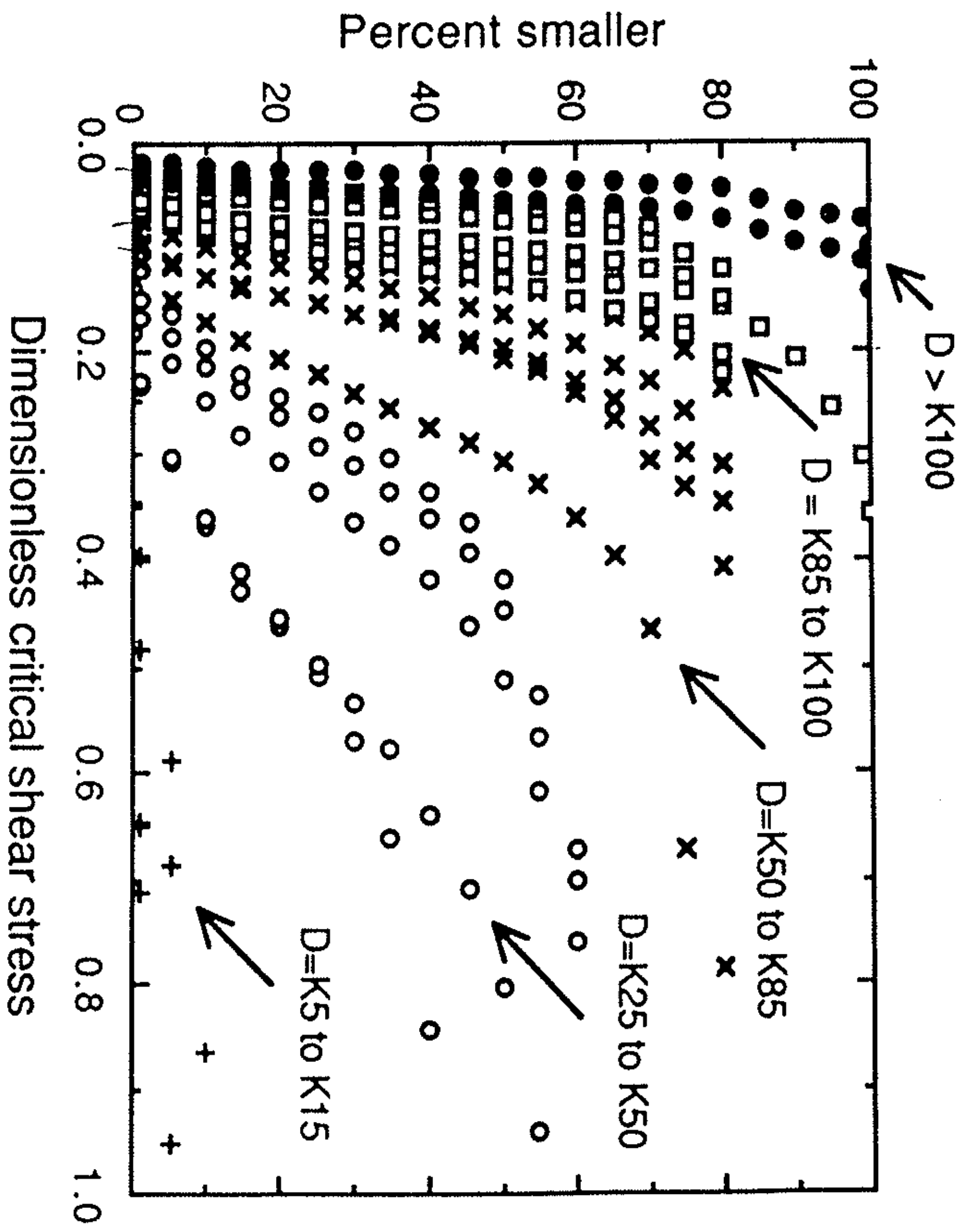

Percent smaller
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
Dimensionless critical shear stress
D > K100
D = K85 to K100
D=K50 to K85
D=K25 to K50
D=K5 to K15

Figure 16

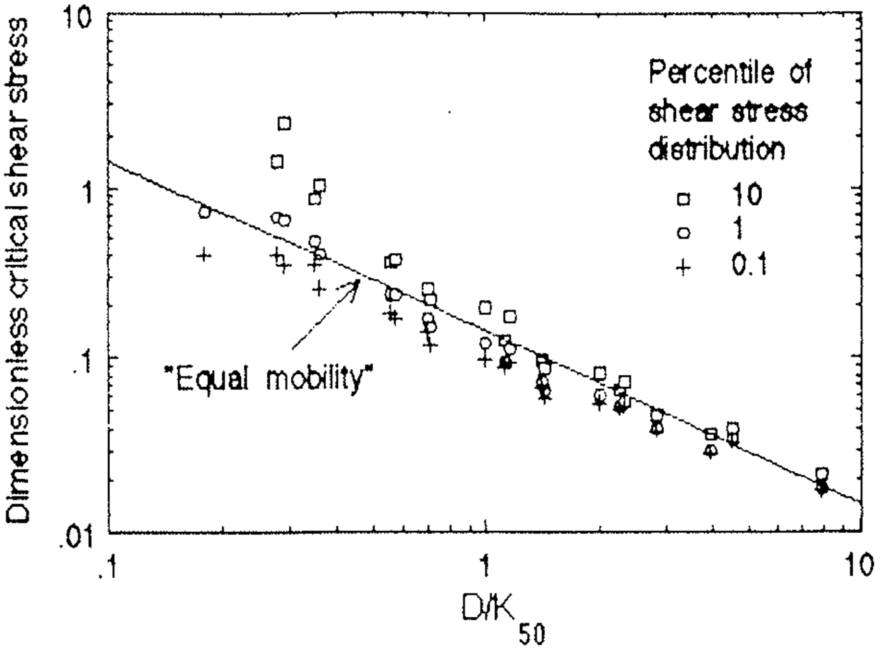

Dimensionless critical shear stress
10
1
.1
.01
.1
1
10
D/K50
Percentile of
shear stress
distribution
□ 10
○ 1
+ 0.1
"Equal mobility"

Figure 17

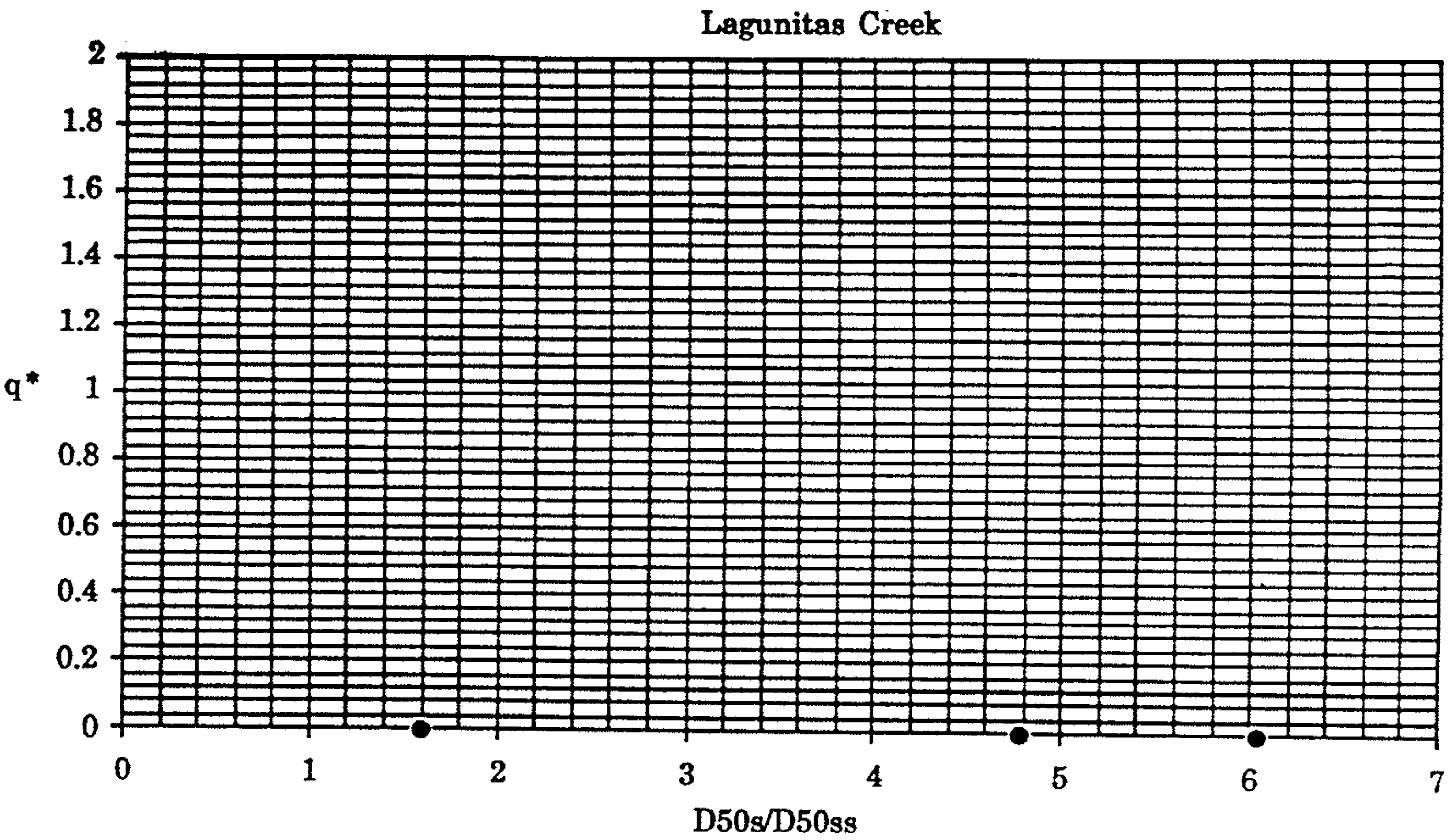

Lagunitas Creek

Figure 18 (After Ki (1990))

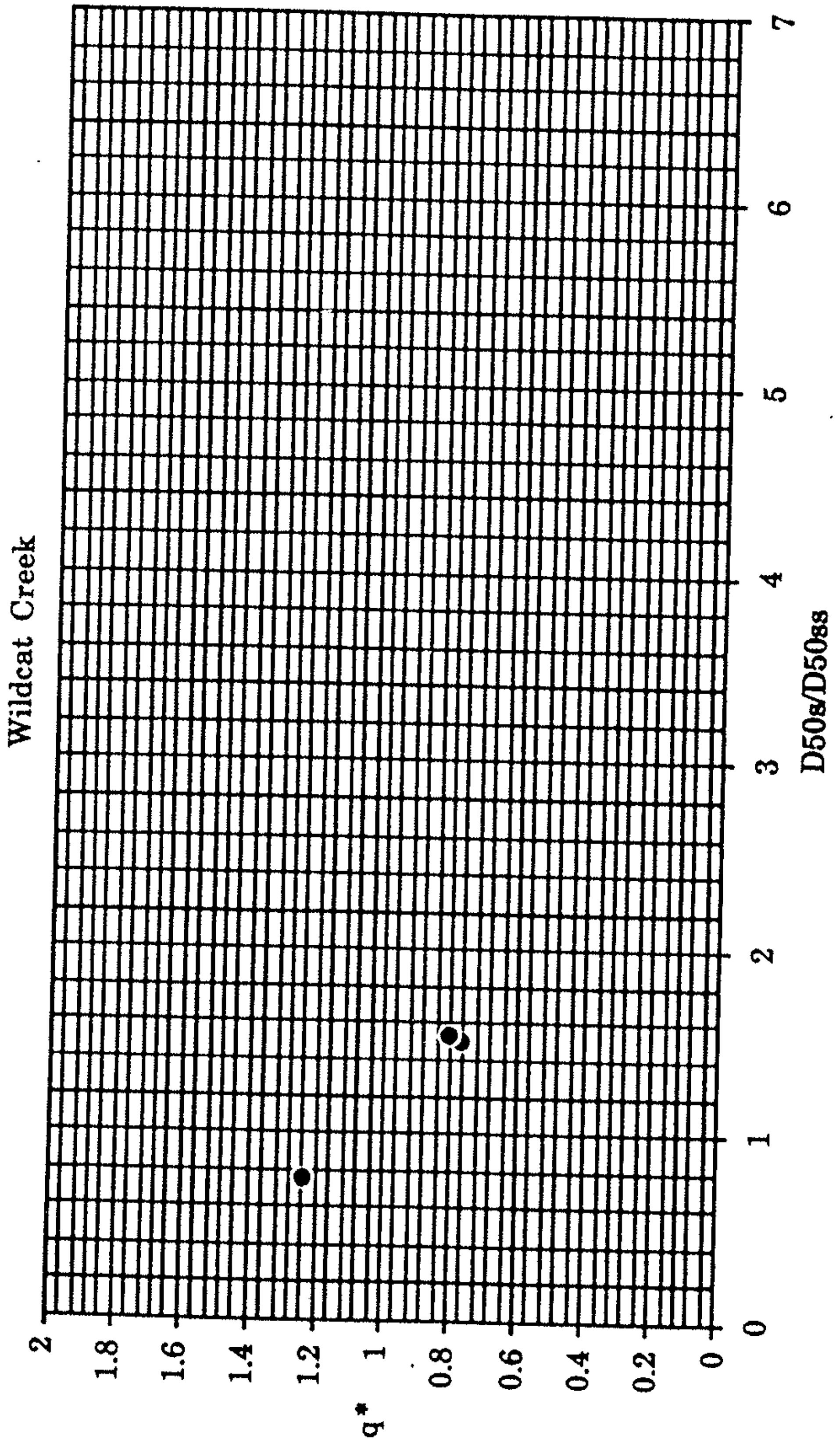
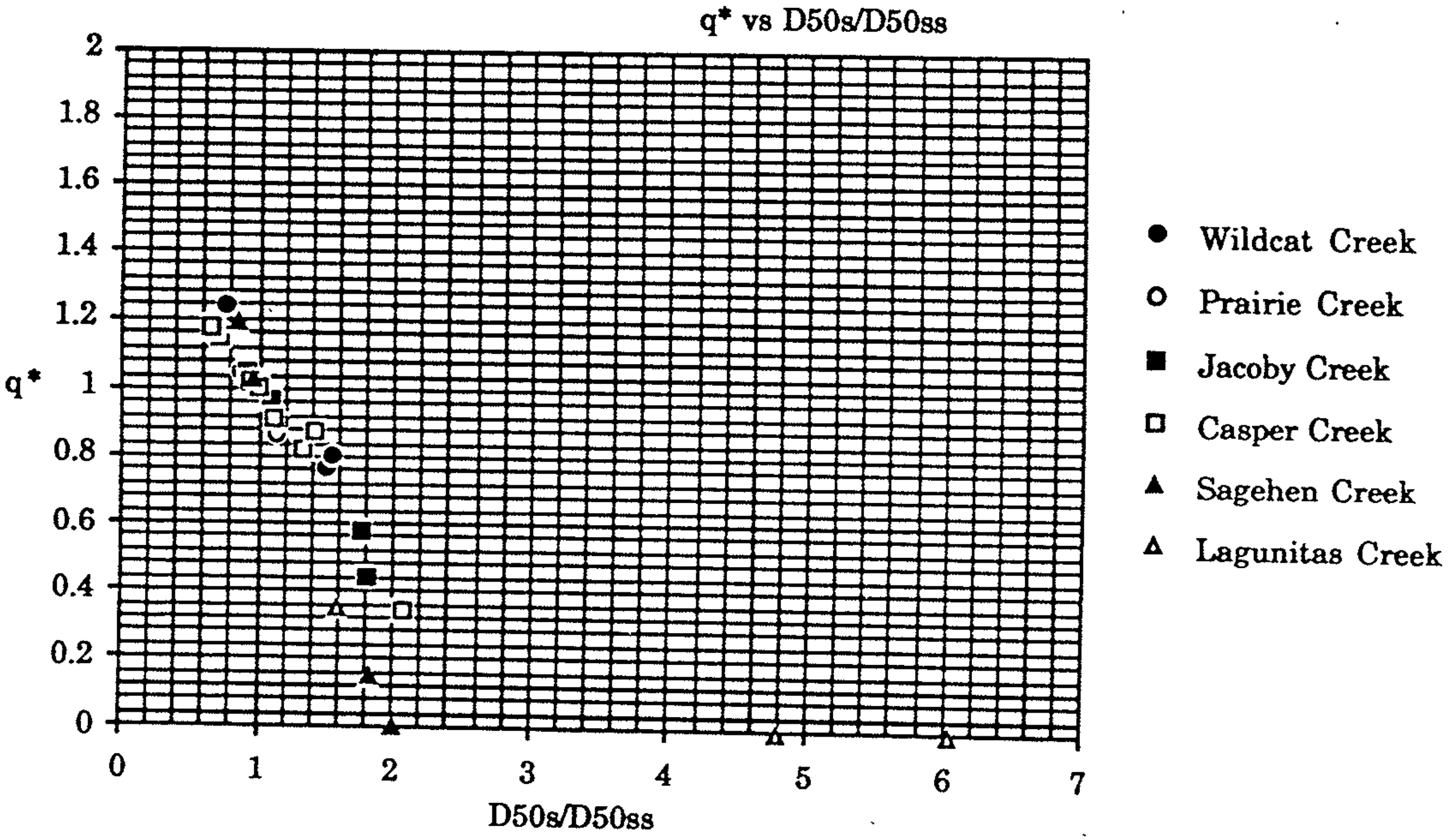


Figure 19 (After Kinerson (1990))


q* vs D50s/D50ss
q*
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
D50s/D50ss
● Wildcat Creek
○ Prairie Creek
■ Jacoby Creek
□ Casper Creek
▲ Sagehen Creek
△ Lagunitas Creek

Appendix A