

Deuterium, oxygen-18, and tritium in Stripa groundwater*

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Abstract—Deuterium, oxygen-18 and tritium determinations show that groundwaters in the fractures of the Stripa granite are of meteoric origin, not affected by secondary isotope effects (evaporation or isotope exchange). Deep groundwaters have lower ¹⁸O and ²H contents than recent, shallow groundwaters. The differences are most likely due to recharge during cooler climatic conditions. However, no age information can be derived because recharge could have occurred before the last major climatic improvement following the last deglaciation, during minor climatic variations during the more recent past, or could be the result of regional groundwater flow.

Low ¹⁸O contents are paralleled by increasing salinities with highest salinities limited to a narrow fracture zone at a depth of about 800 m below ground surface. Most saline waters sampled appear to represent mixtures of a saline component with an isotopically depleted water and local fresh water.

The presence of young groundwaters is indicated by bomb produced ³H. All surface boreholes contain tritium, indicating residence times <35 years. However, tritium is also found in some boreholes drilled at the 300 m mine levels and its presence may be due to flows induced in response to heater tests. Low but detectable ³H contents (about 0.1 to 1 TU) in V2 at about 850 m below ground surface are discussed either as subsurface production and/or as a result of admixtures of small amounts of recent water to old groundwater.

INTRODUCTION

THE ABUNDANCE of the stable isotopes deuterium (²H) and oxygen-18 (¹⁸O) in groundwaters is largely determined by recharge conditions and processes in the soil zone. Both ²H and ¹⁸O contents of water display conservative, geochemical behaviour unless isotopic exchange with different oxygen and hydrogen bearing minerals or compounds in the subsurface modifies their concentrations either during very long residence times or by geochemical reactions at elevated temperatures (IAEA, 1981). Such analyses can be used to characterize different groundwater systems as well as to obtain information about recharge times and potential age distributions. This is essential information for the definition of hydrogeological systems; therefore, stable isotope analyses are an integral part of all hydrogeological studies at Stripa.

Tritium (³H, half-life of 12.43 years) is an isotope commonly used in hydrology to distinguish between recent water and older water (recharge after or before 1952) or to date groundwater up to about 70 years old (IAEA, 1983a,b). In the Stripa project, tritium analyses provided a cost effective tool for the recognition of young groundwaters in the fracture systems of the Stripa granite.

MEASURING TECHNIQUES

All water samples for ¹⁸O and ²H determinations were prepared and measured according to standard procedures (see e.g., MOSER and RAUERT, 1980; IAEA, 1981). Participating laboratories were the Gesellschaft für Strahlen-und Umweltforschung mbH München, the International Atomic Energy Agency, the Université de Paris-Sud and the University of Waterloo.

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Analytical reproducibility in each laboratory is better than $\pm 0.2\%$ for $\delta^{18}\text{O}$ and $\pm 1.0\%$ for $\delta^2\text{H}$ (2σ criterion). However, there are minor differences between laboratories. This was shown in an intercomparison of ¹⁸O and ²H data between different laboratories (NORDSTROM *et al.*, 1985). However, these differences do not affect our interpretation of the results.

Samples which were expected to contain higher ³H contents were directly measured in commercial liquid scintillation counters (± 15 TU) or were electrolytically enriched before LSC counting (± 2 TU). For the detection of lower ³H contents, gas counting is preferred because of its higher sensitivity (± 0.1 TU). For details about measuring techniques see, e.g., EICHINGER *et al.* (1981) or WOLF *et al.* (1981).

The results of the isotopic analyses are summarized in Tables 1 and 2.

DISCUSSION

Stable isotope data

Preliminary interpretations of isotopic results from Stripa groundwaters were presented by FRITZ *et al.* (1979, 1983). The data discussed here are summarized in Figs. 1 and 2.

NORDSTROM *et al.* (1989) discuss chemical parameters and document significant differences in chemical composition between shallow and deep groundwaters. Such differences are also apparent in the isotopic data. However, the discussion of the isotopic data is complicated by the fact that only a very limited number of precipitation samples were collected at Stripa. Reference could only be made to BURGMAN *et al.* (1981) who generated a map of average annual $\delta^{18}\text{O}$ values in Sweden. From it an average annual $\delta^{18}\text{O}$ value of about -11.5% can be deduced as being characteristic for Stripa precipitation.

In general, the ¹⁸O and ²H contents of groundwater in porous aquifers closely reflect the isotopic composition of the average annual precipitation in the recharge area (YONGE *et al.*, 1986; FRITZ *et al.*, 1987). Minor differences can exist where recharge is very selective and seasonally variable (e.g., FONTES, 1980).

Table 1. $\delta^{18}\text{O}$, $\delta^2\text{H}$ values and pH contents of Stripa surface waters, shallow groundwaters at the Stripa site and of groundwaters from southern Sweden. (Selection from values measured in different laboratories (see NORDSTROM *et al.*, 1985). If a sample has been analysed by more than one laboratory, mean values or the values with the lowest standard deviation are listed).

Sample Description	Date	$\delta^{18}\text{O}$ ‰ SNOW	$\delta^2\text{H}$ ‰ SNOW	$\text{pH} \pm 2\sigma$ (TC)
Ponds and Lakes				
Tailing pond 3	77-09-07	-9.2	-76.3	
	78-06-16	-10.8	-78.0	
	78-11-23	-9.3	-76.0	
Streams				
Herrgard Sauna	77-09-07	-9.1	-73.4	
Danshutgard Bridge	77-09-07	-9.1	-73.4	
	78-11-23	-9.6	-77.0	
	82-06-10	-10.7	-80.8	
	83-03-23	-11.2	-81.8	
Into tailings ponds	79-05-06	-12.7	-93.0	54 $\pm$ 16
Watertable wells and seeps				
WT - 2	79-05-05/18	-14.2		57 $\pm$ 16
WT - 3	79-05-01	-12.5		
WT - 7	78-08-24	-11.8	-81.3	
Seep at SBH 3	79-05-06	-12.1	-89.0	65 $\pm$ 16
Private water supply wells				
Private well 1	77-09-27	-10.8	-81.3	12.6 $\pm$ 0.4
	79-05-18	-9.6	-82.0	13 $\pm$ 16
	82-06-10	-11.56	-82.5	
Private well 2	77-09-28	-11.0		
	77-10-24/27	-10.9	-80.1	38 $\pm$ 20
Private well 3	77-09-28	-10.8		
	77-10-26	-10.9	-76.3	103 $\pm$ 22
	79-05-16	-13.4		
Private well 4	79-05-17	-11.4		4 $\pm$ 16
	82-06-08	-12.91	-93.4	
Private well 5	77-10-06/12	-11.0	-82.7	98 $\pm$ 4
	79-05-15	-13.1		53 $\pm$ 16
SBH-3				
89-104 m	79-05-23/27	-11.6	-82.0	48 $\pm$ 8
Drip water at old mine level and flowing water in old mine				
Mine discharge	77-09-07	-9.1	-74.6	
135 m level, drip	79-05-14	-11.5		86 $\pm$ 20
157 m level, drip	79-05-11	-11.5	-83.0	77 $\pm$ 20
310 m level, drip	79-05-11	-11.0	-79.0	159 $\pm$ 20
360 m level, drip	77-11-17/18	-10.9	-79.4	
	79-05-18			86 $\pm$ 18
360-410 m level, drip	77-09-08	-10.8		
	77-11-17	-10.7	-79.4	
	79-05-15	-11.0	-79.0	58 $\pm$ 16
Flooded drift at 380 m	78-11-24	-11.4	-82.0	
Groundwater from southern Sweden				
Hasselby, Crystalline rock	83-04-20	-11.27	-61.1	4.1 $\pm$ 0.6
Wilhelmslund, Cambrian sandstone	83-04-21	-12.57	-87.3	2.1 $\pm$ 0.6
Kaga, Crystalline rock	83-04-21	-15.12	-109.7	5.1 $\pm$ 0.8
Norra Stene, Crystalline rock	83-04-22	-14.53	-106.5	8.3 $\pm$ 0.8
St. Sundby, Crystalline rock	83-05-02	-12.03	-88.1	23.7 $\pm$ 1.7
Hammaro, Crystalline rock	83-05-03	-12.44	-90.2	6.5 $\pm$ 0.7
Skofteby, Quatern. sediments	83-05-04	-9.08	-63.5	0.0 $\pm$ 0.6
Hangelosa, Crystalline rock	83-05-04	-9.94	-70.0	2.3 $\pm$ 0.6
Sædetofta, Quatern. sediments	83-05-04	-9.83	-68.8	12.3 $\pm$ 1.1
Rockagården, Quatern. sediments	83-05-05	-8.99	-63.0	0.3 $\pm$ 0.6
Aker, Quatern. sediments	83-05-05	-8.44	-60.6	0.5 $\pm$ 0.6

This is also true for "aquifers" in crystalline rocks, despite fundamental hydraulic differences between porous and fractured media. For example, if groundwater recharge occurs through sandy soils, it will take only 2–5 m of unsaturated zone to smooth out (primarily through hydrodynamical dispersion) seasonal variations observed in precipitation. In crystalline rocks this "critical depth" can lie much deeper. SAXENA (1984) presents data from several boreholes in crystalline rocks in the Finnsjon area of Central Sweden where, depending on regional hydraulic gradients and fracture characteristics, seasonal variations can persist to depths in excess of 70 m. The isotopic composition of groundwater at the critical depth is within about $\pm 1\%$ of the average precipitation predicted by BURGMAN *et al.* (1981).

In the Stripa project several sampling points have been monitored for about 8 years and it will be shown that seasonal variations are not recognized in discharges at test site depths

exceeding 300 m. However, the introduction of "artificial" hydraulic gradients can permit fracture flow to these and greater depths. RAUERT and STICHLER (1974), FONTES *et al.* (1979) and MACDONALD *et al.* (1987) observe rapid vertical movements over distances of more than 1000 m where mining and tunnelling created hydraulic sinks.

Heater testing performed in the Stripa excavation also appears to have influenced flow regimes. Figure 3 shows ^{18}O and tritium data for the 14 m borehole M3 and documents that the concentrations of both isotopes changed at the time the heater experiments were performed. A similar change occurred also in chloride contents as shown by NORDSTROM *et al.* (1989).

Surface water and shallow groundwater

The histograms of Fig. 1 show that the shallow groundwaters have the largest isotopic variation of any groundwater type sampled at Stripa. This is a reflection of the preservation of seasonal variations as they occur in local precipitation. All wells in this group have depths of less than 100 m. Indications are thus that in this area the critical depth lies by at least 100 m. This is not surprising considering the topography of the area which should assist in the development of rather deep, active flow systems.

In the Stripa mine, groundwaters with bomb produced tritium penetrate at least to a depth of about 360 m (see Fig. 3, and below). Their movement is likely induced by artificial hydraulic gradients and isotopic data cannot be related to the natural "critical depth". However, it is remarkable that active inflow at 300–400 m depths in the old mine has $\delta^{18}\text{O}$ values between -10.7 and -11.5% and was isotopically constant for samples collected during a two-year period. These values are very close to those estimated for average annual precipitation, and considering the observations by SAXENA (1984), one can suggest that values between about -11 and -12% can be expected for deeper, modern groundwater in the Stripa pluton. This does not exclude local deviations, especially where recharge is dominated by a "seasonal source" such as snow melt or is subject to evaporation effects.

The effects of evaporation are recognized in surface waters collected in this study (Fig. 2). Evaporated water can also be found in some shallow wells (e.g. PW 1), where it is an exception because the majority of all δ -values of shallow groundwaters are close to or on the meteoric water line.

Where groundwater movement occurs under unsaturated conditions in fractured media it may also be argued that evaporation in response to temperature gradients could have modified the initial isotopic composition of the recharge (FONTES *et al.*, 1979). This would primarily be valid for the mine drips in old workings. However, the small scatter of isotopic composition in samples collected in different drifts and depths as well as the apparent similarity to the composition of average annual precipitation lend little support to such reasoning.

Deep groundwaters

The graphic presentation of ^2H and ^{18}O data in Figs. 1 and 2 suggests that the deep groundwaters are depleted in ^{18}O and ^2H compared to the amounts in estimated average annual

Table 2. $\delta^{18}\text{O}$, $\delta^2\text{H}$ values and $^*\text{H}$ contents of Stripa mine waters from different boreholes. (For the selection of isotopic analyses see caption of Table 1).

Borehole	Interval (m)	Date	$\delta^{18}\text{O}$ ‰ SMOW	$\delta^2\text{H}$ ‰ SMOW	$^*\text{H} \pm 2\sigma$ (TU)
M 3	77-09-21/26	-11.8	-86.9	0.7 $\pm$ 0.6	
	77-10-19	-11.8	-87.7	0.5 $\pm$ 0.6	
	77-11-29	-11.9			
	78-01-24	-11.9			
	78-02-24	-11.9			
	78-05-30	-12.2	-87.2		
	78-08-15	-12.4			
	78-09-19	-12.3			
	78-11-17	-12.3	-88	10.5 $\pm$ 1.3	
	78-11-27	-12.4			
	78-12-20			10.3 $\pm$ 1.3	
	79-02-12	-12.2			
	79-05-02/17	-12.2	-90	10.2 $\pm$ 2.2	
	79-11-21	-12.3	-90		
	81-06-04	-12.3	-87		
	81-07-09	-12.60	-90.6		
	82-06-10	-12.32	-87.7		
	83-03-23	-12.20	-85.9		
	83-11-09	-12.02	-88.9	9.1 $\pm$ 0.6	
	84-02-14	-12.1	-90		
	84-02-23			9.2 $\pm$ 0.9	
	85-06-11	-12.42	-90.5	8.9 $\pm$ 0.5	
	85-08-07	-12.37	-90	8.6 $\pm$ 0.5	
	85-09-17	-12.23	-90.8	8.5 $\pm$ 0.5	
	85-11-14	-12.16	-91.8	9.0 $\pm$ 0.5	
	86-01-16	-12.20	-90.0	8.9 $\pm$ 0.6	
	86-04-10	-12.29	-91.0		
R 1	78-05-30	-12.1	-87.9		
	78-08-29	-12.1	-86.0		
	78-09-19	-12.0	-87.0		
	78-11-17	-12.2	-86.0	8 $\pm$ 16	
	78-12-08	-12.3	-86.0	-6 $\pm$ 16	
	79-05-17	-12.3	-87.0	6 $\pm$ 16	
	81-06-04	-11.9	-82.0		
R 3	78-08-16	-12.3	-90.6		
R 9	79-05-22	-12.5	-92.0		
HG-3	78-06-16	-12.3	-88.8		
HG-4	78-06-16	-12.2	-87.7		
SGU-Hor1. 338 m	77-12-07	-12.1	-88.0		
Vent. drift combined	78-11-24	-12.2	-90.0		
S 1	78-09-15	-12.1	-87.0		
S 4	78-09-14	-12.3			
	78-11-27	-12.1			
S 5	78-09-14	-12.5	-89.0		
	78-11-27	-12.4			
E 1 Collar 355.7 m	3 - 300	81-11-11/17	-12.75	-94.7	17 $\pm$ 2
	0 - 267	84-03-06	-12.34	-90.4	19.4 $\pm$ 1.4
	127.5 - 129.5	82-06-10	-12.60	-90.9	20.6 $\pm$ 1.8
	open	82-03-23	-12.00	-86.4	42.6 $\pm$ 3.1
		84-02-14	-12.30	-92.0	
		85-06-11			19.7 $\pm$ 1.5
		86-01-15			7.7 $\pm$ 0.5
F 2	83-11-05				13.8 $\pm$ 2.9
N 1 collar 355.5 m	3 - 300	81-08-19	-12.6	-89.5	
		82-06-03/10	-12.90	-93.7	0.19 $\pm$ 0.11
		83-03-23	-12.75	-90.0	
	123 - 125	82-08-30	-13.59	-98.6	0.25 $\pm$ 0.14
	203 - 205	82-09-06	-13.50	-97.7	0.16 $\pm$ 0.10
	271.1 - 273.1	82-09-14	-13.11	-94.8	0.15 $\pm$ 0.08
	274 - 276	82-09-23	-13.37	-97.4	0.23 $\pm$ 0.09
	10 - 119	84-02-14	-13.5	-98	
	120 - 150	84-02-14	-13.5	-97	
	151 - 251	84-01-26	-12.43	-90.5	0.19 $\pm$ 0.10
		84-02-14	-12.5	-93	
	252 - 300	84-01-26	-12.47	-90.3	0.12 $\pm$ 0.10
		84-02-14	-12.9	-94	
V 1 collar 356.7 m	409 - 506	81-06-03	-12.8	-93	
		81-07-13	-13.0	-94	
		81-08-19	-13.0	-94	
		81-08-28	-12.92	-92.0	0.7 $\pm$ 0.1
		81-09-08/21	-12.93	-93.4	0.92 $\pm$ 0.18
	5 - 506	81-11-17	-13.08	-91.9	
		82-06-10	-13.10	-93.0	
	10 - 505	83-03-05	-12.9	-95	
		83-03-22	-12.93	-91.2	
		83-10-03		-91.0	1.3 $\pm$ 0.2
		83-10-19		-94.0	1.3 $\pm$ 0.3
		83-11-05		-91.3	1.3 $\pm$ 0.2
		83-12-07		-94.0	1.3 $\pm$ 0.2
		84-01-11		-90.3	1.1 $\pm$ 0.2
		84-02-08		-91.3	1.1 $\pm$ 0.2
		84-02-14		-93	
	430 - 505	85-05-14			2.5 $\pm$ 0.3
		85-05-10	-12.9	-94.0	2.3 $\pm$ 0.3
		85-08-06	-12.98	-94.1	2.1 $\pm$ 0.2
		85-11-14	-12.95	-92.8	2.0 $\pm$ 0.2
		86-04-11		-93.1	
V 2 collar 407.7 m	8 - 39	78-06-06	-12.6	-90.7	
		78-11-20	-12.4	-90.0	
		79-09-06/14	-12.6	-92.0	
	6.3 - 50	77-09-22/10	-12.1	-88.9	
	332 - 359	79-03-16	-12.2		
	401 - 428	78-11-20	-13.2	-95.0	
		79-05-17	-13.3	-97.0	
		81-06-03	-13.3	-97.0	
	356 - 470	81-11-30	-12.9	-93.1	
	358 - 471	81-11	-13.19	-96.2	
	0 - 822	83-03		-90.0	
	6 - 822	82-04-21	-12.84	-91.9	0.95 $\pm$ 0.14
	406 - 410	82-11-24	-13.22	-93.6	0.0 $\pm$ 0.6
	413 - 416.74	82-12-14	-13.30	-95.9	0.88 $\pm$ 0.27
	490 - 493.74	83-01-19	-13.13	-94.2	0.12 $\pm$ 0.09
	549 - 552.74	83-02-07	-13.03	-93.2	0.26 $\pm$ 0.11
	382 - 423	84-02-14	-13.10	-94.0	
		84-02-28		-94.0	0.20 $\pm$ 0.11
	424 - 499	83-11-28		-94.0	0.06 $\pm$ 0.10
		84-02-14	-13.10	-94.0	
	500 - 561	84-02-14	-13.0	-94.0	
		84-02-28		-93.5	0.08 $\pm$ 0.09
	562 - 822	83-11-29	-92.4		0.20 $\pm$ 0.10
		84-02-14	-12.8	-92.0	
	389 - 397	85-05-14	-12.95	-95.1	0.79 $\pm$ 0.13
		85-06-06	-13.02	-94.4	0.46 $\pm$ 0.11
		85-08-08	-12.99	-96.0	0.97 $\pm$ 0.15
		85-09-18	-13.02	-96.7	0.73 $\pm$ 0.35
		85-11-13	-13.15	-92.5	0.70 $\pm$ 0.12
		86-01-15			0.34 $\pm$ 0.11
		86-04-10	-13.22	-94.4	
	402 - 410	85-05-14	-13.20	-96.6	0.34 $\pm$ 0.26
		85-06-07	-13.24	-94.5	0.80 $\pm$ 0.30
		85-08-08	-13.24	-92.2	0.36 $\pm$ 0.11
		85-09-18	-13.25	-95.8	0.54 $\pm$ 0.15
		85-11-13	-13.26	-95.0	0.48 $\pm$ 0.12
		86-01-15			0.11 $\pm$ 0.10
		86-04-10	-13.16	-93.8	
	490 - 498	85-05-14	-13.2	-92.9	0.36 $\pm$ 0.11
		85-06-10	-13.32	-93.3	0.33 $\pm$ 0.11
		85-08-07	-13.24	-93.9	0.32 $\pm$ 0.11
		85-09-18	-13.26	-95.4	0.14 $\pm$ 0.13
		85-11-13	-13.23	-94.2	0.34 $\pm$ 0.28
		86-01-15			0.07 $\pm$ 0.09
		86-04-10	-13.34	-96.9	
	550 - 558	85-05-14			0.57 $\pm$ 0.29
		85-06-07	-13.31	-93.4	0.42 $\pm$ 0.11
		85-08-10	-13.27	-95.9	0.72 $\pm$ 0.33
		85-09-18	-13.19	-94.8	0.10 $\pm$ 0.11
		85-11-14	-13.24	-94.3	0.16 $\pm$ 0.10
		86-01-15	-13.05	-93.3	0.04 $\pm$ 0.09
		86-04-10	-13.33	-94.6	
	559 - 822	85-05-14	-13.1	-92.9	0.85 $\pm$ 0.30
		85-06-10	-13.2	-93.6	0.24 $\pm$ 0.26
		85-08-07	-13.09	-94.8	0.47 $\pm$ 0.12
		85-09-17	-13.1	-95.0	0.38 $\pm$ 0.16
		85-11-14	-12.95	-94.0	0.21 $\pm$ 0.10
		86-01-15	-13.02	-92.9	0.02 $\pm$ 0.09
		86-04-10	-13.08	-92.9	

precipitation in most shallow groundwater and in waters discharging from boreholes at the 300 m levels. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are on or close to the global meteoric water line (Fig. 2). Deviations from the line most likely reflect analytical uncertainties and minor differences between laboratories rather than secondary modifications through water-rock interactions.

Furthermore, the ^{18}O and ^2H contents of groundwaters are rather variable between samples from different boreholes and

depths, depending on the depth intervals that were sampled. However, analyses of samples from specific levels tend to agree very well. Furthermore, the data for boreholes such as M3 or specific levels in V2 indicate isotopic homogeneity within analytical errors and thus consistent differences over a 5-year period. Minor variations can occur in response to mining and testing activities.

The constancy of isotopic compositions of groundwaters of specific depths or boreholes is a compelling argument for

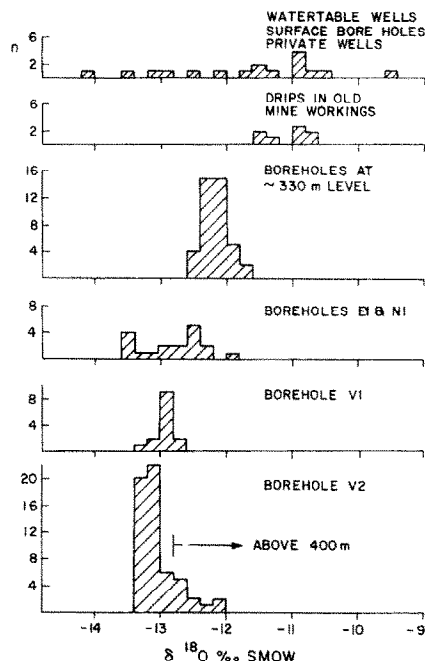


FIG. 1. Histogram of $\delta^{18}\text{O}$ values of groundwaters at Stripa. All samples listed in Tables 1 and 2 are shown.

the existence of isotopically different waters with differing ages or origins. As already pointed out by FRITZ *et al.* (1979) such a comparison excludes a simple two-component mixing. A much more complex picture emerges. Figure 4 shows that a weak correlation exists between chlorinity and $\delta^{18}\text{O}$ contents in samples from borehole V2. If accepted, extrapolation to lower salinities does not lead to the $\delta^{18}\text{O}$ values of waters discharging at the 330 m level *nor* the average value for shallow groundwaters in the area. Instead, the data would substantiate that different fracture systems carry waters of differing origins and histories.

Fractures below 800 m discharge water with elevated but differing salinities. This is most likely due to mixing of dif-

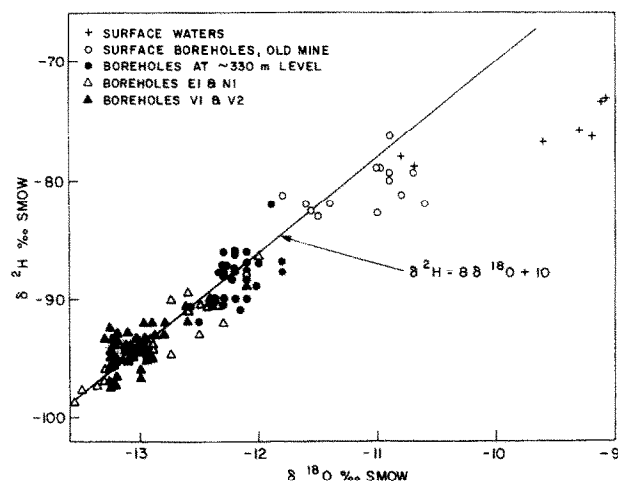


FIG. 2. $\delta^{18}\text{O}$ values are plotted versus $\delta^2\text{H}$ values. Only samples collected between short packer-intervals are shown.

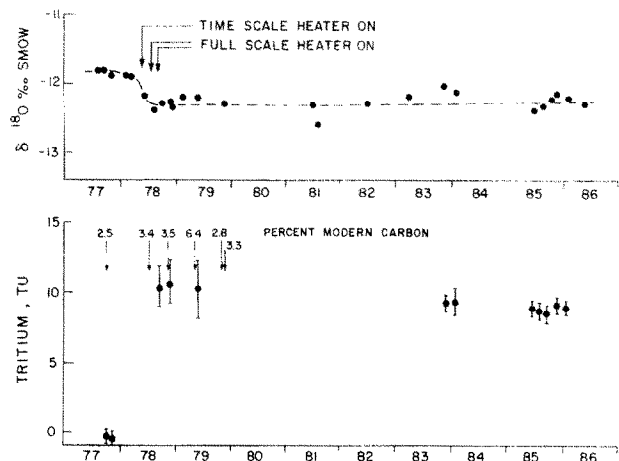


FIG. 3. Tritium contents and $\delta^{18}\text{O}$ values for M3 water during the 1977–1985 observation period. Note that the borehole is only 14 m deep but discharged several 100,000 liters of water during that time. Also indicated are ^{14}C data obtained on dissolved inorganic carbon (see FRITZ *et al.*, 1989) which show that the inflow of water with tritium did not significantly increase ^{14}C contents.

ferent fluids. However, it is not possible to calculate the end-member isotopic compositions of the saline components because their individual salinities are unknown.

According to Fig. 4, the saline endmember is depleted in ^{18}O (and ^2H , see Fig. 2). Thus, it is difficult to argue for mixing with typical sedimentary basin brines because these generally have much higher $\delta^{18}\text{O}$ values (e.g., KHARAKA and CAROTHERS, 1986). Fluids similar to those encountered in the crystalline rocks of the Canadian Shield may have to be considered (FRITZ and FRAPE, 1982; FRAPE and FRITZ, 1987), although there the brines have $\delta^{18}\text{O}$ values close to about -10‰ , whereas in Stripa $\delta^{18}\text{O}$ values below -13‰ are required. No brines with such low ^{18}O contents are known from other environments. Thus, unless a three-component mixing system exists (brine + low ^{18}O water + local groundwater) the data seem to suggest that the salt in the Stripa waters was added by a "dissolution" process from an unknown salt source, "leaching" of fluid inclusions or simple rock-water interactions. The water in which it dissolved is

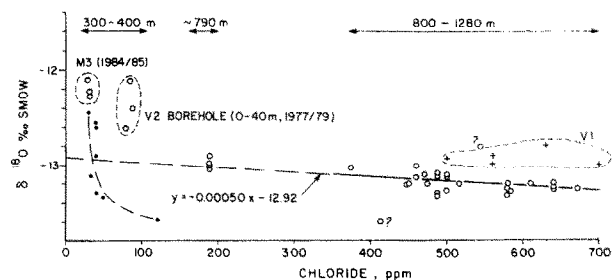


FIG. 4. Comparison of chloride concentrations with $\delta^{18}\text{O}$ values. Chemical analyses are from NORDSTROM *et al.* (1985) and internal Stripa sampling documents. Indicated are approximate depth intervals. The filled circles refer to samples from borehole N1 (with trend line), open circles are for the V2 borehole (with regression analysis) and V1 data are shown as crosses.

depleted in heavy isotopes compared to modern groundwater in the area; most likely it had a meteoric origin. Its salinity before arrival at the point of mixing or sampling is unknown.

The question then arises: How significant are the isotopic differences between shallow and deep groundwaters?

BURGMAN *et al.* (1981) established a temperature coefficient of $0.55 \delta^{18}\text{O} \text{ K}^{-1}$ for a network of Swedish meteorological stations. If applied here, the isotopic difference between shallow and deep groundwaters would indicate a change or difference in average annual temperature of 2–4 Kelvins, always assuming that the groundwaters reflect the isotopic compositions of average annual precipitation. Paleotemperature calculations based on rare gas data closely agree with these estimates (FRITZ *et al.*, 1979; ANDREWS *et al.*, 1989). Temperature changes of this magnitude probably last occurred following deglaciation of the area about 10,000 years ago, but may also have existed temporarily more recently.

In addition, the observed $\delta^{18}\text{O}$ difference of about 1–2‰ between shallow and deep waters agrees well with differences observed in Central Europe (ANDREWS *et al.*, 1984; EICHINGER *et al.*, 1984; ROZANSKI, 1985) and in the U.K. (BATH *et al.*, 1979), where groundwaters which formed during interstadials (>25 ka) and during postglacial cold periods (between 10 and 12 ka) also have lower ^2H and ^{18}O contents than modern groundwater. If applied to Stripa, the deep Stripa groundwaters could then be at least 10 ka old.

However, these lower $\delta^{18}\text{O}$ values are not necessarily a "paleoclimatic" signature suggesting recharge more than about 10,000 years ago or during more recent minor climatic fluctuations but could be accounted for if seasonally varying recharge were to occur and/or regional groundwater flows arrived at Stripa. However, at present no arguments can be advanced for a significant role of seasonally varying recharge with a dominance of winter rains in the deep groundwaters. The similarity in isotopic compositions of waters in the old mine workings and the estimated average annual precipitation appears to exclude this hypothesis as an explanation for isotopic differences between shallow and deep groundwaters. Similarly there are not yet any supporting arguments for the existence of regional flow systems which would show the required altitude effect of 400–600 m, assuming a gradient of 2 to 3‰ depletion in ^{18}O for an altitude increase of 1000 m.

Minewater at 300–360 m

The origin of the waters which discharge from different boreholes at the 300–360 m levels pose a special problem because, although they are isotopically intermediate between the shallow and deep groundwaters, the data do not fall on a simple mixing line, if salinity and $\delta^{18}\text{O}$ values are compared (see Fig. 4). As already noted, discharges (see Table 2) display a remarkable constancy of their isotopic composition with time. This is especially true for the waters in the 14 m borehole M3 which since 1977 discharged several times 10^5 liters of water.

At present many discharges in the 300 m level boreholes, especially those of E1 and M3 have significant tritium contents (see below); their $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are also similar but lower than those seen in shallow groundwater and mine

drips. Note, however, that when sampling in M3 started in 1977 no tritium was detected and radiocarbon contents were as low as 2.55 percent modern carbon—values usually encountered in waters which are many thousands of years old (see also FRITZ *et al.*, 1989). No recent radiocarbon data are available, but it has been pointed out above that it is likely that modern surface waters reach these levels today possibly as a result of changing flow regimes in response to heater tests (Fig. 3) and/or mining activities.

Furthermore, salinities for all 300 m level boreholes are well above those encountered in "normal" shallow groundwaters. Thus, either a salt source exists within the granite or one must assume that some mixing with more saline water occurred. A direct comparison with the shallower waters is then no longer possible.

The problem is further compounded by analyses done on samples collected from specific intervals in borehole N1 (Table 2 and Fig. 4). The $\delta^{18}\text{O}$ values range from –12.5 to –13.5‰, *i.e.* between values seen in M3, and the deep waters. These data could indicate that some of the fractures encountered in N1 discharge waters which are "similar" to the deep saline waters. The chlorinites are highest in the isotopically light samples and could lend some support to the view that deep, saline waters discharge in this borehole.

However, such an explanation may be too simple because Cl contents are much lower than are seen in water which has $\delta^{18}\text{O}$ values typical for the deep saline water (Fig. 4). Instead, extrapolation of saline water data to low chloride contents does indicate that a three-component mixing system exists where deep, non-saline and isotopically depleted groundwaters mix locally with variable amounts of very saline water and modern groundwaters. This complex scenario would require that isolated flow-regimes and specific fracture systems have variable or different degrees of access to a salt source or, *vice versa*, that variable amounts of "brine" mix into isolated systems carrying different types of fresh water.

Tritium contents

The ^3H concentrations in water from different boreholes (Tables 1 and 2) show the influence of bomb-produced ^3H in the boreholes E1, F2 and M3. On the basis of these results the statement in FRITZ *et al.* (1979) that the groundwater at the 330 m level is essentially free of tritium must be revised. Most remarkable is that the ^3H concentration in M3 appeared to have increased from 0.6 TU, just before the heater tests in 1978, to about 9 TU, immediately following the tests. Since then, the tritium concentrations remained surprisingly constant.

The highest tritium concentration (42 TU) at the 300 m level was measured in the borehole E1 and may be due to recent water in an old tunnel ("forgotten drift") filled with several thousand m^3 of recent water and which is located at a distance of 10–15 m from the borehole (T. OLSSON, priv. commun.).

Remarkably low ^3H concentrations (about 0.2 TU), constant over the entire borehole length, have been found in borehole N1. For this water a minimum ^3H model age of 60 years (piston flow model) can be calculated using the following assumptions:

- a) Values from southern Sweden are comparable to the ^3H input values in Central Europe (WEISS *et al.*, 1979);
- b) diffusive loss of ^3H in fractures (NERETNIEKS, 1981) is negligible;
- c) no mixing occurs between waters with different ^3H contents and the ^3H concentration decreases only due to radioactive decay.

Because small contamination of the samples during sampling, transport and storage (compare WEISS *et al.*, 1976) cannot be excluded, the low ^3H concentration found in borehole N1 may indicate a maximum value for the subsurface production of ^3H in this groundwater. ANDREWS *et al.* (1989) bracket the limit of ^3H subsurface production between 0.07 and 0.7 TU with the lower value being the more likely one.

No or minor influences of bomb-produced ^3H were found in the samples from boreholes V1, V2 and N1. The ^3H contents in borehole V1 are between 0.7 and 2.5 TU with the highest ^3H concentrations being measured between May and November 1985 in the borehole interval 430–505 m. In 1981, the ^3H concentrations measured in the borehole interval 409–506 m were only 0.7–0.9 TU. The ^3H content in the interval 100–505 m also have a relative high ^3H concentration (1.3 TU) and no time variation between October, 1983, and February, 1984. The ^3H contents in V2 are generally lower and vary between <0.1 and 1 TU.

Figure 5 shows the ^3H contents in the borehole V2 sampled in different depths and at different times. If the maximum subsurface produced ^3H concentration is on the order of 0.7 TU (ANDREWS *et al.*, 1989) then the measured ^3H concentrations in the borehole V1 and partly also in the borehole V2 strongly suggest the inflow of recent groundwater. Flow paths for such water are unknown, but it appears necessary that natural infiltration occurred through fractures.

The lowest tritium contents are seen in saline waters about 900 m below ground surface (*i.e.*, borehole intervals below 490 m). This depth coincides with the highest salinity zone

and the interval in which waters with very low $\delta^{13}\text{C}$ values are found (see FRITZ *et al.*, 1989). This documents the total absence of young waters in these fractures as well as the lack of interconnectivity between fracture systems in the Stripa granite, an observation of fundamental importance for the evaluation of containment capabilities of crystalline rocks.

CONCLUSIONS

Isotopic analyses are well suited to characterize different groundwaters in the project area. The ^{18}O and ^2H contents show that the Stripa groundwaters are normal meteoric waters which have not been subjected to surface evaporation or secondary isotopic exchange processes with rocks and minerals. Their isotopic compositions reflect recharge conditions.

The deep groundwaters at Stripa have lower ^{18}O and ^2H contents than young, local waters. This difference is probably not the result of the preservation of seasonal isotopic differences in the recharge waters or the presence of regional flow-systems.

The lower contents of heavy isotopes in the deep groundwaters are most likely due to groundwater recharge under climatic conditions which were cooler than exist today in the Stripa area. Thus, the deep waters could have been recharged before the last major climatic improvement following deglaciation or may have formed during subsequent minor climatic fluctuations. They could then be several thousand years old.

At the Stripa site low ^{18}O and ^2H contents tend to be paralleled by increasing salinities. This is probably due to the mixing of saline and non-saline groundwaters with differing isotopic compositions. The saline component would need to have $\delta^{18}\text{O}$ values below -13‰ . No source for brines or very saline waters with such composition is known. Instead, the data lead to the interpretation that the observed chemical compositions are due not only to the mixing of two different water types but also to geochemical reactions, dissolution of salts and/or leaching of fluid inclusions.

In this context a three-component mixing system can be envisaged, whereby low ^{18}O -freshwater receives a dissolved load either through minor admixtures of brines, fluid inclusions or a non-homogeneous salt source (*e.g.* rock-water interaction) and then encounters variable amounts of local groundwater before entering the boreholes.

This interpretation would provide a logical framework for the remarkable differences which exist for both chemistry and isotopic compositions in groundwaters collected from "adjacent" fracture systems. These changes occur over very short distances (less than 10 m) and indicate that interconnectivity between different fracture systems is limited. However, the occurrence of saline water depleted in ^{18}O in different boreholes indicates hydraulic continuity of different fracture systems and may reflect hydraulic connection between boreholes even where hydraulic testing was not sufficient to substantiate this.

Surface and shallow groundwaters have the expected high ^3H concentrations and are mainly recharged after 1952. Active circulation of recent water is detected down to a depth of at least 100 m.

^3H analyses from Stripa mine waters show clearly, that ^3H is present, sometimes in substantial amounts. Groundwaters

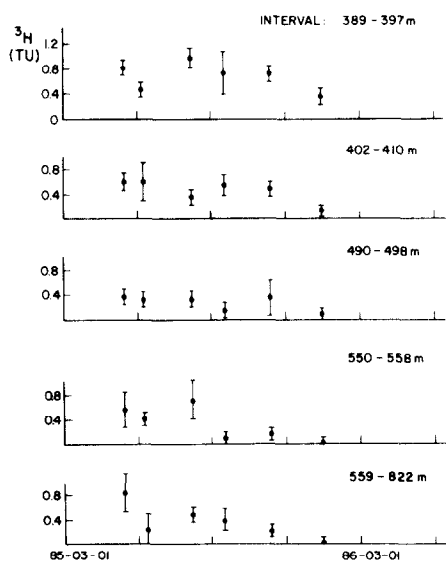


FIG. 5. Tritium contents in waters entering borehole V2. Only samples collected during 1985/86 are shown.

from some boreholes have bomb-produced ^3H which indicates residence times of less than about 35 years (recent recharge). Groundwaters from other boreholes have low but detectable ^3H contents even at depths approaching 1000 m. These low ^3H contents may result from subsurface ^3H production and/or by admixture of small amounts of recent water to old groundwater. This finding has important consequences for discussions relating to the hydrology of repository sites for various wastes in crystalline environments.

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