Dirty-water events at Rocky Mountain Hot Springs and their correlation with other short-lived phenomena

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The Radium (British Columbia) and Miette (Alberta) hot springs occasionally produce "dirty" water that carries varying amounts of solid particles in suspension. Dirty-water events in the period 1959–1983 were caused either by heavy rains (or rapid snowmelt) or by earthquakes with magnitudes of 6.9 or greater, between 740 and 2300 km distant from the springs, in Alaska, Idaho, and Montana. Rainfall-induced events at Miette appear to require at least 34 mm of rain within a 48 h period. Associated decreases in water temperatures and dissolved-solids concentrations and changes in the ionic and isotopic compositions of the spring waters result from mixing of deep thermal water with cooler, less mineralized shallow water. By contrast, the earthquake-triggered events did not have significant thermal or geochemical effects. Suspended solids in the dirty waters represent surficial materials (including vegetation debris) and possibly residues from dissolution of carbonate rocks. At Miette Hot Springs the dirt contains secondary sulfur species (native sulfur and gypsum) derived from the HS$^-$ content of the spring water.

Les sources thermales de Radium (Colombie-Britannique) et de Miette (Alberta) produisent occasionnellement des eaux "troubles" qui contiennent différentes quantités de particules solides en suspension. Les apparitions des eaux troubles pendant la période de 1959–1983 furent causées par des pluies intenses (ou des fontes nivales rapides), ou par des tremblements de terre de magnitude 6,9 ou plus en Alaska, Idaho et Montana soit à des distances de 740 à 2300 km des sources thermales. Il faut au moins 34 mm de pluie en une période de 48 h pour provoquer l'apparition d'eau trouble à Miette. Les baisses de température de l'eau et des teneurs en solides dissous associées, ainsi que les changements de la composition ionique et isotopique de l'eau des sources, résultent d'un mélange des eaux thermales de grande profondeur avec des eaux plus froides, moins minéralisées et de plus faible profondeur. Au contraire, l'apparition d'eau trouble due à des tremblements de terre ne présente pas ces effets thermiques ou géochimiques importants. Les particules en suspension dans les eaux troubles représentent des matériaux de surface (incluant des débris de végétaux) et possiblement des résidus de dissolution de roches carbonatées. Dans les eaux thermales de Miette on observe parmi les suspensoïdes des minéraux secondaires de soufre (soufre natif et gypse) dérivés du contenu en HS$^-$ de l'eau des sources.

[Traduit par le journal]

Introduction

The Radium Hot Springs in Kootenay National Park, British Columbia (latitude 50°38'07"N, longitude 116°02'21"W), and the Miette Hot Springs in Jasper National Park, Alberta (latitude 53°07'50"N, longitude 117°46'12"W), occasionally produce discoloured, sediment-contaminated water for short periods of time. Two dirty-water events that affected the Radium Hot Springs for periods of up to several days were reported by Swenson (1964) and van Everdingen (1972). Apparently, such sediment contamination can be triggered by other short-lived phenomena, e.g., large earthquakes or rapid infiltration during heavy rainfall or rapid snowmelt.

Effects of major earthquakes on water levels in wells at considerable distances from their epicentres were reported after the 1959 Hebgen Lake (Montana) earthquake (da Costa 1964; Swenson 1964), after the great 1964 Alaska earthquake (Scott and Render 1964; Gabert 1965; Vorhis 1967), and after the 1979 St. Elias earthquake in southeastern Alaska (Logel 1980). Effects on springs, usually in the form of turbidity and discolouration (red, brown, or black) of the spring water were reported by Swenson (1964) and Marler (1964) for the Hebgen Lake earthquake and by Vorhis (1967) and van Everdingen (1972) for the 1964 Alaska earthquake.

The turbidity and colour presumably represent fine clastics in transit in the karst and possibly solution residues and (or) precipitates dislodged from fractures or conduit walls by the ground shaking and associated oscillating movements of the water. Temperature, dissolved-solids content, and discharge rate would be affected if new connections were established with sources of water of different temperature and mineralization.

Earthquake effects should appear shortly after the initial shocks, and they can be either short lived or long term (Marler 1964).

During rapid infiltration of rain or snowmelt, surficial materials can be carried into fractures or solution channels in bedrock near hot-spring outlets (van Everdingen 1972, p. 99). The admixture of the relatively cool, fresh water would cause a drop in spring-water temperature and mineralization, and possibly an increase in discharge rate. Such effects can be expected to appear up to several hours after the start of the rapid snowmelt or heavy rainfall.

Because of the relatively short-lived nature of such events, the information recorded has generally been limited to visual observations of sediment contamination and a few temperature measurements made by local staff of the bathing establishments at the hot-spring sites. During recent dirty-water events that occurred at Miette Hot Springs and Radium Hot Springs in 1982 and 1983, some additional information was obtained and samples were collected for the determination of chemical and isotopic composition of the spring water; isotopic composition of local rainfall; concentration, composition, and particle-size distribution of the sediment; and isotopic composition of sulfur species contained in the sediment.

This paper presents observations on dirty-water events that occurred at the Radium and Miette hot springs between 1959 and 1983. Although sediment and cold-water problems are apparently also experienced at the Sulphur Mountain Hot Springs in Banff National Park, Alberta (e.g., van Everdingen 1970, 1972), information on such occurrences is, un-

TABLE 1. Dirty-water events at Miette Hot Springs, Jasper National Park, and Radium Hot Springs, Kootenay National Park,

Date	Events at Miette Hot Springs		Events at Radium Hot Springs	
	Start and duration[a]	Other observations	Start and duration[a]	Other observations
1. 18−08−1959	Unknown	Dirty water[c]	About 00:40 MST; 36−48 h	Dark chocolate-brown water; 1°C rise in temperature, some increase in flow rate[d]
2. 27−03−1964	Early morning of 28−03; about 2 days	Spring 2 dirty; minor drop in temperatures[c]	About 23:00 MST; about 1 day	Reddish brown, very muddy water; 6°C drop in temperature[e]
3. 13−06−1964	—	—	Late afternoon; intermittently for 3 days	Extremely muddy; 16°C drop in temperature[e]
4. 03−07−1964	—	—	About 17:00 MST; intermittently for 2 days	Turbidity in hot pool; noticeable drop in temperature[e]
5. 31−05−1965	Start not known; about 1½ days	Dirty water; 8−10.5°C drop in temperatures[c]	—	—
6. 05−08−1969	Start not known; about 7 days	Very dirty water; 15−34°C drop in temperatures[f]	—	—
7. 30−07−1972	16:00 MDT; less than 1 day	Water turned black; no temperature change noted[c]	Start not known; less than 1 day	Silty, muddy water; no temperature change noted[f]
8. 12−08−1972	15:00 MDT; less than 1 day	Water turned black; no temperature change noted[c]	—	—
9. 28−02−1979	Shortly before 15:00 MST; 2−3 days	Water "discoloured"; no obvious temperature change[c]	15:40 MST; less than 1 day	Brownish black muddy water; no temperature or flow-rate change noted[c]
10. 14−09−1979	—	—	02:30 MDT; about 1 day	Some muddiness in hot pool; small drop in temperature[c]
11. 05−05−1980	—	—	18:00 MDT; duration not known	Murky water in hot pool; no temperature change noted[c]
12. 03−06−1980	About 13:30 MDT; about 10 days	Water turned black; 15−21.5°C drop in temperatures[c]	—	—
13. 16−06−1980	—	—	Start and duration not known	Sedimentation in hot pool; no temperature change noted[c]
14. 04−07−1982	15:00 MDT; 7 days, with short interruption on 07−07	Water muddy, later extremely dirty; 6.5−10.5°C drop in temperatures[c]	—	—
15. 15−07−1982	Late evening; about 1 day	Water murky to very muddy; 3.5−6.5°C drop in temperatures[c]	—	—
16. 28−10−1983	Shortly before 10:00 MDT; less than 1 day	Water turned black; 1°C drop in temperatures[c]	About 10:00 MDT; less than 1 day	Murky water in hot pool and spring source; no temperature or flow-rate change[c]

[a]Times given are local times: MST = Mountain Standard Time = Universal Time (UT) minus 7 h; MDT = Mountain Daylight Time = UT minus 6 h.
[b]Precipitation during 2 day periods preceding the events (rounded off to nearest mm) and epicentre distances are indicated separately for Miette (M) and Radium (R); figures in parentheses indicate significant rain after the start of an event.
[c]Information supplied by Parks Canada staff.
[d]From Swenson (1964, p. 161).
[e]From van Everdingen (1972, pp. 96, 99).
[f]Occurrence of dirty-water event confirmed *after* study of other information had indicated its likelihood.

fortunately, "...either not recorded, or is only retained for a short period of time" (Superintendent, Banff National Park, personal communication, 10 July 1980).

The available information allows correlation of most of the dirty-water events with the short-lived phenomena that caused them. The analytical results serve to explain some of the observed thermal and geochemical effects, and they give an indication of the source(s) of the sediments discharged by the hot springs.

Sources of data

Data on spring-water temperatures and on the occurrence of sediment problems were provided by Parks Canada staff at Jasper, Radium, and Calgary. Water temperatures were reportedly measured in each of the three Miette Hot Springs only occasionally before 1968 and weekly from June to August 1968, from May 1969 to March 1970, and from May 1972 onwards. Temperatures have been measured daily during recent dirty-water events. At Radium, temperatures are mea-

1959–1983, and their correlation with large earthquakes and rainfall

Precip., (mm H_2O)[b]		Earthquake information			
		Time[a]	Location of epicentre	Richter magnitude	Distance from springs (km)[b]
M	10	23:37:15 MST on 17-08-59	44.83°N, 111.08°W (Hebgen Lake, Montana)	7.1	M 1042
R	4				R 743
M	0	20:36:13 MST	61.05°N, 147.48°W (Anchorage, Alaska)	8.5	M 1987
R	0				R 2258
R	15	—	—	—	—
R	8	—	—	—	—
M	34	—	—	—	—
M	77 (+103)	—	—	—	—
M	2	15:45:16 MDT	56.77°N, 135.19°W (near Sitka, Alaska)	7.6	M 1222
R	0				R 1467
M	2	03:42:07 MDT	51.3°N, 179.3°W (Andreanoff Islands)	5.8	M 4063
					R 4285
M	4	14:27:07 MST	60.64°N, 141.60°W (St. Elias Mts., Alaska)	7.1	M 1656
R	0				R 1930
R	0	—	—	—	—
R	0	—	—	—	—
M	67 (+127)	—	—	—	—
R	0	—	—	—	—
M	40 (+34)	—	—	—	—
M	38	—	—	—	—
M	11	08:06:06 MDT	44.05°N, 113.89°W (Borah Peak, Idaho)	6.9	R 1043
R	3				R 744

sured daily in the hot pool and approximately weekly in a spring-water collector constructed in 1968.

Before 1980, spring-water temperatures were measured by Parks Canada staff using thermometers calibrated in Fahrenheit degrees, and rounded off to the nearest whole degree, introducing a potential error of ±0.5°F (±0.28°C). Since 1980, measurements have been made with thermometers calibrated in Celsius degrees, and rounded off to the nearest whole degree, which introduces a potential error of ±0.5°C. Although the resulting data allow generalized conclusions, they would not allow detailed interpretation of the thermal effects in terms of mixing ratios.

Weather data (precipitation and temperature) were obtained from the Climatological Station reports for the stations closest to each spring site. For the Miette Hot Springs these were stations at the Jasper townsite, at the Sulphur Creek bridge camp, and at the Miette Hot Springs campground. For the Radium Hot Springs, data recorded at the west gate of
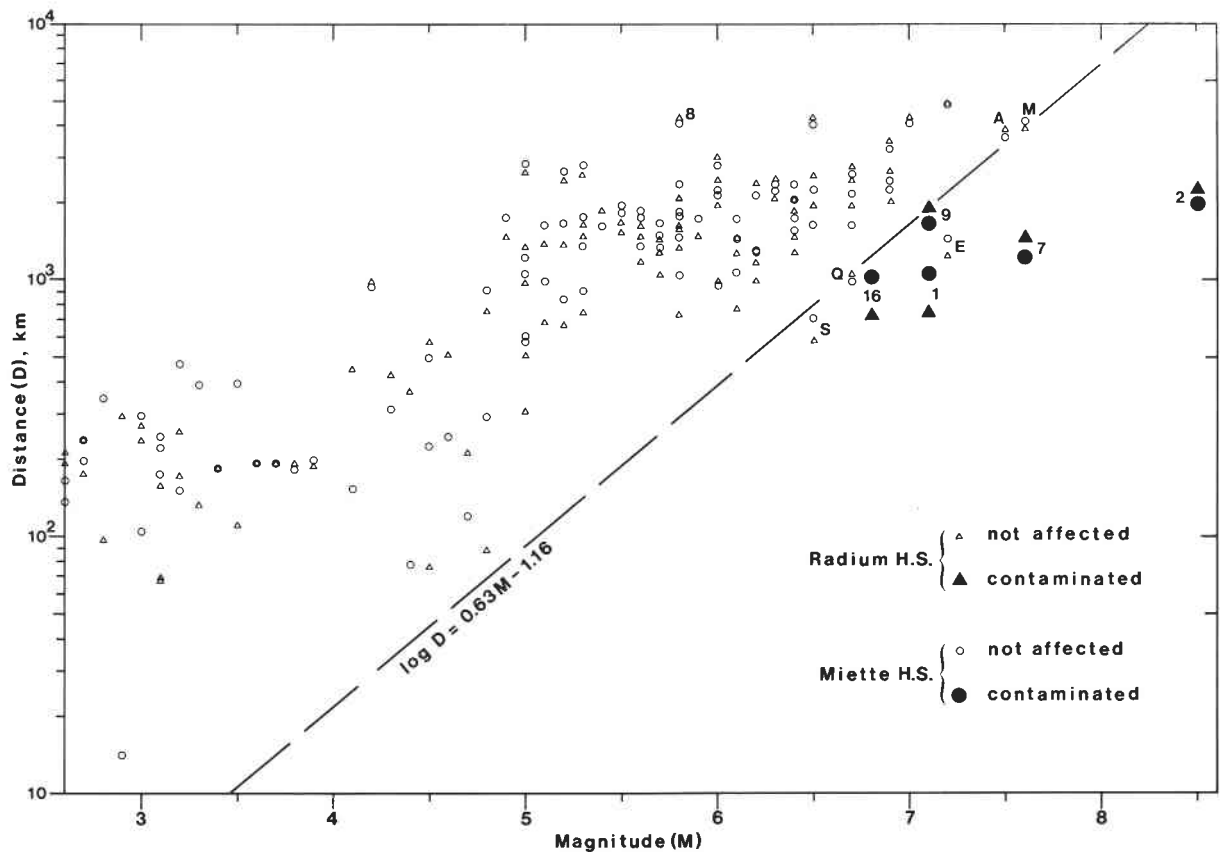
FIG. 1. Distance of epicentre from Miette and Radium hot springs vs. magnitude for selected earthquakes in North America, 1959−1983 (for explanation of letters and numbers see text and Table 1).

Kootenay National Park were used.

Earthquake data for periods during which dirty-water events occurred were provided by W. G. Milne, Pacific Geoscience Centre, Department of Energy, Mines and Resources Canada, in Sidney, British Columbia. Additional information was obtained from available catalogues of earthquakes in North America (Canada 1959−1982; Mexico 1959−1981; U.S.A. 1959−1983).

Correlation of events

Observations on the dirty-water events that occurred at Miette Hot Springs and Radium Hot Springs during the period 1959−1983 are listed in Table 1, together with information on large earthquakes and precipitation preceding the events. The initial observations obtained from Parks Canada did not list the August 1969 rainfall-induced event at Miette or the July 1972 earthquake-triggered event at Radium. The likely occurrence of these events was deduced from available information on precipitation, spring-water temperatures, and earthquakes. Both were confirmed after a further check of the observation records.

Table 1 indicates that earthquakes in Montana, Alaska, and Idaho triggered dirty-water events at both Miette and Radium in August 1959, March 1964, July 1972, February 1979, and October 1983. Correlation of the August 1972 dirty-water event at Miette with the Andreanoff Islands earthquake is questionable, as discussed below. Snowmelt might have played a minor role in the March 1964 and February 1979 events, but this is unlikely because daily mean temperatures were still well below freezing.

The earthquake-triggered events lasted from less than 1 to

about 3 days. They were characterized primarily by discharge of sediment-contaminated water. Where noted, temperature effects were minor.

A plot of magnitude versus epicentre distance from the hot springs for selected earthquakes in North America is presented in Fig. 1. The position of point 8 in Fig. 1 indicates that the Andreanoff Islands earthquake was probably not responsible for the August 1972 dirty-water event at Miette Hot Springs.

The data in Fig. 1 do not allow one to draw a definite boundary line separating earthquakes that triggered dirty-water events from those that did not. The tentative boundary line drawn in Fig. 1 suggests that dirty-water events may be caused at Radium and Miette by earthquakes for which

$$M \geq (\log D + 1.16)/0.63$$

where M is magnitude and D is distance in kilometres between the epicentre and the spring site under consideration.

According to its position in Fig. 1 (point E) the Eureka, California, earthquake of November 1980 should have caused dirty-water events at both Miette and Radium. The fact that it did not may indicate that the multiple dirty-water events experienced by the hot springs during the preceding 20 months had left the spring-system aquifers relatively clean. It is also possible that the position of the Eureka epicentre, across the cordillera from the springs, accounts for a more rapid attenuation of the available energy. A similar explanation could well apply to earthquakes near Seattle (point S in Fig. 1, magnitude 6.5), west of the Queen Charlotte Islands (point Q, magnitude 6.7), in the Aleutian Islands (point A, magnitude 7.5), and in Mexico (point M, magnitude 7.6).
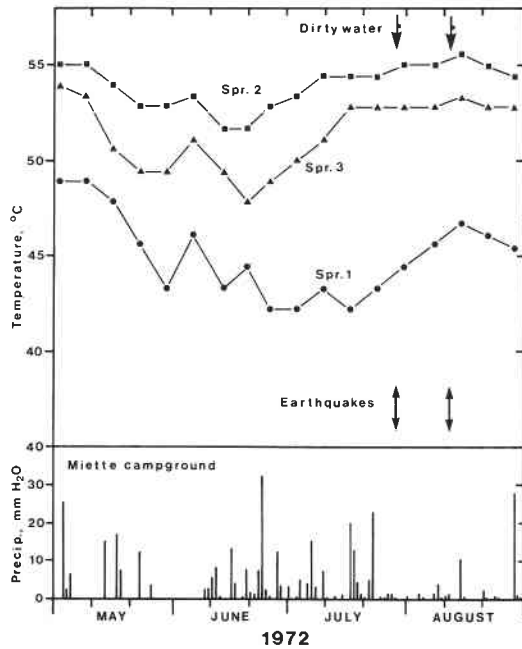
FIG. 2. Physical data for the 1972 dirty-water events at Miette Hot Springs.

FIG. 3. Physical data for the 1979 dirty-water event at Miette Hot Springs.

Rainfall has been confirmed as the cause for dirty-water events at Radium Hot Springs in only two cases, in June and July 1964 (Table 1). These events occurred when silt-laden drainage from the valley slopes above the Radium Highway (93) flowed down a hole in the highway ditch, which provided direct access to one of the subsurface spring-water channels. Sealing of the ditch bottom and installation of a culvert eliminated this local cause of dirty-water events.

The relatively minor events at Radium in September 1979 and in May and June 1980 were not related to recorded earthquakes or precipitation. Rapid snowmelt may have induced the May 1980 event. Possible alternative causes (e.g., unusually heavy traffic, construction activity, or blasting) have not been confirmed for the other two events.

No direct correlation was found between the 1980 dirty-water events at either Radium or Miette and the major eruptions of Mount St. Helens, Washington, that occurred on 18 May, 25 May, 12 June, 22 July, and 16 October 1980 (data from Christiansen and Peterson 1981).

Heavy rainfall caused dirty-water events at Miette in May 1965, August 1969, June 1980, and twice in July 1982. Snowmelt may have contributed to the May 1965 event. The data in Table 1 suggest that rainfall of 34 mm or more within 48 h is required to cause a dirty-water event at Miette. However, not every rainfall occurrence of this magnitude or larger will trigger such an event. In fact, during the period from 1970 to 1979, precipitation exceeding this required minimum magnitude occurred at Miette on at least 12 occasions without associated dirty-water events. Other conditions, such as the extent of saturation of the soil and bedrock system, will presumably influence the rainfall effect.

The rainfall-induced events at Miette lasted from 1 to 10 days. They were characterized not only by discharge of sediment-contaminated water but also by noticeable decreases in water temperatures and by changes in the chemical and isotopic compositions of the spring waters.
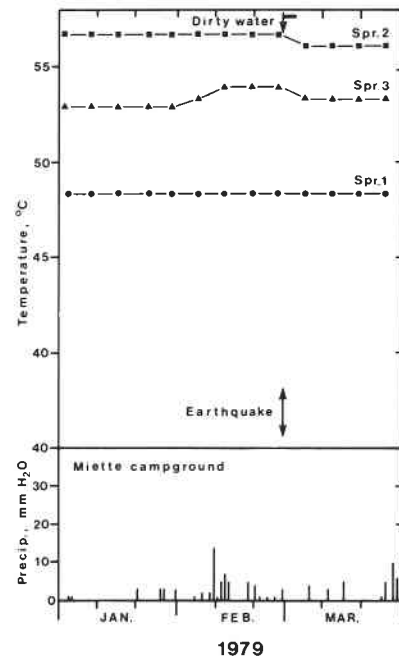
Effects of earthquake-triggered events

Water temperatures

As indicated earlier, earthquake-triggered dirty-water events had only minor effects on spring-water temperatures. This point is illustrated by temperature plots for Miette Hot Springs for the periods May–August 1972 (Fig. 2) and January–March 1979 (Fig. 3). During the most recent event of this type, in October 1983, water temperatures decreased by only 1°C at Miette, while the temperature remained constant at Radium.

Flow rates

No change was recorded in the combined discharge rate from the Radium Hot Springs during the October 1983 event. It is not known whether the rate of discharge of any of the three springs at Miette varied during that event, because no facilities exist there for the measurement of discharge rates.

Water chemistry

The 1983 dirty-water events were the first earthquake-triggered events during which water samples were collected for chemical and isotope analyses. At Radium, a further sample was collected 1 week after the event. Results of the analyses are presented in Tables 2 and 3 for Miette Hot Springs and in Table 4 for Radium Hot Springs.

Although the samples from Miette Hot Springs were too small for complete major-ion analysis, comparison of the partial analyses with the background ranges based on analyses of pre-1982 samples in Table 2 clearly indicates that only minor dilution was taking place. Comparison of the 1983 analyses for Radium Hot Springs with the background ranges based on analyses of pre-1983 samples in Table 4 shows that the concentrations of most ions were less than 15% below the earlier recorded maxima for the Radium Hot Springs. Concentrations were somewhat closer to the maxima in the 5 November sample.

In both cases the minor dilution may have been caused by the dirty-water events. It is also possible that the dilution did reflect

TABLE 2. Physical and chemical data for Miette Hot Springs[a]

	Ranges for pre-1982 samples from springs 1–3	Minima, July 1982			Minima, 28 Oct. 1983		
		Spring 1 July 6[c]	Spring 2 July 5	Spring 3 July 5	Spring 1[d]	Spring 2[d]	Spring 3[d]
Temperature (°C)	44.4–53.9	40.0	48.2	42.4	48	54	51
Conductivity (μS/cm)	1720–2086	1200	1370	1130	2160	2230	2180
pH (units)	6.7–6.9 (6.9–8.2)[b]	7.2[b]	7.2[b]	7.4[b]	6.7	6.8	6.8
Constituents (mg/L)							
Ca	330–423	221	278	223	348	366	338
Mg	54.5–76.0	45.0	56	43.9	64	66	63
Na	8.0–12.2	5.5	6.9	5.5	—	—	—
K	12.0–17.1	7.9	10.0	7.7	—	—	—
HCO_3	116–148	176.9	158.6	170.8	—	—	—
SO_4	840–1178	560	710	550	1180	1200	1120
Cl	3.0–5.6	2.6	3.2	2.5	—	—	—
F	2.3–4.6	2.1	2.6	2.2	—	—	—
SiO_2	39.0–72.0	34	40	33	—	—	—
Sum	1456–1865	1055.0	1265.3	1038.6	(1592)	(1632)	(1521)

[a]Analyses by Water Quality Branch, Inland Waters Directorate, Environment Canada, Calgary; samples collected by Parks Canada staff: 5 July 1982 and 28 October 1983.
[b]Laboratory values; original pH may have been somewhat lower than this.
[c]On 5 July 1982, samples were collected only from springs 2 and 3; it is likely that values for spring 1 were lower on 5 July than on 6 July.
[d]Samples insufficient for complete analyses.

TABLE 3. Environmental isotope data for Miette Hot Springs

Source and date of sample	^3H (TU ± 10)	δ^2H (‰ SMOW ± 3.0)	$\delta^{18}O$ (‰ SMOW ± 0.2)		$\delta^{34}S$ (‰ CDT ± 0.2)	
			In H_2O	In SO_4^{2-}	In SO_4^{2-}	In HS^-
Water samples						
Pre-1982	0	−169	−21.5 to −21.4	+14.2	+17.0 to +18.9[a]	−11.4 to −7.7[a]
Spring 1, 6–7–82	50	−157	−20.2	—	—	—
Spring 2, 6–7–82	3	−162	−21.1	—	—	—
Spring 3, 6–7–82	41	−160	−20.5	—	—	—
Rain, 11:00, 6–7–82	41	−118	−15.8	—	—	—
Rain, 15:30, 6–7–82	49	−121	−15.2	—	—	—
Spring 1, 28–10–83	13	−160 (−162)	−21.2	—	—	—
Spring 2, 28–10–83	6	−166	−21.3	—	—	—
Spring 3, 28–10–83	5	−158	−21.0	—	—	—
Mineral samples				In Ca SO_4	In $CaSO_4$	In S^0
Yellow "clay," spring 3[a]	—	—	—	—	—	−10.9
Secondary gypsum, spring 3	—	—	—	−15.0	−15.3	—
Sulfur from pool, 6–7–82	—	—	—	—	—	−12.1
Gypsum from pool, 8–7–82	—	—	—	−14.7	−13.7	—
Sulfur from pool, 28–10–83	—	—	—	—	—	−12.2 (−12.0)
Gypsum from pool, 28–10–83	—	—	—	−10.9	−13.1	—

NOTES: Analyses for ^2H, ^3H, and ^{18}O in water by Environmental Isotope Laboratory, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario (R. Drimmie); others by Stable Isotope Laboratory, Physics Department, The University of Calgary, Calgary, Alberta (M. A. Shakur). TU = tritium units; SMOW = standard mean ocean water; CDT = Cañon Diablo troilite.
[a]Analyses by H. R. Krouse, Physics Department, University of Alberta, Edmonton, Alberta.

normal seasonal variations in spring-water chemistry. In the absence of chemical data for the period immediately preceding the events it is impossible to determine the actual cause of the dilution.

Isotopic composition of the water

The isotope analyses for the 1983 samples from Miette Hot Springs (Table 3) and Radium Hot Springs (Table 4) show that in both cases the spring water was diluted with a small percentage of water with somewhat less negative δ^2H and $\delta^{18}O$ values and a small ^3H content.

Effects of rainfall-induced events

Water temperatures

The only rainfall-induced events for which detailed data are available occurred at Miette Hot Springs. Those events resulted in temporary decreases in spring-water temperatures of between 3.5 and 34°C (Table 1). The character of the temperature variations during such events is illustrated by temperature plots for the periods March–July 1980 (Fig. 4) and June–August 1982 (Fig. 5). During the latter period a second event occurred before the water temperatures had recovered fully from the first event.

TABLE 4. Physical, chemical, and environmental isotope data for Radium Hot Springs[a]

| | Ranges for pre-1983 samples from springs 1–4 | 28 Oct. 1983 (combined flow) | | | | 5 Nov. 1983 12:30 |
		10:30	11:30	12:00	14:30	
Temperature (°C)	35.3–46.5	45.0	45.0	45.0	45.0	45.0
Conductivity (µS/cm)	766–980	884[b]	881[b]	886[b]	875[b]	932
pH (units)	6.8–7.05	7.4[b]	7.5[b]	7.5[b]	7.8[b]	6.9
Constituents (mg/L)						
Ca	109–150	136	137	138	134	143
Mg	22.2–36.3	32.9	32.8	32.8	33.0	33.9
Na	9.4–16.0	17.0	14.0	14.0	14.0	15.0
K	2.1–3.3	3.3	2.8	2.8	2.7	2.8
HCO_3	206–221	213.3	213.3	207	207	207
SO_4	230–356	310	304	304	306	336
Cl	6.9–12.6	12.0	12.0	12.0	11.0	11.0
F	0.3–0.8	0.33	0.37	0.37	0.37	0.41
SiO_2	27.0–54.0	36	36	36	37	40
Sum	629.1–807.5	760.8	752.3	747.0	745.1	789.1
Stable isotope abundances						
δ^2H (‰ SMOW)		−151	−150	−153	−151	−151
$\delta^{18}O$ (‰ SMOW)		−19.1	−19.4	−19.4	−19.5	−19.5
^3H (TU)		4	7	0	0	0

NOTES: SMOW = standard mean ocean water; TU = tritium units.
[a]Chemical analyses by Water Quality Branch, Inland Waters Directorate, Environment Canada, Calgary, Alberta; 1983 samples collected by Parks Canada staff; isotope analyses by Environmental Isotope Laboratory, University of Waterloo, Waterloo, Ontario.
[b]The pH values may be too high and conductivities too low due to 10 day delay between collection and analyses.

Water chemistry

The three chemical analyses listed in Table 2 for samples collected during the first rainfall-induced event of 1982 show the lowest dissolved-solids concentrations recorded so far for the three Miette Hot Springs. Concentrations may have been even lower during the first day of the event, when water temperatures were several degrees lower than during the sample collection (Fig. 5).

Comparison of these analyses with the background ranges for pre-1982 samples in Table 2 shows that the concentrations of all but one of the major ions were lower than the minima recorded earlier; in some instances they were less than half the maximum recorded values. Bicarbonate concentrations were all higher than the earlier measured maximum. A gradual recovery was indicated by the analyses for three later samples. The decrease in dissolved-solids concentration and the associated changes in chemical composition are illustrated for spring 2 by lines "a" and "b" in Fig. 6. The changes in water chemistry and the decreases in temperature can only be explained by assuming that the "normal" spring water was diluted with a cooler water having a lower dissolved-solids concentration but a higher HCO_3^- content.

Several attempts were made to deduce the actual chemical composition of the cooler water and the mixing ratios represented by the available samples. It quickly became apparent that the compositions of the 1982 samples could not be derived through simple mixing of normal spring water (represented by line "a" in Fig. 6) with a shallow water of fixed composition. This dilemma could only be resolved by assuming either that the composition of the shallow water varied with time, or that the normal spring water already represented dilution of deep thermal water with a small percentage of shallow water, or both. The latter assumption appears most likely to be correct. The results of any mixing calculations for these samples are therefore open to considerable doubt.

The results of one of the calculation attempts are illustrated in Fig. 6; it was assumed that line "a" represents a mixture of 85% thermal water (indicated by line "c") and 15% shallow water (indicated by line "d"). The sample of 5 July 1982 (line "b") would then represent an approximate 1:1 mixture of the two calculated components. The analyses for springs 1 and 3 in Table 2 represent mixtures containing less than 50% thermal water.

All that can be stated with certainty, however, is that the 5 July 1982 sample from spring 2 represents an approximate 50% dilution with fresher water with proportionately higher HCO_3^- and Mg^{2+} and lower SO_4^{2-} contents. In view of the relatively small associated decreases in spring-water temperatures (Table 2; Fig. 5) it is concluded further that the shallow water must have acquired an elevated temperature of 20–25°C before it mixed with the thermal water. This would be possible through an extended residence time in the subsurface in this thermally anomalous area.

Both the temperature and the chemical composition of the shallow-water component could also vary during the course of a dirty-water event. As the shallow water is being fed more rapidly through the shallow subsurface by the piston-flow effect of the rainfall, its ability to acquire heat and dissolved solids from the aquifer materials will be reduced. Consequently it is possible that the gradually decreasing amount of shallow water mixing with the thermal water during the later stages of a dirty-water event will be progressively cooler and somewhat more dilute. This effect could also cause the recoveries of the discharge temperature and dissolved-solids concentration to proceed at different rates. This suggestion is supported by observations during the 1982 dirty-water event that indicated that further drops in temperature occurred while the SO_4^{2-} concentrations were already recovering. It is concluded, therefore, that a particular combination of spring-water temperature and ionic concentration does not necessarily indicate a specific
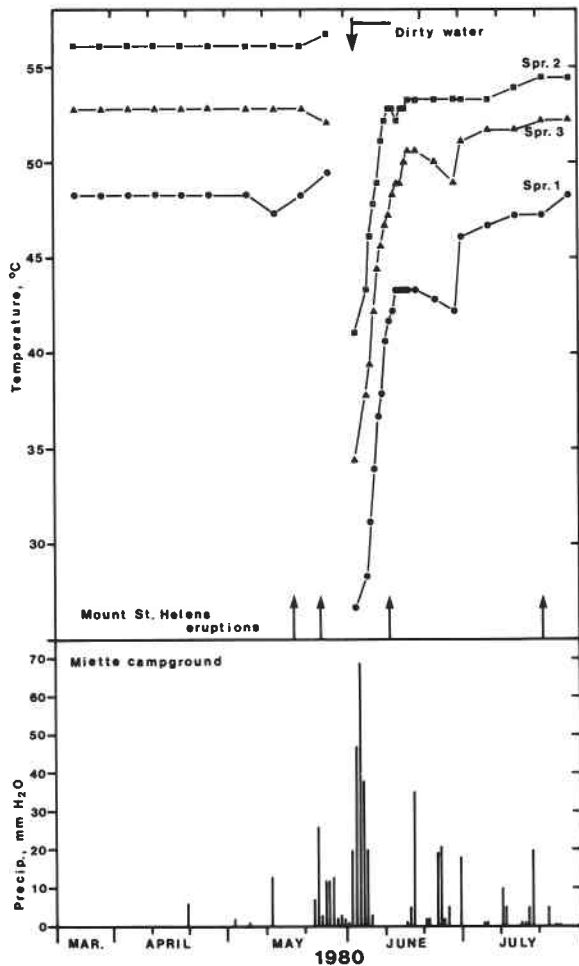
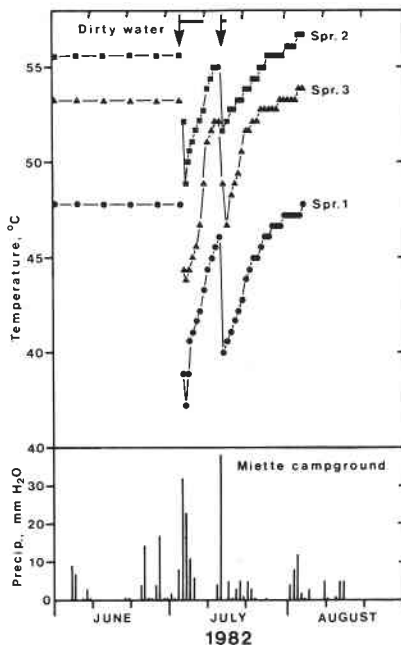FIG. 4. Physical data for the 1980 dirty-water event at Miette Hot Springs.

FIG. 5. Physical data for the 1982 dirty-water events at Miette Hot Springs.
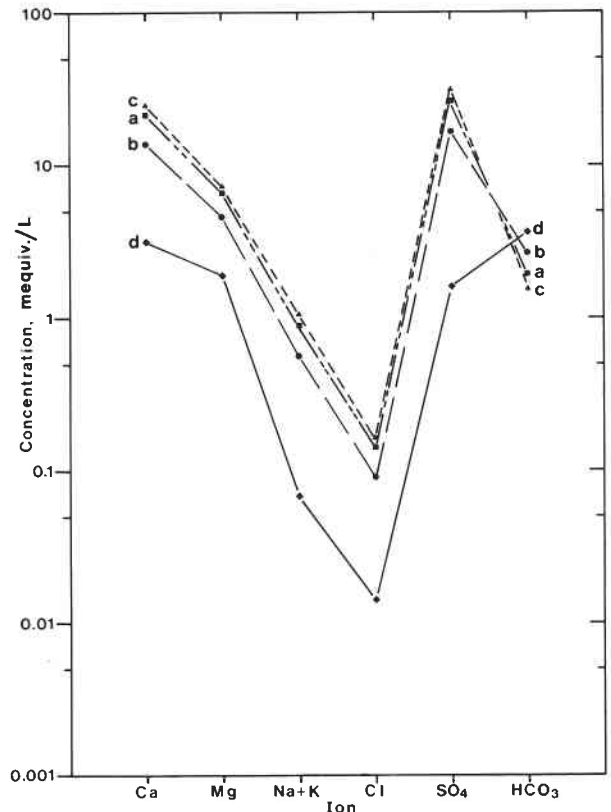

FIG. 6. Water chemistry of Miette Hot Springs: (a) spring 2, maximum measured concentrations; (b) spring 2 on 5 July 1982; (c) calculated composition of deep thermal water; and (d) calculated composition of shallow groundwater.

mixing ratio.

The additions of cooler, less mineralized water suggested by the chemical analyses and temperature data could have resulted in increased discharge from the springs. As stated earlier, flow-rate measurements are not available to check this possibility.

Isotopic composition of the water

Isotope analyses for the 1982 samples from Miette Hot Springs are listed in Table 3. Comparison of the ^3H data for 6 July 1982 with pre-1982 data reveals large increases in ^3H content in the waters from springs 1 and 3, suggesting mixing of the normal spring water with a water having a considerably higher ^3H content. A simple calculation, using a mixing ratio of 1:1 and average ^3H contents of 0 and 45 tritium units (TU) for the undiluted and diluted spring waters, respectively, produces a possible maximum ^3H content for the shallow water of 90 TU. This value is about twice as high as the ^3H contents found in contemporary rain samples (Table 3). It is concluded that the shallow water represented precipitation that fell either during the preceding summer or one or more years earlier, when ^3H contents in precipitation tended to be higher.

The ^3H value for spring 2 on 6 July 1982 suggests little or no dilution, contradicting the chemical evidence. At the present time no reasonable explanation can be given for this contradiction.

For the interpretation of the δ^2H and $\delta^{18}O$ data for the springs it is useful to compare them first with available background data for precipitation. Figure 7 presents a plot of δ^2H versus $\delta^{18}O$ for the spring-water and rain samples listed in Tables 3 and 4; it also shows fields for "snow" and "rain" for the
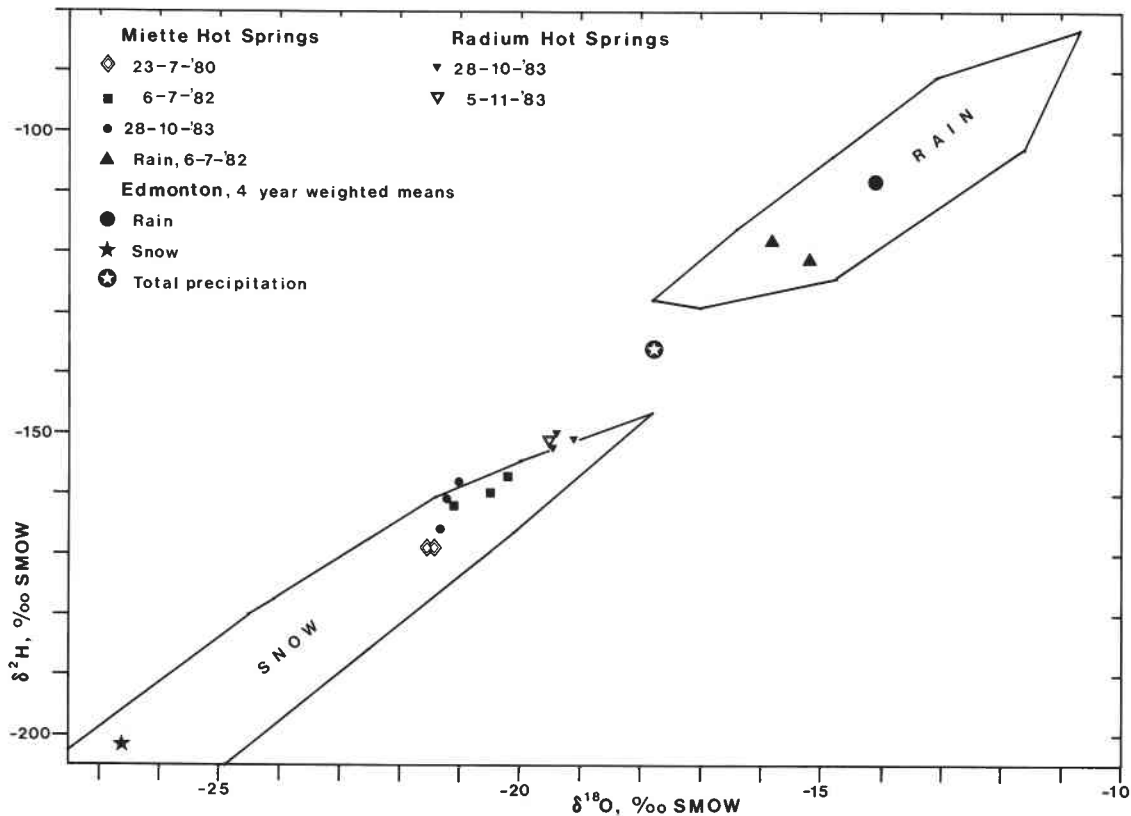
FIG. 7. Plot of δ^2H vs. $\delta^{18}O$ for waters from Miette and Radium hot springs. Ranges and weighted means for snow and rain at Edmonton are indicated for comparison (based on data for the period 1961–1966, from Environmental Isotope Data Series, International Atomic Energy Agency).

Edmonton Industrial Airport, the nearest station for which such information is available. The position of the points for the spring-water samples, in the upper portion of the "snow" field in Fig. 7, suggests that snowmelt makes a considerable contribution to the recharge for the flow systems that discharge at Miette and Radium hot springs.

The δ^2H and $\delta^{18}O$ data for the 1982 and pre-1982 samples from Miette in Table 3 could be interpreted as indicating some dilution by rain water for spring 1 and progressively less dilution for springs 3 and 2, respectively. As suggested earlier, however, the water that diluted the normal spring water during the dirty-water event was likely not the rain falling at the same time, but rather snowmelt or precipitation that had infiltrated earlier and that was being flushed into the spring channels at an accelerated rate. If the mixing ratio is again assumed to have been about 1:1, then the average δ^2H and $\delta^{18}O$ values for the undiluted (pre-1982) and diluted (6 July 1982) spring waters (Table 3) would require that the shallow water had δ^2H and $\delta^{18}O$ values of about -150 and $-19.7‰$, respectively. According to Fig. 7, these values represent a mixture of snowmelt and rain.

Character and sources of the "dirt"

Sediment content

The sediment content of the Miette spring water during the rainfall-induced event of July 1982, determined on a single water sample collected from the swimming pool on 8 July, was 7.5 g/L. At the time of sampling, sediment concentrations may of course have been different in the two springs (2 and 3) that fed the pool. Analysis of the sample for particle-size distribution in the sediment indicated 14% sand, 33% silt, and 53%

clay.

Sediment concentration in two samples collected at Miette during the earthquake-triggered event of 28 October 1983 was approximately 6.0 g/L. The bulk of the sediment consisted of greyish yellow aggregates, with only a small proportion of silt-sized and clay-sized particles.

The concentration of sediment in samples taken at Radium on 28 October 1983 was approximately 0.06 g/L. The only particles larger than 0.05 mm were blue paint flakes (derived from the hot-pool walls).

Mineral composition

The mineral composition of the sediment samples, determined by X-ray diffraction (XRD) analysis, are presented in Table 5. The XRD results for the 1983 samples were confirmed by a number of scanning electron microscope (SEM) spot analyses.

The presence of small particles of decaying vegetation suggests that a portion of the quartz, silicate, and carbonate contents of the 6 July 1982 samples from Miette may have been derived from unconsolidated deposits in the area. Much of the quartz, silicate, and carbonate contents in the remaining samples from Miette and in the sample from Radium likely represent residues from the dissolution of carbonate bedrock. The small pyrite content in the 1982 samples from the catch basin of spring 3 may have resulted from reaction of spring-water H_2S with ferrous materials at the site.

The results in Table 5 suggest that most of the native sulfur (in the greyish yellow aggregates) available at Miette Hot Springs in July 1982 was removed during an early stage of the rainfall-induced event, before the first samples were collected

TABLE 5. Mineral composition of sediments produced by Miette Hot Springs and Radium Hot Springs during dirty-water events of July 1982 and October 1983[a]

| | Miette Hot Springs | | | | | Radium Hot Springs |
| | Swimming pool from springs 2 and 3 | | | Basin of spring 3 | | Swimming pool |
	$6-7-82$[b]	$8-7-82$	$28-10-83$	$6-7-82$[b]	$8-7-82$	$28-10-84$
Dolomite	27	11	2	21	27	17
Calcite	17	—	—	—	1	2
Gypsum and other sulfates	2	47	Present	—	28	5
Pyrite	—	—	—	3	1	—
Sulfur	Present	—	60	Present	—	3
Quartz	52	23	25	76	29	43
Silicates	2	19	13	tr	14	30

[a]Semi-quantitative results (in %) from X-ray diffraction analyses by A. Heinrich and J. Wong, Institute of Sedimentary and Petroleum Geology, Calgary, Alberta.
[b]Samples contained particles of decayed vegetation (leaf stems, etc.) and yellow aggregates high in native sulfur. Some of the original amount of native sulphur may not have been deposited because of its low density.

on 6 July. Gypsum was primarily discharged during a later stage, as shown by the samples collected on 8 July 1982. In 1983, samples were collected early enough after the start of the earthquake-triggered event to catch the initial sediment with a high sulfur content. Only minor percentages of native sulfur and gypsum were found in the 1983 sediment samples from Radium Hot Springs.

Isotopic composition of sulfur species

Results of stable-isotope analyses of sulfur species from the Miette samples are given in Table 3. The negative $\delta^{34}S$ values for the sulfur aggregates are similar to that for the yellow "clay," an algal or bacterial deposit coating rock surfaces around the orifice of spring 3. The sulfur content of this material is probably derived from the HS^- content of the spring water, with similar $\delta^{34}S$ values (Table 3, pre-1982).

The negative $\delta^{34}S$ and $\delta^{18}O$ values for the gypsum from the Miette pool indicate that this is not a precipitate resulting from evaporation of the spring water, which would show positive $\delta^{34}S$ and $\delta^{18}O$ values (Table 3, pre-1982). The gypsum is a secondary mineral, produced by a sequence of reactions described recently for a spring area north of Norman Wells (Northwest Territories) by van Everdingen et al. (1982). In this process, H_2S escaping from the spring water is oxidized to H_2SO_4, which reacts with exposed carbonate rocks to form calcium sulfate with negative $\delta^{34}S$ values similar to those of the dissolved HS^-. A large proportion of the oxygen used in the oxidation of the airborne H_2S is derived from water vapour, giving the resulting sulfate a negative $\delta^{18}O$ value approaching that of the spring water. Similar gypsum with negative $\delta^{34}S$ and $\delta^{18}O$ values was found on carbonate rock inside the orifice of spring 3 (Table 3).

The amount of sediment collected from Radium Hot Springs on 28 October 1983 was too small to allow isotope analyses of the sulfur species.

Conclusions

Earthquakes in Montana, Idaho, and Alaska for which $M \geq (\log D + 1.16)/0.63$ may trigger dirty-water events at both Miette and Radium hot springs. Earthquakes on the Pacific side of the cordillera apparently require larger magnitudes to trigger such events. The earthquake-triggered events are primarily characterized by the occurrence of sediment in the spring waters.

Rainfall of 34 mm or more within 48 h may induce a dirty-water event at Miette Hot Springs; however, precipitation exceeding this rate will not necessarily produce such an event. The rainfall-induced events are characterized by the occurrence of sediment contamination and by decreases in spring-water temperatures and changes in dissolved-solids content. The latter effects reflect mixing of thermal water with cooler, near-surface water with a lower mineral content and different composition.

The observed changes in chemistry indicate an approximate 1:1 mixture for the event that occurred at Miette Hot Springs in early July 1982. Isotope analyses for that event can only be explained by assuming a piston-flow effect that forces shallow water (representing earlier precipitation) into the thermal-water system at an accelerated rate. The temperature data also suggest that the shallow water had resided in the subsurface for some time before it started mixing with the thermal water. Because of these effects, a particular combination of water temperature and ionic concentration cannot be expected to reflect a specific mixing ratio.

Three factors may account for the much higher sediment concentrations produced by Miette Hot Springs than by Radium Hot Springs. Firstly, a major proportion of the Miette sediment consisted of secondary sulfur species derived from the HS^- content of the spring water; the Radium Hot Springs water has a much lower SO_4^{2-} content and it contains no HS^-, hence the production of secondary sulfur species is minimal. Secondly, the composition of the 1982 sediments suggests that the spring system at Miette is more accessible for sediment input from the surface. Finally, differences in the rock types traversed by the water of the two spring systems may result in differences in the type and quantity of residues left by subsurface dissolution.

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Staff of Parks Canada in Calgary, Jasper, Miette Hot Springs, and Radium Hot Springs provided most of the information for the pre-1980 occurrences of dirty water; in 1982 and 1983, water and sediment samples were collected by Parks Canada staff for this study. Special thanks go to D. Wellock in

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