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A Laboratory investigation of depositional characteristics of fine sediment from a harbour using a rotating circular flume

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MANAGEMENT PERSPECTIVE

Title: A LABORATORY INVESTIGATION OF DEPOSITIONAL CHARACTERISTICS OF FINE SEDIMENT FROM A HARBOUR USING A ROTATING CIRCULAR FLUME

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Current Status: Many hydrophobic contaminants are attached to fine sediments which are transported into Great Lakes harbours along with the tributary waters. Settling of sediment in the harbours depends on physical, chemical and biological factors. An important aspect of modelling water quality and the transport of the contaminants is the formation of flocs and the resultant effects on settling velocity and deposition rates. These processes cannot be estimated theoretically. We used a unique rotating flume to study the effects of turbulence on floc formation and settling velocity for sediment from Port Stanley harbour. This paper adds to our knowledge of the effects on floc formation of shear stress, seasonality, and storage time as they relate to the transport properties of fine sediment from Port Stanley harbour.

Next Steps: The paper will be submitted to a refereed journal.

A LABORATORY INVESTIGATION OF DEPOSITIONAL CHARACTERISTICS OF FINE SEDIMENT FROM A HARBOUR USING A ROTATING CIRCULAR FLUME

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ABSTRACT: The deposition and floc formation of fine sediment from Port Stanley harbour were investigated using a rotating circular flume. Seasonal effects, storage time and shear stress were varied. Biological activity was monitored as an aid to explain the results. The sample storage in the flume resulted in an increased flocculation for the two finer samples. A sample with a higher percentage of silt did not flocculate to the same extent as the finer samples. Flocculation was also influenced by the presence of bacteria, however further investigation is required to determine their relative importance compared to the presence of fines.

INTRODUCTION:

Fine sediments entering a harbour through tributaries undergo a variety of transport processes depending on the physical, chemical and biological conditions of the harbour water. Because of the reduction in the turbulence level and the shear stresses responsible for the transport of the sediment within the harbour, the sediments start to settle while the size distribution of the sediment flocs is modified by the prevailing conditions of hydrodynamics, chemistry and biology of the harbour water. Changes in the floc size distribution in turn affect the settling rate and the net deposition of the sediment to the harbour bed. A knowledge of the transport characteristics of the sediment in a harbour is important for modelling the water quality in the harbour because many of the hydrophobic contaminants are attached to sediments and are transported along with the sediment. With the present state of knowledge, it is not possible to make theoretical predictions of settling velocities and the deposition rate of sediment (see, for example, WASP4, and Parker, 1994). One of the alternatives is to determine these parameters by measuring them using specialized flumes such as a rotating circular flume.

Laboratory circular flumes have been used extensively in the past to study the depositional characteristics of fine cohesive sediments. Some examples of such studies are: Partheniades and Kennedy, 1966; Partheniades et al., 1968; Mehta and Partheniades, 1975; Lick, 1982; Krishnappan and Engel, 1994. In the majority of these studies, the sediments were removed from the natural environment and were tested in such flumes in fluids that might or might not have the same chemical and biological properties of the natural water. Because of this, the flocculation mechanism of the sediment might not have been reproduced correctly in the flume. Moreover, the effect of sample storage prior to and during the experimental program was not very well studied. In the present study the depositional characteristics of fine sediments from Port Stanley harbour in Ontario, Canada were tested in a rotating circular flume using the water from the harbour as the suspending medium to preserve the chemical and biological characteristics of the harbour water. The effect of sample storage prior to and during the experimental program was studied in a systematic manner by monitoring the changes in the bacterial count and uronic acid concentrations in the sediment water mixture during the course of the experimental program. The depositional experiments were repeated for three different samples of sediment water mixture collected at three different times of the year to investigate the seasonal effects on the depositional behaviour.

COLLECTION OF SAMPLES AND FIELD CONDITIONS:

The Port Stanley harbour is situated on the north shore of the middle basin of Lake Erie (Fig. 1). It has a surface area of about 35 000 m^2 of water, and a portion is dredged to a depth of 6 m below datum. It is located at the mouth of Kettle Creek, whose discharge varies widely, from 0.5 to 1.0 m^3 /s in the summer to as much as 80 m^3 /s during storm events.

Samples of sediment and water were collected on the east side of the inner harbour. A submersible pump was used to get samples from the bottom. The pump was lowered over the edge of the harbour wall to the bottom, about one-half a metre away from the wall, where the water depth was 3.2-3.4 m. The samples were collected in 100 litre barrels. During the filling of each barrel, the pump rested on the bottom and was raised 10-20 cm and lowered to the bottom once or twice to disturb the top layer of the bottom sediment so that some of it would be pumped into the barrels along with the water and suspended sediment. Samples were collected on three separate dates: December 1995 (laboratory tests in January 1996); July 1996; November 1996 (laboratory tests in December 1996). The three samples will be referred to as the January, July and November samples respectively. The samples were stored at 4°C for the short duration between collection and start of the tests. The field conditions are summarized in terms of the water temperature and dissolved oxygen in the following table.

Table 1. Summary of harbour conditions during sampling and sample properties:

Sample	Water temperature, deg. C	Dissolved oxygen, mg/l	Primary Particle Size, microns	Comments
January	0.18-0.25	13.82-13.91	18.1	90% Ice covered
July	12.57(hypolimnion)- 17.60(epilimnion)	7.5 (hypolimnion) 7.08 (epilimnion) 6.7 (thermocline)	4.4	Thermocline at about 2 m depth
November	5.25-5.30	12.09-12.16	3.9	well mixed

The primary sediment particle size shown in the fourth column of the Table 1 was measured using a laser diffraction instrument. The median size of the January sample, 18.1 microns was considerably larger than the other two samples (4.4 microns for July sample and 3.9 microns for November sample). This is primarily due to a higher percentage of silt sized particles.

ROTATING CIRCULAR FLUME EXPERIMENTS:

Description of the flume:

The rotating, circular flume used for this study is 5.0 m in mean diameter, 0.30 m in width and 0.30 m in depth. It rests on a rotating platform, which is 7.0 m in diameter. A counter rotating annular cover fits inside the flume with close tolerance (~ 1.5 mm on either side) and makes contact with the water surface. By rotating the annular cover and the flume in opposite directions at different speeds, it is possible to generate nearly two-dimensional flow fields with different turbulent shear stresses and turbulence intensities. A schematic diagram of the flume is shown in Fig. 2. Complete details of the flume and the characteristics of flows that can be generated in it can be found in Krishnappan (1993).

Instrumentation:

The flume is equipped with a Laser Doppler Anemometer (LDA) to measure the flow field. The LDA used is a two channel system operating in back-scatter mode. The laser and the optics are mounted on an optical bench, which is positioned on the rotating platform beside a glass window attached to the flume wall. The optical bench can be traversed both in vertical and horizontal directions and the velocities in the tangential and vertical planes can be measured over an entire cross-section. Measurements made using the instrument were employed to verify a 3-D numerical model of turbulent flows in rotating flume assemblies. (Petersen and Krishnappan (1994) and Krishnappan et al (1994)).

The flume is also equipped with a Malvern Particle Size Analyzer to measure the size distribution of the suspended particles in the flume. The operating principle of the instrument is based on the Fraunhoffer Diffraction Theory (Weiner, 1984). The instrument is mounted in a cradle beneath the flume and is operated in a continuous flow-through mode. In this mode of operation, the flow-through cell of the instrument is connected to a sampling tube fitted through the bottom of the flume. The tube extends into the flow up to the mid depth and faces the flow at the centre line of the flume. The sediment suspension is drawn continuously from the flume by gravity through 5 mm tygon tubing. The suspension, after passing through the sample cell empties into a holding reservoir and is then pumped back into the flume. The length of sampling tube upstream of the cell is kept to a minimum to avoid any possible changes in the structure of the flocs due to the flow field that exists within the tube. With this arrangement, the instrument is capable of measuring the in-situ size distribution of sediment flocs in the flume.

The flume is also fitted with sampling ports for drawing sediment water mixture for the purpose of determining the concentration of the suspended sediment and for bacterial count and uronic acid concentration measurements. The sediment concentration was determined using filtration and weighing.

Experimental Procedure:

Prior to the start of the experiments, the sediment water suspension was thoroughly mixed by first re-suspending any deposited sediment using a brush and then further breaking-up of flocs by mixing the suspension using an electric blender. This procedure was applied for all the tests so that the starting condition for all the tests was consistent. The top cover was then lowered until it penetrated the water surface by about 3 mm to ensure proper contact with the water in the flume. Care was taken to remove all trapped air. This was done by simply rotating the top cover while the flume was kept stationary. The depth of water inside the flume was adjusted to 12.0 cm. To begin a test, the flume and the top cover were rotated in opposite directions at their maximum speeds for twenty minutes to thoroughly mix the sediment and the water and to further break up the flocs. During this high speed operation, sediment samples were collected for sediment concentration measurements every five minutes. During the same time, the size distribution of the suspended sediment in the water column was measured using the Malvern Particle Size Analyzer every two minutes. Samples were also collected for bacterial count and the uronic acid concentration measurements. After 20 minutes flume and cover speeds were reduced to a particular bed shear stress and operated for a period of approximately five hours. During this time the sediment concentration and size distributions were measured every ten minutes. The samples were maintained at room temperature during and between tests.

BIOLOGICAL MONITORING:

Bacterial Count Measurements:

As an indication of the total biological activity in the samples, the bacteria were counted in the samples, using sub-samples analysis when the samples were collected at the harbour and at the beginning and end of the first day of testing each week. For the January and July samples a method to count the total living bacteria was used.

For the November sample this technique was not available and a technique to count fecal coliform was used (reference requested from Arnold). While the two methods cannot be compared, intra-sample trends can be observed.

Uronic Acid Concentration Measurements:

In general uronic acids are indicators for the acid polysaccharides (a component of the extracellular polymeric substances) which help to bind the particles together. The uronic acid component is believed to be the compound that is "sticky" and thus is critical for the flocculation mechanism (Leppard, 1997). If there is a trend in the uronic acid values one may expect to see the same trend in the floc size distribution.

Sub-samples were separated for analysis when the samples were collected at the harbour and at the beginning and end of the first day of testing each week. The method of Filisetti-Cozzi and Carpita (1991) was used.

RESULTS:

Each sample was tested at three different bed shear stresses: Low Shear (0.056 N/m^2), Medium Shear (0.121 N/m^2) and High Shear (0.213 N/m^2). Each test was repeated twice with a time gap of one week in between the tests at the same shear stress to examine the influence of sample storage in the flume during the experimental program. Therefore, for each sample nine tests were carried out for a total of 27 tests for the three samples. A summary of all the test conditions is given in Table 2.

Suspended sediment concentration:

The variation of concentration of suspended sediment as a function of time during deposition is shown for the January sample in Fig. 3. The results for all nine tests are shown in this figure. The concentration is normalized using the concentration at the start of the experiment and it can be seen from this figure that the concentration decreases at a faster rate at the beginning and reaches a nearly steady state value near the end of the test. The steady state concentration is a function of bed shear stress and provides an estimate of the amount of sediment that would stay in suspension indefinitely for a given shear stress. In this case, for the low shear stress, the fraction of the material that would stay in suspension indefinitely is about 40%. This value goes up to 60% for the medium shear stress and 80% for the high shear stress. Fig. 3 also shows that the variability due to sample storage is not significant as the concentration versus time curves for a particular shear stress carried out at one week time intervals do not deviate significantly from each other.

The concentration versus time curves for the July sample are shown in Fig. 4. Unlike the January sample, the results of the July sample do show the impact of the sample storage. The concentration versus time curves for a particular shear stress show greater variability among the tests carried out at one week time intervals. The steady state concentrations are slightly different from those of the January sample.

Table 2: Summary of test conditions:

TEST NO.	DATE	SAMPLE ID	BED SHEAR STRESS ID	INITIAL CONCENTRATION (MG/L)	INITIAL MEDIAN SIZE (MICRONS)
1	12/1/96	January	Low Shear	206	14
2	19/1/96	January	Low Shear	211	14
3	26/1/96	January	Low Shear	190	14
4	11/1/96	January	Medium Shear	216	14
5	18/1/96	January	Medium Shear	203	16
6	25/1/96	January	Medium Shear	197	15
7	10/1/96	January	High Shear	212	13
8	17/1/96	January	High Shear	216	16
9	24/1/96	January	High Shear	203	15
10	11/07/96	July	Low Shear	175	17
11	18/07/96	July	Low Shear	165	19
12	25/07/96	July	Low Shear	159	21

13	10/07/96	July	Medium Shear	182	22
14	17/07/96	July	Medium Shear	162	21
15	24/07/96	July	Medium Shear	158	24
16	09/07/96	July	High Shear	193	17
17	16/07/96	July	High Shear	179	16
18	23/07/96	July	High Shear	164	20
19	21/11/96	November	Low Shear	178	13
20	28/11/96	November	Low Shear	145	14
21	05/12/96	November	Low Shear	145	16
22	20/11/96	November	Medium Shear	200	15
23	27/11/96	November	Medium Shear	154	15
24	04/12/96	November	Medium Shear	149	17
25	19/11/96	November	High Shear	207	11
26	26/11/96	November	High Shear	172	13
27	03/12/96	November	High Shear	151	15

For low shear stress, the fraction of sediment that would stay indefinitely in water column is slightly higher at around 45% (average of the three tests). The values for the medium and high shear stresses are around 65% and 85% respectively.

The results for the November sample are similar to those of the July sample and the concentration versus time curves for this sample are shown in Fig. 5.

Size Distribution of suspended sediment:

The median size of the particle size distributions versus time curves for the nine tests of the January sample is shown in Fig. 6. Results from all nine tests are given in this figure. The median size decreased as a function of time (decreases from about 15 microns to about 10 microns) for the lower shear but the opposite trend (increases from 15 microns to 20 microns) occurred for the medium and high shear tests. The decreasing trend of the median size for the low shear stress test can be interpreted as due to the settlement of larger particles leaving the finer particles in suspension (i.e. settling as discrete particles). The increasing trend of the median size for medium and high shear stresses, on the other hand, suggests that the sediment in suspension has undergone the process of flocculation and the sediment settles as flocs (floc settling). The medium and high shear stresses provide the necessary turbulence for the promotion of the flocculation process. The storage of sample in the flume has affected the flocculation process somewhat. The sizes of flocs formed in the second and third week tests are larger than the ones formed in the first week of the experimental program.

The size distribution results in terms of the median size versus time curves for the July sample are shown in Fig. 7. The results show similar trend as the January sample, but the magnitude of the changes is much larger. In the low shear stress tests, median size has dropped from about 20 microns to about 10 microns and in the medium and high shear tests the median size has increased from about 20 microns to 50 microns. Since the median size of the primary particle size distribution of this sample is only 4.4 microns, the sediment has behaved as a flocculated material even during the low shear stress tests. Since the turbulence level during the low shear stress tests is low, further flocculation of the sediment in suspension did not take place and the larger denser flocs settled leaving behind the smaller weaker flocs in suspension.

The size distribution results for the November sample are shown in Fig. 8. These results are also similar to the other two samples and the magnitude of changes in the median size is about half way between those corresponding to the January and July samples.

Bacterial count measurements:

The bacterial counts measured for the three samples from the time of sample collection are plotted as a function of time in days is shown in Fig. 9. Note that the November sample was tested for fecal coliform and the ordinate scale is different from the other two. The counts for the January sample showed a gradual increase whereas the November sample showed a gradual decrease throughout. The counts for the July sample were high from the field and remained so for the first two tests, and dropped in the third week. Typically (6 out of 9 times) there was an increase in the count from before and after a run on a given day. This may be a reflection of the five hours of mixing to which the sample was exposed.

Uronic acid results

The trends in uronic acid results are shown in Fig. 10. The values for the January sample are relatively constant through the tests. The July concentration dropped off from the harbour to the first week then remained relatively constant. For the November sample, the concentration is relatively constant from the time of collection in the harbour through the first week, followed by a decrease at the second week and remaining relatively constant leveling in the third week.

DISCUSSION:

The January sample contained a higher percentage of silt size particles and the median size of the primary particles was about four times larger than those of July and November samples. Yet in terms of the amount of material that would stay in suspension indefinitely for a given shear stress, this sample is not substantially different from the other two samples. This may be because the July and November samples are readily flocculated as can be inferred from the size distribution data. The median sizes of the July and November samples in the medium and high shear stress tests at steady state conditions are about double that of the January sample under the same shear stress conditions.

The higher flocculation tendency of the July and November samples may be due to the higher percentage of fines in the sediment. The bacterial count could have also played a role. Indeed, for the July sample, which exhibited the highest flocculation tendency had the highest bacterial count during first two weeks of the experimental program. The uronic acid concentration was also the highest for July sample initially, although it did drop to levels similar to the other samples during the tests. The similarities of the uronic acid concentrations during the tests suggest that this bulk measurement was not successful as an indicator of the differences in flocculation found in the three sets of tests. It is possible that extracellular proteins replaces uronic acid-rich polymers as the "sticky" substances of flocculation; it is also possible that the 3-D disposition of uronic acid-rich polymers in a small floc is more important than the total uronic acid content per floc.

CONCLUSION:

Controlled experiments of fine sediment deposition in the Rotating Circular Flume showed that the duration of sample storage and the sample variability had affected the depositional behaviour of the sediment. The sample storage in the flume resulted in an increased flocculation for the two finer samples. The sample with higher percentage of silt did not flocculate to the same extent as the finer samples and it was interesting to note that the amount of material that was in suspension indefinitely was not substantially different for the coarse sample than for the fine samples. This is a surprising result as one would have expected to see an increased deposition for the coarser sample. Obviously, the increased flocculation of the finer samples resulted in an increased amount of deposition and compensated for the difference in the initial size distribution of the samples. The results of the present experiments also indicate that the flocculation of the Port Stanley harbour sediments could have been affected both by the presence of bacteria and the amount of fines in the original sample. The relative importance of the two in the flocculation of the Port Stanley sediment needs to be further investigated.

ACKNOWLEDGEMENTS:

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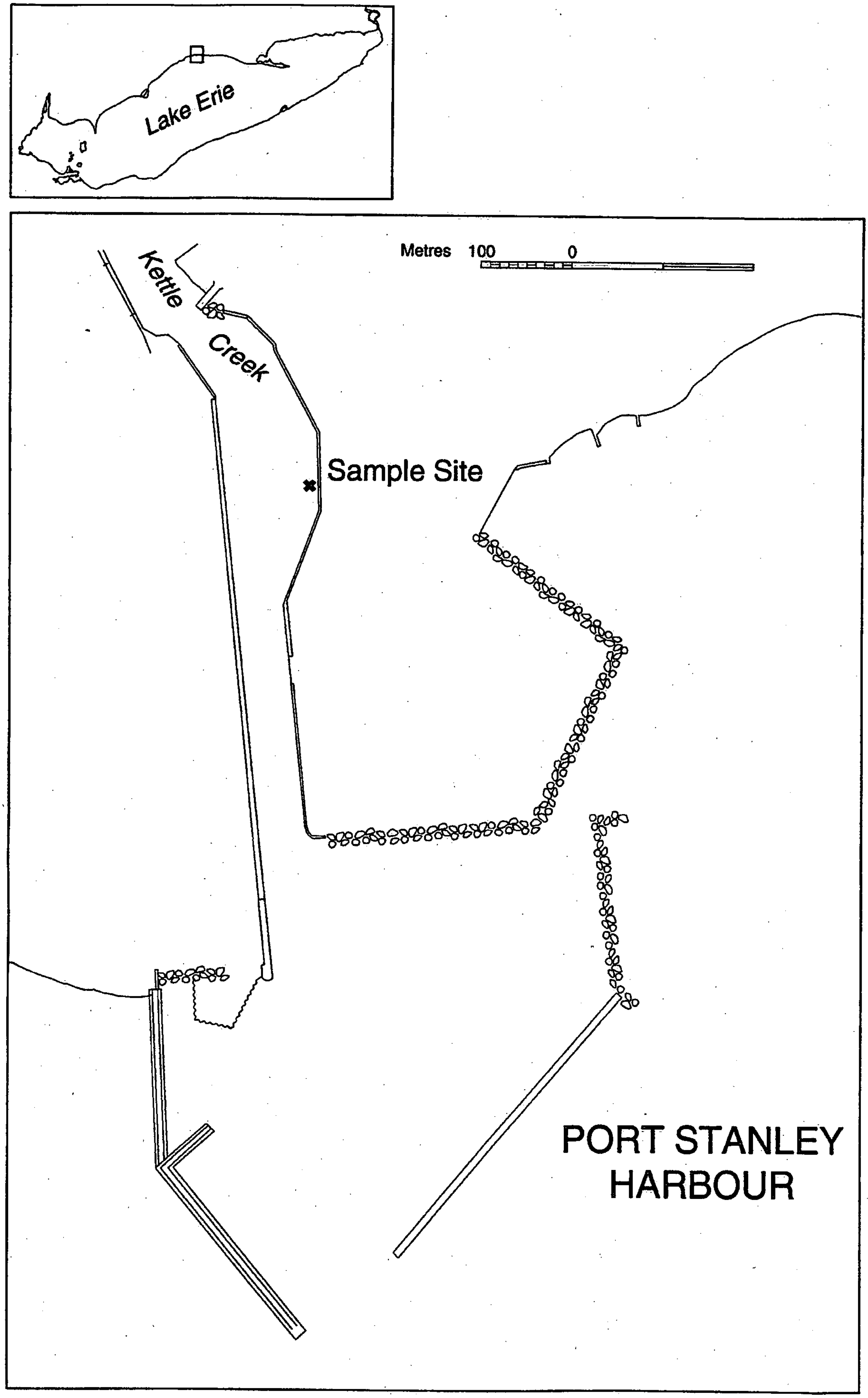
FIGURES

1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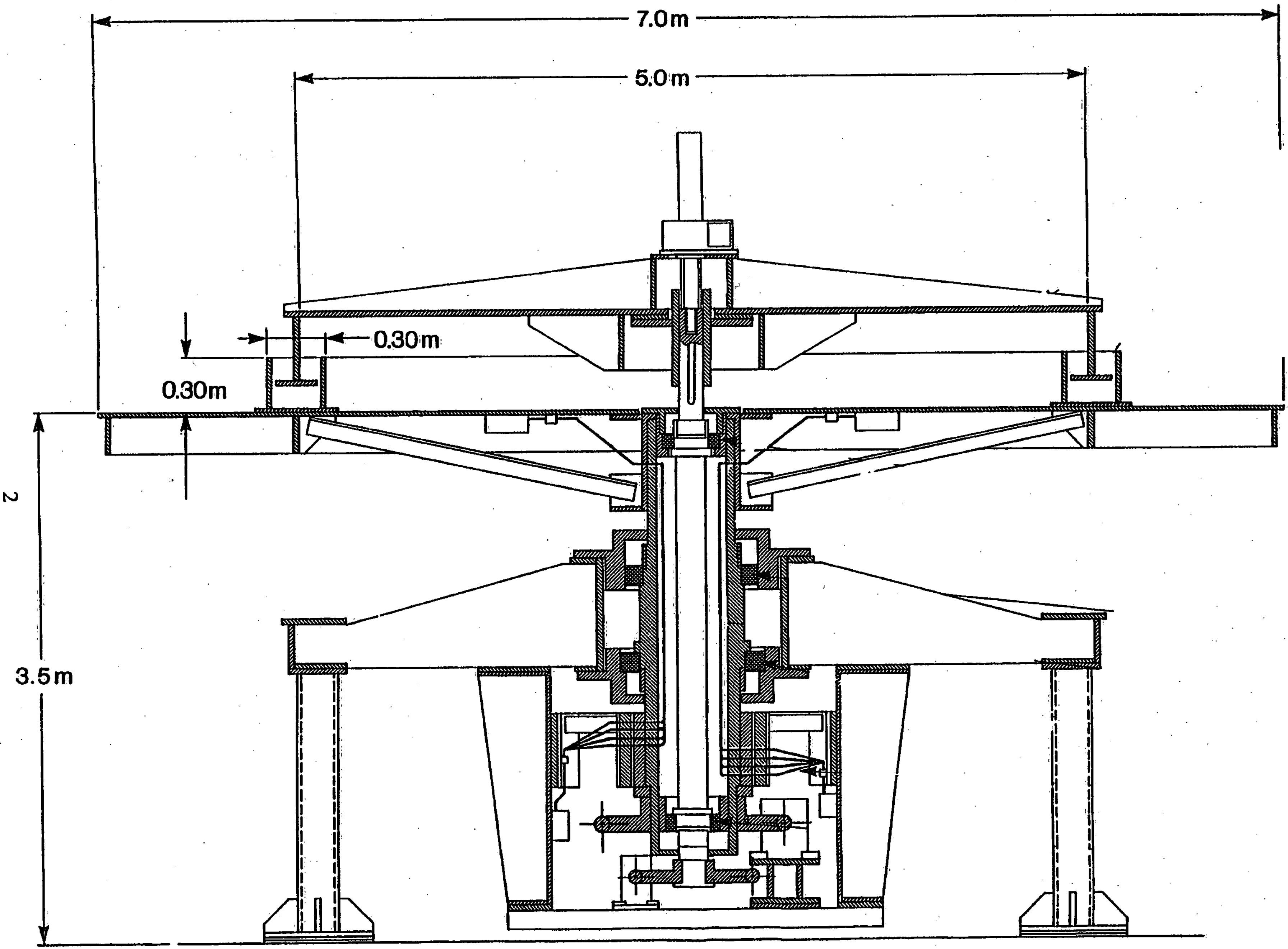
Kettle Creek
Sample Site
PORT STANLEY
HARBOUR



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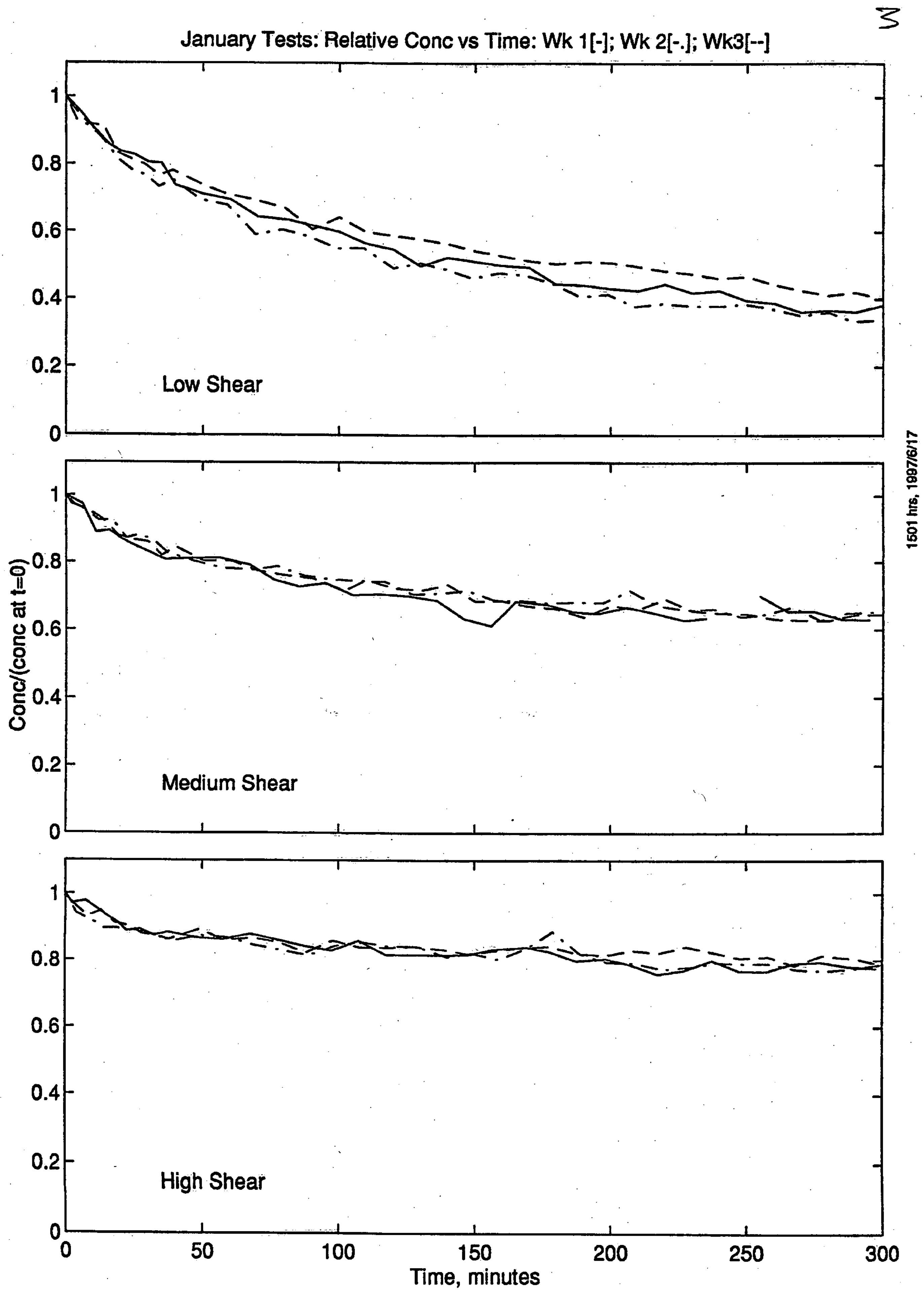
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Low Shear
Medium Shear
High Shear
Conc/(conc at t=0)
Time, minutes
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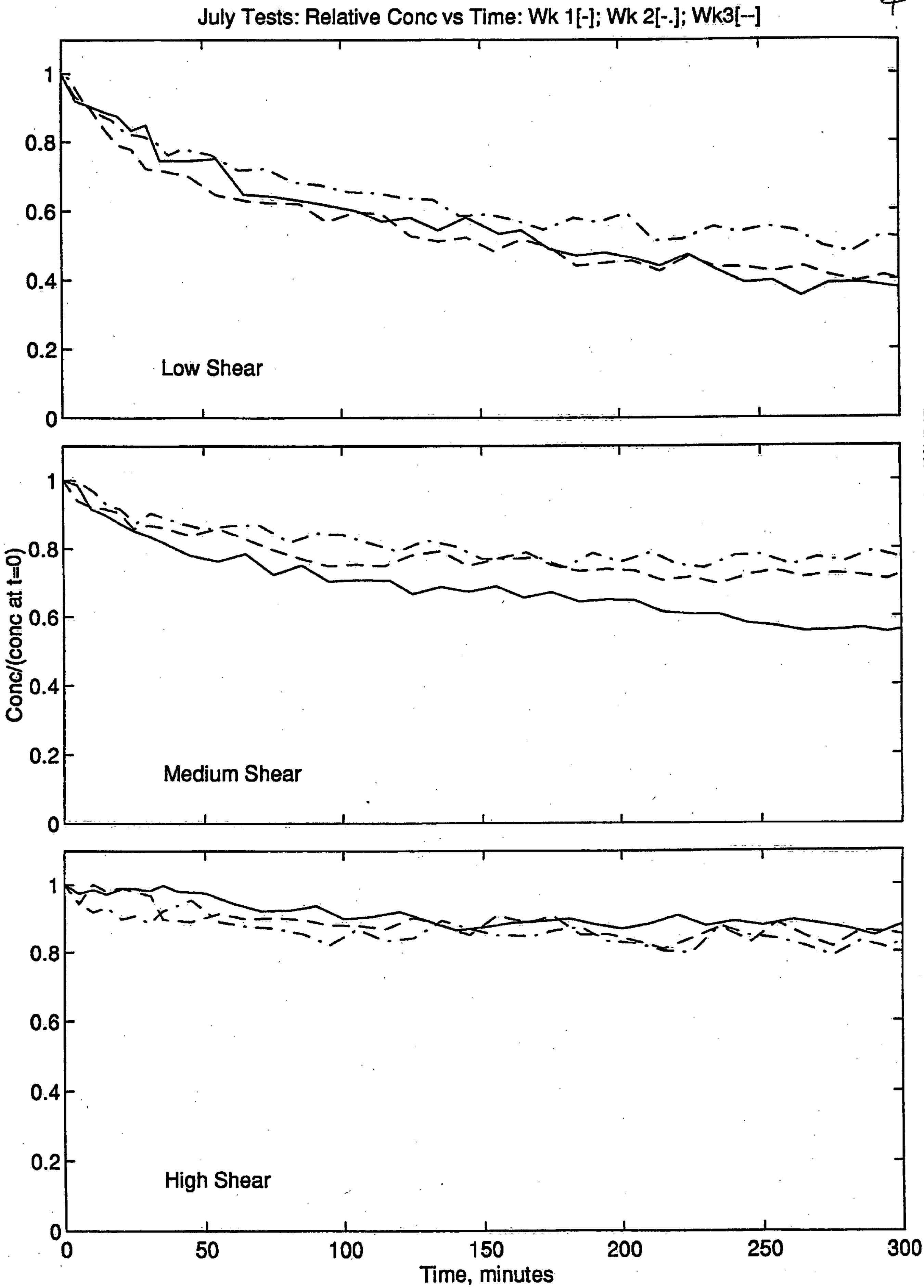
0.4
0.6
0.8
1
0
50
100
150
200
250
300
1501 hrs, 1997/6/17
3


July Tests: Relative Conc vs Time: Wk 1[-]; Wk 2[-.]; Wk3[--]
Low Shear
Medium Shear
High Shear
Conc/(conc at t=0)
Time, minutes
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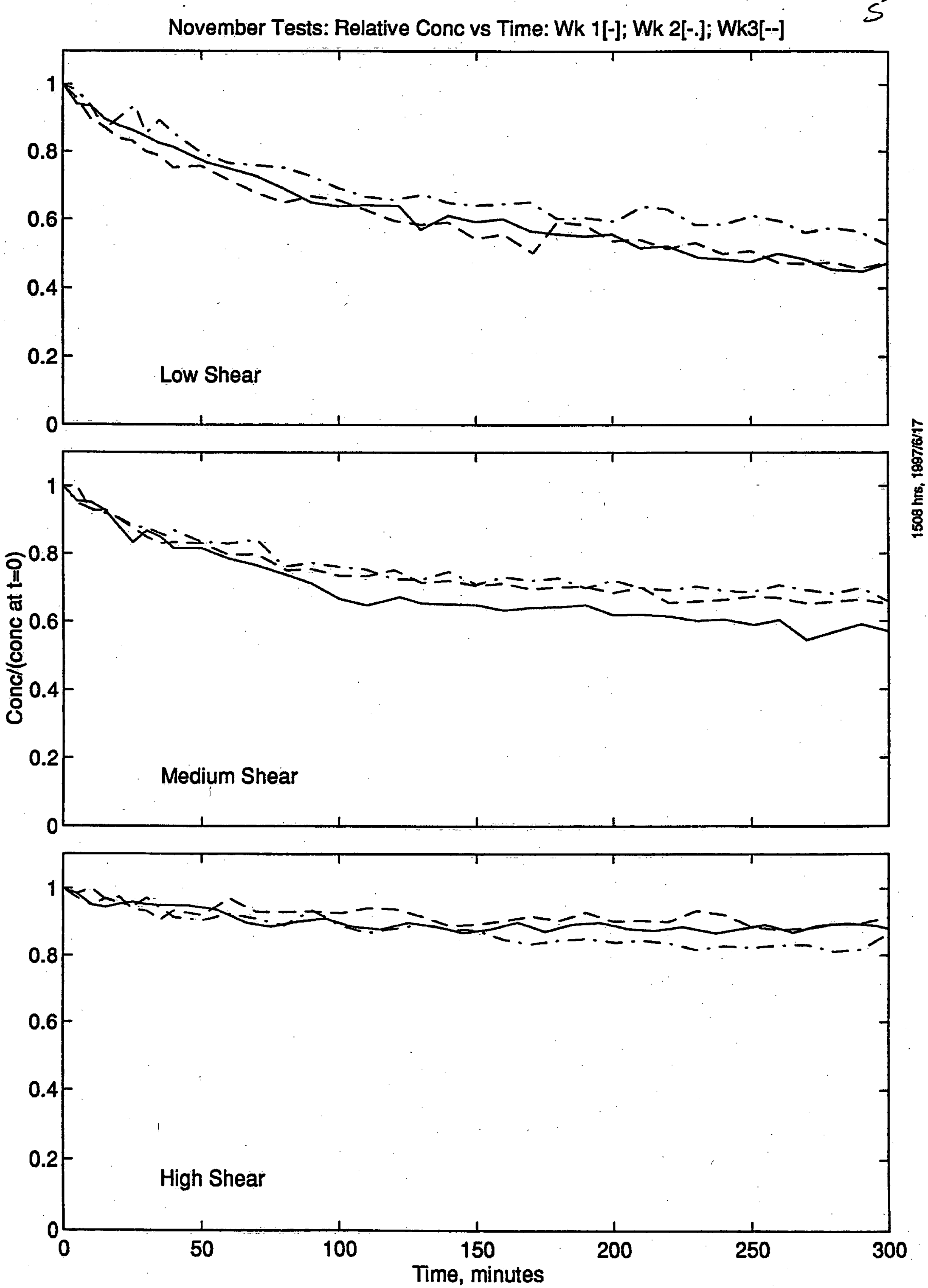
0.4
0.6
0.8
1
0
50
100
150
200
250
300
1507 hrs, 1997/6/17


November Tests: Relative Conc vs Time: Wk 1[-]; Wk 2[-.]; Wk3[--]
Low Shear
Medium Shear
High Shear
Conc/(conc at t=0)
Time, minutes
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
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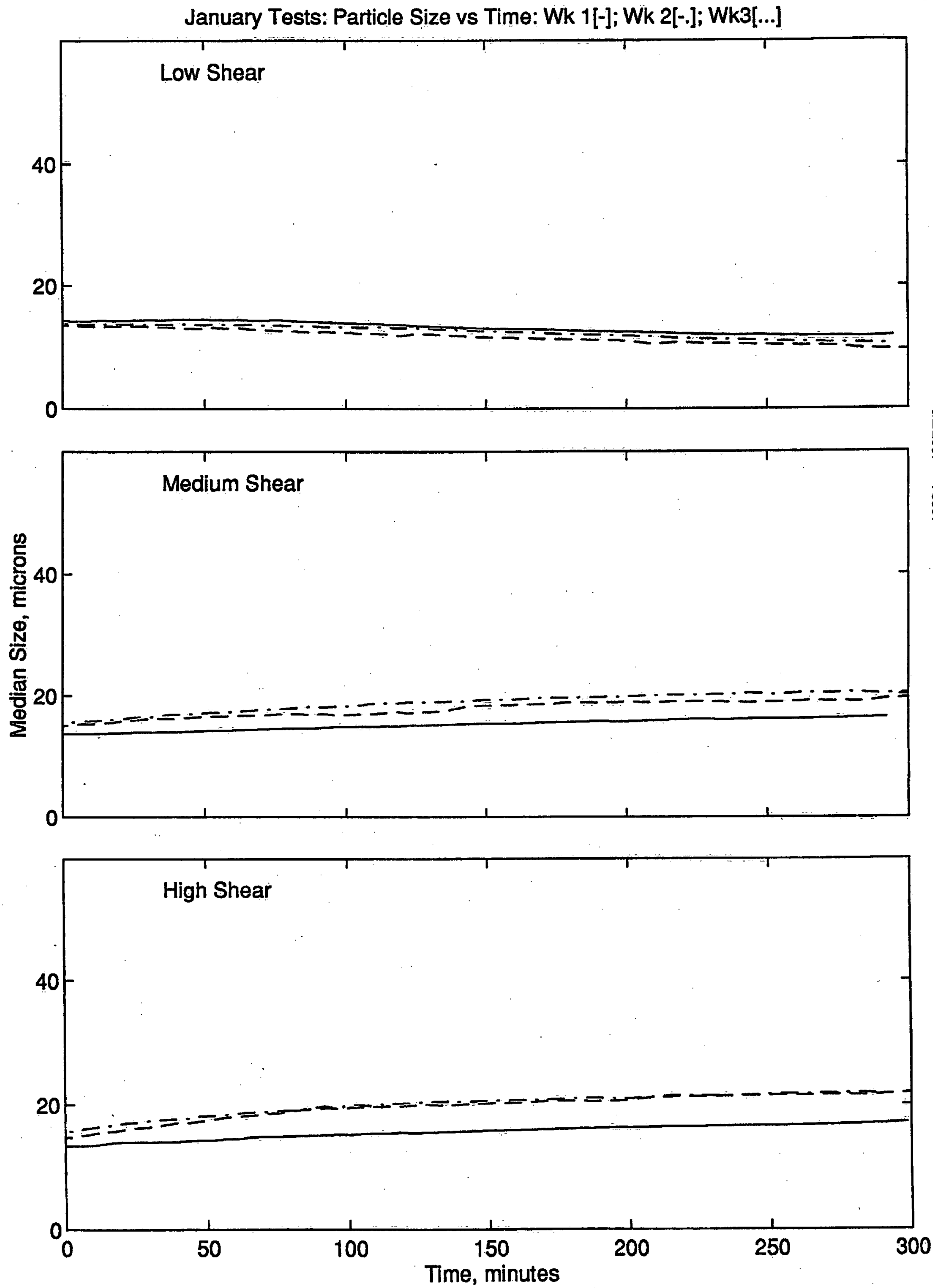

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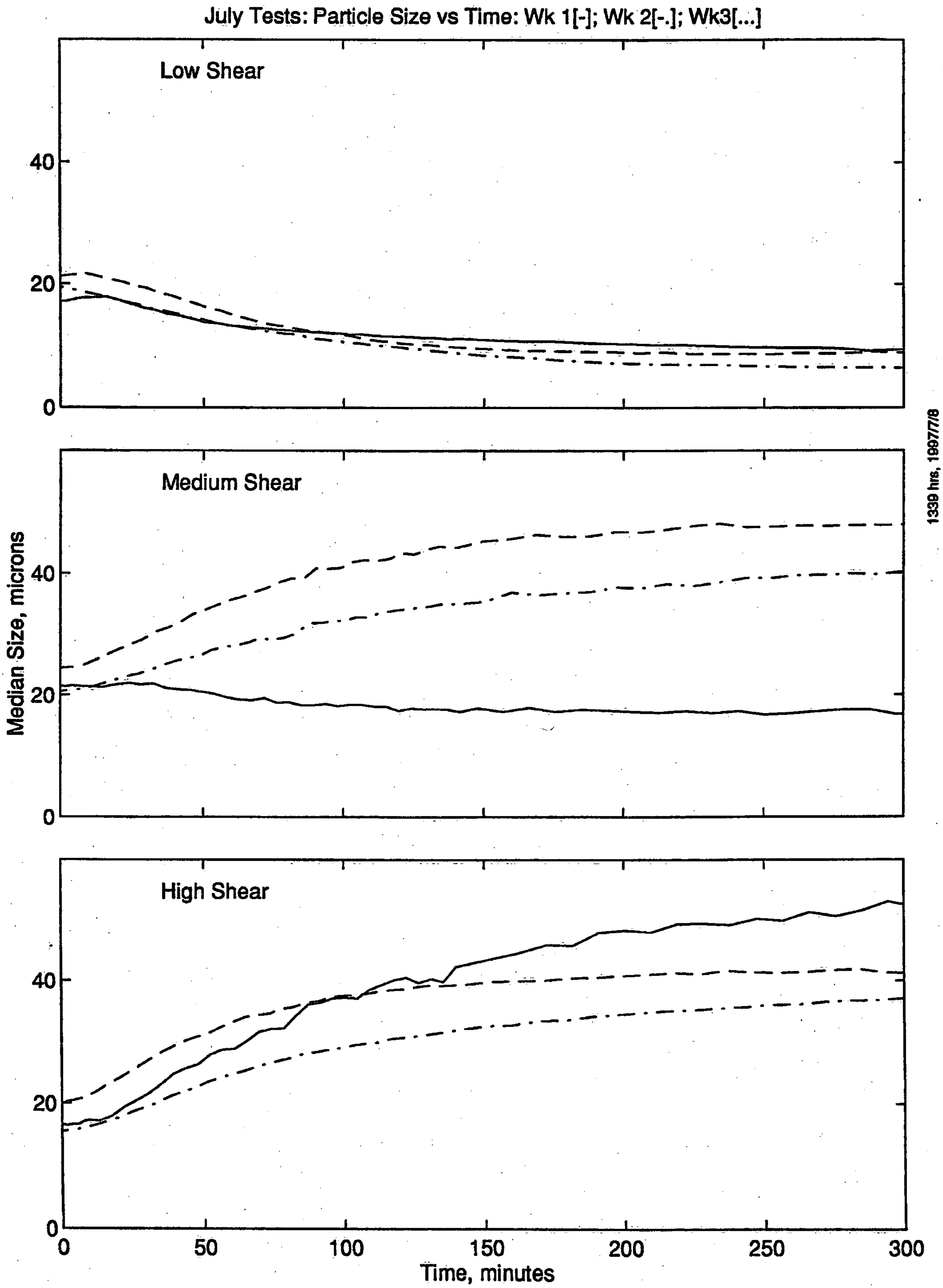
July Tests: Particle Size vs Time: Wk 1[-]; Wk 2[-.]; Wk3[...]
Low Shear
Medium Shear
High Shear
Median Size, microns
Time, minutes
0
20
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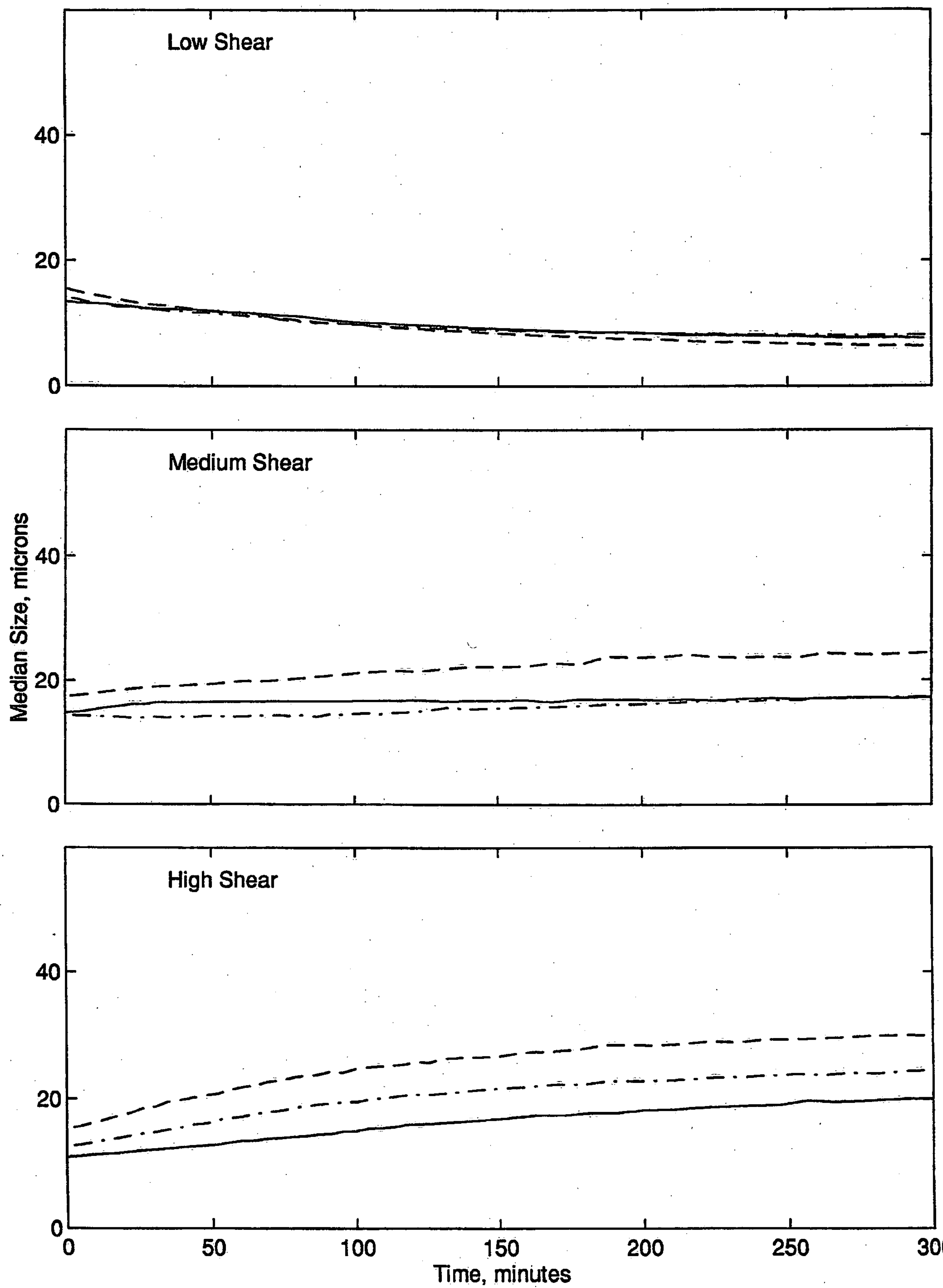
0
50
100
150
200
250
300
1339 hrs, 1997/7/8

November Tests: Particle Size vs Time: Wk 1[-]; Wk 2[-.]; Wk3[...]



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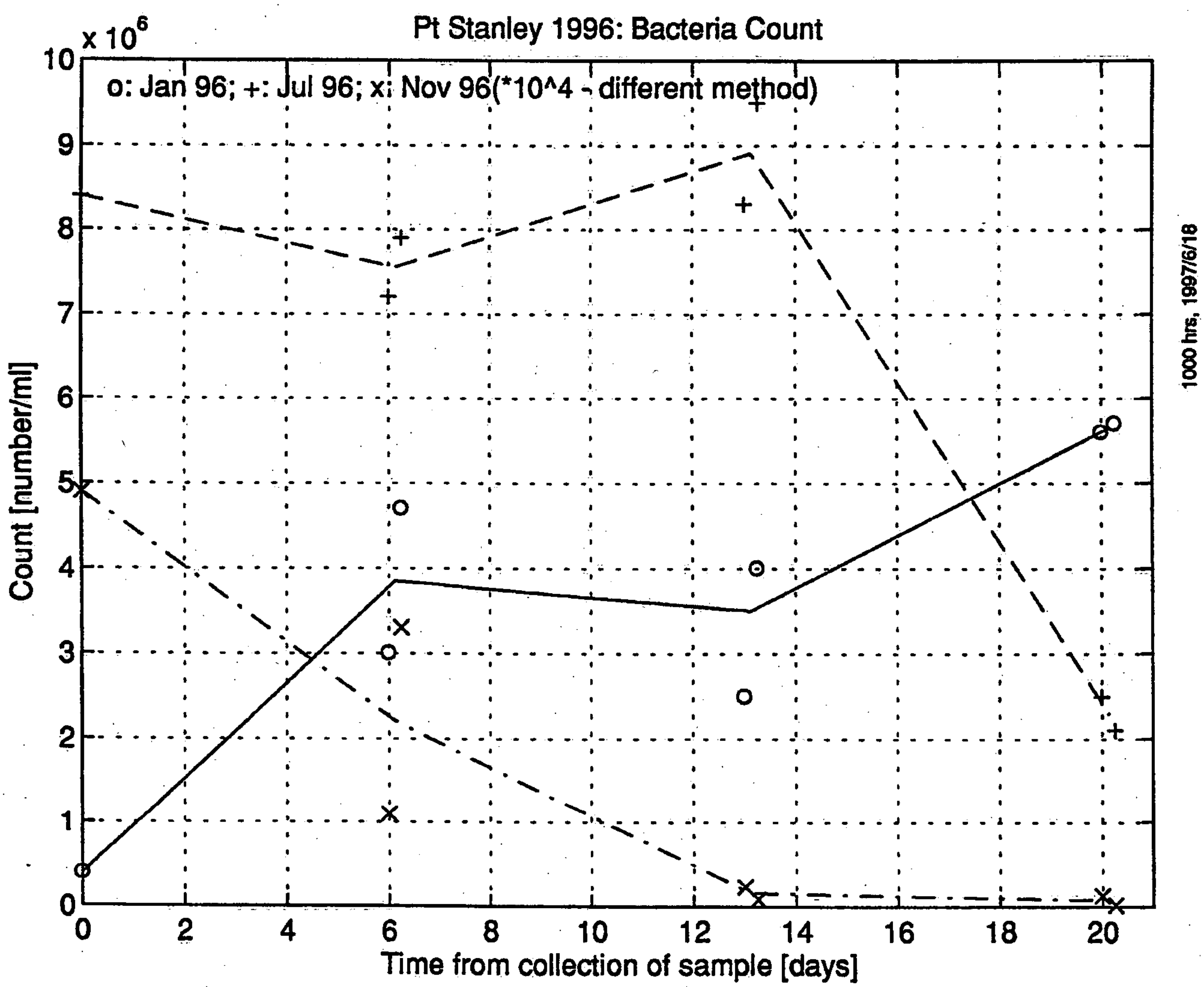
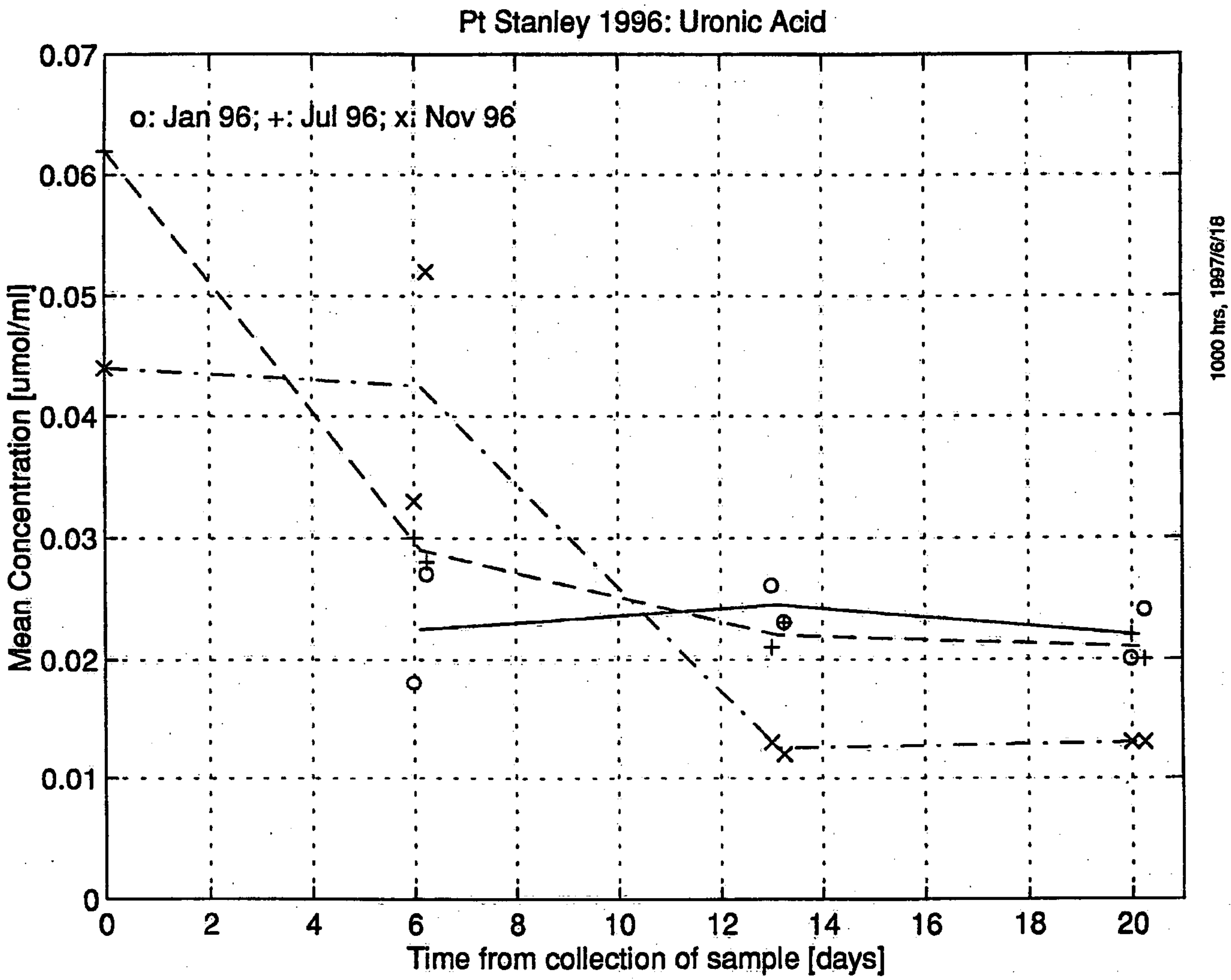

Pt Stanley 1996: Bacteria Count
x 10^6
o: Jan 96; +: Jul 96; x: Nov 96(*10^4 - different method)
Count [number/ml]
Time from collection of sample [days]
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16
18
20
1000 hrs, 1997/6/18


Pt Stanley 1996: Uronic Acid
o: Jan 96; +: Jul 96; x: Nov 96
Mean Concentration [umol/ml]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12
14
16
18
20
Time from collection of sample [days]
1000 hrs, 1997/6/18

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