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# Mineralogical Study of Boreholes B98-13 and B98-12
# Frontier Hard Chrome Site
# Vancouver, Washington

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## DISCLAIMER

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# ABSTRACT

The mobility of chromium in ground water is an important consideration for evaluating remedial options for the Frontier Hard Chrome industrial site, Vancouver, Washington. One factor in assessing metal mobility is the degree of chromium reduction and secondary mineralization in a silt unit and underlying sand and gravel aquifer that extends from the site toward the Columbia River. Samples of fill at 16 feet, silt at 21-22 feet, and the underlying aquifer material at 25-26 feet in boreholes B98-13 and B98-12 were collected for chemical and mineralogical analysis. Samples were analyzed by ICP-AES for metals concentration, scanning electron microscopy/electron microprobe for mineralogical texture and microanalysis, powder x-ray diffraction for mineral identification, and optical microscopy for textural observations.

Microprobe analysis showed that chromium occurred in metallic particles originating in the fill material, in iron and iron-titanium oxides that are part of the sediments that were transported by natural fluvial processes through the Columbia River Basin, and in fine-grained iron aluminum silicates that were found in fine sand- to clay-size fractions of both the Silt and Aquifer Units. X-ray diffraction analysis showed that the fine-grained fraction of these units contained an abundant suite of detrital clay minerals including primarily illite, chlorite, and smectite, and lesser kaolinite. The presence of chlorite and smectite is consistent with the microprobe observation of iron-bearing aluminum silicates in the fine grained fraction of the samples. Chromium concentration in the fine-grained material was elevated to a level consistent with chromium in the bulk material and about 10-20 times nearby background concentrations. Though much higher concentrations are found in the metallic particles and iron-titanium oxides, the sparse amount of these phases suggests that an important contributor to the bulk chromium content resides in the clay minerals.

# INTRODUCTION

Remedial planning for the Frontier Hard Chrome site in Vancouver, Washington, requires an understanding of the geochemical processes affecting the fate of chromium in the subsurface. Disposal of chrome-plating liquids has left an area of ground water contamination underlying about 30 acres of industrial land along the north shore of the Columbia River. After years of little apparent extension of a concentrated ground water plume of chromium, interest developed in acquiring a more detailed understanding of the nature of chromium mobility at the site. The objective of this study is to identify metal-bearing phases in the Fill, Silt and Aquifer Units. The emphasis is on chromium compounds as well as other minerals that might provide reactive material for enhancing chromium reduction and precipitation of secondary phases. The goal is to determine if there is evidence for the occurrence of natural attenuation at the site.

Some of the terms used here may warrant clarification. The term “minerals”, by strict definition, refers to naturally occurring compounds. Although man-made compounds such as some waste materials found in fill are not natural minerals, they are described here by their mineral analog in cases where compound identification can be analytically matched to a unique mineral composition and structure. “Phase” is used here in the general sense for a particular composition of mineral or other compound regardless if naturally occurring or man-made.

Primary minerals or phases are those believed to be an original part of the solid matrix. Secondary minerals or phases are those believed to have formed as coatings or void fillings after formation of the solid matrix, or as in-situ alteration products of primary phases.

# METHODS AND MATERIALS

## Study Design

Samples were collected from the Fill, Silt, and Aquifer Units in two boreholes located downgradient from the source of chrome-plating wastes, the property formerly housing the Frontier Hard Chrome facility. A sampling and analysis plan for the study was prepared by Roy F. Weston (1998). The samples were analyzed for metals concentration by ICP-AES, and for mineralogy by scanning electron microscopy/electron microprobe (SEM/EPMA), x-ray diffraction (XRD), and low-power optical microscopy. A sample preparation procedure was used to separate grain sizes as a means of concentrating mineral phases associated with particular size ranges. The separation procedure was expected to potentially concentrate more reactive material, and possibly secondary minerals, in the smaller size fractions. Accordingly, a fine-grained separate was prepared to provide a concentrate of secondary minerals. The coarser-grained separates, on the other hand, provided larger-sized material expected to have intact coatings or alteration rims made up of relatively harder secondary minerals.

## Field Work

Samples were collected with a 2.5 inch inside-diameter split-spoon sampler driven through an 8-inch hollow-stem auger (Roy F. Weston, 1999). On April 27, 1998, six samples for chemical and mineralogical analysis were collected from boreholes B98-13 and B98-12, located 100-200 feet southeast of the Frontier Hard Chrome building and approximately 3000 ft north of the Columbia River (Figure 1). Seven additional samples were collected from boreholes B98-20A and B98-21A on April 30 and B98-21B on May 28, approximately 900 feet south and downgradient of B98-12 and B98-13 (Figure 1). These later samples were submitted for chemical analysis and archived for possible mineralogical analysis pending review of the chemical data. Mineralogical analysis of the distal samples was not conducted because of their low chromium content.

For the samples that underwent mineralogical analysis, Table 1 lists the sample numbers, depths, and unit descriptions from the field report (Roy F. Weston, 1999). Three units were sampled in each of the two boreholes. The units include fill at a depth of 16 feet, silt at 21-22 feet, and the Aquifer A-zone at 25-26 feet. In order to provide information on variability within a sampled unit, two portions of the sample from the Silt Unit (SBR1-9813-0210) from borehole B98-13 were prepared for analysis. Therefore a total of six field samples and one duplicate were carried through the mineralogical procedures.

## Laboratory Methods

Approximately 500 g of each sample were separated by wet sieving to produce five size fractions: gravel (>2 mm), coarse sand (0.5-2 mm), fine sand (0.07-0.5 mm), and silt and clay (<0.07 mm). The gravel fraction was further divided at about 10 mm into larger gravel and smaller gravel. No gravel fragments were larger than about 20 mm. Each size-separate was assigned a new lab number for a total of 35 laboratory samples generated from the original six field samples and one duplicate (Table 1).

The size separates were well mixed and split for optical microscopy and x-ray diffraction analysis at the Manchester Laboratory, and for scanning electron microscopy/electron probe microanalysis at Cannon Microprobe, Seattle. The larger gravel clasts (>10 mm) were split with a diamond saw. The remaining sand and gravel fractions were split with a riffle splitter, and the silt and clay fractions were split by quartering. Table 1 lists the percent weights resulting from the size separation.

X-ray diffraction analysis was accomplished at the Manchester Laboratory with a Scintag X1 powder diffractometer using Co*Kα* radiation at a wavelength of 1.78897 angstroms (Å), generated at 36 ma and 45 kv. Several diffractograms were also acquired early in the project with Cu*Kα* radiation at 1.54056 Å at 40 ma and 45 kv. Diffractograms were recorded at scan speeds of 15 degrees and 0.5-1 degrees of two-theta ($^{o}2\theta$) units per minute over a 2-76 degree range. The XRD method provided qualitative identification of minerals greater than about five percent in concentration. Identifications were made by matching measured diffraction patterns with a database maintained by the International Centre for Diffraction Data (1996), and by comparison with the literature as noted. Clay mineral identifications were verified by chemical and thermal treatments that alter the structural thickness of clay minerals in a diagnostic manner as described by Brindley and Brown (1980) and Moore and Reynolds (1986). The clay minerals were expanded by intercalation with ethylene glycol, and contracted by heating at $150^{o}$, $300^{o}$, and $550^{o}$ C.

A Frantz LB-1 magnetic barrier separator was used for selected samples to provide mineral concentrates for both XRD and microprobe analysis. Additional separation of the finest fractions was accomplished by vacuum filtration of re-suspended particulates in deionized water onto 0.45 µm cellulose filters. A Wild M5-A stereomicrosope was used for optical microscopy with incident light in order to describe and document samples and XRD specimens. The XRD laboratory report is in Appendix A and contains a list of analyzed separates, matched phases, annotated diffractograms, and notes on microscopic observations.

Scanning electron microscopy/electron microprobe analysis was performed at Cannon Microprobe, Seattle, using an ARL SEMQ electron microprobe at 20 kv and 50 na beam current. Both grain mounts and polished sections were prepared as specimens. Scanning electron microscope images were made in the backscattered electron detection mode (BSE images) by which image contrast is a function of atomic number. Microanalysis was accomplished with the probe using a Kevex energy-dispersive x-ray spectrometer (EDS) for rapid detection of several elements, and four wavelength-dispersive x-ray spectrometers (WDS) for quantitation of chromium, manganese, barium, and iron. The WDS analytical volume is about one cubic micrometer. The microprobe report is in Appendix B and contains a narrative discussion of the distribution of chromium, lists of WDS analyses for four elements, a group of BSE images, x-ray map images for chromium and manganese, and a group of EDS spectra.

## RESULTS

The borehole samples consist of granular material that spans a size range from clay to pebbles (Table 1). The Fill Unit has the coarsest material, and the Silt Unit has the finest. Samples from the Fill Unit have primarily dark gray to black sand and gravel with about 14-19% fines of silt and clay. Samples from the Silt Unit have dark gray to dark grayish brown silt and clay with 61-67% fines. Samples from the Aquifer Unit have dark brown to dark grayish brown sand and gravel with 23-27% fines.

Visual examination of the gravel fractions indicate the most common rock types in these samples are black basalt, gray andesite, and white to beige quartz and quartz-rich rocks such as quartzite and granodiorite. The Fill Units from both boreholes contained calcite-coated pebbles from chunks of concrete. The Fill also has a large proportion of angular basalt, suggestive of crushed aggregate. Many of the basalt pebbles in the Fill Unit are coated with asphalt. The Silt and Aquifer Units have a much smaller proportion of angular pebbles than the Fill Unit, though angular basalt fragments are still common in the coarse part of the Silt Unit.

Results of the chemical analyses of borehole samples are listed in Table 2. Included with the results for boreholes B98-13 and B98-12 are the more distal samples from B98-21A, B98-21B, and B98-20 (Figure 1). Table 2 shows that chromium concentrations are highest in B98-13 and B98-12 for all Units. Within each borehole, chromium is relatively higher in the Silt Unit and is also preferentially concentrated in the silt and clay fractions of the Fill and Aquifer Units. Other metals that had highest concentrations in boreholes B98-13 and B98-12 include iron, sodium, calcium, potassium, copper, lead, and zinc.

### Distribution of Minerals

Table 3 lists the phases discussed in this report and appendices, including the mineral name, ideal chemical formula, and whether the phase is found by XRD or microprobe analysis. Tables 4 and 5 provide a summary of the XRD and microprobe results, respectively.

With reference to the XRD results in Table 4, the common rock-forming minerals, quartz and feldspar are ubiquitous, occurring as major minerals in all of the samples. Mica and the clay minerals are abundant as minor components in both the Silt and Aquifer Units. From the size distribution (Table 1), the Silt Unit contains over 60% silt- and clay-size grains for which XRD indicates the presence of abundant clay minerals. Prominent among the clay minerals are those that are potentially iron-bearing, chlorite, smectite, and illite. Lesser kaolinite also occurs in the Silt Unit. The Aquifer Unit contains a similar group of clay minerals, but in somewhat less amount than the Silt Unit.

A distinctive feature of the clay minerals is a lack of interstratification. Reaction among clay minerals to form mixed layer clays, or interstratification, is a common occurrence in active soil-forming environments. Lack of interstratification indicates that the clay minerals are detrital rather than authigenic. In other words, these clay minerals probably do not represent secondary mineralization at the site, but rather were transported into the area by fluvial processes.

XRD examination of coatings found calcite coatings to be common. The Fill Unit contains major calcite and trace aragonite and vaterite in coatings associated with remnants of concrete. Vaterite was also detected in coatings in the Silt Unit suggesting that this unit has entrained concrete fragments in the area of Borehole B98-13. The Fill Unit at both boreholes also contains abundant asphalt covered pebbles of angular basalt.

In general, coatings other than calcite or asphalt are not at all common in the borehole samples. Orange and yellow-stained grains occur, but the stains are very thin and did not provide enough mass for identification of a discrete phase by microprobe. A group of such grains was examined by XRD and found to contain chlorite (Table 4-sand and gravel fraction). The association of chlorite with an orange coating suggests that the chlorite is an iron-bearing variety.

No discrete chromium- or manganese-bearing phases were found by XRD, indicating that any such minerals are less than 5% in concentration. Of the minerals identified by XRD, those most likely to provide reactive sites for chromium are the clay minerals which tend to incorporate iron, particularly chlorite and smectite.

With reference to the microprobe results summarized in Table 5, the phases with the highest chromium content are rare grains of chromite, iron-titanium oxides, spinel, and iron metal. Figure 2 shows backscattered electron (BSE) images of representative textures of these phases in the Silt Unit. Chromite (Figure 2A, grain with about 57% chromium), and iron-titanium oxides and spinel (Figure 2B, zoned grain with up to 15% chromium) may be naturally occurring as they would be consistent with the abundant basaltic content of the borehole material. Iron metal (Figure 2C, 4.6% chromium) is probably associated with the man-made fill material. Chromium-bearing metallic grains were identified not just in the Fill Unit, but also in the Silt and Aquifer Units (Table 5).

The microprobe data show that some of the metallic grains which have high chromium content are depleted of chromium around their edges, indicating the grains underwent leaching. For example, an x-ray map of chromium distribution in a grain of metallic iron (image X-1 in Appendix B) from the Fill Unit shows decreased chromium in the corroded rim of the grain. Similarly, some grains of chromium-bearing metallic iron were also found to have iron oxide or iron aluminum silicate crusts which were depleted of chromium (Figure 2C), indicating either the occurrence of leaching or at a lack of secondary chromium mineralization.

In contrast to the rare chromium-rich grains, a fine-grained iron-bearing aluminum silicate phase (FeAlSi in Table 5) was identified by microprobe to be the most common chromium-bearing phase, but with relatively lower chromium content (Figure 2D, 0.5% chromium). Inspection of the WDS quantitative results for chromium in the microprobe report

(Appendix B) shows that many of the chromium values for iron-bearing aluminum silicate in the Silt Unit in B98-13 (sample 56) are in the range of 0.05% (500 ppm) or less. Although this amount of chromium is low relative to discrete chromium minerals such as chromite, 500 ppm is still more than ten times a probable natural background for the Vancouver area. The average chromium content of the iron aluminum silicate is difficult to determine from the data; the probe report suggests a value of about 0.15% for the Silt Unit in B98-13 (sample 56). The chromium content of iron aluminum silicate in the Silt Unit in B98-12 (sample 72) appears to be higher than in B98-13 but still less than a percent. The iron aluminum silicate phase is also found in the Aquifer Unit at both boreholes (Table 5). The microprobe report indicates that some of the iron aluminum silicate phase had no detectable chromium at all, indicating concentrations below the reported chromium detection limit of 200-400 ppm by WDS.

## DISCUSSION

The distribution and textural characteristics of the iron-bearing aluminum silicate phase identified by microprobe indicate that it is the same material that was identified as clay minerals by XRD. The microprobe results show that the phase is most concentrated in the Silt Unit and the SEM images show it to be very fine grained. XRD data show that corresponding clay minerals are most abundant in the Silt Unit. Although the iron aluminum silicate material is too fine-grained to yield a discrete description by microprobe, XRD provides identification of a unique set of minerals (illite, chlorite, smectite, and kaolinite) with chlorite and smectite the two most likely to have high iron content.

Since the microprobe found a few hundred to a few thousand parts per million chromium in the iron aluminum silicate, the data suggest that iron-bearing chlorite and smectite may be preferentially incorporating chromium. Not only is the concentration of these clay minerals elevated in the Silt Unit relative to the other Units, but also the bulk chromium content of the Silt Unit exceeds that of the other units in each respective borehole (Figure 3). Additionally the silt-size fractions of the coarser units contain elevated chromium relative to the bulk samples (dotted pattern in Figure 3). Therefore both the mineral and chemical distribution demonstrate that chromium is preferentially associated with fines containing the clay minerals, chlorite and smectite.

The mineralogical data do not establish the specific type of interaction between chromium and the clay minerals. For example, chromium-bearing chlorite could occur in which chromium is an essential part of the chlorite structure. Such binding might provide relative long-term immobility for precipitated chromium. Alternatively, chromium could occur as a coprecipitate in the clayey material, an adsorbed phase on a clay mineral surface, or an exchangeable ion. The various types of binding would have different degrees of permanence for immobilizing chromium, depending on reactivity with future ground water composition. Because of detection limits, the chromium concentrations would have to be higher than those found in these boreholes in order to determine the nature of chromium binding by the mineralogical methods used here.

## CONCLUSIONS

With respect to the objectives of the study, several chromium-bearing phases have been found and can be placed in three general groups:

1. Metallic materials associated with man-made fill,
2. Chromite, iron and titanium oxides, and other igneous minerals associated with basalts, and
3. Iron-bearing clay minerals.

A second objective was to determine if phases were present that could be expected to react with chromium in an attenuation process. The iron-bearing clay minerals in the Silt and Aquifer Units represent such phases and they are common.

The goal of the study was to determine if there is sufficient evidence for the natural attenuation of chromium. Sufficient evidence is not available from the mineralogical data at hand. Chromium appears to be somewhat concentrated in the clay minerals, which is consistent with an attenuation process. However, the concentrations are not sufficient to determine the nature of the binding or the presence of a discrete chromium-bearing mineral. Therefore the permanence of attenuation under present or future conditions could not be determined.

## REFERENCES

Brindley, G.W. and Brown, G., 1980, Crystal structures of clay minerals and their x-ray identification: Mineralogical Society, Monograph No. 5, 495 p.

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Moore, Duane M. And Reynolds, Robert C., Jr., 1986, X-ray diffraction and the identification and analysis of clay minerals: New York, Oxford University Press, 332 p.

Reynolds, R.C., Jr. and Reynolds, Robert C., III, 1996, Newmod for Windows. The calculation of one-dimensional x-ray diffraction patterns of mixed-layer clay minerals: R.C. Reynolds, Jr., 8 Brook Road, Hanover, New Hampshire, 25 p.

Roy F. Weston, 1998, Final sampling and analysis plan, addendum 5, Frontier Hard Chrome, Vancouver, Washington: prepared for U.S. Environmental Protection Agency, Work Assignment No. 46-38-027N, 13 p., 1 fig., 3 tabs., 1 app.

Roy F. Weston, 1999, Site conditions technical memorandum, June 1998 soil sampling results, Frontier Hard Chrome, Vancouver, Washington: prepared for U.S. Environmental Protection Agency, Work Assignment No. 46-38-027N, 4 p., 2 figs., 4 tabs., 3 app.

## Figures

1. Index map of the Frontier Hard Chrome
2. Selection of BSE images
3. Distribution of chromium concentration with depth

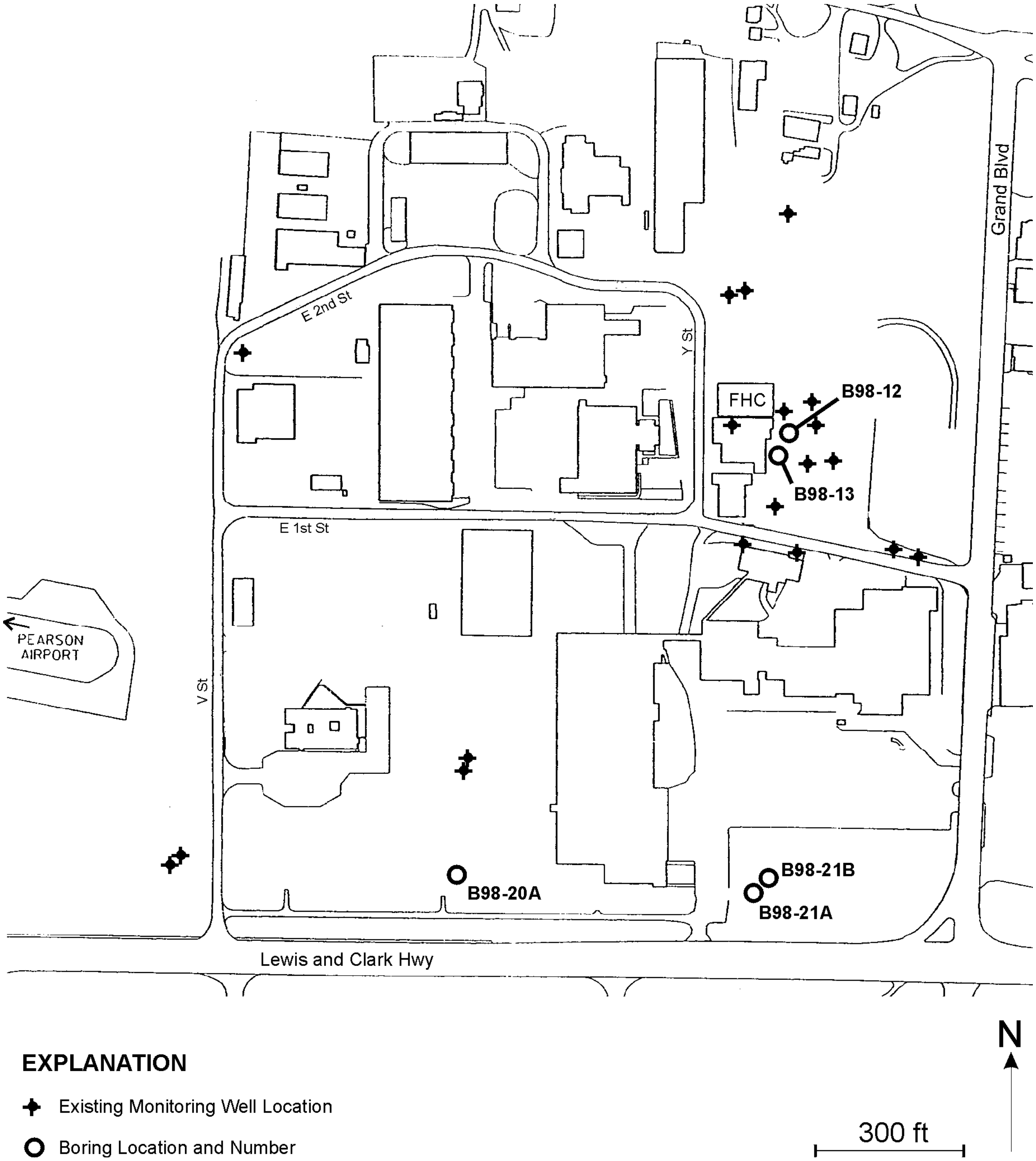

Figure 1. Index map of the vicinity of the former Frontier Hard Chrome building (FHC) and nearby boreholes. Samples from B98-13 and B98-12 underwent mineralogical analysis. Map is modified from Roy F. Weston (1999); newer roads along the south border of map are not shown.

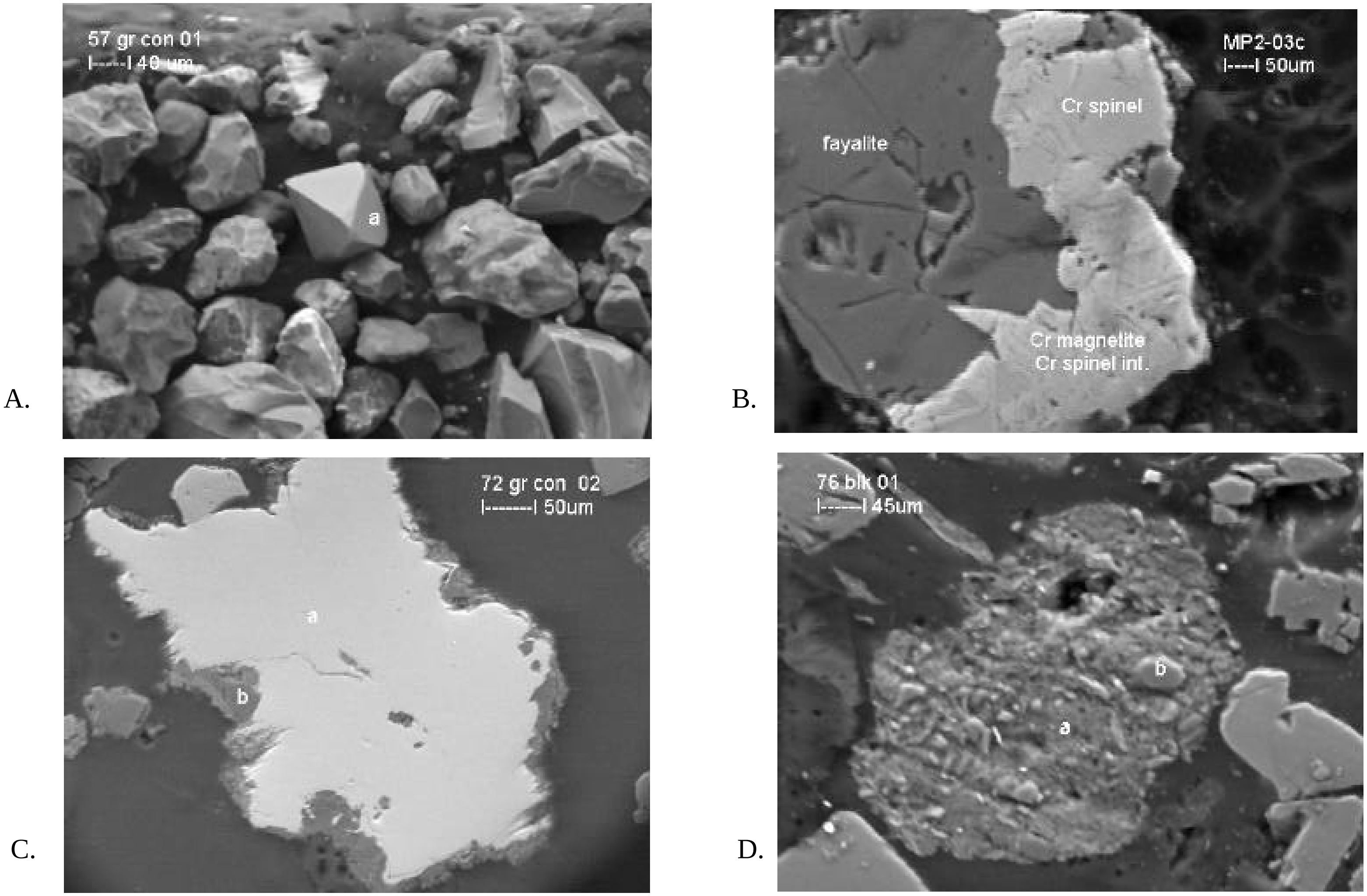

Figure 2. Selection of BSE images that show representative textures of chrome-bearing phases.

| | | %Cr |
|---|---|---|
| A. 98182357, B98-13, Silt Unit | Chromite at (a). | 57 |
| B. 98182356, B98-13, Silt Unit | Cr-bearing spinel zones in Cr-bearing magnetite on fayalite. | 15 |
| C. 98182372, B98-12, Silt Unit | Cr-bearing iron (a) rimmed with Cr-free Fe Al silicates (b). | 4.6 |
| D. 98182376, B98-12, Aquifer Unit | Fe Al silicates (a) with trace Cr in soft matrix. Quartz grain at (b). | 0.5 |

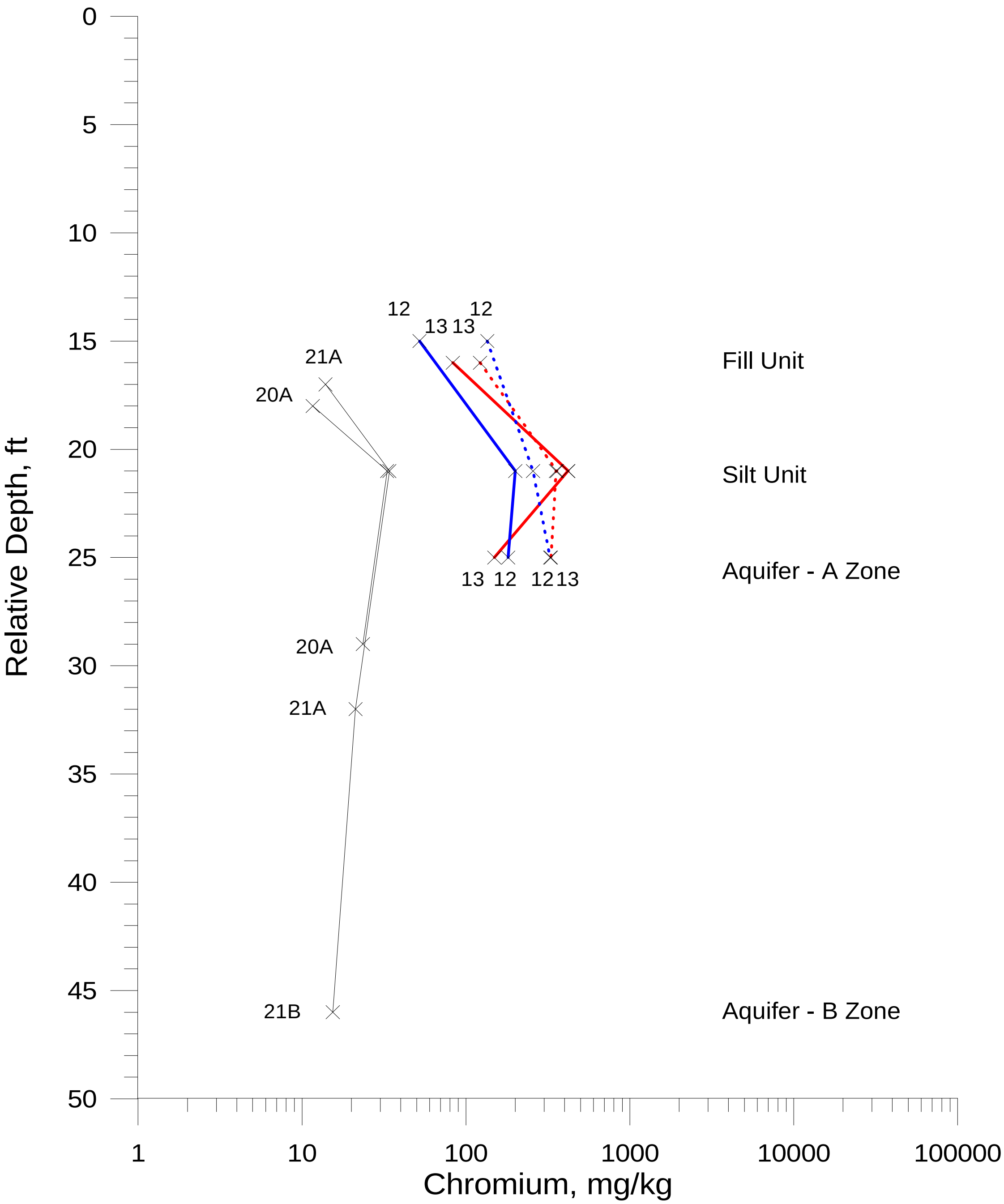

Figure 3. Distribution of chromium concentration with relative depth. Concentration profiles are labeled for boreholes B98-13, B98-12, B98-20A, B98-21A, and B98-21B (deep). Solid lines are for bulk samples from all wells; dotted lines are for the combined silt and clay size fractions from B98-13 and B98-12. Depths are normalized relative to the Silt Unit in B98-13 at 21 ft.

## Tables

1. Field sample and corresponding laboratory sample numbers
2. Inorganic analyses of soil samples
3. Phases discussed in report and appendices
4. Summary list of minerals identified by XRD
5. Summary list of minerals identified by SEM/EPMA

Table 1. Field samples and corresponding laboratory size-separates selected for mineralogical analysis by x-ray diffraction (XRD) and scanning electron microscopy/electron microprobe (EM). Field lithologic descriptions by Roy F. Weston (1999) are in bold.

| Lab Number EPA | Field Number Weston | Size Fraction mm | Cum Size cum% | XRD analysis | EM analysis |
|---|---|---|---|---|---|
| **Borehole B98-13** | | | | | |
| **Fill Unit at 16 ft** | | **silty sand with gravel** | | | |
| 98184301 | SBR1-9813-0160 | field sample | | | |
| 98182379 | SBR1-9813-0160 | 4 cut pebbles | | x | |
| 98182350 | SBR1-9813-0160 | >2 | 47.3 | x | x |
| 98182351 | SBR1-9813-0160 | 0.5-2 | 20.6 | | x |
| 98182352 | SBR1-9813-0160 | 0.07-0.5 | 18.2 | x | x |
| 98182353 | SBR1-9813-0160 | <0.07 | 13.9 | x | |
| **Silt Unit at 21 ft** | | **silt** | | | |
| 98184302 | SBR1-9813-0210 | field sample | | | |
| 98182380 | SBR1-9813-0210 | 1 cut pebble | | | |
| 98182354 | SBR1-9813-0210 | >2 | 16.6 | x | |
| 98182355 | SBR1-9813-0210 | 0.5-2 | 5.1 | x | |
| 98182356 | SBR1-9813-0210 | 0.07-0.5 | 14.7 | x | x |
| 98182357 | SBR1-9813-0210 | <0.07 | 63.5 | x | x |
| **Silt Unit at 21 ft** | | **silt** | | | |
| 98184302DU | SBR1-9813-0210 | field sample | | | |
| 98182381 | SBR1-9813-0210 | 1 cut pebble | | | |
| 98182358 | SBR1-9813-0210 | >2 | 15.8 | | |
| 98182359 | SBR1-9813-0210 | 0.5-2 | 7.6 | | |
| 98182360 | SBR1-9813-0210 | 0.07-0.5 | 9.7 | x | |
| 98182361 | SBR1-9813-0210 | <0.07 | 66.9 | x | |
| **Aquifer A-zone at 25 ft** | | **silty gravel** | | | |
| 98184303 | SBR1-9813-0250 | field sample | | | |
| 98182382 | SBR1-9813-0250 | 6 cut pebbles | | | |
| 98182362 | SBR1-9813-0250 | >2 | 55.3 | | |
| 98182363 | SBR1-9813-0250 | 0.5-2 | 9.1 | | |
| 98182364 | SBR1-9813-0250 | 0.07-0.5 | 12.7 | x | x |
| 98182365 | SBR1-9813-0250 | <0.07 | 23.0 | x | x |
| **Borehole B98-12** | | | | | |
| **Fill Unit at 16 ft** | | **silt with gravel** | | | |
| 98184304 | SBR1-9812-0160 | field sample | | | |
| 98182383 | SBR1-9812-0160 | 7 cut pebbles | | x | |
| 98182366 | SBR1-9812-0160 | >2 | 32.6 | | |
| 98182367 | SBR1-9812-0160 | 0.5-2 | 24.5 | | |
| 98182368 | SBR1-9812-0160 | 0.07-0.5 | 24.4 | x | |
| 98182369 | SBR1-9812-0160 | <0.07 | 18.5 | x | |
| **Silt Unit at 22 ft** | | **silt** | | | |
| 98184305 | SBR1-9812-0220 | field sample | | | |
| 98182384 | SBR1-9812-0220 | 2 cut pebbles | | | |
| 98182370 | SBR1-9812-0220 | >2 | 20.1 | | |
| 98182371 | SBR1-9812-0220 | 0.5-2 | 6.0 | | |
| 98182372 | SBR1-9812-0220 | 0.07-0.5 | 12.7 | x | x |
| 98182373 | SBR1-9812-0220 | <0.07 | 61.2 | x | |
| **Aquifer A-zone at 26 ft** | | **silty gravel** | | | |
| 98184306 | SBR1-9812-0260 | field sample | | | |
| 98182385 | SBR1-9812-0260 | 8 cut pebbles | | | |
| 98182374 | SBR1-9812-0260 | >2 | 49.8 | | |
| 98182375 | SBR1-9812-0260 | 0.5-2 | 8.4 | | |
| 98182376 | SBR1-9812-0260 | 0.07-0.5 | 15.2 | x | x |
| 98182377 | SBR1-9812-0260 | <0.07 | 26.6 | x | x |

Table 2. Inorganic analyses of soil samples collected April-May, 1998, Frontier Hard Chrome site (from Weston, 1999).

| lab number | sample | al | sb | as | ba | be | cd | ca | cr | cr6 | co | cu | fe | pb | mg | mn | ni | k | se | na | th | va | zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | borehole-depth | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulk Samples |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98184301 | 13-16 | 18600 | 4.5 | 5.3 | 172 | 0.918 | 0.3 | 8060 | 83.2 | 4 | 13.4 | 33.1 | 36400 | 285 | 4630 | 505 | 23.4 | 1200 | 10 | 468 | 4 | 116 | 162 |
| 98184302 | 13-21 | 24500 | 4.5 | 5.1 | 209 | 1.35 | 0.44 | 8500 | 421 | 26.1 | 17.6 | 65.4 | 40900 | 26.1 | 5960 | 1190 | 32.5 | 1560 | 10 | 341 | 4 | 97.8 | 112 |
| 98184302d | 13-21dup | 23300 | 4.5 | 5.7 | 204 | 1.35 | 0.3 | 8380 | 420 |  | 17.9 | 64.8 | 40000 | 24.3 | 5800 | 1210 | 32.1 | 1470 | 15 | 321 | 4 | 96.1 | 111 |
| 98184303 | 13-25 | 21400 | 4.5 | 4 | 234 | 1.05 | 0.2 | 5030 | 149 | 17.8 | 14.8 | 33.3 | 37800 | 9.1 | 4890 | 640 | 21.1 | 1120 | 10 | 475 | 4 | 117 | 75.3 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Fine Fraction |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98182353 | 13-16 | 40500 | 4.5 | 4.8 | 388 | 1.55 | 1.31 | 11800 | 122 |  | 15.5 | 142 | 45000 | 257 | 4770 | 922 | 27.4 | 1840 | 10 | 452 | 4 | 117 | 390 |
| 98182357 | 13-21 | 29300 | 4.5 | 8 | 207 | 1.4 | 0.23 | 7320 | 360 |  | 9.07 | 55.3 | 38100 | 39.4 | 5770 | 357 | 28.7 | 1460 | 14 | 249 | 4 | 78.5 | 116 |
| 98182361 | 13-21dup | 25700 | 4.5 | 10 | 210 | 1.34 | 0.27 | 8430 | 355 |  | 11.3 | 47.4 | 38900 | 42.8 | 5930 | 503 | 28 | 1690 | 11 | 284 | 4 | 83.8 | 122 |
| 98182365 | 13-25 | 39200 | 4.5 | 4 | 427 | 1.5 | 0.3 | 5740 | 331 |  | 16.9 | 56.5 | 43500 | 33.8 | 5770 | 897 | 28 | 1590 | 10 | 330 | 4 | 103 | 105 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulk Samples |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98184304 | 12-16 | 12200 | 4.5 | 4 | 130 | 0.691 | 0.75 | 27700 | 52 | 4 | 11.3 | 34.3 | 30600 | 254 | 4290 | 395 | 21.7 | 869 | 10 | 635 | 4 | 85.9 | 161 |
| 98184305 | 12-22 | 19400 | 4.5 | 4 | 192 | 1.21 | 0.52 | 7290 | 200 | 4 | 13.8 | 73.1 | 43000 | 46.6 | 5390 | 457 | 26.1 | 1570 | 10 | 388 | 4 | 89.1 | 120 |
| 98184306 | 12-26 | 20000 | 4.5 | 6.4 | 188 | 1.18 | 0.2 | 5370 | 181 | 11.6 | 14.1 | 28.9 | 38100 | 8.7 | 5060 | 474 | 25.2 | 1090 | 10 | 471 | 4 | 125 | 74.6 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Fine Fraction |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98182369 | 12-16 | 25400 | 4.5 | 7.2 | 325 | 1.06 | 1.6 | 45200 | 135 |  | 15.7 | 74.3 | 38400 | 729 | 5510 | 740 | 31.6 | 1540 | 10 | 746 | 4 | 101 | 336 |
| 98182373 | 12-22 | 25000 | 4.5 | 4.6 | 230 | 1.43 | 0.56 | 7380 | 257 |  | 14 | 47.6 | 37400 | 58.2 | 5980 | 459 | 25 | 1700 | 10 | 343 | 4 | 95.8 | 134 |
| 98182377 | 12-26 | 31100 | 4.5 | 4 | 275 | 1.46 | 0.23 | 5900 | 327 |  | 16.5 | 42.3 | 40100 | 15.4 | 5550 | 635 | 26.9 | 1380 | 11 | 385 | 4 | 108 | 88.7 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulk Samples |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98184307 | 21A-7.5 | 11800 | 4.5 | 4 | 104 | 0.62 | 0.2 | 3630 | 13.9 |  | 8.83 | 14.1 | 22200 | 21.6 | 2830 | 323 | 12.7 | 593 | 10 | 384 | 4 | 66.4 | 61.4 |
| 98184308 | 21A-12 | 28500 | 4.5 | 11 | 229 | 1.63 | 0.2 | 5550 | 34.1 |  | 16.3 | 30.7 | 39500 | 13 | 6750 | 778 | 24.6 | 1270 | 10 | 255 | 4 | 102 | 84.4 |
| 98184309 | 21A-22.5 | 15300 | 4.5 | 5.6 | 150 | 1.16 | 0.2 | 6250 | 21.2 |  | 14.3 | 27.2 | 39900 | 7.5 | 5120 | 520 | 19.1 | 1150 | 10 | 730 | 4 | 131 | 68.9 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98184310 | 20A-6.5 | 5650 | 4.5 | 4 | 71 | 0.36 | 0.2 | 2710 | 11.6 |  | 5.58 | 8.26 | 13400 | 4.8 | 2430 | 182 | 10.4 | 579 | 10 | 312 | 4 | 36.9 | 42.6 |
| 98184311 | 20A-10 | 26600 | 4.5 | 5.5 | 239 | 1.58 | 0.28 | 5830 | 33 |  | 15.3 | 32.3 | 35400 | 14 | 6620 | 820 | 26.9 | 1420 | 10 | 281 | 4 | 87.5 | 81.8 |
| 98184312 | 20A-17.5 | 19100 | 4.5 | 5.4 | 170 | 1.15 | 0.2 | 5180 | 23.5 |  | 13.3 | 23.2 | 35600 | 5.7 | 4620 | 474 | 18.4 | 815 | 10 | 658 | 4 | 111 | 63.8 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98224550 | 21B-38 | 7370 | 4.5 | 4.8 | 83.8 | 0.526 | 0.2 | 3620 | 15.4 |  | 8.64 | 15.5 | 18900 | 4.5 | 5460 | 277 | 20.6 | 1040 | 10 | 331 | 4 | 46.2 | 35.8 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | mg/L |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 98182378 | sieve blank | 20 | 45 | 40 | 1 | 1 | 2 | 70.6 | 5 |  | 5 | 9 | 10 | 25 | 25 | 1.1 | 10 | 700 | 100 | 87.7 | 40 | 3 | 9.5 |
| 98182378d | sieve blank dup | 20 | 45 | 40 | 1 | 1 | 2 | 70.7 | 5 |  | 5 | 8.2 | 10 | 25 | 20 | 1.3 | 10 | 700 | 100 | 87.3 | 40 | 3 | 11 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| detection limit |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Table 3. Phases discussed in this report. The abbreviations and analytical procedures (XRD or EM) are noted. Phases described by EM that are not discrete identifiable minerals are noted by -- . The phase, FeAlSi, is placed under clay minerals because of the fine-grained texture apparent in SEM images.

| XRD | EM | SILICATES | | IDEAL FORMULA |
|---|---|---|---|---|
| | | Silica | | |
| x | | QZ | quartz | $SiO_2$ |
| x | | CR | cristobalite | $SiO_2$ |
| | | Other Silicates | | |
| x | | FS | feldspar | $(K,Na,Ca)Al(Al,Si)_3O_8$ |
| x | x | PX | pyroxene | $(Ca,Mg,Fe)_2(Si,Al)_2O_6$ |
| x | x | AM | amphibole | $(Na,Ca)_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ |
| x | | MI | mica | $K(Al,Mg,Fe)_{2\text{-}3}(Al,Si)_4O_{10}(OH,F)_2$ |
| | x | FA | fayalite | $Fe_2SiO_4$ |
| | | Clay Minerals | | |
| x | | IL | illite | $(K,Na,Ca)(Mg,Fe,Al)_{2\text{-}3}(Al,Si)_4O_{10}(OH)_2$ |
| x | | SM | smectite | $Ca_{0.5}(Mg,Fe)_3(Si,Al)_4O_{10}O(OH)_2.4H_2O$ |
| x | | CH | chlorite | $(Mg,Fe)_6AlSi_3O_{10}(OH)_8$ |
| x | | KA | kaolinite | $Al_2Si_2O_5(OH)_4$ |
| | x | FeAlSi | iron-bearing aluminum silicate | -- |
| | | OXIDES | | |
| x | x | MT | magnetite | $Fe_3O_4$ |
| x | | MH | maghemite | $Fe_2O_3$ |
| x | x | CT | chromite | $FeCr_2O_4$ |
| | x | ILM | ilmenite | $FeTiO_3$ |
| | x | TMT | titanomagnetite | $Fe(Fe,Ti)_2O_4$ |
| | x | SP | spinel | $MgAl_2O_4$ |
| | x | FeHox | iron hydroxide | -- |
| | | CARBONATES | | |
| x | | CA | calcite | $CaCO_3$ |
| x | | AR | aragonite | $CaCO_3$ |
| x | | VT | vaterite | $CaCO_3$ |
| | x | SI | siderite | $FeCO_3$ |
| | | METALS | | |
| | x | FE | iron or steel | -- |
| | x | Cr/Ti | chromium/titanium phase | – |

Table 4.  Summary list of minerals as identified by x-ray diffraction (Appendix A).

**Explanation:**

| | | | | | |
|---|---|---|---|---|---|
| Phases | am-amphibole | ca-calcite | il-illite | mt-magnetite | sm-smectite |
| | ar-aragonite | ch-chlorite | ka-kaolinite | px-pyroxene | vt-vaterite |
| | ct-cristabolite | fs-feldspar | mi-mica | qz-quartz | |

Amount of phases  major mineral +++  minor mineral ++  trace mineral +
Not Analyzed  --

| Borehole | silica | | silicate | | | clay mineral | | | | oxide | carbonate | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth | qz | ct | fs | px/am | mi | il | sm | ch | ka | mt | ca | ar | vt |
| | **Silt and Clay Size Fraction (<0.07 mm)** | | | | | | | | | | | | |
| **B98-13** | | | | | | | | | | | | | |
| **16 ft** | +++ | + | +++ | + | + | + | + | + | | + | + | | |
| **21 ft** | +++ | + | +++ | + | ++ | ++ | ++ | ++ | + | + | | | |
| **21 ft dup** | +++ | + | +++ | + | ++ | ++ | + | ++ | + | + | | | |
| **25 ft** | +++ | + | +++ | + | ++ | ++ | ++ | ++ | | | | | |
| **B98-12** | | | | | | | | | | | | | |
| **16 ft** | +++ | + | +++ | + | + | + | + | + | | + | ++ | | |
| **22 ft** | +++ | + | +++ | + | + | + | ++ | ++ | | + | ++ | | |
| **26 ft** | +++ | + | +++ | + | ++ | ++ | ++ | ++ | + | + | + | | |
| | **Fine Sand Size Fraction (0.07-0.5 mm)** | | | | | | | | | | | | |
| **B98-13** | | | | | | | | | | | | | |
| **16 ft** | +++ | | +++ | + | + | | | + | | + | + | | |
| **21 ft** | +++ | + | +++ | ++ | ++ | | ++ | ++ | | + | | | |
| **21 ft dup** | +++ | + | +++ | + | ++ | | ++ | ++ | | + | + | | |
| **25 ft** | +++ | | +++ | + | ++ | | ++ | ++ | | + | ++ | | |
| **B98-12** | | | | | | | | | | | | | |
| **16 ft** | +++ | + | +++ | + | + | | | + | | + | + | | |
| **22 ft** | +++ | + | +++ | ++ | ++ | | ++ | ++ | | + | + | | |
| **26 ft** | +++ | + | +++ | + | ++ | | ++ | ++ | | + | + | | |
| | **Sand and Gravel Size Fraction (>0.5 mm)** | | | | | | | | | | | | |
| **B98-13** | **orange oxide-coated grains** | | | | | | | | | | | | |
| **21 ft** | +++ | | ++ | + | + | | + | + | | | | | |
| **B-98-13** | **white carbonate-coated grains** | | | | | | | | | | | | |
| **16 ft** | ++ | ++ | +++ | | | | + | | | | +++ | | + |
| **21 ft** | ++ | + | +++ | + | | | + | | | | +++ | | + |
| **B98-12** | | | | | | | | | | | | | |
| **16 ft** | +++ | ++ | +++ | | | | + | | | | +++ | ++ | + |
| **B-98-13** | **black uncoated basalt grains** | | | | | | | | | | | | |
| **21 ft** | + | + | +++ | ++ | | | + | | | + | | | |

Table 5. Summary list of minerals containing chromium and manganese in samples from Frontier Hard Chrome, as identified by scanning electron microscopy/electron microprobe analysis (see Appendix B).

**Explanation:**

| | | |
|---|---|---|
| Phases | am-amphibole<br>cr/ti-chromium/titanium phase<br>ct-chromite<br>fa-fayalite<br>fe-iron or steel<br>fealsi-iron-bearing aluminum silicate<br>fehox-iron hydroxide. | px-pyroxene<br>il-ilmenite<br>mt-magnetite<br>tmt-titanomagnetite or titanian magnetite<br>si-siderite<br>sp-spinel |
| Amount of phases | common phase ++ rare phase + | |
| Amount of element in phases | Cr and Mn occur in major to minor amounts where shaded, and trace amounts where not shaded. | |
| Not Analyzed -- | | |

| **Borehole** | **Chromium-bearing Phases** | | | | | | | | | **Manganese-bearing Phases** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Depth** | **px/am** | **fealsi** | **fehox** | **mt** | **ilm** | **tmt** | **ct** | **fe** | **other** | **px/am** | **fealsi** | **fehox** | **mt** | **ilm** | **tmt** | **ct** | **fe** | **other** |
| | **Silt and Clay (<0.07 mm)** | | | | | | | | | **Silt and Clay (<0.07 mm)** | | | | | | | | |
| **B98-13** | | | | | | | | | | | | | | | | | | |
| **16 ft** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| **21 ft** | | **++** | | | | **+** | **+** | | | | **++** | | | | **+** | **+** | | |
| **25 ft** | | | | | | **+** | **+** | **+** | | | | | | | **+** | **+** | **+** | |
| **B98-12** | | | | | | | | | | | | | | | | | | |
| **16 ft** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| **21 ft** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| **25 ft** | | **+** | | | | **+** | | | | | **+** | | | | **+** | | | |
| | **Fine Sand (0.07-0.5 mm)** | | | | | | | | | **Fine Sand (0.07-0.5 mm)** | | | | | | | | |
| **B98-13** | | | | | | | | | | | | | | | | | | |
| **16 ft** | | | **+** | | | **+** | **+** | | | | | **+** | | **+** | **+** | | | |
| **21 ft** | **+** | **++** | | **+** | **+** | **+** | **+** | **+** | **sp** | **+** | **++** | | **+** | **+** | **+** | | **+** | |
| **25 ft** | **+** | **+** | | | **+** | **+** | | **+** | **cr/ti** | **+** | | | | **+** | **+** | | **+** | |
| **B98-12** | | | | | | | | | | | | | | | | | | |
| **16 ft** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| **21 ft** | **+** | **++** | **+** | | | **+** | | **+** | si | **+** | **++** | | | **+** | **+** | | **+** | si |
| **25 ft** | | **+** | | | | | | | | | **+** | | | | | | | |
| | **Sand and Gravel (>0.5 mm)** | | | | | | | | | **Sand and Gravel (>0.5 mm)** | | | | | | | | |
| **B98-13** | | | | | | | | | | | | | | | | | | |
| **16 ft** | **+** | | | **+** | | **+** | | | **fa?** | | | | **+** | **+** | **+** | | | |