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Quantitative Mineralogy of the Yukon River System: Variations with Reach and Season, and Sediment Source Unmixing

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ABSTRACT

The mineralogy of Yukon River basin sediment was studied by quantitative X-ray diffraction. Both bottom sediments and suspended sediments were analyzed using the RockJock computer program. The bottom sediments were collected from the main stem and from selected tributaries during a single trip down river, from Whitehorse to the Yukon delta, during the summer of 2001. Suspended sediments were collected at three stations on the Yukon River and from a single station on the Tanana River at several times during the summer of 2002.

Changes in mineralogy of Yukon River bottom sediment are mostly related to sediment dilution or concentration effects from tributary sediment, and very little chemical weathering is indicated. Carbonate minerals compose about 2 weight percent of the sediment near Whitehorse, but increase to 14 percent with the entry of the White River tributary above Dawson. Thereafter, the proportion of carbonate minerals decreases downstream to a value of about 1 percent near the mouth for the Yukon River. Quartz and feldspar contents of bottom sediments vary greatly with the introduction of Pelly River and White River sediment, but thereafter either increase irregularly (quartz from 20 to about 50 percent) or remain relatively constant (feldspar at about 35 percent) with distance downstream. Clay content increases irregularly downstream from about 15 to about 30 percent. The chief clay mineral is chlorite, followed by illite + smectite, and little to no kaolinite. The total organic carbon content of the bottom sediments remains relatively constant with distance for the main stem (1 to 2 percent), but fluctuates greatly for the tributaries.

The mineralogies of the suspended sediments change with the season. For example, the quartz content varies by 20 percent, with a minimum in mid-summer. Calcite content varies by a similar amount, and has a maximum corresponding to the quartz minimum. These modes are related to the relative amount of sediment flowing from the White River system, which is relatively poor in quartz, but rich in carbonate minerals. Suspended feldspar is relatively constant at most stations throughout the collecting season, but total clays vary by as much as 25 percent.

A calculation technique was developed to determine the proportion of various sediment sources in a mixed sediment by unmixing its quantitative mineralogy. Results from this method indicate that at least three sediment sources can be unmixed quantitatively. With this technique, the mineralogies of bottom sediments can be used to calculate the relative flux of suspended sediment from different tributaries, thereby identifying the provenance of suspended sediments.

INTRODUCTION

The Yukon River basin, the fourth largest in North America, drains an area of about 855,000 km^2 and has a total length of over 3000 km [for an excellent overview of the Yukon system, see Brabets et al. (2000)]. The river begins in northern British Columbia and flows in a northwesterly direction into Alaska, where it turns near the entry of the Porcupine River to flow generally southwest to outlet in the Bering Sea. The mean annual sediment discharge into the Bering Sea is about 55 million metric tons, most of which is deposited in the summer months. About 18 million metric tons are deposited annually on flood plains. The Yukon River has several large tributaries (Fig.1), but just two tributaries contribute the largest amounts of sediment (Table 1): the White River, and its tributary the Donjek, carry sediment from the glaciated Wrangell-St. Elias Mountains to the south, and the Tanana River drains the glaciated Alaska Range to the southeast. Three other sources contribute significant amounts (>1,000,000 metric tons annually) of sediment to the Yukon River, the Pelly River, the Porcupine River and the Koyukuk River. Many tributary basins, such as the Porcupine and the Koyukuk, are underlain by continuous permafrost (see Table 5 in Brabets et al. 2000).

The U. S. Geological Survey (USGS) initiated a project to study the Yukon River system in 2001 as a part of the National Stream Quality Accounting Network (NASQAN) program (http://water.usgs.gov/nasqan). The project will establish baseline values for water quality in the basin in order to detect changes that may occur during possible melting of permafrost in response to climate change. As a part of this project, five stations in Alaska (at Eagle, Stevens Village and Pilot Station on the Yukon River, with other stations on the Porcupine River and at Nenana on the Tanana River) were established to sample water and suspended sediment at intervals during the summer months. In addition, river sediments were sampled by two USGS volunteers in the summer of 2001 during a kayaking trip from the city of Whitehorse (Yukon Territory, Canada) to the Bering Sea. They collected 50 samples, here termed bottom sediments, from sandbars and beaches from the main stem of the Yukon River and its tributaries. This paper studies the quantitative mineralogy of the suspended and bottom sediments to learn how mineralogy may change during transport in a long river system, how main stem mineralogy is influenced by tributaries, and how the mineralogy of suspended sediment may change with the season. In addition, a method is developed for modeling sediment flux in the system by quantitatively unmixing sediment sources from mixed sediments.

METHODS

Suspended sediment (Table 2) was collected during the 2002 season according to standard USGS protocols. The methods described by Edwards and Glysson (1988) were used for the collection of flow-integrated samples at all stations. A minimum of two-person field teams collected samples to reduce the opportunity for contamination of low-concentration analytes, following the protocols of Horowitz et al. (1994). The suspended samples were processed according to established USGS protocols (USGS 1997-99). The bottom sediments (Table 3) were collected from river bars and beaches below the waterline. They were dried, and then passed through a 500 micrometer sieve, recovering almost all of the sample except for some pebbles collected from the upper reaches of the Yukon River near Whitehorse.

Quantitative mineralogy was determined by X-ray diffraction (XRD) for both sets of samples. The samples were prepared for analysis according to the methods described by Srodon et al. (2001). Briefly described here, 3 g of sample was mixed with 0.333 g of an internal standard (zincite). The mixture then was ground with 4 mL of methanol in a McCrone mill for 5 minutes, oven dried at 85 degrees C, passed through a 4 mm sieve, and then side loaded by tapping into an aluminum holder. Samples were X-rayed from 5 to 65 degrees two theta with Cu K-alpha radiation (40 kV, 30 mA) using a Siemens D500 X-ray diffraction system with a graphite monochromator, 1 degree slits, a step size of 0.02 degrees two theta, and a counting time of 2 seconds per step.

The XRD data were converted into weight percent minerals using the RockJock computer program (Eberl 2003). Briefly, the program compares integrated X-ray intensities for minerals present in a sample with that of an internal standard (zincite), and weight percents are calculated from previously measured mineral intensity factors (MIFs; also termed reference intensity ratios, RIRs). Integrated X-ray intensities for individual minerals were determined by fitting stored XRD patterns for pure minerals to the measured XRD pattern by using the Solver option in Microsoft Excel. The Solver minimized the degree of fit parameter between measured and calculated patterns by varying the intensities of the stored standard patterns by multiplying each of these patterns by a separate factor. This analysis was carried out in two regions of the XRD pattern, 20 to 65 degrees two theta for non-clay analysis, and 58 to 65 degrees two theta for clay analysis. The RockJock technique has been checked for accuracy using artificial mixtures, and generally gives answers that are within one or two weight percent of actual values (Eberl 2002). A sum for an analysis that is close to 100 percent is a further check because weight percents for each mineral are calculated independently with respect to the zincite internal standard. All samples were analyzed for the same mineral suite, and three examples of bottom sample analyses are given in Table 4. The complete data set and the RockJock program are available at ftp://brrcrftp.cr.usgs.gov/pub/ddeberl/ .

The results of carbonate mineral (calcite + Mg-calcite + dolomite) quantitative XRD analyses were checked using a carbon analyzer, with good results (Fig. 2; correlation coefficient $r^2 = 0.92$). In this method, total inorganic carbon (TIC) was determined by acidification (CM5130 Acidification Module) and measurement of CO_2 contained in the gas stream. The weight percent calcite was calculated by multiplying TIC by 8.3333.

Some of the discrepancy between the two methods (Fig. 2) results from attributing all of the carbonate from the carbon analyzer determinations to the mineral calcite, whereas, on average, most samples contain about 1.4 times as much calcite as dolomite. Total carbon (TC) was determined by combustion using a CM5120 Furnace Apparatus. The weight percent total organic carbon (TOC) was calculated using the equation: TOC = (TC-TIC) x 1.724.

Sediment mineralogy was unmixed quantitatively using the MinUnMix program (available at the ftp site given above). This procedure quantitatively determines the fractions of component sediments in a mixture. For example, quantitative mineralogy was measured for bottom sediments collected from the Yukon River and a tributary above their confluence, and from sediment collected below the confluence. The weight percent of each mineral in the upstream Yukon sediment was multiplied by a factor (f), and that in the tributary was multiplied by a second factor (g). The factors were constrained to be positive, and to sum to unity. The amounts of each mineral in the upstream samples then were summed, and the sums were compared to the measured mineralogy of the downstream Yukon sediment by having the Solver option in Excel minimize a degree of fit parameter between the measured and calculated quantitative mineralogy by varying the factors. The degree of fit is defined as the sum of absolute value of the difference in weight percents between the measured and calculated mineralogy, divided by the sum of the weight percent of the measured mineralogy. The method was extended to unmix from 2 to 5 sediment sources.

Illite crystallite thicknesses were measured by Fourier analysis of 001 X-ray diffraction peak shape according to the Bertaut-Warren-Averbach peak broadening method

(Drits et al. 1998) using the MudMaster computer program (Eberl et al. 1996). Samples were treated with the polymer polyvinylpyrrolidone (PVP-10) to remove swelling from the illite particles prior to XRD analysis (Eberl et. al. 1998).

RESULTS AND DISCUSSION

Bottom sediments

The weight percents of the major minerals in the bottom sediments are plotted against distance from Whitehorse. The carbonates near Whitehorse are about 2 weight percent of the sediment (Fig. 3A). With the entry of the White River tributary at 493 km this value jumps to approximately 14 percent. The White River itself carries about 14 percent carbonate sediment, indicating that the sudden increase in Yukon carbonate is related to mixing with sediment from this tributary. Thereafter, the total carbonate in the Yukon sediments drops quickly to about to about 10 percent, after which the carbonate content remains approximately constant at 10 percent with distance downstream until the Tanana River, which carries about 3 percent carbonate, enters the Yukon River at 1851 km. Here the carbonate content of the Yukon sediment decreases by half. Beyond the Tanana confluence, the calcite content varies between 1 and 7 percent, finally finishing with a value at Pilot Station that is nearly the same as its initial value at Whitehorse. The percentages of calcite and dolomite roughly track each other throughout the course of the river (Fig. 3B).

Quartz (Fig. 4) starts at a value of about 35 percent near Whitehorse, suddenly increases to 65 percent when the Pelly River enters, and then decreases to about 20 percent with the entry of the White River. Throughout the rest of the reach, the quartz content gradually increases to a value of about 50 percent at Pilot Station.

Feldspar initially has the opposite trend from quartz (Fig. 5A), starting at about 45 percent, then decreasing to 15 percent with the entry of the Pelly River, and then increasing again to about 45 percent with the confluence of the White River. Thereafter feldspar stays roughly constant between 30 and 40 percent. The sediment generally contains about twice as much plagioclase as alkali feldspar (Fig. 5B).

Total clays (Fig. 6A) start at about 15 percent, and increase irregularly downstream, ending at about 27 percent at Pilot station. The clays are dominated by chlorite, with subordinate (illite + smectite), and very little kaolinite (Fig. 6B). The lack of kaolinite is expected for an arctic region where weathering is mostly mechanical rather than chemical (e.g., Eberl 1984).

Total organic carbon (TOC), plotted for the main stem and tributaries as a function of distance from Whitehorse (Fig. 7), indicates that the bottom sediment in the tributaries is, on average, twice as rich in TOC than is the sediment in the main stem, and it is more variable.

Suspended sediments

According to Brabets et al. (2000), the suspended sediments are the most significant part of the overall sediment load carried by the Yukon River and its tributaries. For example, the bedload of the Tanana River near Fairbanks is only 1 to 2 percent of the suspended load.

The change in suspended load concentrations for the 2002 season is shown in Fig. 8 for three stations on the Yukon River (Eagle, Stevens Village and Pilot Station), and for the station on the Tanana River at Nenana. The suspended sediment load at Stevens Village and Pilot Station stays fairly constant throughout the season, but that at Eagle has a maximum at the end of July. The Tanana River has two maxima, one in May, and another at the end of June. The first peak is in response to snow melt runoff, and the second less pronounced peak results from glacial melt.

The weight percents of the suspended minerals, described in Table 2, are plotted for the same stations for various sampling times during the 2002 season. Quartz content varies by about 20 percent during the sampling season, and has minima at all stations in the middle of the summer (Fig. 9). These minima appear to correlate neither with sediment concentration (Fig. 8), nor with maximum discharge, which occurs in early June (see Fig. 21 in Brabets et al. 2000), but do correlate with carbonate maxima for the Yukon River samples, and to a clay maximum for the Tanana River samples. A current velocity of about 5 km/hr (a reasonable value) can be calculated from the migration of the quartz minima for the stations on the Yukon River.

Weight percents of suspended carbonates remain steady with the changing season at 2 percent for the Tanana River, but have maxima in early July for the Eagle and Stevens Village stations (Fig. 10). As was discussed above, these maxima correlate with the minima for quartz (Fig. 9). The maximum for the Pilot Station samples is towards the end of September (Fig. 10), when it has the same carbonate concentration as suspended sediments from the other Yukon stations. The Pilot Station maximum may be related to reduced flow of calcite-poor sediment from the Tanana River system during the Fall, leading to a smaller dilution effect.

Suspended feldspars are fairly constant (about 25 to 33 percent) during the sampling season, except for the Eagle station which has a minimum in May and a maximum at the end of July (Fig. 11). The total clay mineral content has a variable pattern (Fig. 12). The decrease in clays at Pilot Station in September may be related to a decreased input from the Tanana River at this time of year.

Comparison between bottom and suspended sediments

Figure 13 compares the weight percent non-clays for bed and suspended (average value) sediments at the four stations where suspended sediment was collected. As is to be expected, the non-clays generally are more highly concentrated in the bottom sediments, although for the Tanana River the bottom and suspended sediments have nearly equal amounts of non-clays.

Unmixing sediment sources

When the main stem and a tributary merge, sediment from each source is mixed downstream from the confluence. It is possible to calculate the proportion of each upstream source in the downstream sediment from the quantitative mineralogy using the MinUnMix program described in the Methods section. For example, the mineralogy of sample YR10, which was collected downstream from the mixing zone, should be a mixture of that found in samples YR8 and YR 9, which were collected from the Yukon River and the White River, respectively, above their confluence (Table 4). These calculated proportions are compared with actual measurements of sediment load to test the method (columns 3 and 4 in Table 1). For example, the proportion of Yukon River sediment downstream from the White River--Yukon River confluence calculated from the annual sediment load [Table 1; 3,180,00/(3,180,00 + 14,500,00 + 11,420,000) = 0.11) compares well with a value of 0.16 that was calculated from the mineralogy given in Table 4 using the MinUnMix program. Similar calculations were made where possible for other confluences with similar results (Table 1). The proportions match surprisingly well, especially considering that the measured proportions were calculated from suspended load, and that most of the unmixed proportions were calculated from the mineralogy of the bottom sediments. Artificial mixtures were prepared from the bottom sediments, X-rayed, and then their mineralogies were unmixed using MinUnMix to further test the method, with excellent results (Table 5). The data show that the unmixing method can be tested using artificial mixtures of end-members. One can accurately unmix up to three samples, but the method becomes inaccurate, at least for the samples chosen here, if 4 and 5 samples are used in the mixtures (Table 5).

The sources for suspended sediments were unmixed using bottom sediment mineralogies in an attempt to explain the quartz minimum and calcite maximum in the suspended sediment data (Figs 9 and 10). Using the sediment fractions given in Figure 14 and the quantitative mineralogy of the sediment sources, the minimum and maxima for quartz, carbonates and feldspars could be modeled (Fig. 15).

Similar calculations for the Stevens Village and Pilot Station data also indicate that the general shape of the quartz minima and carbonate maxima (Figs. 9-11) could be modeled, but the feldspar data could not. Although sediment source modeling is a promising technique, further modeling was not attempted because of the many uncertainties involved in the calculation, such as the assumptions that bottom sediment composition approximates suspended sediment mineralogy, and that tributary suspended mineralogy does not change with the season. More exact results would be obtained if "primary" sediment sources in the Yukon system were identified. Such a source would be a tributary in which the suspended sediment does not change in the relative proportions of minerals through the season, although the concentration of sediment could vary. For example, the White River where it joins the Yukon River may not be such a primary source because it has a large tributary, the Donjek River, from which sediment was not collected. Likewise, the Tanana River has the Nenana River as a large tributary. The relative sediment flux from these streams above their confluence could change with the season, leading changes in mineralogy downstream. Once such primary suspended mineralogies have been measured, the important sediment flows in the Yukon system can be modeled more precisely. If the primary sources are constant in sediment concentration, as well as in sediment mineralogy, then water fluxes also could be calculated.

Illite thickness measurements

The mean thicknesses and thickness distributions of illite crystallites were measured for suspended and bottom sediment by the Bertaut-Warren-Averbach XRD method (MudMaster computer program; Eberl et al.1996,1998). A typical distribution shape is shown in Figure 16A. An alpha-beta^2 plot (Eberl et al. 1998b) for the distributions is shown in Figure 16B. Alpha is defined as the mean of the natural logarithms of the thicknesses, and beta^2 is their variance. The data form a linear trend to the left of the field expected for illite crystal growth in hydrothermal or diagenetic systems (Bove et al. 2002; Srodon et al. 2000). With further study, it may be possible to use such plots to distinguish between authigenic and transported illites in rocks. Generally, illites from Yukon suspended sediments are thicker and have a larger variance than those found in bottom sediments (Fig. 16B).

Mean illite crystallite thicknesses for suspended sediment change with the season (Fig. 16C). The suspended illites at Eagle have a relatively constant thickness with the season, varying from 5 to 6 nm, but thicknesses in suspended sediments in the Tanana River seem to vary with total clay content of the suspended sediment (compare Figs. 12 and 16C). The illites in the Tanana River have the greatest range in thicknesses, changing by a factor of about 2 to 3 during the collecting season. The changes in suspended illite thicknesses at Pilot Station reflect changes in illites coming out of the Tanana River, and demonstrate the influence of the composition of Tanana River sediment on sediment at the mouth of the Yukon River.

Weathering of minerals

The bottom sediment mineralogy for carbonates and feldspar indicates that little chemical weathering is occurring in the Yukon River. If calcite was dissolving one might expect that dolomite, which is less soluble that calcite, would increase relative to calcite in the bottom sediments, which may be observed only where the White River, and possibly where the Tanana River, enter the system (Fig. 3B). Likewise, plagioclase is more soluble than alkali feldspar, but shows no tendency to disappear at a faster rate with reach (Fig. 5B).

SUMMARY AND CONCLUSIONS

The mineralogy of Yukon River bottom sediments and suspended sediments changes with distance downstream from Whitehorse, and the suspended sediment mineralogy varies with the time of year. These changes are readily explained by concentration and dilution of mineralogies by flow from tributaries. For example, the entry of the White River dramatically increases bottom sediment carbonate content, and entry of the Tanana decreases it (Fig. 3A). The quartz and feldspar contents of Yukon River bottom sediments fluctuate greatly with entry of the Pelly and White Rivers (Figs. 4 and 5). In these regions, the Yukon River is near its source, is relatively small, and therefore its sediment composition can be strongly influenced by tributaries. The minima found in mid-summer for quartz in suspended sediment (Fig. 9), and the related maxima found for calcite (Fig. 10) are related to changes in flow of the White River (plus its tributary the Donjek River), which is relatively poor in quartz and rich in carbonates, in relation to the other major tributaries. The cause for changing illite crystallite thicknesses with season (Fig. 15) is unknown, but probably is related to changing sediment fluxes for tributaries flowing into the Tanana River.

This preliminary study indicates that the technique of unmixing of sediment sources by using quantitative mineralogy is an efficient method for determining relative sediment loads and sediment sources. This technique can be refined by finding the primary sources for suspended sediment, which are defined as tributaries in which the sediment does not change in mineralogy (but may change concentration) through the season. When these sources have been identified and measured, sediment flux in the main stem may be modeled easily and studied less expensively by using several measurements of suspended sediments at key locations.

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Figure 14. Fraction of sediment sources [upper Yukon River, White River and calculated sediment of unknown source] as a function of time of year for suspended sediment collected at Eagle.

Figure 15. Measured versus calculated changes in mineralogy with season for the Eagle fixed station. A. quartz; B. carbonates; C. feldspar.

Figure 16. A. Typical illite crystallite size distribution measured for a suspended sediment by an X-ray peak broadening technique (see text). B. Plot of alpha and beta^2 values for crystallite size distributions for illites found in suspended sediments (open circles), bottom Yukon sediments (filled circles) and tributary bottom sediments (filled triangles). $\alpha = \sum f(T)T$ and $\beta^2 = \sum (T - \alpha)^2 f(T)$, where T is illite crystallite thickness, and *f(T)* is the frequency of the thickness. C. Change in mean illite crystallite thicknesses in suspended sediment for the 2002 season for four fixed stations.

Table 1. Estimated annual suspended-sediment loads for selected sites in the Yukon River basin (first two columns from Brabets et al. 2000), and measured and calculated ratios for sediment sources.

Name (location in Alaska unless indicated)	Annual load (metric tons)	Measured proportion of Yukon suspended sediment*	Calculated proportion of Yukon bottom sediment[†]
Yukon at Whitehorse, YT	56,000		
Pelly R., YT	1,100,000	0.05	0.00
Yukon R. above White R., YT	3,180,000		
White R. + Donjek R., YT	14,500,000 + 11,420,000[‡]	0.11	0.16
Stewart R., YT	900,000		
Yukon R. at Dawson, YT	30,000,000		
Yukon R. at Eagle	30,000,000		
Porcupine R.	7,200,000	0.81	0.96
Chandalar R.	900,000		
Yukon R. at Rampart	30,000,000		
Tanana R.	34,500,000	0.47	0.50 (0.54)[§]
Yukon R. at Ruby	60,000,000		
Koyukuk R.	1,800,000	0.97	1.00
Yukon R. at Pilot Station	54,500,000		

*Proportion = weight of downstream Yukon suspended sediment/(weight of upstream Yukon suspended sediment + weight of tributary suspended sediment) using data from column 2.

[†]Same proportion as above, but calculated by unmixing of XRD quantitative mineral data for bottom sediment (see text).

[‡]Donjek calculated by difference from Table 10 in Brabets et al. 2000.

[§]Parenthesis refers to suspended sediment, unmixed from the Yukon R. at Pilot Station using XRD quantitative mineral data for suspended samples for the Yukon R. at Stevens Village and for the Tanana R. All these samples were collected at approximately the same time.

Table 2. Suspended sediment collected during the 2002 season.

Sample no.: YRS-	Location	Date collected	Time collected
32	Yukon R. at Eagle	5/22/02	1420
41	Yukon R. at Eagle	7/10/02	1120
47	Yukon R. at Eagle	8/1/02	1150
48	Yukon R. at Eagle	8/1/02	1200
55	Yukon R. at Eagle	8/28/02	1340
30	Porcupine R. at Fort Yukon	6/6/02	1500
31	Porcupine R. at Fort Yukon	6/26/02	1310
35	Yukon R. at Stevens Village	6/4/02	1630
36	Yukon R. at Stevens Village	6/24/02	1330
44	Yukon R. at Stevens Village	7/18/02	1400
46	Yukon R. at Stevens Village	7/30/02	1510
53	Yukon R. at Stevens Village	8/23/02	1440
54	Yukon R. at Stevens Village	8/24/02	1450
57	Yukon R. at Stevens Village	9/5/02	1450
33	Tanana R. at Nenana	5/14/02	1500
34	Tanana R. at Nenana	5/29/02	1550
42	Tanana R. at Nenana	7/16/02	1430
45	Tanana R. at Nenana	7/29/02	1310
51	Tanana R. at Nenana	8/21/02	1330
52	Tanana R. at Nenana	8/22/02	1340
56	Tanana R. at Nenana	8/30/02	1450
37	Yukon R. at Pilot Station	6/12/02	1340
38	Yukon R. at Pilot Station	6/20/02	1850
40	Yukon R. at Pilot Station	7/1/02	1900
43	Yukon R. at Pilot Station	7/16/02	1130
49	Yukon R. at Pilot Station	8/8/02	1420
50	Yukon R. at Pilot Station	8/8/02	1430
58	Yukon R. at Pilot Station	9/24/02	1630

Table 3. Location of bottom sediments collected during the 2001 season.

Sample number: YR-	Location	Km from Whitehorse
1	Yukon R. at Whitehorse	0
2	Yukon R. above Teslin R.	111
3	Teslin R.	118
4	Yukon R. below Teslin R.	126
5	Yukon R. above Pelly R.	333
6	Pelly R.	337
7	Yukon R. below Pelly R.	344
8	Yukon R. above White R.	485
9	White R.	493
10	Yukon R. below White R.	495
11	Yukon R. below Stewart R.	502
12	Yukon R. above Dawson	606
13	Yukon R. below Dawson	613
14	Forty Mile R.	644
15	Yukon R. at Eagle	764
16	Tatonduk R.	817
17	Nation R.	862
18	Kandik R.	921
19	Charles R.	944
20	Coal Creek	967
21	Wood Chopper Creek	980
22	Yukon R. at Circle	1079
23	Yukon R. above Porcupine R.	1211
24	Porcupine R.	1222
25	Yukon R. below Porcupine R.	1229
26	Birch Creek	1281
27	Beaver Creek	1392
28	Tributary, name unknown	1406
29	Yukon R. at Dalton Bridge	1602
30	Hess Creek	1666
31	Yukon R. above Tanana R.	1837
32	Tanana R.	1851
33	Yukon R. below Tanana R.	1868
34	Tozitna R.	1880
35	Nowitna R.	2018
36	Melozitna R.	2098
37	Yukon R. at Ruby	2102
38	Yukon R. at Galena	2210
39	Yukon R. above Koyukuk R.	2260
40	Koyukuk R.	2272
41	Yukon R. below Koyukuk R.	2302
42	Nulato R.	2334
43	Yukon R. at Kaltag	2408
44	Yukon R. at Grayling	2721
45	Annk R.	2754
46	Yukon R. at Holy Cross	2796
47	Innoko R.	2799
48	Yukon R. at Russian Mission	2915
49	Yukon R. at Pilot Station	3111
50	Andreafsky R.	3151

Table 4. Sample RockJock analysis for Yukon River bottom sediments.

MINERALS	YR8	YR9	YR10
Non-clays:			
Quartz	51.0	18.4	23.7
Microcline (ordered)	1.8	0.5	1.8
Microcline (intermediate)	2.4	2.2	2.3
Sanidine	2.4	1.5	1.3
Orthoclase	0.0	0.0	0.0
Anorthoclase	5.2	10.3	10.4
Albite	5.6	7.1	7.4
Oligoclase	4.1	3.9	2.4
Andesine	2.5	0.0	0.0
Labradorite	1.8	10.4	10.2
Bytownite	1.5	5.2	5.2
Anorthite	0.0	0.0	0.0
Calcite	0.4	7.5	6.8
Mg-calcite	0.7	1.0	0.4
Dolomite	2.7	5.5	5.1
Amphibole	2.1	2.1	1.8
Pyroxene	0.3	2.0	1.9
Magnetite	0.0	0.3	0.0
Hematite	0.0	0.5	0.3
Goethite	0.5	0.3	0.2
Total non-clays	84.9	78.8	81.4
Clays:			
Kaolinite	0.0	0.7	2.1
Ferruginous smectite	0.3	0.9	4.5
Illite (+ Al-smectite)	5.9	5.5	0.0
Chlorite CCa-1	0.0	0.0	0.0
Chlorite CCa-3	0.1	0.0	0.0
Chlorite CCM	0.0	0.0	0.0
Chlorite CO	0.1	0.1	0.0
Chlorite Tusc	8.1	8.9	4.1
Chlorite A	2.8	3.3	2.8
Total Clays:	17.3	19.2	13.6
Total:	102.2	98.0	95.0
Non-clay degree of fit:	0.077	0.074	0.072
Clay degree of fit:	0.045	0.039	0.037

Table 5: Analysis of artificial mixtures by the mineralogical unmixing technique.

Samples mixed	Proportions artificially mixed	Unmixed proportions from artificial mixtures
YR2 + YR3	0.40 + 0.60	0.30 + 0.70
YR8 + YR9	0.20 + 0.80	0.19 +0.81
YR23 + YR24	0.90 + 0.10	0.92 + 0.08
YR31 + YR32	0.50 + 0.50	0.55 + 0.45
YR9 + YR24 + YR32	0.33 + 0.33 + 0.33	0.39 + 0.29 + 0.32
YR9 + YR24 + YR32 + YR40	0.25 + 0.25 + 0.25 + 0.25	0.16 + 0.10 + 0.55 + 0.19
TR6 + YR9 + YR24 + YR40 + YR50	0.2 + 0.2 + 0.2 + 0.2 + 0.2	0.44 + 0.28 + 0 + 0.03 + 0.26

Figure 1

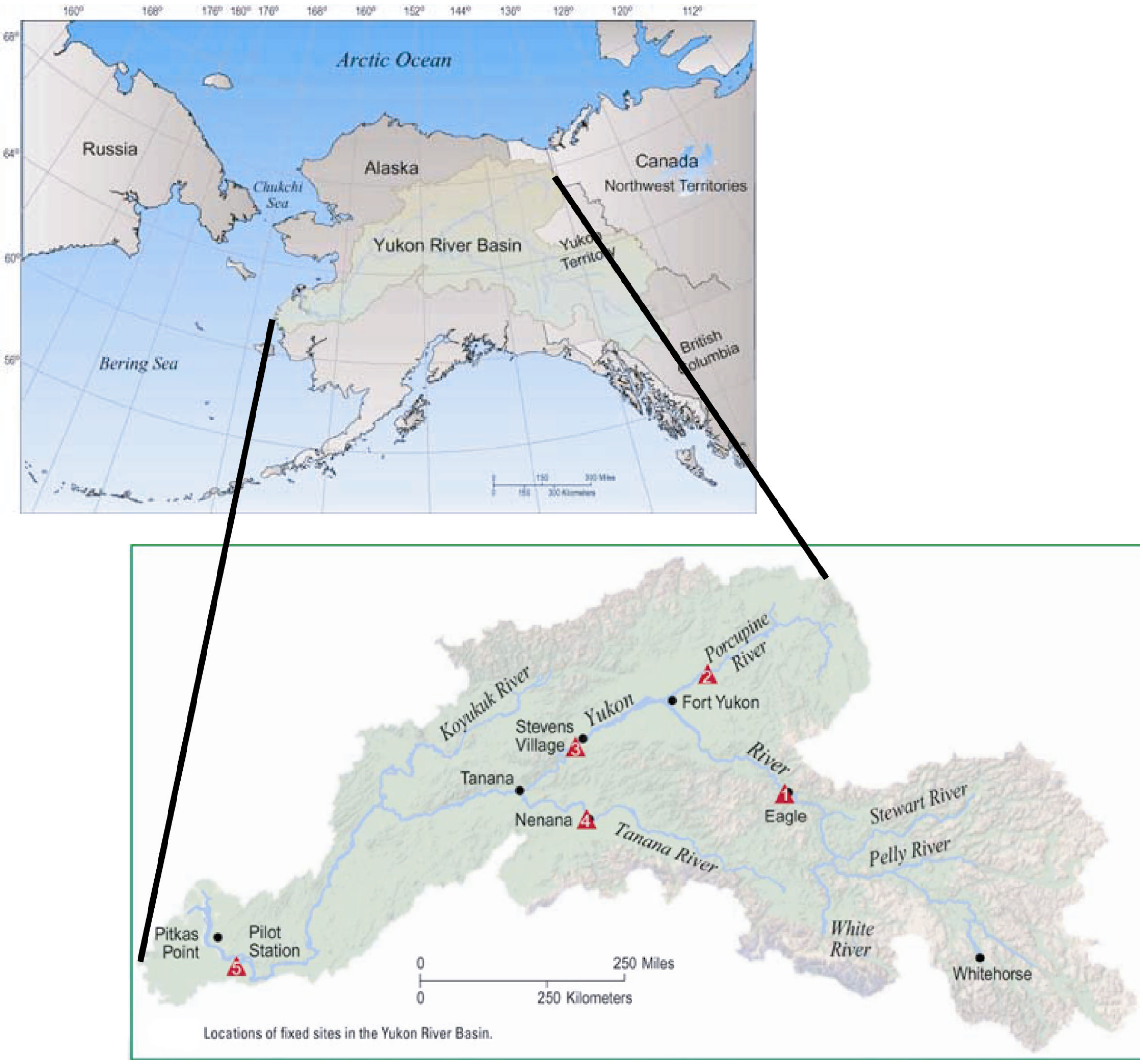
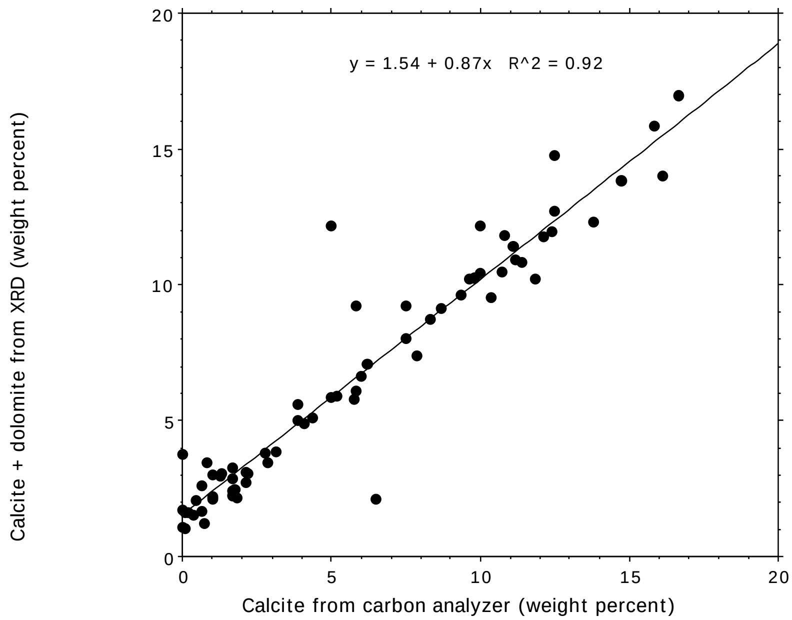

Arctic Ocean
Russia
Alaska
Canada
Northwest Territories
Chukchi Sea
Yukon River Basin
Bering Sea
British Columbia
Porcupine River
Fort Yukon
Koyukuk River
Yukon
Stevens Village
River
Tanana
Eagle
Stewart River
Nenana
Tanana River
Pelly River
White River
Pitkas Point
Pilot Station
Whitehorse
0 250 Miles
0 250 Kilometers
Locations of fixed sites in the Yukon River Basin.

Figure 2



y = 1.54 + 0.87x R^2 = 0.92
Calcite + dolomite from XRD (weight percent)
Calcite from carbon analyzer (weight percent)
0
5
10
15
20

Figure 3A

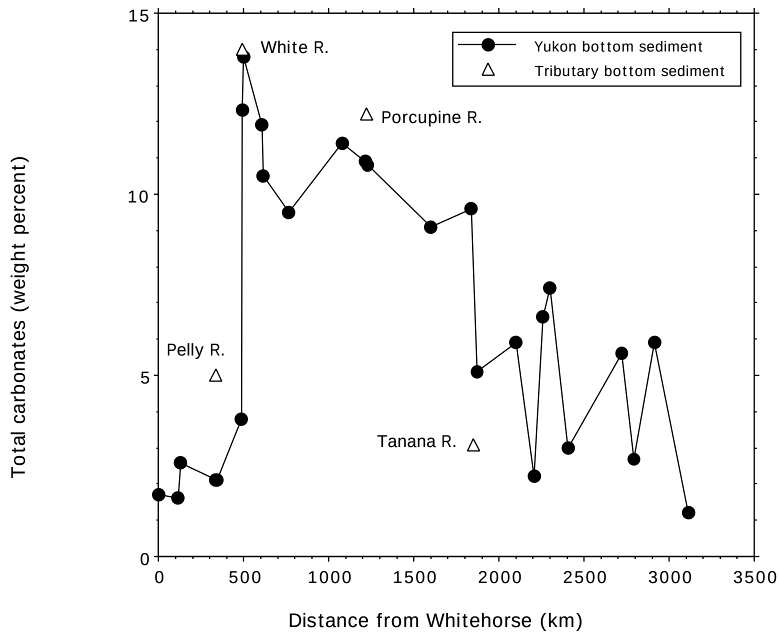


Figure 3B

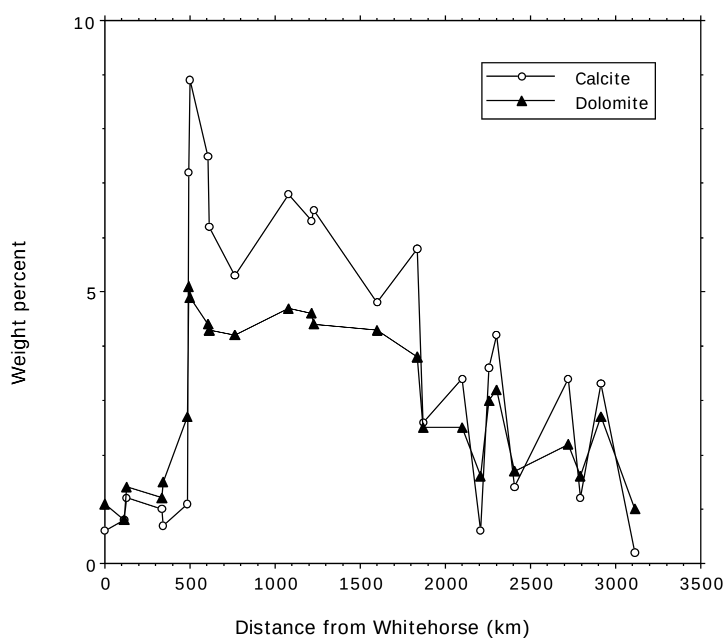
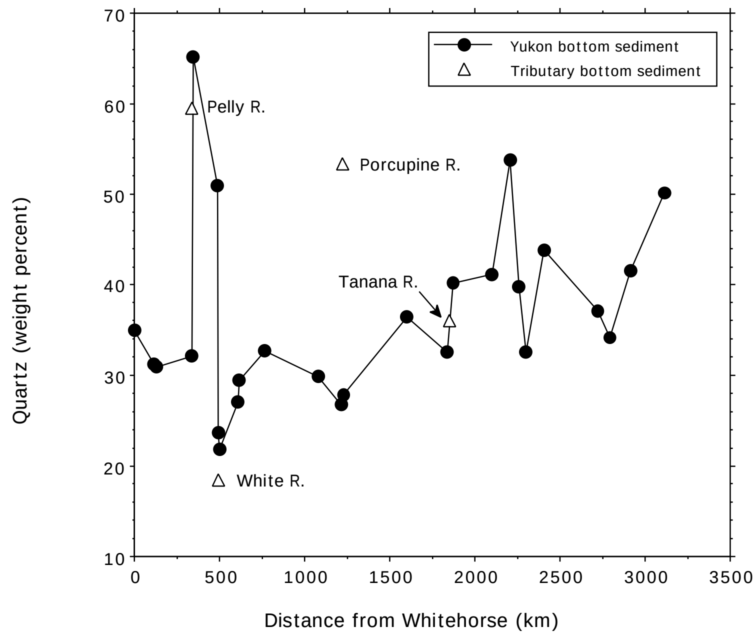


Figure 4



Yukon bottom sediment
Tributary bottom sediment
Pelly R.
Porcupine R.
Tanana R.
White R.
Quartz (weight percent)
Distance from Whitehorse (km)
70
60
50
40
30
20
10
0
500
1000
1500
2000
2500
3000
3500

Figure 5A

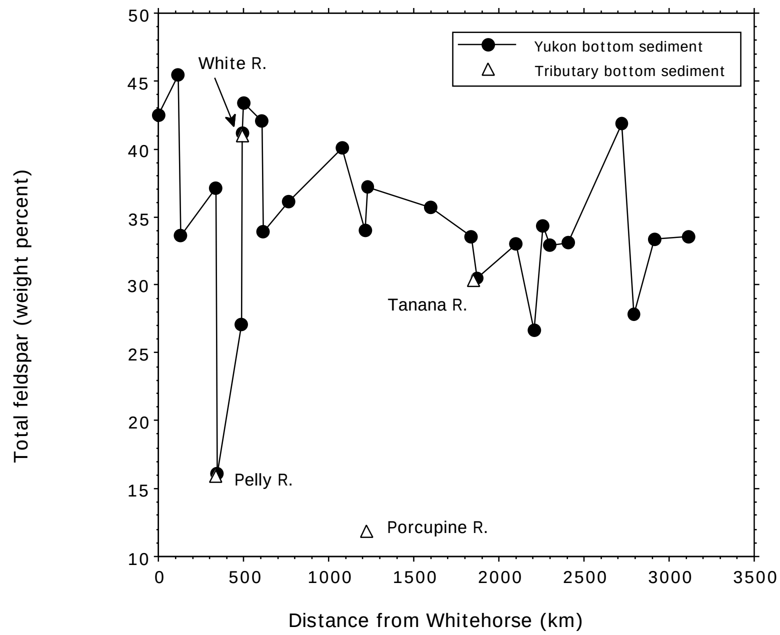


Figure 5B

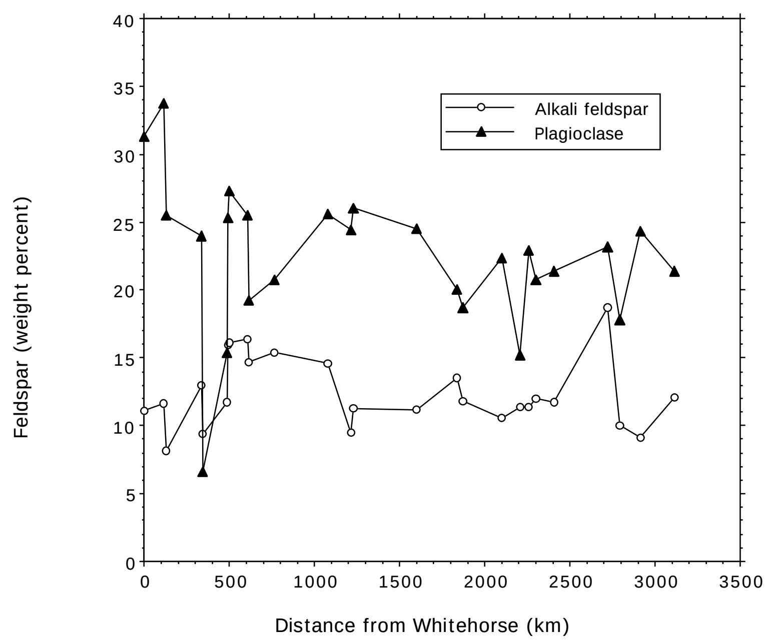


Figure 6A

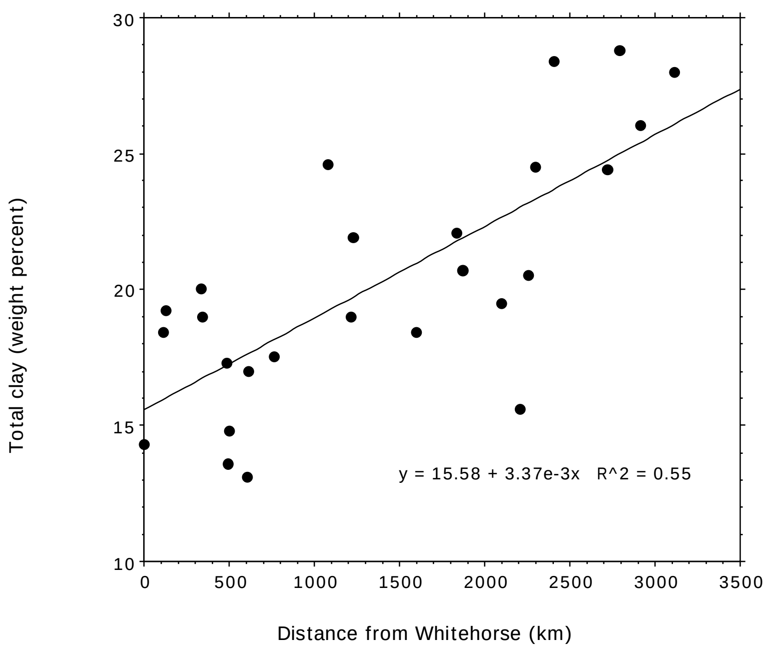


Figure 6B

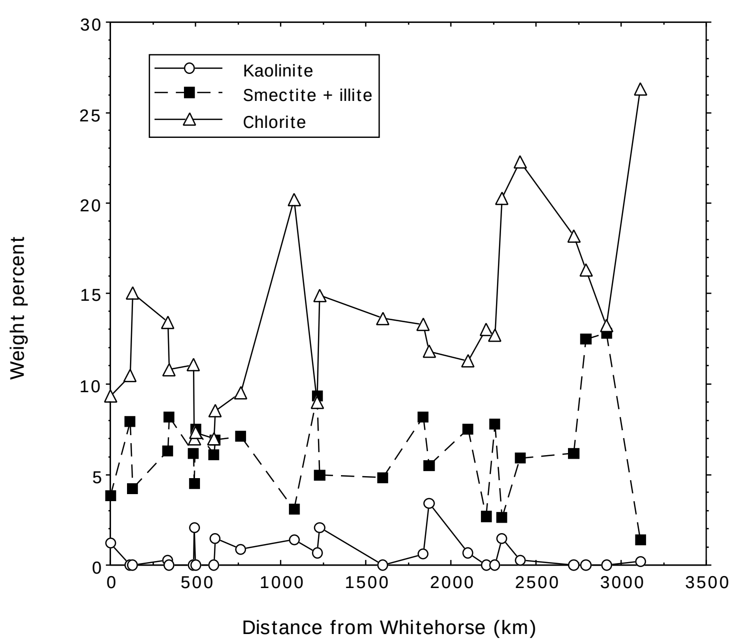


Figure 7

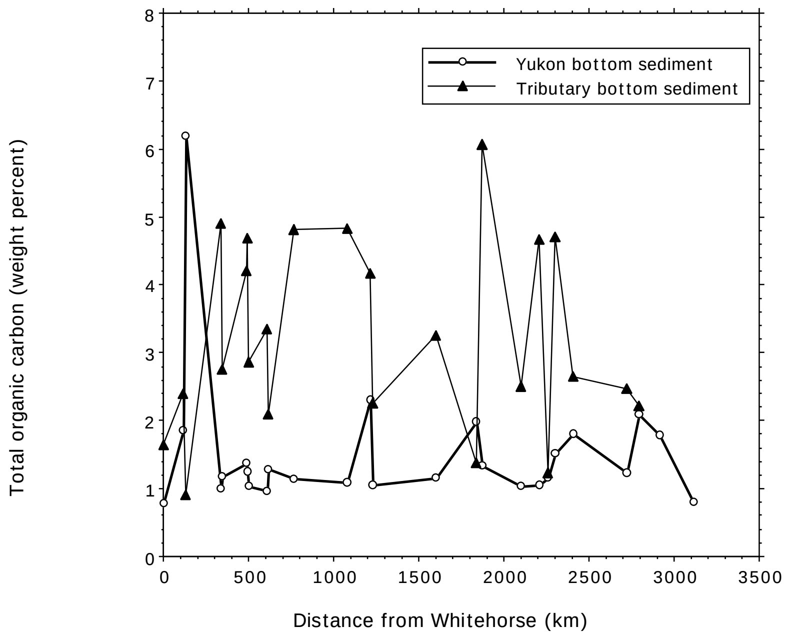


Figure 8

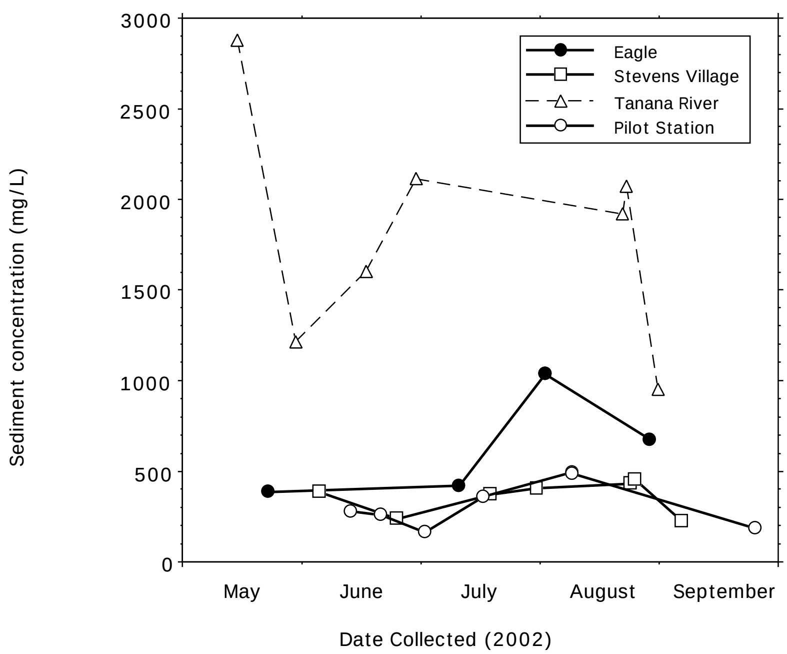


Figure 9

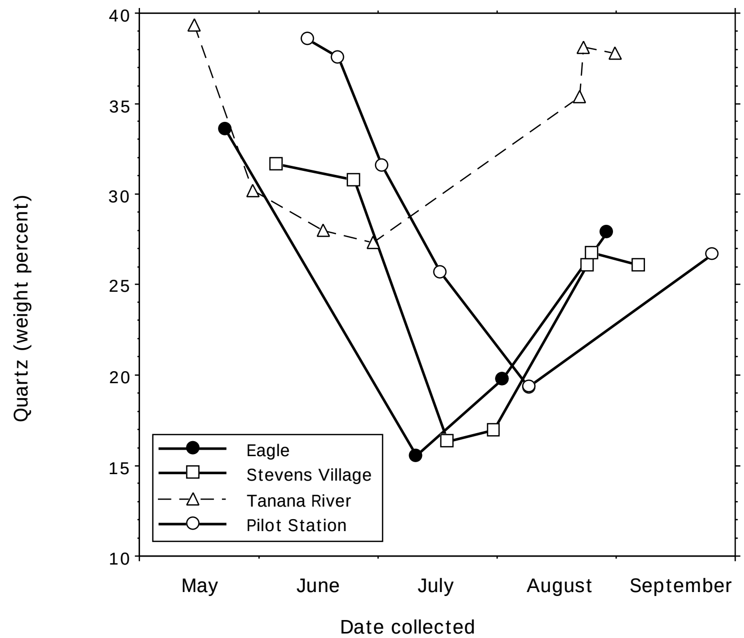


Figure 10

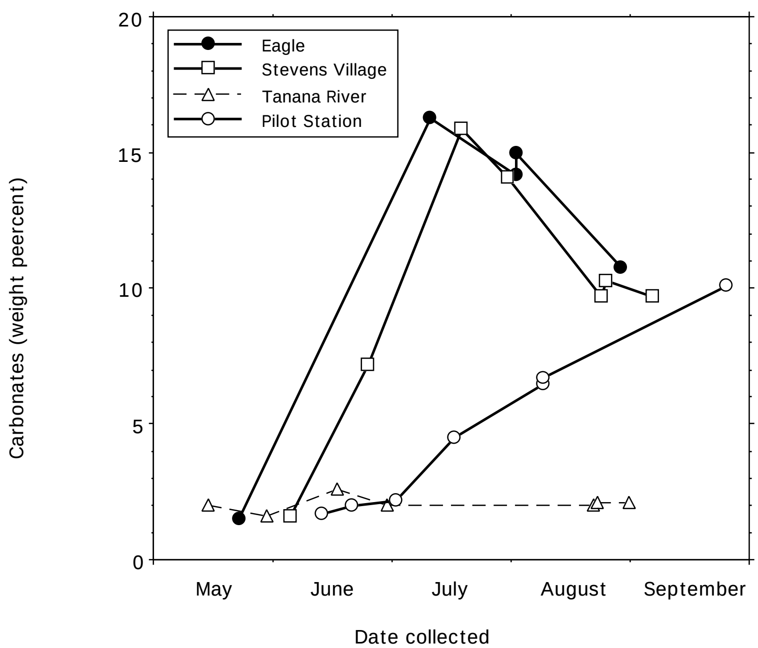


Figure 11

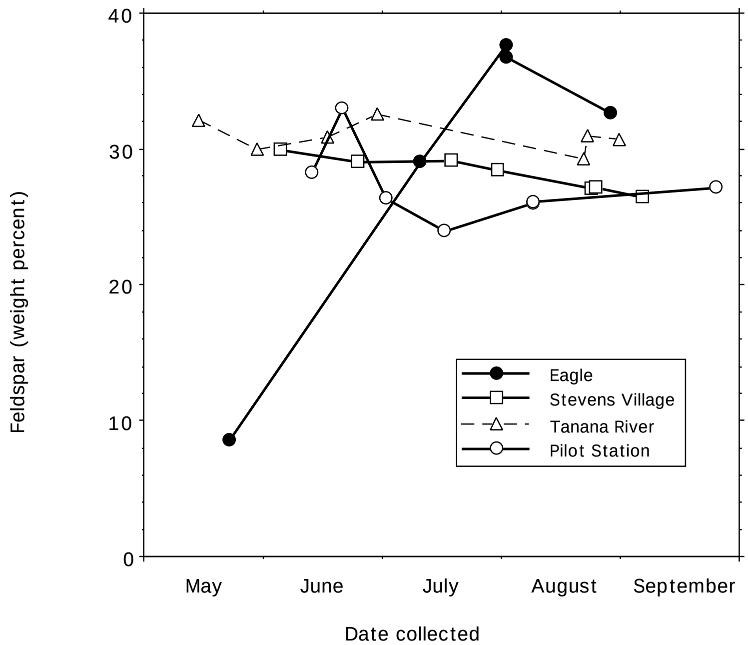


Figure 12

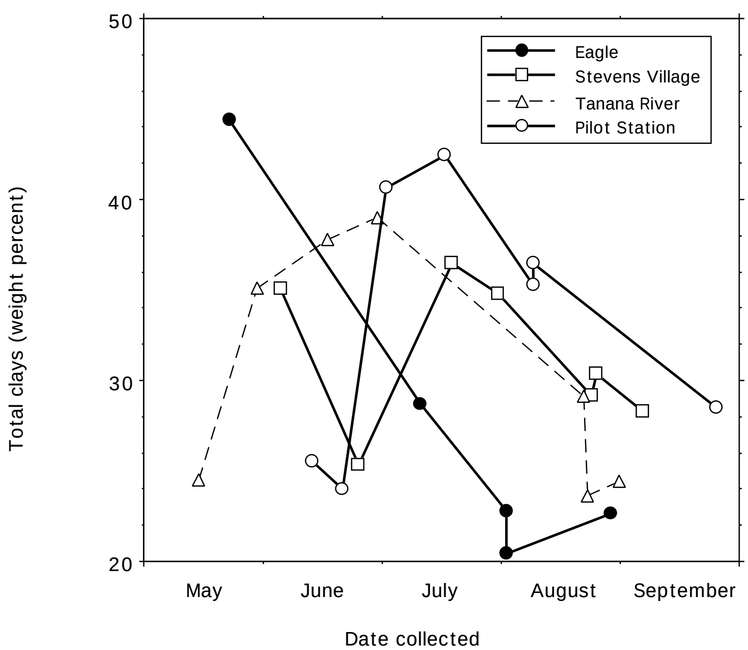


Figure 13

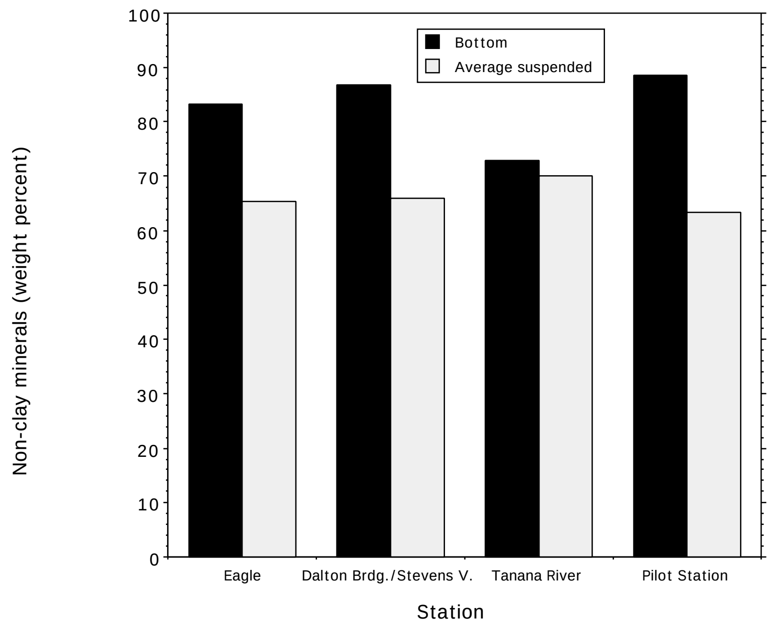


Figure 14

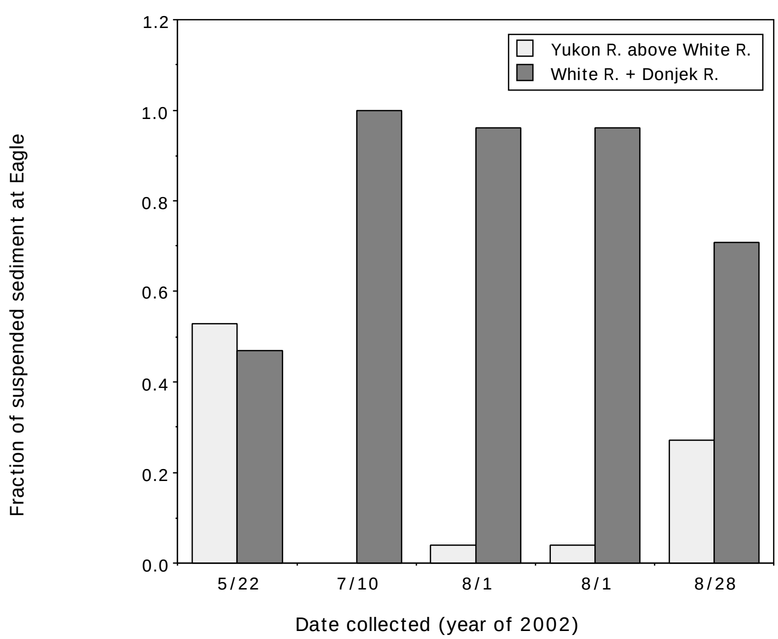


Figure 15A

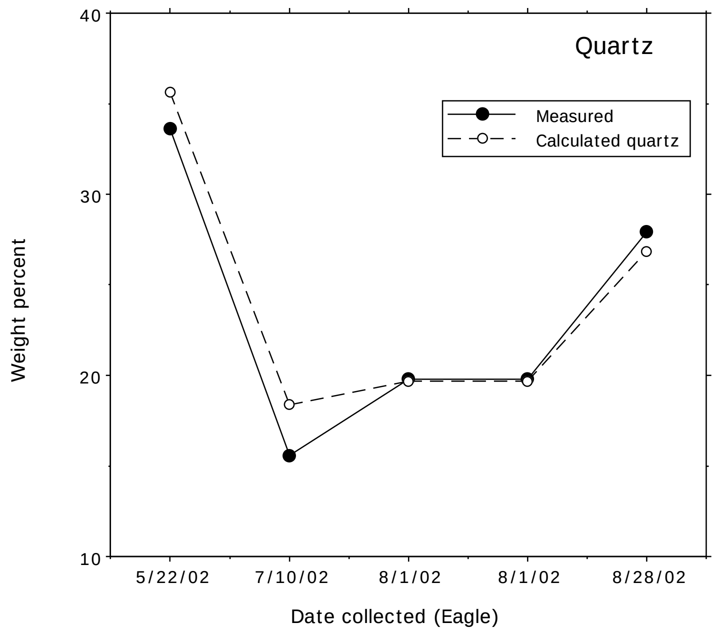


Figure 15B

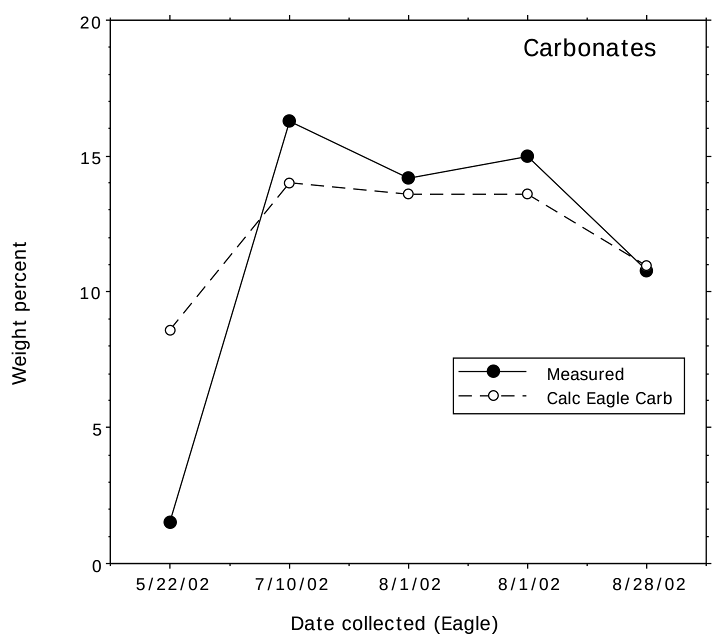


Figure 15C

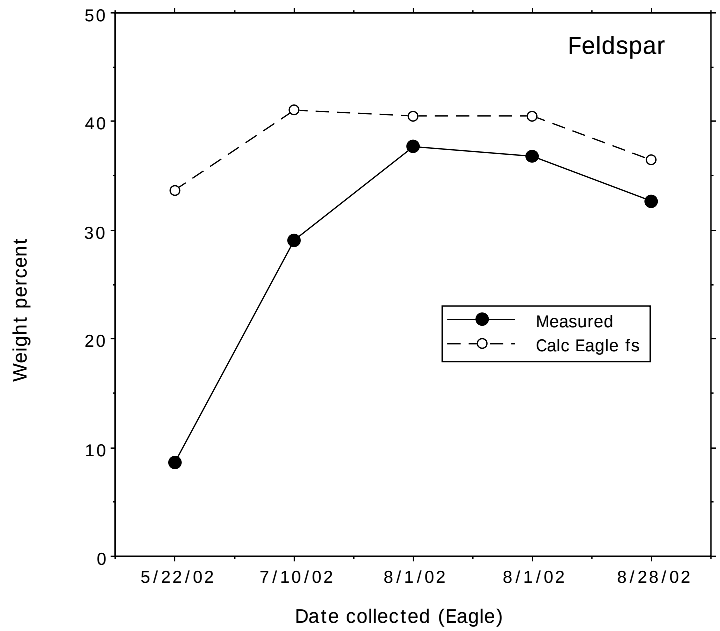


Figure 16A

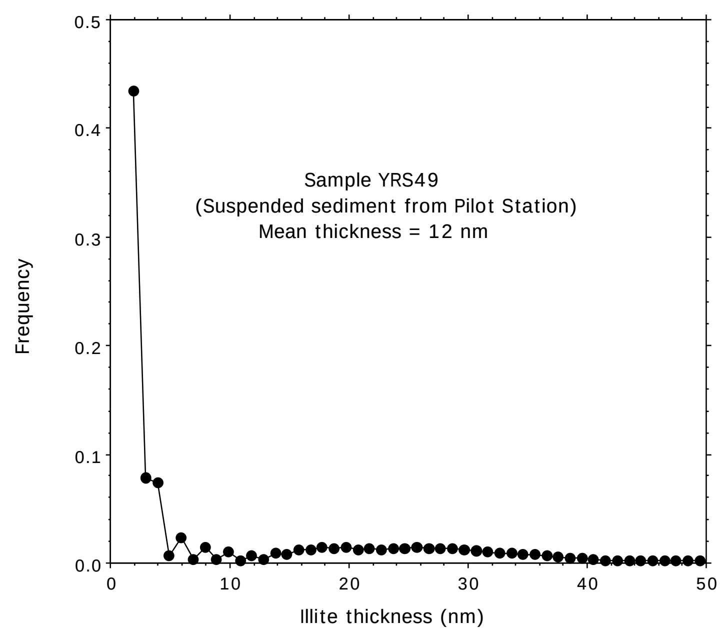


Figure 16B

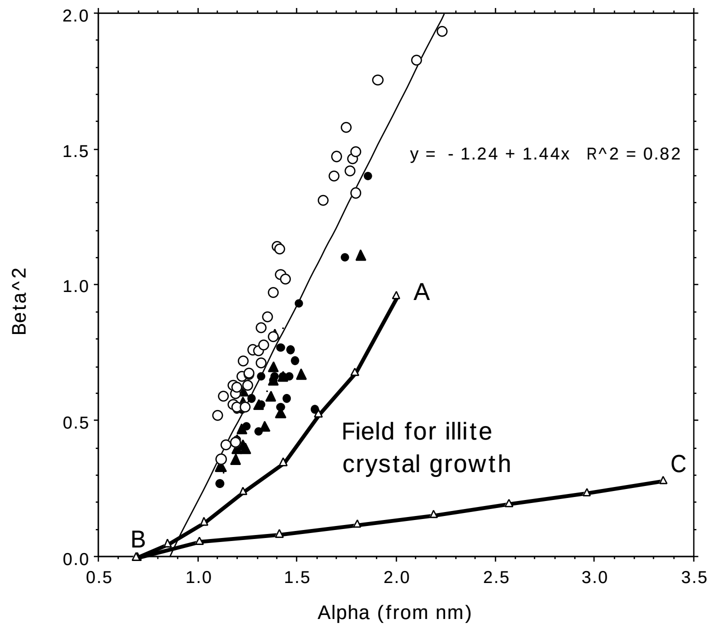


Figure 16C