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DISTRIBUTION CHARACTERISTICS OF <63µm SUSPENDED SEDIMENT IN SELECTED RIVERS

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MANAGEMENT PERSPECTIVE

Sampling for sediment associated nutrients and contaminants in rivers requires collection of suspended sediment samples. Sediment agencies typically collect through the vertical water column where as water quality agencies typically collect samples near the surface of the water column. This paper examines the distribution statistics of surface samples relative to samples taken through the vertical section. The objective is to provide an estimate of error associated with near-surface sampling of the silt and clay fractions of the suspended sediment load in rivers.

PERSPECTIVE GESTION

Pour échantillonner les nutriments et les contaminants associés aux sédiments fluviaux, il faut prélever des échantillons de sédiments en suspension. Ce prélèvement se fait normalement à diverses hauteurs dans la colonne d'eau, alors que l'échantillonnage d'eau pour analyse de sa qualité s'effectue près de la surface. Cet article porte sur la distribution statistique des matières dans les échantillons prélevés en surface par rapport à ceux recueillis à diverses profondeurs. Il vise à apprécier l'erreur causée dans l'évaluation des fractions de silt et d'argile dans la charge de sédiments en suspension par échantillonnage au voisinage de la surface des fleuves ou des rivières.

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ABSTRACT

The fine sediment (<63μm) fraction of the suspended sediment load is important for water quality purposes due to the high adsorptive capacity of these particles. Sampling of this size fraction usually assumes that a uniform vertical concentration gradient exists within this size fraction. This study includes an examination of the distribution statistics of the fine particle fraction through the vertical for six Canadian rivers; a significant difference between the observed distribution and a theoretically uniform distribution for the silt+clay fraction is noted. The distribution was more uniform for the clay fraction. The possible physical interpretation of these observations is discussed as well as the potential implications for sampling purposes.

Key words: suspended sediment, sediment chemistry, sampling theory, rivers, statistics.

RÉSUMÉ

La fraction des sédiments fins (< 63 µm) de la charge de sédiments en suspension est importante en matière de contrôle de la qualité de l'eau vu la grande capacité d'adsorption qu'ont ces particules. Généralement, ceux qui prélèvent des échantillons ayant ces dimensions le font en supposant qu'il existe à la verticale un gradient de concentration uniforme en fonction de la taille des sédiments. Cette étude inclut un examen de la distribution statistique de la fraction des particules fines à la verticale de six fleuves ou rivières du Canada. Pour la fraction silt/argile, on note une différence significative entre la distribution observée et la distribution uniforme supposée. La distribution est plus uniforme dans le cas de la fraction argile. L'interprétation physique qu'il est possible de faire de ces résultats fait l'objet d'une discussion de même que leurs conséquences en ce qui a trait à l'échantillonnage.

INTRODUCTION

The <63 µm fraction of the suspended sediment load in rivers is usually considered to be the most important for chemical transport purposes due to the high adsorptive capacity of this size fraction for trace metals and organic contaminants such as hydrophobic agricultural pesticides. Sampling of the fine particle fraction of the suspended sediment load has thus become an integral part of water quality monitoring and management strategies. However, in order for the importance of the fine particle fraction of the suspended load to be adequately represented, accurate sampling techniques must be used.

Conventional sampling techniques assume that a surface grab sample is representative of sediment concentrations throughout the entire depth of flow and that the fine sediment fraction (<63 µm) is evenly distributed through the full depth of the channel (Guy & Norman, 1970; Culbertson *et al*., 1972; Ongley *et al*., 1981; Ongley, 1982). Recent work by Ongley *et al*. (1990) noted that significant variations of the <63 µm fraction do occur within a vertical section although, for five of the six rivers they examined, the surface value fell within ± 15% of the vertical mean 89% of the time. However, this work has not examined the distribution statistics of the fine particle fraction which are required for sampling design purposes. It is the characteristics of this distribution through the vertical which forms the focus of this study.

For the purpose of this study, the fine particle fraction was defined purely on a size basis and no study was made of the variations in mineralogy and organic content within the <63 μm fraction. Also, while not discounting the chemical importance of the sand fraction in some rivers (eg. Horowitz, 1989), this study is concerned only with the silt + clay size fraction of the suspended load. Furthermore, this study focuses only on the physical characteristics of the distribution and omits any discussion of the distribution of the adsorbed chemicals within the <63 μm size range. Although Horowitz et al. (1989) have shown that the sediment distribution does not always reflect the sediment chemistry, the chemical issues fall outside the scope of this study.

OBJECTIVES

The principal objective of this study is to examine the concentration distribution of the fine particle fraction of the suspended sediment load through the vertical and to compare the observed distribution to that which could be theoretically predicted. Statistics are obtained for both the silt + clay and the clay fraction of the fine sediment load in order determine the relative importance of these two size fractions. These objectives facilitate a better understanding of the physical processes responsible for fine sediment transport in rivers and implicitly provide an assessment of the validity of current sampling methods for the fine sediment fraction.

SOURCES OF DATA

The data used in the study were obtained from updated sediment records of the Sediment Survey Section of the Water Survey of Canada and were taken from the same six stations as those used by Ongley et al. (1990) namely; the North Saskatchewan River at Prince Albert, the South Saskatchewan River at Highway 41, the Red River at Ste. Agathe, and the Fraser River at Hope, Mission and Marguerite. These sites were selected to reflect geographical diversity as well as number of verticals per section and the length of record available for these sites (Table 1, Figure 1). The data consist of point integrated sediment concentrations, collected using US P-61 and US P-63 samplers, for a series of several verticals at each sampling site. Data are available for high flow conditions only.

The samples obtained were sized according to the standard WSC practice of gravitational settling (bottom withdrawal) without chemical dispersion, and were rotated end over end prior to settling (Environment Canada, 1987). Destruction of flocs and the inclusion of stable aggregates of clay sized particles in the silt fraction could therefore be expected and may potentially bias the results.

THEORETICAL CONSIDERATIONS

The distribution of the fine particle fraction has been predicted theoretically. Ippen's equations (in Rouse, 1937) show that the vertical concentration gradient approaches uniformity for particles with very low settling velocities under highly turbulent conditions. Since fine sediment particles (<63 μm) have a low settling velocity and since the data for this study were collected at high flow conditions a relatively uniform vertical distribution could be theoretically expected in the rivers under study and a surface sample might be assumed to be representative of the vertical mean.

Assuming that deviation of the surface sample from the vertical mean is a random process, a frequency distribution of the deviations of the surface sample from the vertical mean could be expected to be normally distributed around a mean value of zero. In this case the probable error associated with a surface sample for a given river could be estimated from the standard deviation of the distribution. However, the theoretical distribution described by Ippen does not take into account the fact that the Von Karmen constant (k) varies with sediment concentration nor that flow in natural channels is often unsteady (i.e. varies with time).

METHODOLOGY

The data used in this study consisted of point integrated data recorded at approximately six different depths within each vertical. Five verticals were sampled at each station and sampling took place on one or two high flow days each year. At least five consecutive years of record are available for each station. For the purpose of this study the surface sample was considered to be the uppermost sampling location (maximum depth

0.3 m) and the sample obtained at the base of each vertical profile ("bed" sample) was discarded to ensure that only the suspended fraction of the sediment load was included in calculating the vertical mean. The mean concentration of both the silt + clay and the clay fraction was calculated for each vertical and the deviation of the "surface" sample of each vertical from the mean of the vertical was computed. Since Ongley et al. (1990) noted that in rivers with high silt + clay concentrations, large absolute deviations could be small in percentage terms, percent curves were also calculated. These deviations, combined over all dates and for all sampled verticals, were then plotted as frequency distributions for each of the six sampling locations. The theoretical distribution for the observed number of values was calculated using a theoretical mean value of 0 and a standard deviation equal to one quarter of the difference between the maximum and minimum observed values (to produce the most conservative estimate of standard deviation). A chi-squared test was used to compare the actual observations to the theoretical distribution.

The effect of discharge was examined by plotting the deviation of the surface sample from the vertical mean vs discharge for each of the rivers sampled. The correlation coefficient (r) of the relationship was then calculated.

The degree of cross sectional variability within the streams was examined by comparing the distribution of the deviation of the surface sample from the vertical mean for the deepest vertical to the same distribution over all sampling verticals. It was assumed that a significant difference between the two would indicate significant amounts of cross sectional variation. The comparison was made using a Wilcoxon rank sum test since this test does not assume that the two populations being compared have a normal distribution.

RESULTS

The frequency distributions of the observed deviations for each of the sampling sites and the summary statistics for each of these distributions (Figures 2-5, Table 2) show that, in general, the frequency distribution of the silt + clay fraction does not conform to the expected normal distribution. The chi-squared test comparing the observed distribution to the theoretically predicted one showed that the difference between the two distributions was significant (at p=0.05) for both the absolute and percentage curves. The mean values of absolute deviation for the silt + clay fraction range between -36.5 mg/1 for the North Saskatchewan River at Prince Albert and 1.0 mg/1 for the Fraser River at Marguerite. For the percentage deviation curves the mean value ranges between -10.2% for the Fraser River at Mission and 2.8% for the Fraser River at Marguerite.

As noted by Ongley et al. (1990) the curves of the clay fraction show a greater tendency for over-representation by the surface sample (i.e. positive mean values) compared to the silt + clay fraction. The mean value for the absolute deviation curves ranges between -5.2 mg/1 for the South Saskatchewan River at Highway 41 and 10.5 mg/1 for the Red River at Ste Agathe. The percentage deviation curves show a range of means from -2.1% for the Fraser River at Mission and 16.9% for the Fraser River at Hope. The curves for the clay fraction also show a closer approximation to the theoretically predicted curves with both the absolute and percentage curves for the Fraser River at Marguerite and Mission and the absolute deviation curve for the Red River at Ste. Agathe showing no significant deviation from the theoretically predicted distribution at the p=0.05 level. A p=0.05 level of significance was selected as a compromise between possible type I and type II errors.

The Wilcoxon rank sum test comparing the deepest vertical distribution of the silt + clay curve to the distribution over all sampled verticals showed that for the most part these two populations must be considered identical at the p=0.05 level. In the silt + clay fraction only the absolute curve of the Fraser River at Hope and the percentage curves of the North and South Saskatchewan rivers showed significant differences between the deepest vertical and all sampled verticals. In the clays fraction a significant difference was noted only for the absolute curves of the North Saskatchewan River at Prince Albert and the Fraser River and Marguerite.

The comparison of the amount of deviation of the surface sample from the vertical mean with discharge showed little relationship between the two. Plots of discharge vs deviation generally appeared random and correlation coefficients (r) were consistently less than 0.35.

DISCUSSION

The results suggest that several of the common assumptions about the movement of fine sediments in stream channels may not be valid. The most notable of these is the assumption that there is little or no vertical settling of the fine sediment fraction. The predominantly negative skewness and mean values for the silt + clay curves suggest that a surface sample generally underestimates the mean vertical concentration of the silt + clay fraction. This may be a result of settling of the silt fraction. Since, with the exception of the Red River, all of the rivers have significantly higher silt concentrations than clay concentrations (Table 1) the silt + clay curve could be expected to predominantly reflect the behaviour of the silt fraction.

The frequency distribution curves of the clay fraction more closely approximate a normal distribution than those of the silt + clay fraction. However, the distribution of the Red River (which, in contract to the other rivers, has higher clay than silt concentrations) does not have the most negative skewness value of the silt + clay distributions nor are all of the clay curves normally distributed. There may, therefore, be processes occurring within the clay fraction which cause the settling behaviour of this fraction to deviate from the theoretically predicted uniform vertical distribution. One such process may be flocculation of particles within the clay fraction. The sizing technique used by Environment Canada in analyzing suspended sediment samples involves shaking the sample prior to sizing which may break down flocs into smaller particles. These particles would then be considered to form part of the fine sediment fraction even though their settling behaviour in the river would more closely approximate that of coarser particles.

Flocculation was shown by Lee et al. (1981) and Migniot (1968) to be a function of mineralogy and total sediment concentration (since, if there are only infrequent collisions between particles, there will be little flocculation). Since no examination was made of the mineralogy of the samples this factor can not easily be examined. Figure 6 shows the relationship between the mean of the silt + clay distribution and the average total sediment concentration over the period of record for each of the rivers studied. The linear relationship suggests that there is greater under-representation of the vertical mean by the surface sample in rivers with relatively large total sediment concentrations. In addition the rivers with the lowest mean sediment concentrations are also those with the least negative values for the mean of the clay distribution. Flocculation may therefore be an important process affecting settling velocities. This process is not accounted for in Ippen's equation and thus could be expected to result in deviations from the theoretically predicted behaviour of the fine particle fraction.

The more consistent over-representation of the mean by the surface sample in the clay than in the silt + clay fraction raises questions about the source of the clay fraction. Over-representation by the surface sample may indicate that the clay fraction is introduced into the stream from the surface. This may be produced by bank collapse which occurs in most prairie streams. Another possible source for fine sediment at the surface is upwelling of fine sediment as a result of boils and vortices. These boils are produced by the vortex created behind large particles on the stream bed as a result of the shear stress of the flowing water on the particle. The subsequent upwelling can bring large quantities of fine sediment up from the bed of the channel to the surface (Desloges, personal communication). Since the predominant bed material in all of these channels is sand sized or coarser if this mechanism is responsible for the higher surface concentrations of clay it would suggest significant fine storage on the bed of the channel as suggested by Jobson & Carey (1989).

The results of this study tend to support Horowitz et al.'s (1989) observation of an even distribution of fine sediment through the cross section in the Cowlitz and Arkansas rivers. The deepest vertical data and the data for all verticals appear to come from the same population at most of the study sites suggesting that there is no significant cross sectional variation in the distribution of the fine sediment fraction (<63 µm) in the rivers under study.

It is also noteworthy that extreme values for the mean for the silt + clay fraction (i.e. deviation from the vertical mean) do not correspond to the same sites as extreme values for the mean for the clay fraction. This may suggest that different processes occur in each of these size fraction. This may be the result of a difference in source, settling velocity and degree of flocculation between the two size fractions as noted earlier. It is also possible that turbulence within the stream affects the two size fractions differently. Turbulence within the water column is accounted for in Ippen's equation by the v. term which will be proportionately more important in contributing to a uniform distribution in the silt fraction than in the clay fraction since the settling velocity, w, of the silt fraction is larger. Turbulence will therefore not necessarily have an equal influence on the clay as on the silt + clay fraction.

CONCLUSIONS AND IMPLICATIONS FOR SAMPLING STRATEGY

These observations may have significant implications for fine sediment sampling for chemical and ecotoxicology purposes since they call into question many of the assumptions upon which these sampling protocols are based. Conventional water quality sampling techniques assume that concentrations of the <63 µm fraction are evenly distributed through the vertical and that one position in the cross section can be used to characterize the entire width of flow.

The observation that there is generally little significant cross sectional variability would suggest that sampling from the centroid of flow may be a valid technique at least at the high flow conditions represented in our data. However, the significant deviations within the vertical suggest that significant error may be associated with a dip sample especially for the silt + clay fraction. The negative skewness of most of the silt + clay fraction curves suggests that a surface dip sample will likely under-represent the vertical mean. This is in agreement with the observations of Lapointe et al. (1989) who noted an approximately 12% negative bias between dip samples and depth integrated samples from the same site. The more normal distribution of deviations of the surface sample from the vertical mean in the clay fraction suggests that the dip sample may provide a more representative sample in this size fraction. A few of the silt + clay curves also exhibited mean values near zero and thus a dip sample may provide a representative sample of the silt + clay fraction when averaged over many samples. However, at any specific date significant error may be associated with a dip sample. Since the distributions are not normally distributed it is not possible to assign a standard $\pm$ error to the surface sample. Also since the distributions are not uniform between rivers it is not possible to apply a standard transformation to all rivers. As a result it is not possible to assign an error limit to a dip sample.

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Table 1 - Study Site Information

Station	Period of Record	# of records	Usual # of verticals	Total of verticals	Drainage Area (km)	Max. Section Width (m)	Suspended Sediment Concentration - All data - Clay Min	Clay Max	Silt Min	Silt Max	Silt+Clay Min	Silt+Clay Max	Bed Material	Depth of Deepest Vertical Max	Depth of Deepest Vertical Min	Estimated Froude Number
Red River at Ste Agathe	1962-76	11	5	53	117000	91.4	125	796	19	421	294	1158	sand	3.75	12.89	0.116
S. Sask. R. at Hwy 41	1966-71	9	5	45	66000	140.2	134	1125	82	2003	233	2981	sand	3.96	6.83	0.212
N. Sask. R. at Prince Albert	1963-84	17	5	85	131000	189.9	12	626	139	1317	267	1640	sand	2.53	5.64	0.197
Fraser River at Marguerite	1971-84	12	5	60	114000	155.4	13	183	89	581	120	750	gravel	4.88	11.28	0.378
Fraser River at Hope	1967-78	16	6	93	217000	473.9*	8	211	48	588	79	723	gravel	13.96	22.19	0.062
Fraser River at Mission	1965-84	20	5	100	228000	365.8	12	201	41	596	59	768	sand	10.94	18.56	0.122

after: Ongley et al. 1990

Table 2 - Summary Statistics

Station	Curve of	Mean	Standard Deviation	Skewness
Silt + Clay				
Fraser River at Mission	Absolute	-30.41	30.46	-0.19
	Percent	-10.22	8.14	-0.04
N. Sask. R. at Prince Albert	Absolute	-36.48	129.73	-4.14
	Percent	-0.15	0.7	-6.38
Red River at Ste Agathe	Absolute	-8.02	73.82	-5.62
	Percent	-1.54	12.97	-5.47
Fraser River at Hope	Absolute	0	n.a.	-1.46
	Percent	1.49	n.a.	3.58
Fraser River at Marguerite	Absolute	1.04	27.79	2.65
	Percent	2.77	27.79	0.29
S. Sask. R. at Hwy 41	Absolute	-32.16	117.97	0.46
	Percent	1.26	32.76	1.04
Clay Fraction				
Fraser River at Mission	Absolute	-1.92	13.6	0.01
	Percent	-2.06	25.12	0.13
N. Sask. R. at Prince Albert	Absolute	-2.36	27.13	-2.13
	Percent	0.39	16.14	2.84
Red River at Ste Agathe	Absolute	10.47	40.5	1.03
	Percent	2.87	13.8	2.13
Fraser River at Hope	Absolute	0.31	1.89	1.53
	Percent	16.89	86.26	4.76
Fraser River at Marguerite	Absolute	-1.27	22.78	0.11
	Percent	-0.51	32.2	0.13
S. Sask. R. at Hwy 41	Absolute	-5.24	32.56	-0.19
	Percent	0.65	23.94	0.24

Figure 1 - Map showing study sites

Figure 2 - Frequency distribution of percentage deviation of the surface sample from the vertical mean - silt+clay fraction

Figure 3 - Frequency distribution of absolute deviation (mg l^{-1}) of the surface sample from the vertical mean - clay fraction only

Figure 4 - Frequency distribution of percentage deviation of surface sample from the vertical mean - Clay fraction only

Figure 5 - Frequency distribution of absolute deviation of the surface sample from the vertical mean - silt+clay fraction

Figure 6 - Deviation of the surface "silt+clay" sample from the vertical mean ns average total sediment concentration averaged over all rivers and sampling dates

Figure 1 - Map showing study sites

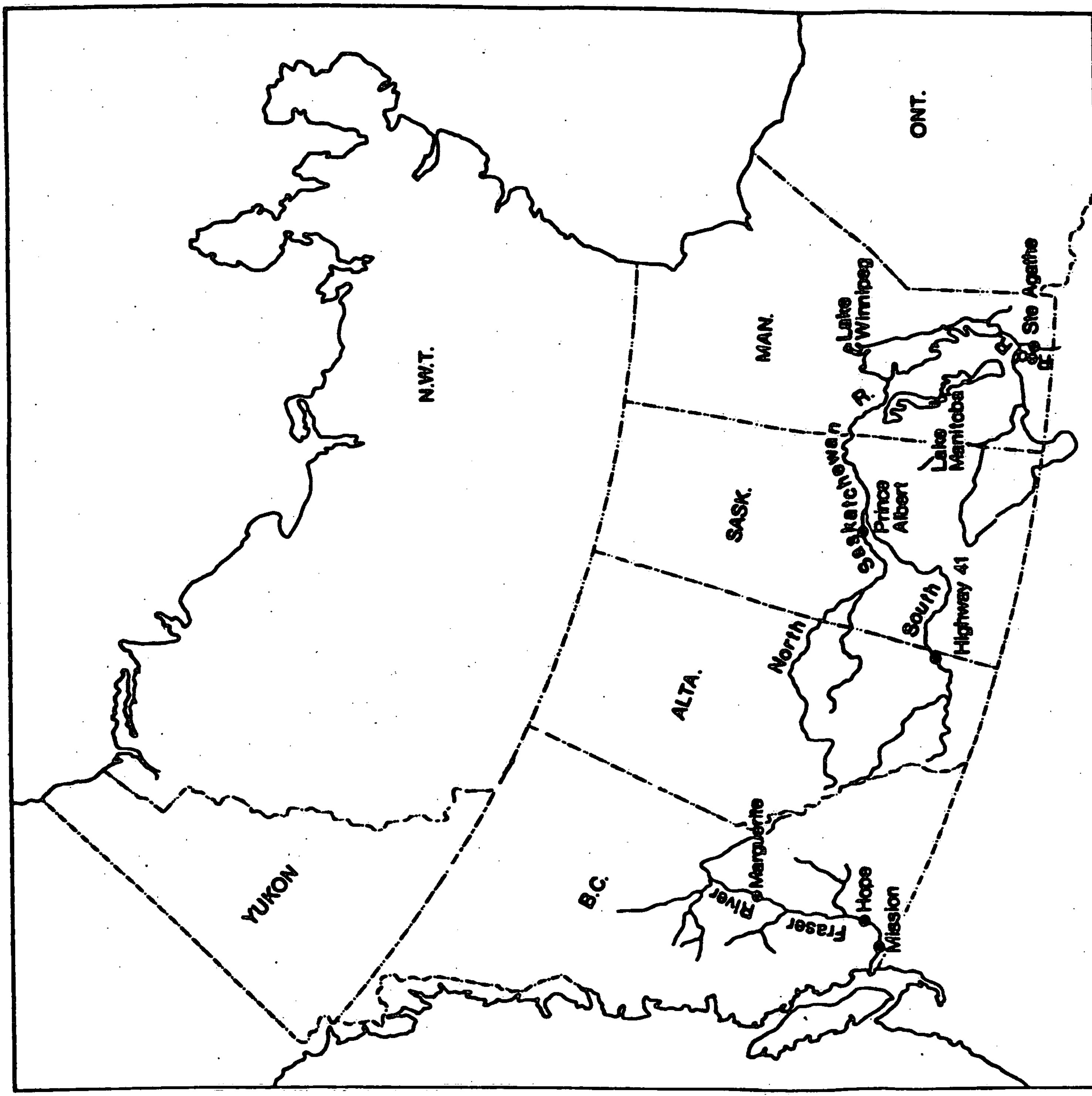


Figure 2 - Frequency distribution of percentage deviation of the surface sample from the vertical mean - silt + clay fraction

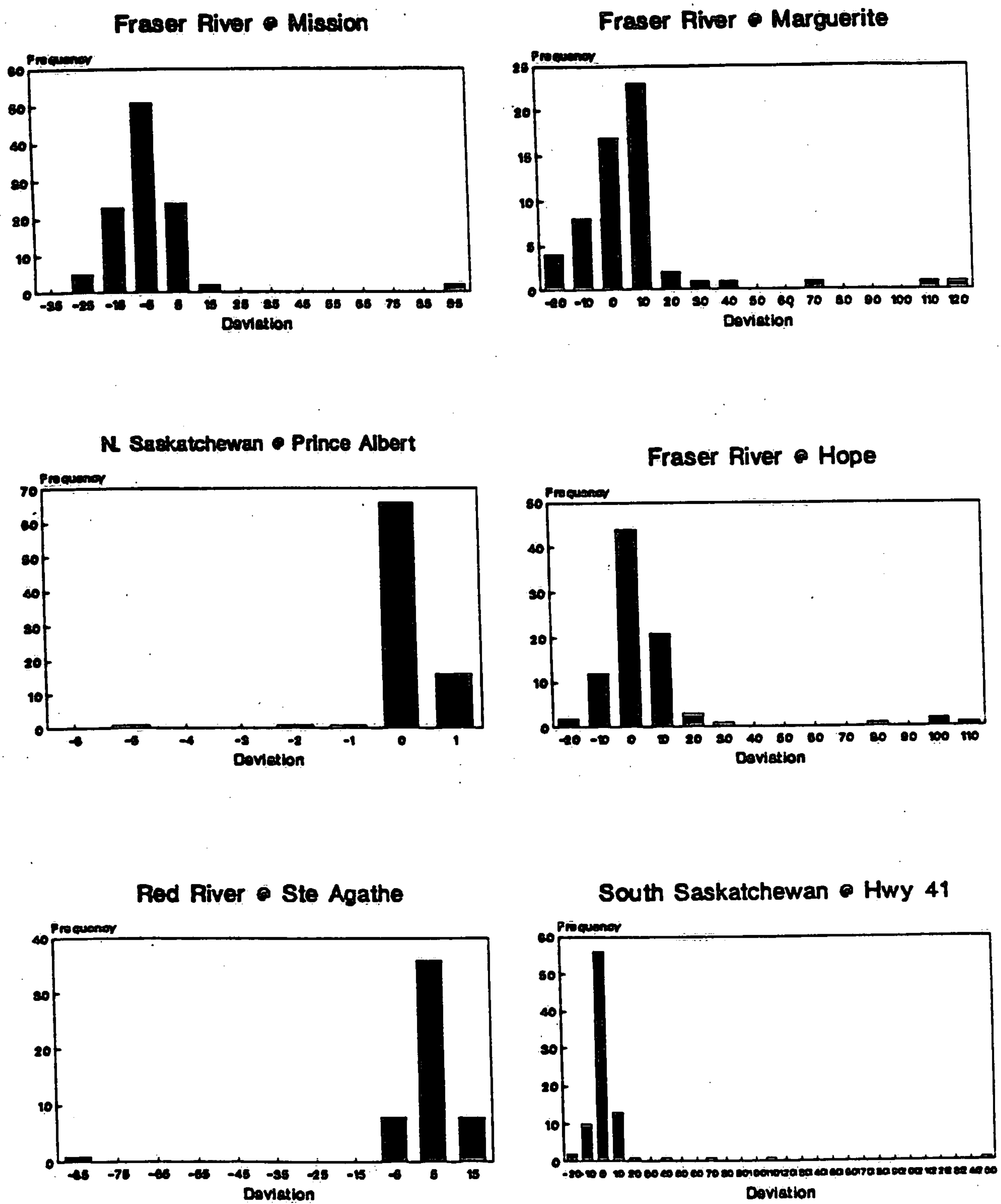


Figure 3 - Frequency distribution of absolute deviation of the surface sample from the vertical mean - clay fraction only

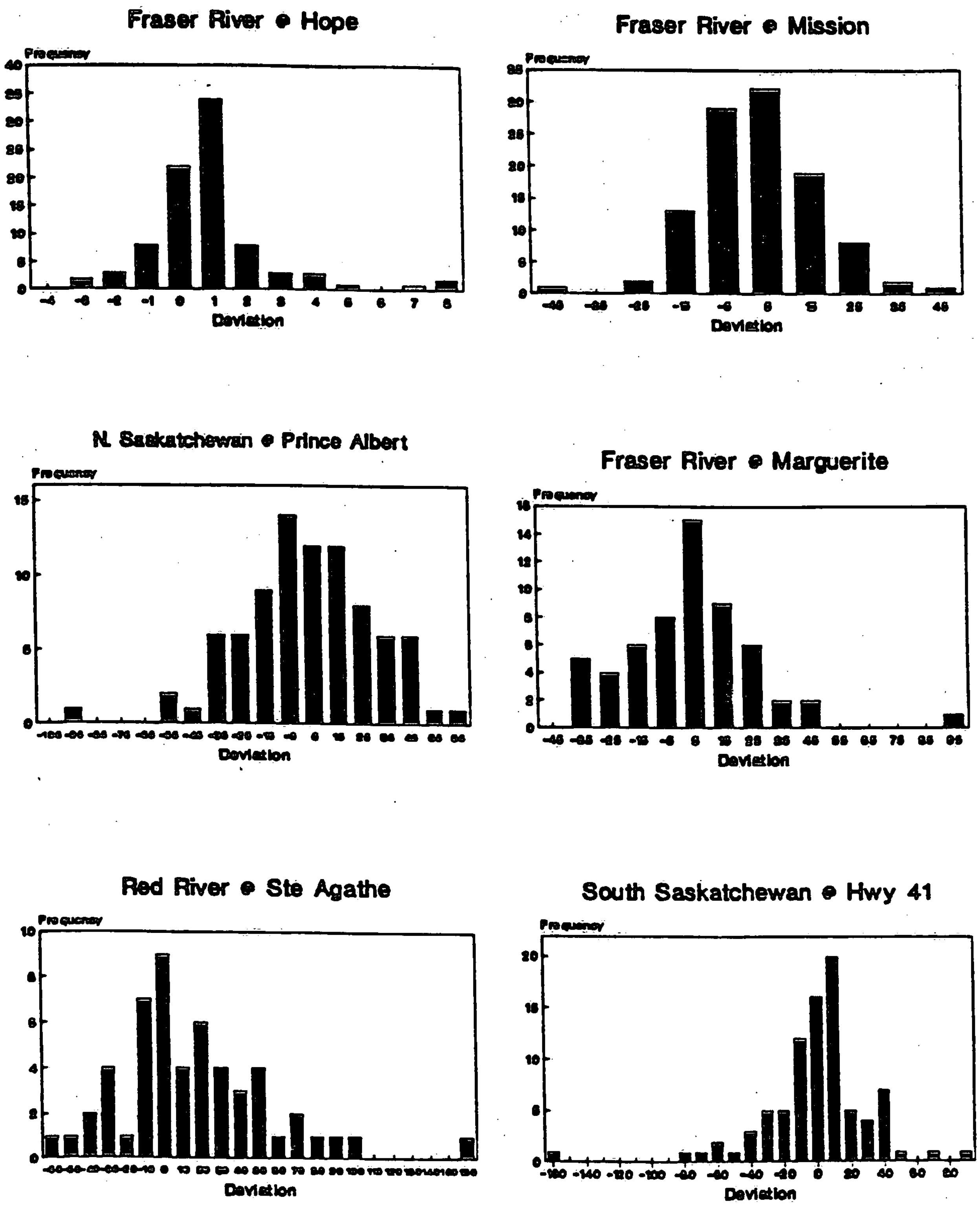


Figure 4 - Frequency distribution of percentage deviation of surface sample from the vertical mean - Clay fraction only

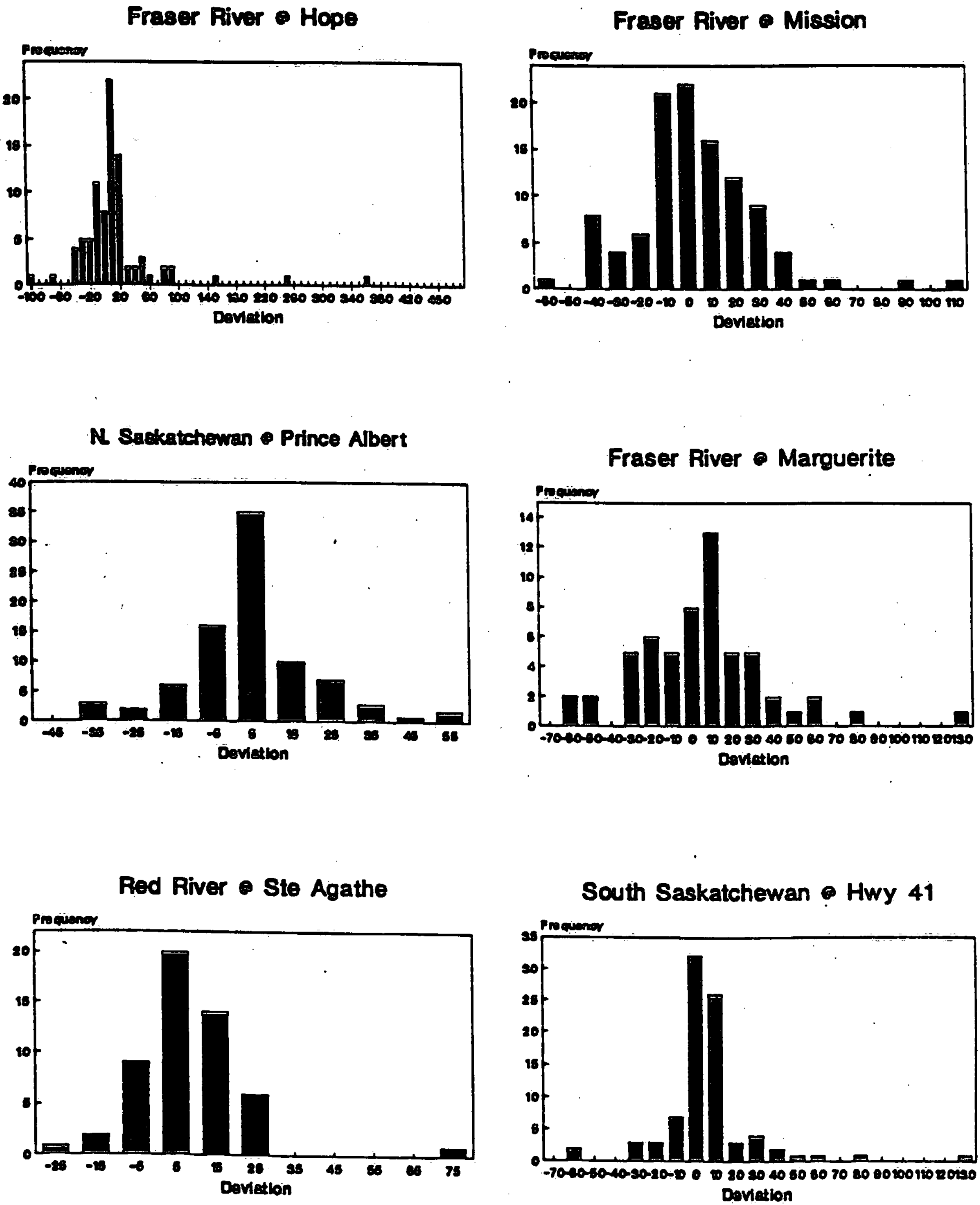


Figure 5 - Frequency distribution of absolute deviation of the surface sample from the vertical mean - silt + clay fraction

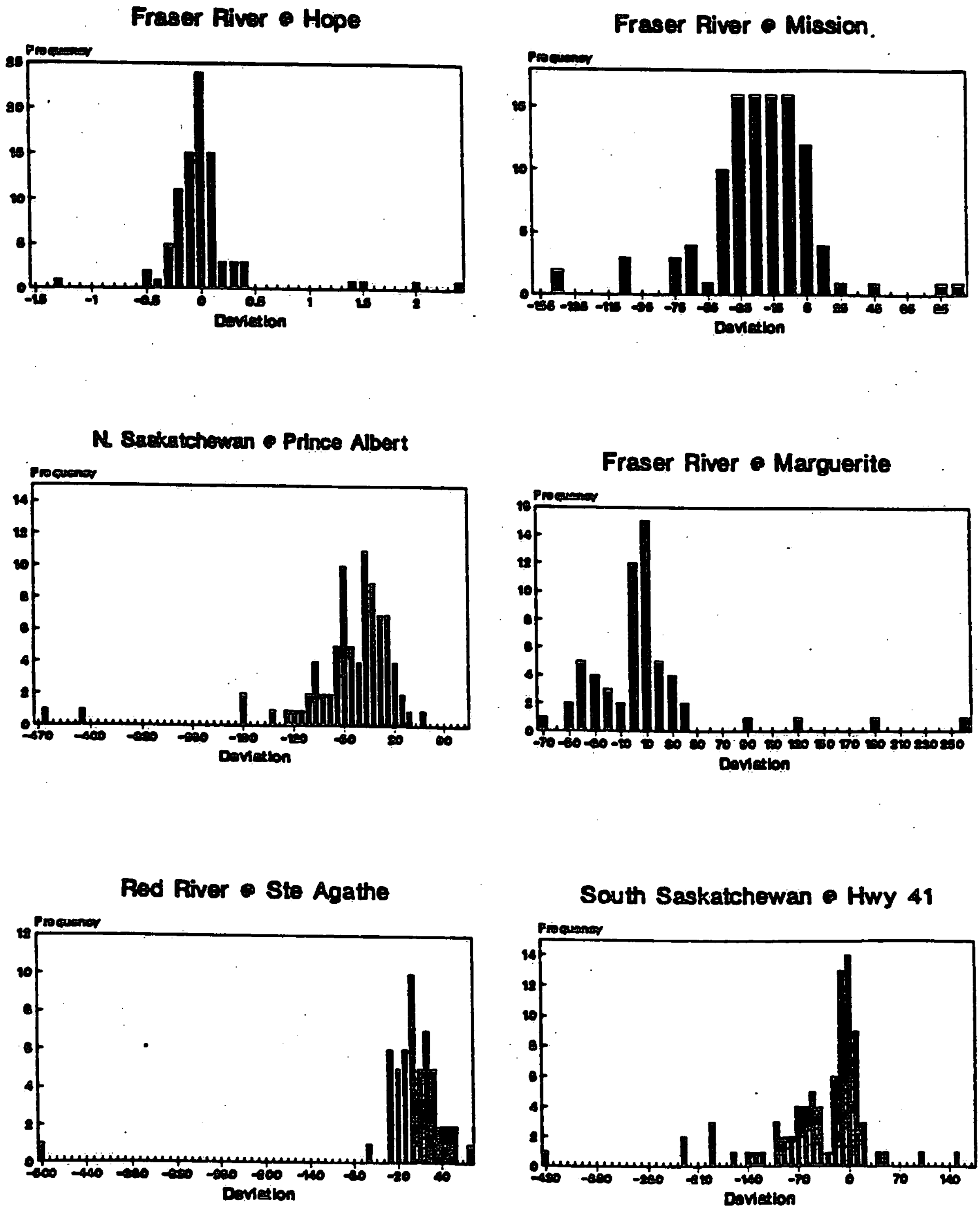
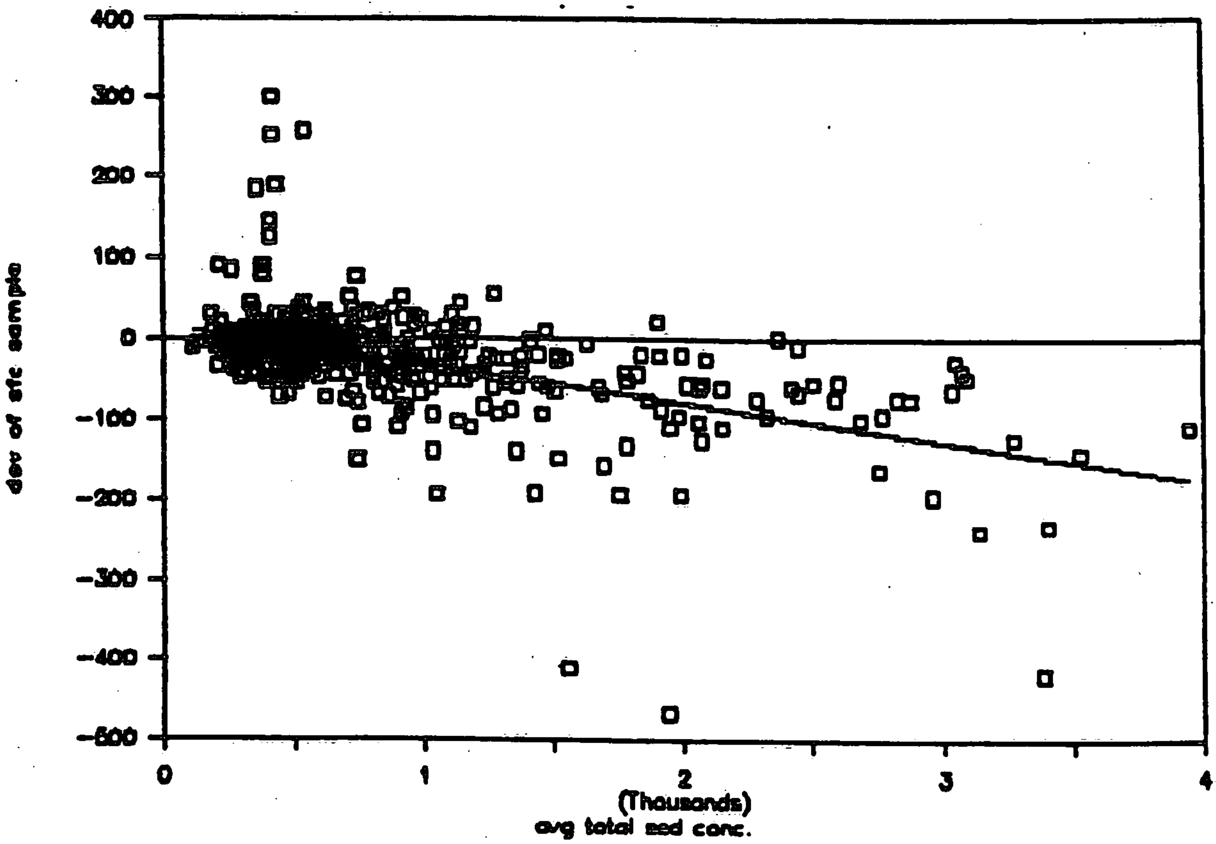


Figure 6 - Deviation of the surface silt+clay sample from the vertical mean vs average total sediment concentration averaged over all rivers and sampling dates

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all rivers
               Regression Output:
Constant                            -9.52791
Std Err of Y Est                    27.74975
R Squared                           0.020473
No. of Observations                       52
Degrees of Freedom                        50

X Coefficient(s)   0.019983
Std Err of Coef.   0.019547
```

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