Characterization of Groundwater Recharge and Flow in a Vermont Upland Watershed Using Stable Isotope Tracing Techniques

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Dedicated to Bob Dylan, UVM Patrick Gym April 17, 1996
"The answer my friend, is blowing in the wind"
(and can be traced isotopically through groundwater in a fractured bedrock setting)

Abstract

This paper is a report of the progress made in the first year of this project which began in June of 1995. Using stable oxygen isotope measurements in precipitation (rain, snow, and snowmelt) and groundwater (wells), I am attempting to estimate bedrock groundwater flow rates and determine sources of recharge in the upper watershed of the Browns River in northwestern Vermont. Most of the work has focused on the uppermost portion of the study area, specifically the head of the basin above Underhill Center. Analysis of the $\delta^{18}O$ composition of more than 440 collected samples, combined with weather monitoring data, has provided an initial interpretation of relative recharge elevations for the residential wells included in the study. In addition, the relative ages or residence times for waters supplying each well are being interpreted. I have incorporated these data in a dynamic system model in order to consider in more detail the influence of various mechanisms within the basin (e.g. bedrock hydraulic conductivity, fracture interconnectivity, storage) on recharge and flow characteristics. With continued research, I will develop an accurate numerical model of the recharge and flow mechanisms within the hydrogeologic system. The results of this study will illustrate the usefulness of combining isotopic tracing and modeling techniques to understand groundwater recharge and flow in a fractured bedrock setting.

Introduction

Most of the background information on this project was discussed in the proposal document prepared in the fall of 1996. In general, the purpose of my study is to characterize groundwater recharge and flow mechanisms in the fractured bedrock setting of the study area. The specific area in which most of my work has been focused is the head of the Browns River watershed above Underhill Center, Vermont, in a basin ranging from 270 to 1340 meters (above msl) on the slopes of Mount Mansfield (Figure 1). The topography of the study area is controlled by bedrock which is overlain by glacial till of varying thickness with some glaciofluvial and glaciolacustrine deposits in the lower elevations. The bedrock is a deformed and metamorphosed schist of the Underhill formation (Thompson and Thompson, 1991). Structurally, this rock exhibits a folded north-south striking bedding schistosity which dips in general to the west away from the Green Mountain Anticlinorium. The rock is fractured by tension joints resulting from Taconic and perhaps Acadian post-metamorphic adjustments, as well as more recent vertical cross joints (Stanley and Ratcliffe, 1983; Christman, 1959; Christman and Secor, 1961). It is assumed that these recent fracture sets may represent the most significant zones of water storage and transport in the bedrock flow.

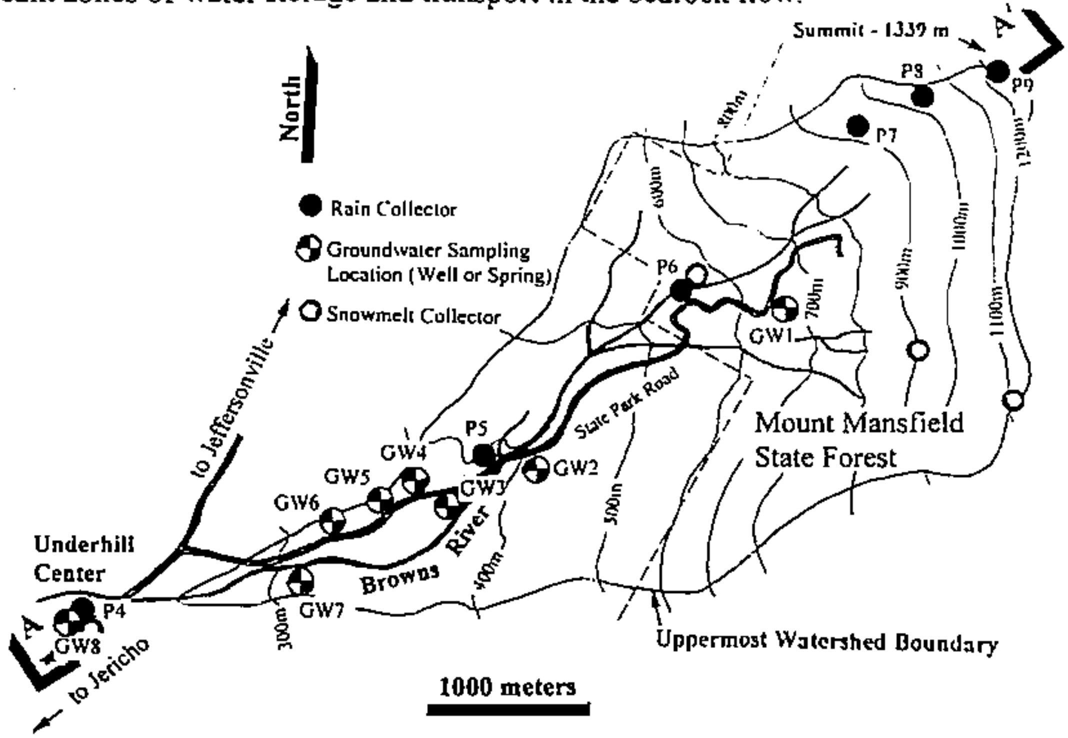

Figure 1 - Project Area Map

Groundwater flow in a fractured bedrock setting is complex and therefore not easily modeled by conventional approaches. The hypothesis under which I am conducting my research is essentially that groundwater recharge and flow mechanisms in this type of setting can be accurately characterized using a combination of isotopic tracing techniques and various modeling approaches. This, of course, must be combined with a conceptual understanding of the bedrock structure and its control of groundwater flow. Most of the residents in the study area rely on the bedrock aquifer as their primary drinking water source. This area and others like it are being rapidly developed, thus creating a more urgent need for understanding these systems. This project began in June of 1995 with funding for the first year through a USGS Vermont Water Resources grant. I believe that I have made significant progress toward understanding the behavior of groundwater in this fractured bedrock setting using the investigative techniques mentioned above. With continued research, I am confident that an accurate model of this hydrogeologic system can be developed.

Review of Project Objectives

The specific objectives as stated in the proposal were threefold:

1) Characterize the isotopic signature of precipitation and groundwater with elevation and time.

2) Use the collected data discussed above, along with the geometry of the bedrock aquifer and surficial cover, to determine groundwater recharge, storage, and transport characteristics in this type of setting.

3) Provide at least a preliminary understanding of groundwater recharge and flow characteristics necessary to develop plans for future water supply development in the towns of Underhill Center, Underhill and Jericho. This will include creating a groundwater flow model for predictive simulations.

The following sections will describe how the above objectives have been addressed in the first year of research.

Water Sampling and Analysis

In July of 1995, I began collection of precipitation samples on a weekly basis at 16 stations in Jericho and Underhill in order to determine the spatial and temporal distribution of rain and snow volumes and to monitor the isotopic composition of recharge to groundwater. Rain is collected in a buried glass bottle fed by a plastic funnel. Snow is collected via coring of the snow pack, and as meltwater in lysimeters placed at the ground surface.

Water and snow samples are measured for $\delta^{18}O$ composition (ratio of heavy to light oxygen isotopes) at the University of Vermont isotope laboratory. I have observed a fairly consistent decrease in $\delta^{18}O$ composition with elevation in weekly samples which is suspected to be a response to colder average temperatures at the high elevations in the basin.

After approximately 4 months of monitoring, the number of precipitation monitoring stations was reduced, as significant variation in $\delta^{18}O$ composition was only observed in the steeper portions of the watershed (i.e. from Underhill Center to the top of Mt. Mansfield). Rain collection was continued at 10 of the original 16 stations. Snow is collected at 6 stations, and snowmelt at 4 stations. The locations of collection stations within the area of focused study are shown in Figure 1.

As of the end of March, 1996, a total of approximately 350 rain, snow and snowmelt samples had been collected. Of these, approximately 300 had been analyzed for $\delta^{18}O$ composition. Figure 2 shows the variation in isotopic composition for these samples over time at collection stations P1, P4, P6, P7, and P8 (as designated in Figure 1).

In October of 1995, I began collecting and analyzing samples of groundwater from 9 residential water supply wells and springs within the basin. Most of the wells and springs are located in the lower elevations of the basin with the exception of GW1 which is located in Underhill State Park on the slopes of Mt. Mansfield (Figure 1). The $\delta^{18}O$ measurements in groundwater also vary with time, likely reflecting the seasonal signature of the infiltrating waters from the upland recharge areas. Approximately 130 samples have been collected and analyzed from the wells. Figure 3 (previous page) presents the isotopic records in the 6 wells with the most complete data sets, designated as GW1, GW3, GW5, GW6, GW7 and GW8 in Figure 1.

Interpretation of Data

In order to relate the temporal variation of the isotopic composition of recharge with that in groundwater, the isotopic record of infiltrating waters (recharge) can be weighted according to volume measurements. Rain and snowmelt represent sources of direct recharge to the groundwater system. Using volume measurements collected with each sampling round, the deviation from the average weekly $\delta^{18}O$ composition at a station can be multiplied by the ratio of the sample volume to the average weekly volume:

$$(\delta^{18}O - \delta^{18}O_{ave})/(V/V_{ave})$$

A plot of the normalized volume-weighted $\delta^{18}O$ compositions for monitoring stations P1, P4, P6, P7, and P8 is shown in Figure 4. Figure 5 is a second presentation of the variation of $\delta^{18}O$ composition in the wells, plotted as deviation (positive or negative) from the average weekly $\delta^{18}O$ in each well. The positive and negative "spikes" in Figure 4 should be reflected in wells if the isotopic signature of recharge is transferred through the groundwater system. Of course, these plots will be improved by the collection of a full year (or more) of precipitation data, as the accuracy of the weekly averages will improve. It is anticipated that a large negative spike will occur in samples collected from the spring melt. This spike may be the most traceable event in the groundwater isotopic record.

The average composition of groundwater in a well should be determined by its reeharge source elevation. Assuming equal residence times, the magnitude of variation in a well should be inversely proportional to the degree of mixing through interconnected fractures in the bedrock aquifer. Alternatively, groundwater in deep, isolated fracture systems may exhibit a well preserved temporal isotope variation, regardless of residence time. Figure 6 relates the range of isotopic variation in wells to their average composition over the period of monitoring. Although not strong, a general correlation is observed where wells with lower average $\delta^{18}O$

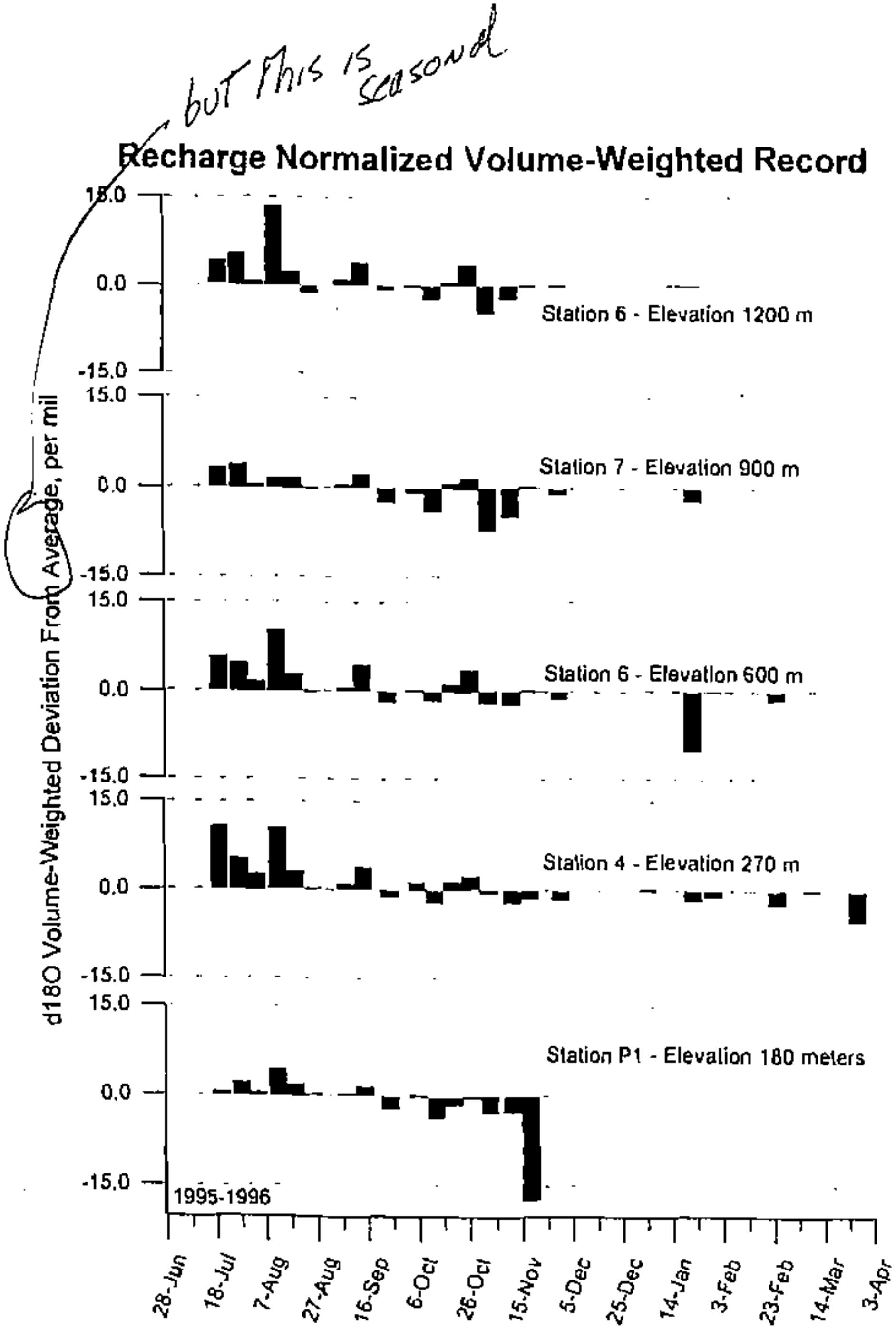

Figure 4 - $\delta^{18}O$ Composition in Precipitation Samples Normalized to Weekly Average $\delta^{18}O$ and Weighted by Volume

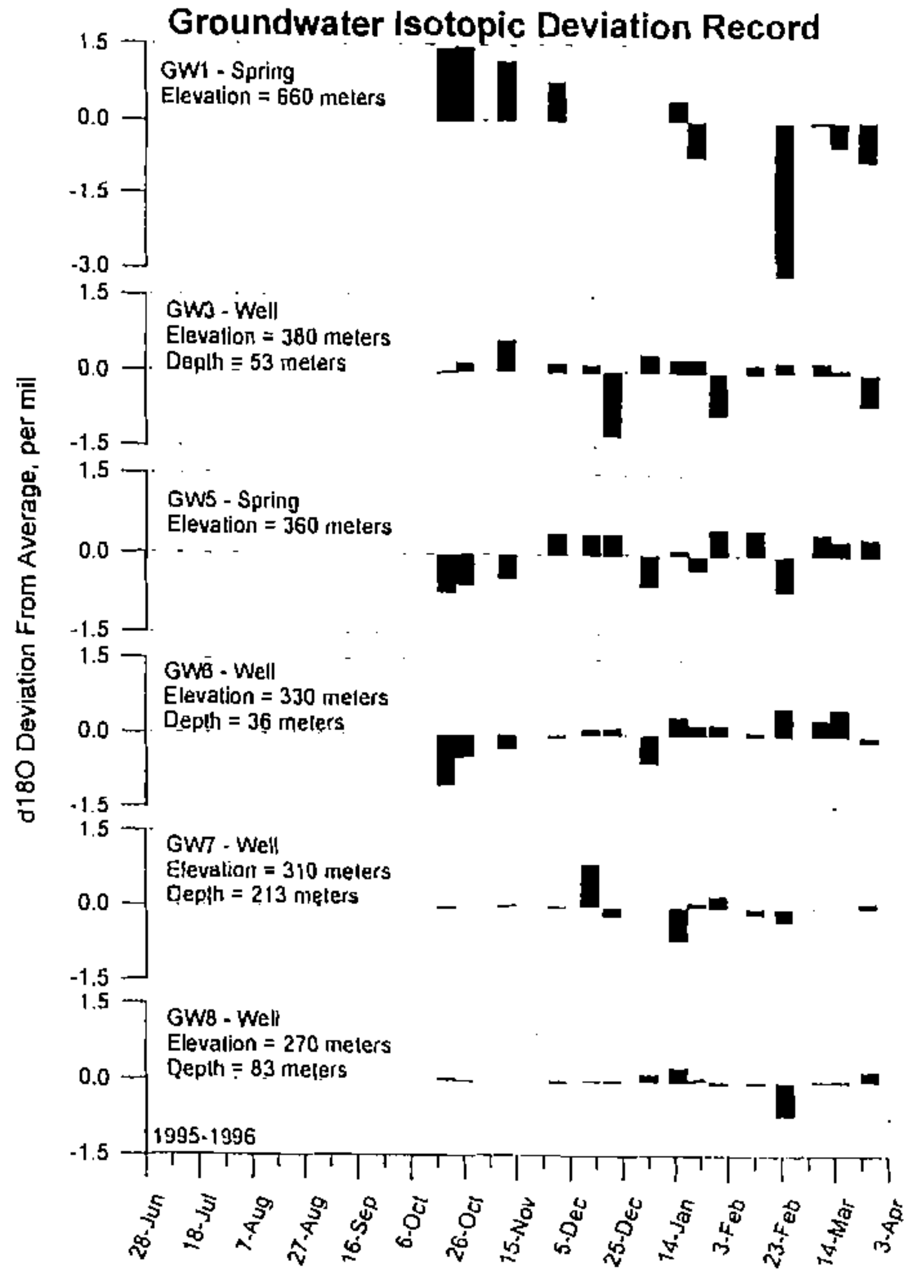

Figure 5 - $\delta^{18}O$ Composition in Groundwater Samples - Deviation from Weekly Average

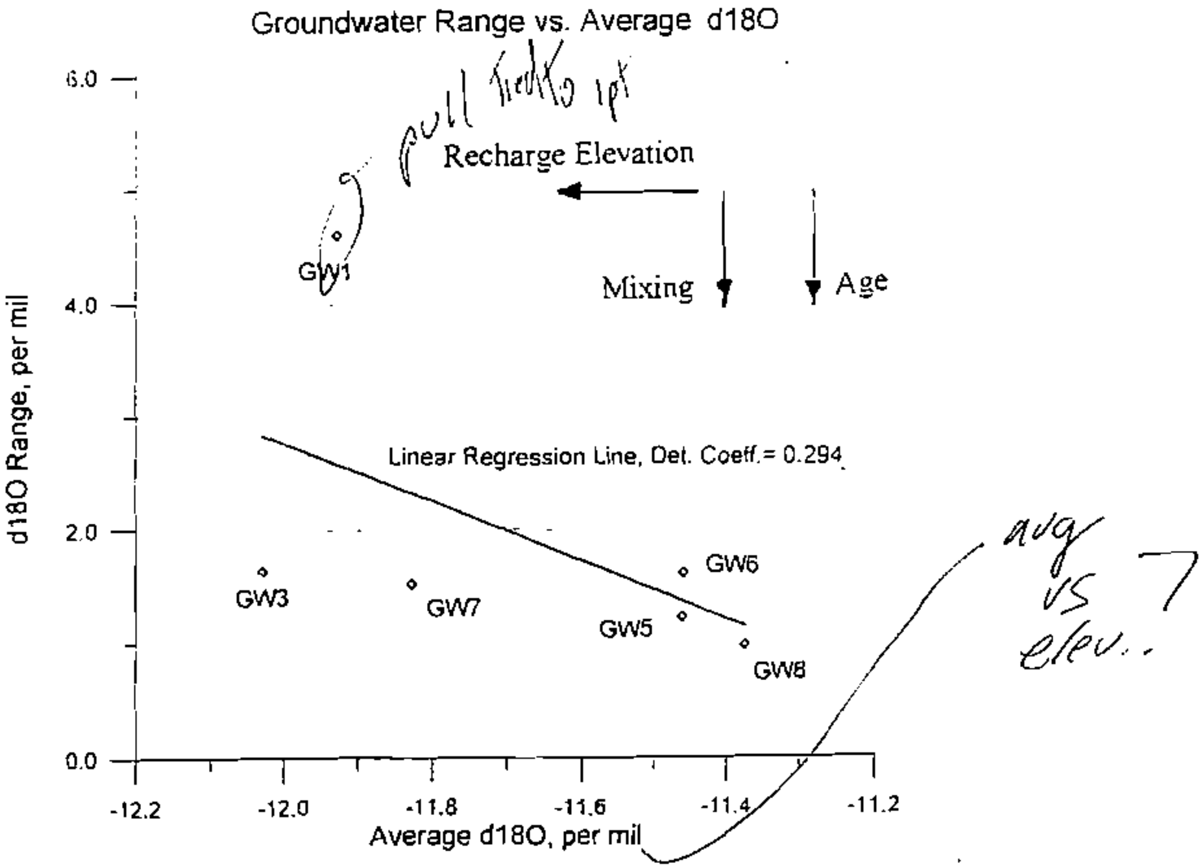

Figure 6 - Groundwater $\delta^{18}O$ Composition Range vs. Average

composition (higher recharge elevations) respond more dynamically to recharge input. The wells with a higher magnitude of response may be supplied with younger water (i.e. short residence time with little opportunity for mixing) or water flowing in deep, isolated fracture systems. Again, at least one full year of data collection is necessary to study these patterns further.

The relationship of well depths and isotopic composition were also examined. Neither a correlation between well depth and average weekly $\delta^{18}O$ composition, nor a correlation between well depth and the range of $\delta^{18}O$ variation, were observed. This may indicate that wells are typically supplied by one predominant fracture or fracture zone in their vertical domain, rather than from a combination of several fracture networks. Or, since the wells are open to the entire vertical fractured bedrock interval into which they are installed, all of the wells may be supplied from a network of several fractures which are equally contributing in the immediate vicinity of each well.

Dynamic System Model

During the spring semester, I have been developing a dynamic system model to assess the sensitivity of groundwater travel to various parameters within the bedrock system (hydraulic conductivity, fracture interconnectivity, storage, anisotropy, etc.) and to predict future water availability assuming continued residential development in the upper basin. The modeling effort is greatly enhanced with the use of the $\delta^{18}O$ record as a calibration tool. Real data in the form of precipitation records, temperature records, and $\delta^{18}O$ records in recharge and groundwater, are incorporated in the model. Other unknown parameters such as aquifer storage, fracture network patterns, and groundwater flow rates, are varied to test the model's sensitivity. Calibration of the model with collected data is still underway. This approach is providing an improved conceptual understanding of the interaction of processes within the groundwater system.

The next step in the modeling effort is the development of a numerical model specific to the basin. This model will incorporate the dimensions and the interpreted fracture characteristics of the bedrock aquifer, along with pumping wells, streams, rain, evaporation/transpiration, and other features effeeting the mass balance of water in the system. The flow model will be verified using groundwater travel rates as calculated from interpreted residence times via the $\delta^{18}O$ and other isotopic dating techniques to be discussed below.

Plan for Continued Work, Presentations and Funding

Continued isotopic analysis of precipitation and groundwater samples will provide a more robust definition of the relationships discussed above. This information will be combined with further analysis of aquifer bedrock structure and fracture network geometry through field mapping and air photo analysis in the upcoming summer. Based on interpretation of collected data, the numerical groundwater model will then be constructed.

During the summer of 1996, a detailed field analysis of bedrock fracture patterns will be completed in the upper basin. Initially, large scale features will be identified using available orthophotos of the area. Some of this work has already begun. At bedrock exposures (predominantly on Mt. Mansfield where cover is thinnest), aperture and orientation of individual fractures as well as fracture set density will be measured and recorded. The goal of fracture trace analysis is to provide information on potential influence of fracture set orientation and interconnectivity on groundwater flow in the basin. This interpretation will be used in the development of the groundwater model discussed above.

In selected groundwater samples collected over the past year, I will attempt to determine the absolute ages of the water using one or more dating techniques. The two main techniques being considered are the Tritium (^3H) and Tritium/Helium ($^3H/^3He$) dating methods. The ^3H dating method uses a comparison of volume-weighted concentrations of ^3H in water with reconstructed post-1953 ^3H concentrations in the atmosphere (Fontes, 1980). The $^3H/^3He$ technique is based on the radioactive decay of atmospheric ^3H that enters groundwater during recharge and the accumulation with time of its daughter product ^3He (Tolstikhin and Kamensky, 1969).

Age dating will allow an interpretation of the temporal response of groundwater to variations in recharge $\delta^{18}O$ composition to be constrained more precisely. In other words, the age dating will improve the accuracy of groundwater residence times as determined with the stable isotope tracing techniques presently being used.

Preliminary results of the study were presented at the 1995 Geological Society of America (GSA) Annual Meeting and the 1996 University of Vermont Graduate Research Day. Updated results will soon be presented at the Vermont Geological Society's Annual Meeting (April 27, 1996), as well as the Vermont Water Resources and Lake Studies Center Annual Meeting (May 21, 1996).

Funding for research through the summer will be provided by a recent award from the UVM Graduate College. A renewal of the USGS grant to take effect in September, 1996 is now being proposed.

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