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# The transport of mine tailings as suspended sediment in the Belle Fourche River, west-central South Dakota, USA

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ABSTRACT Millions of t of mine tailings that were discharged into Whitewood Creek in South Dakota between the late 1800's and 1978 were transported through the Belle Fourche River or deposited on its flood plain. Arsenic concentrations in overbank deposits along the Belle Fourche River record the dilution of transported mine tailings by uncontaminated alluvium during overbank flow. Arsenic concentrations decrease in a downstream direction and are smallest in sediments that were deposited by the highest streamflow. Background and pre-1978 suspended-sediment data collected at gauging stations on the Belle Fourche River also indicate increasing dilution of mine tailings by uncontaminated alluvium with increasing distance downstream and at higher streamflow. Calculations of pre-1978 mine-tailings transport at two gauging stations along the Belle Fourche River illustrate the capacity of the Belle Fourche River to transport a large, fine-grained sediment load, and the ability of flood plains to store large amounts of fine-grained sediment.

## INTRODUCTION

Millions of t of finely milled mine tailings were discharged into Whitewood Creek at Lead, South Dakota (Fig. 1) between the late 1800's and 1978. During this time, mine tailings were transported

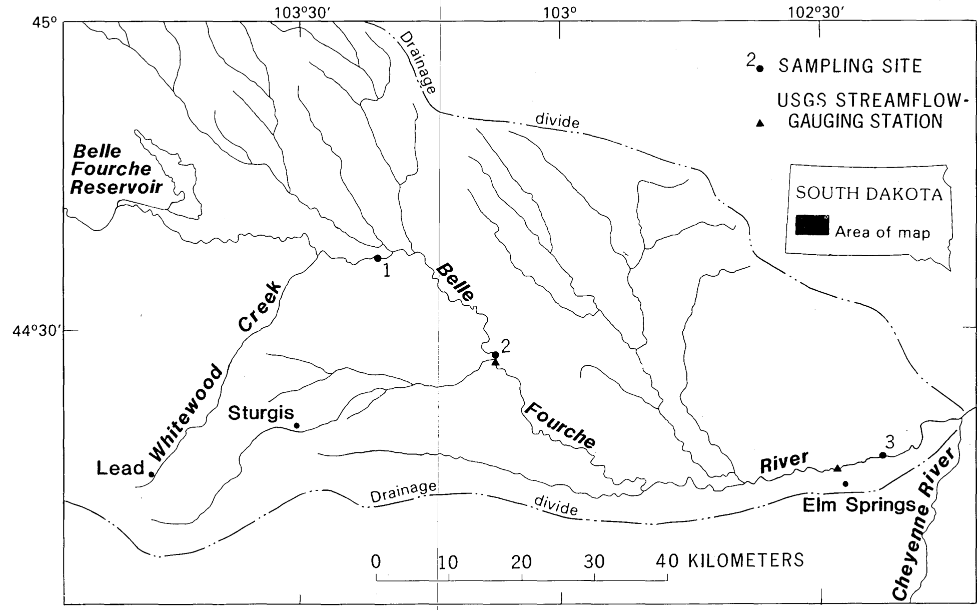

Fig. 1 Location of the study area.

by Whitewood Creek into the Belle Fourche River, and by the Belle Fourche River into the Cheyenne River (Fig. 1) (Goddard, 1987). The mine tailings contain large concentrations of arsenic; their presence in channel and flood-plain sediments has caused environmental controversy and concern. The discharge of mine tailings at Lead has provided an opportunity to observe the response of a river system to a marked increase in the availability of suspended sediment. The transport and deposition of the arsenic-contaminated mine tailings also illustrate the fate of sediment-related pollutants that are introduced into a river system from a point source. The effects of the mine-tailings discharge on the Belle Fourche River are of particular interest because the Belle Fourche River has a greater capacity to store sediment than does Whitewood Creek, and because there was less dilution of mine tailings by uncontaminated alluvium in the Belle Fourche River than in the Cheyenne River.

This paper compares two sources of information on the transport of mine tailings and uncontaminated alluvium in the Belle Fourche River during the period of mine-tailings discharge into Whitewood Creek (between the late 1800's and 1978). Arsenic concentrations in overbank sediments that were deposited along the Belle Fourche River prior to 1978 provide information about the degree to which mine tailings transported by the Belle Fourche River during that period were diluted by uncontaminated alluvium at different levels of overbank flow, and at different distances downstream of the mining area. Suspended-sediment data collected at two U.S. Geological Survey gauging stations (Fig. 1) before and after 1978 also provide information on the transport of mine tailings and uncontaminated alluvium in the Belle Fourche River. The suspended-sediment data are combined with sediment-chemistry data obtained from analyses of flood-plain sediments in order to estimate yearly mine-tailings transport at the two gauging stations prior to 1978.

## THE STUDY AREA

Gold mining in and around Lead, South Dakota, produced the mine tailings discussed in this article. The ore mined and milled at Lead consists mostly of silicate, iron and magnesium carbonate, and metallic sulfide minerals (Noble, 1950). Gold is associated with arsenopyrite (FeAsS) in the ore body. The arsenopyrite in the mine tailings causes them to have arsenic concentrations that can exceed 5000 $\mu$g/g (Goddard, 1987). Stamp mills that produce sand-size and finer particles, and rod-and-ball mills that produce silt-size and finer particles have been used to crush ore at Lead. In recent years, some of the sand-size tailings have been used to backfill mine shafts. By 1976, after 100 years of production, the major mining company in the Lead area had milled about 125 million t of ore (Homestake Gold Mine, 1976).

Starting in the late 1800's and continuing until December 1977, milled tailings were discharged into Whitewood Creek (Fig. 1) via a small tributary. Whitewood Creek was an efficient conduit of mine tailings into the Belle Fourche River because much of the Whitewood Creek channel downstream of Lead is steep and incised into bedrock. The Belle Fourche River, however, is a meandering stream with an alluvial flood plain. The drainage area of the Belle Fourche River increases from about 15 200 km$^2$ just downstream of the mouth of Whitewood Creek to about 18 700 km$^2$ at the confluence of the Belle Fourche River with the Cheyenne River. An irrigation system that was built in 1910 diverts most of the water and sediment at all levels of flow from the Belle Fourche River to the Belle Fourche

Reservoir at a location that is about 30 river km upstream from the mouth of Whitewood Creek (Fig. 1).

Two U.S. Geological Survey streamflow gauging stations are located along the Belle Fourche River downstream from Whitewood Creek (Fig. 1). The average annual flow at the gauging station near Sturgis (the upstream station) is 7.8 $m^3 s^{-1}$ (based on 40 years of record). Depth-integrated suspended-sediment samples were collected at this station during water years 1956-1958 and 1983-1986. The average annual flow at the gauging station near Elm Springs (the downstream station) is 10.2 $m^3 s^{-1}$ (based on 54 years of record). Depth-integrated suspended-sediment samples were collected at this station during water years 1959-1960, 1975-1976, and 1980-1986. High streamflow typically occurs during the spring snowmelt. Intense storms, which occur mostly in the summer months, also cause high streamflows.

## ARSENIC CONCENTRATIONS OF OVERBANK SEDIMENTS

Mine tailings mixed with uncontaminated alluvium have been deposited along flood plains downstream of Lead since the late 1800's. The arsenic-contaminated sediments along the Belle Fourche River have a distinctive orange-brown color that facilitates their identification. Onsite observations indicate that more than one-half of the arsenic-contaminated flood-plain sediments along the Belle Fourche River are contained in overbank as opposed to point-bar sediments. The arsenic-contaminated overbank deposit along the Belle Fourche River is typically as much as 2 m thick and extends about 90 m away from the channel along the insides of meander bends.

Geochemical conditions in and around the contaminated flood-plain deposit indicate that dilution with uncontaminated sediment rather than desorption of arsenic from sediments into the alluvial aquifer is the dominant mechanism for decreasing arsenic concentrations of sediments. Carbonate minerals in the ore body and in nearby rock units, plus the lime that is added to the mine tailings during the milling procedure, limit the desorption of arsenic from sediments by preventing acid formation. The geochemical stability of the arsenic that is associated with sediments in the Belle Fourche River flood plain is reflected by dissolved arsenic concentrations in the alluvial aquifer that are orders of magnitude smaller than those of surrounding sediments (Goddard, 1987). Arsenic concentrations of flood-plain sediments along the Belle Fourche River, therefore, indicate the degree to which the mine tailings that were transported into the Belle Fourche River by Whitewood Creek were diluted by uncontaminated alluvium as they were transported through the Belle Fourche River.

Pre-1978 arsenic-contaminated overbank sediments along the Belle Fourche River were sampled (Marron, 1988) at sites 1, 2, and 3 shown in Fig. 1. Samples were collected at depth increments of 0.4 m or less from auger holes spaced along transects that were perpendicular to the river at these sites. Sediment within 0.3 m of the flood-plain surface was not sampled because it may have been deposited when mine tailings were no longer being discharged at Lead. Three transects, containing 4 to 6 auger holes each, extended away from the channel on the inside of meander bends at each site. Arsenic concentrations were measured using a semiquantitative colorimetric method (O'Leary & Meier, 1986). Within flood-plain cross sections, arsenic concentrations are generally smaller by a factor of 2 to 3 in the part of the arsenic-contaminated deposit that is farthest from, and commonly highest above, the river channel. This trend appears to reflect a greater degree of dilution of the mine tailings by uncontaminated alluvium at the very high levels of streamflow that were required to deposit the sediments with smaller arsenic concentrations in the positions that they occupy relative to the Belle Fourche River channel.

Average arsenic concentrations of the more contaminated, near-channel sediment samples decrease in a downstream direction. These samples, by definition, were collected from auger holes that yielded one or more samples with more than 600 μg/g of arsenic at sites 1 and 2, and more than 400 μg/g of arsenic at site 3. Surveys of augered sites indicate that most of these sediments are presently located between about 1 and 3 m above the thalweg at sites near the gauging stations (sites 2 and 3). According to pre-1978 rating curves for the Belle Fourche River at the gauging stations, these elevations correspond to streamflows between about 30 and 300 $m^3$ $s^{-1}$ at the gauging station near Sturgis and between about 40 and 400 $m^3$ $s^{-1}$ at the gauging station near Elm Springs.

The number of samples in the near-channel, more-contaminated category at sites 1, 2, and 3 were 18, 13, and 13 respectively. Average values plus or minus 1 standard deviation of arsenic concentrations at sites 1, 2, and 3 were 1720 ± 670, 1430 ± 410, and 550 ± 150 μg/g respectively. Downstream decreases in average arsenic concentrations of the arsenic-contaminated overbank sediments appear to reflect greater dilution of the mine tailings by uncontaminated alluvium at greater distances downstream of the mining area. The average arsenic concentration of the near-channel sediments at site 1 are considered to approximate the average arsenic concentration of undiluted mine tailings, because a source of uncontaminated alluvium that was capable of substantially diluting the mine tailings did not exist between site 1 and Lead during the period of interest. Although standard deviations are large, downstream decreases in average arsenic concentrations imply a dilution of about 25% between sites 1 and 2, and a dilution of about 70% between sites 1 and 3. These dilution factors apply to sediment transport by streamflows between about 30 and 300 $m^3$ $s^{-1}$ at the gauging station near Sturgis, and between about 40 and 400 $m^3$ $s^{-1}$ at the gauging station near Elm Springs.

## SUSPENDED-SEDIMENT TRANSPORT DATA

Relations between suspended-sediment data collected at gauging stations on the Belle Fourche River downstream of Whitewood Creek before and after 1978 provide information on the transport of mine tailings and uncontaminated alluvium in the Belle Fourche River prior to 1978. The graphs in Fig. 2 were plotted using suspended-sediment data collected prior to 1978, and in water years 1982-1986. The latter data were collected at least 5 years after the cessation of mine-tailings discharge. During those 5 years, the easily transportable nature of the finely milled mine tailings enabled Whitewood Creek and the Belle Fourche River to remove much of the readily available mine tailings in channel and flood-plain storage sites. Although an indeterminate amount of the sediment transported by the Belle Fourche River during water years 1982-1986 still consisted of mine tailings coming out of channel and flood-plain storage along Whitewood Creek and the Belle Fourche River, the suspended-sediment data collected during that period do provide a reasonable representation of the maximum background suspended-sediment transport (the transport of nonmining or uncontaminated sediment in the Belle Fourche River) before and after 1978.

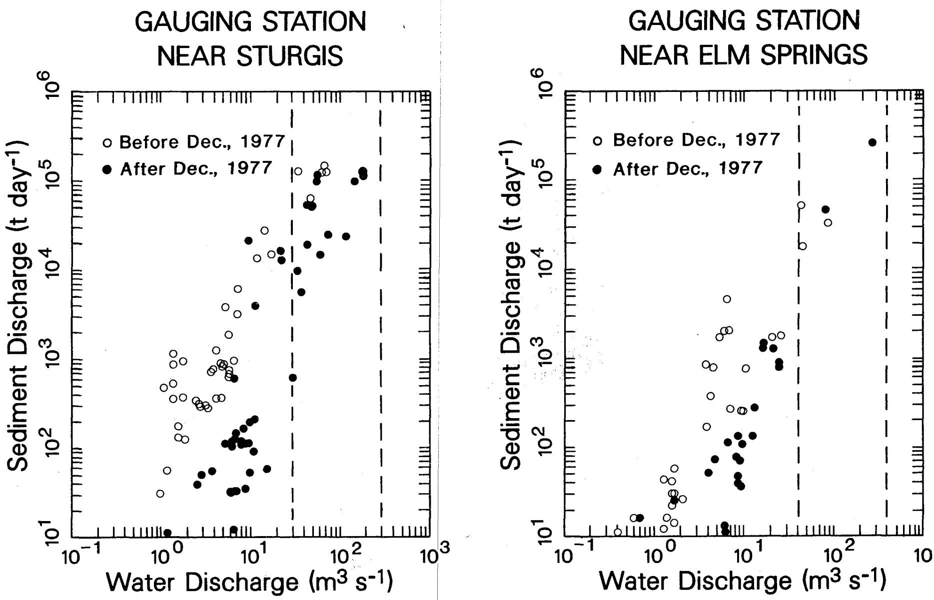

Fig. 2 Suspended sediment data, Belle Fourche River gauging stations. Dashed lines bracket water discharges corresponding to elevations of the more-contaminated, near-channel sediments.

Differences between pre-1978 suspended-sediment transport and background suspended-sediment transport at the gauging station near Sturgis are distinct (Fig. 2). For streamflows less than about 20 $m^3 s^{-1}$, pre-1978 values of suspended-sediment discharge plot about 1.5 log cycles higher than values of background suspended-sediment discharge. It appears, therefore, that prior to 1978, the suspended-sediment load at streamflows smaller than 20 $m^3 s^{-1}$ consisted almost exclusively of mine tailings at the gauging station near Sturgis.

The differences between the two sets of data decrease at higher levels of streamflow. The difference between pre-1978 and background suspended-sediment data for streamflows between about 30 and 300 $m^3 s^{-1}$ (Fig. 2) is consistent with the estimate, obtained using average arsenic concentrations of overbank sediments, of an average 25% dilution of mine tailings by uncontaminated alluvium at those streamflows, prior to 1978. The convergence of the pre-1978 and background suspended-sediment transport data at high streamflows suppports the onsite observation that, within flood-plain cross sections, arsenic concentrations are smallest in deposits of the highest streamflows.

Differences between pre-1978 suspended-sediment transport and background suspended-sediment tranport at the gauging station near Elm Springs are more subtle than those at the gauging station near Sturgis. Pre-1978 values of suspended-sediment discharge for streamflows less than about 30 $m^3 s^{-1}$ are generally greater than values of background suspended-sediment discharge, although there is some overlap in the data sets (Fig. 2). The limited data for streamflows greater than about 30 $m^3 s^{-1}$ indicate similar pre-1978 and background suspended-sediment transport. It appears, therefore, that prior to 1978, mine tailings probably constituted only a small fraction of the sediment transported at streamflows greater than about 30 $m^3 s^{-1}$ at the gauging station near Elm Springs. This conclusion is consistent with the estimate, obtained using average arsenic concentrations of overbank sediments, of an average 70% dilution of mine tailings by uncontaminated alluvium for streamflows between about 40 and 400 $m^3 s^{-1}$ prior to 1978, and an even greater degree of dilution for streamflows greater than about 400 $m^3 s^{-1}$ during this time.

## CALCULATION OF MINE-TAILINGS TRANSPORT

Suspended-sediment data and average arsenic concentrations of overbank sediments were combined to estimate the pre-1978 yearly rate of mine-tailings transport at the two gauging stations on the Belle Fourche River downstream of Whitewood Creek. Pre-1978 suspended-sediment data were used together with streamflow data in order to estimate total suspended-sediment transport. Average arsenic concentrations of overbank sediments were used as a measure of the percentage of the suspended load that consisted of mine tailings at different levels of streamflow. Because of the paucity of data at high streamflow, and problems associated with calculations of suspended-sediment transport (Ferguson, 1987), the estimates of mine-tailings transport presented in this paper are tentative.

Suspended-sediment loads were calculated by defining relations between instantaneous streamflow and suspended-sediment discharge (Fig. 3), using those relations to calculate a daily suspended-sediment load for each average daily streamflow, and summing the daily suspended-sediment loads. The group average method (Glysson, 1987) was used to define the relations between instantaneous streamflow and sediment load. This method, which avoids bias resulting from regression of log-transformed data (Ferguson, 1987),

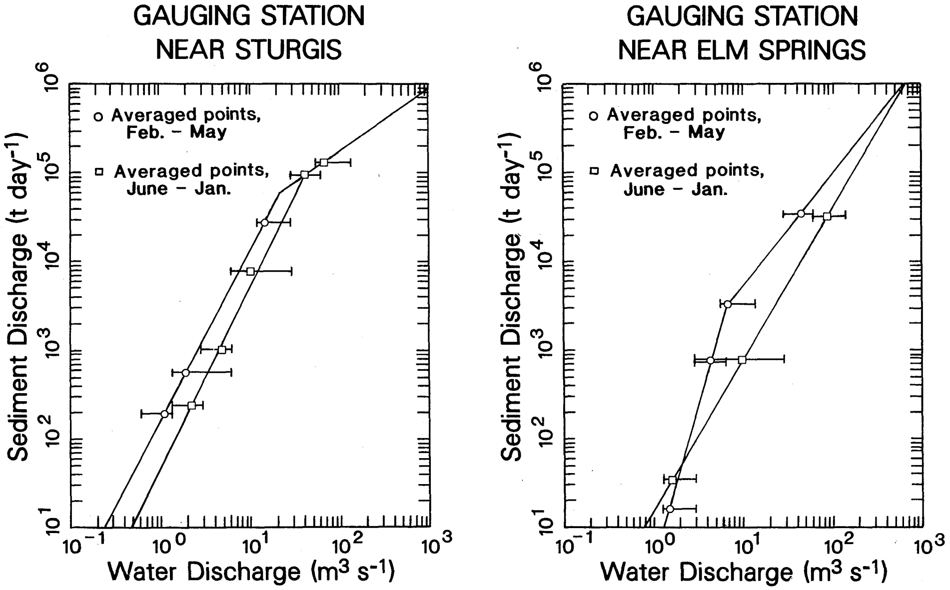

Fig. 3 Suspended-sediment transport curves, Belle Fourche River gauging stations. Horizontal bars bracket range of water discharge over which data was averaged.

entails calculating the arithmetic averages of instantaneous values of streamflow and suspended-sediment discharge for small ranges of streamflow. Streamflow ranges (Fig. 3) were expanded in cases where measurements were few and variable. The averages were plotted on log-log paper, and were connected by straight-line segments. Separate curves were used for February to May and June to January.

At the gauging station near Sturgis, an estimated total of 111 million t of suspended sediment were transported during water years 1947-1977. Of that, about 48 million t were transported by streamflows of less than 30 $m^3$ $s^{-1}$, about 62 million t were transported by streamflows between 30 and 300 $m^3$ $s^{-1}$, and about 1 million t were transported by streamflows greater than 300 $m^3$ $s^{-1}$. Average arsenic concentrations of overbank sediments at site 2 suggest that prior to 1978, about 25% of the suspended-sediment transported by streamflows between 30 and 300 $m^3$ $s^{-1}$, and about 70% of the suspended-sediment transported by streamflows in excess of 300 $m^3$ $s^{-1}$ at the gauging station near Sturgis consisted of uncontaminated alluvium. The combined suspended-sediment load estimates and dilution factors suggest a pre-1978 mine-tailings transport rate of about 3.2 million t $year^{-1}$ at the gauging station near Sturgis.

At the gauging station near Elm Springs, an estimated total of 74 million t of suspended sediment were transported during water years 1935-1977. Of that sediment, about 8 million t were tranported by streamflows that were less than 40 $m^3$ $s^{-1}$, about 43 million t were transported by streamflows between 40 and 400 $m^3$ $s^{-1}$, and about 23 million t were transported by streamflows greater than 400 $m^3$ $s^{-1}$. Average arsenic concentrations of overbank sediments at site 3 suggest that prior to 1978, about 70% of the suspended-sediment transported by streamflows between 40 and 400 $m^3$ $s^{-1}$, and about 90% of the suspended-sediment transported by streamflows in excess of 400 $m^3$ $s^{-1}$ at the gauging station near Elm Springs consisted of uncontaminated alluvium. The combined suspended-sediment load estimates and dilution factors suggest a pre-1978 mine-tailings tranport rate of 0.6 million t $year^{-1}$ at the gauging station near Elm Springs.

The total mine-tailings discharge at Lead during about a 100 year period was about 100 million t. The average rate of mine-tailings discharge, therefore, was about 1 million t $year^{-1}$. In this context, the estimated pre-1978 mine-tailings transport rate of 3.2 million t $year^{-1}$ at the gauging station near Sturgis appears unrealistically large. A likely cause of this disparity relates to the timing of the collection of suspended-sediment data. All five of the pre-1978 suspended-sediment measurements at streamflows greater than 30 $m^3$ $s^{-1}$ at the gauging station near Sturgis were made on 4 July, 1956. Average daily streamflow of more than 30 $m^3$ $s^{-1}$ (which occurred an average of 19 days per year between 1947 and 1978 at that gauging station), had not occurred since May 1954. Channel storage of mine tailings during the 2 years of low flow preceding 4 July, 1956 probably created an unusual reservoir of readily mobilized sediment that resulted in unusually large suspended-sediment concentrations on 4 July, 1956. Although the limited pre-1978 suspended-sediment data for the gauging station near Sturgis yield an estimate of yearly mine-tailings transport that is unrealistically high, the data do demonstrate the capacity of the Belle Fourche River at the gauging station near Sturgis to transport a large sediment load. The estimated mine-tailings transport rate of 0.6 million t $year^{-1}$ at the gauging station near Elm Springs during the period of mine-tailings discharge (between the late

1800's and 1978) is considerably smaller than the average yearly rate of mine-tailings discharge at Lead. Much of the difference between these rates probably is due to flood-plain deposition of mine tailings between Lead and the gauging station near Elm Springs. Millions of t of mine tailings that presently are contained in arsenic-contaminated flood-plain sediments along the Belle Fourche River (Marron, 1987) attest to the capacity of flood plains to store large amounts of fine-grained sediments.

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## REFERENCES

Ferguson, R. I. (1987) Accuracy and precision of methods for estimating river loads. Earth Surf. Processes 12, 95-104.

Glysson, G. D. (1987) Suspended-sediment transport curves. USGS Open-File Rept. 87-218.

Goddard, K. E. (1987) Composition, distribution, and hydrological effects of contaminated sediments resulting from the discharge of gold-mining wastes to Whitewood Creek at Lead and Deadwood, South Dakota. USGS Wat. Res. Invest. Rept. 87-4051.

Homestake Gold Mine (1976) Homestake Centennial, 1876 - 1976. Homestake Mining Co., Lead, South Dakota, USA.

Marron, D. C. (1987) Floodplain storage of metal-contaminated sediments downstream of a gold mine at Lead, South Dakota. In: Chemical Quality of water and the Hydrologic Cycle (ed. by R. C. Averett & D. M. McKnight), 193-209. Lewis Publishers, Inc., Chelsea, Michigan, USA.

Marron, D. C. (1988) Field and laboratory data describing physical and chemical characteristics of a metal-contaminated floodplain deposit downstream from Lead, west-central South Dakota. USGS Open-File Rept. 88-349.

Noble, A. J. (1950) Ore mineralization in the Homestake Gold Mine, Lead, South Dakota. Bull. Geol. Soc. Am. 61, 221-252.

O'Leary, R. M., & Meier, A. L. (1986) Analytical methods used in geochemical exploration, 1984. USGS Circular 948.