
Geochemical Variations in an Alpine Lake and Watershed Underlain by Siliciclastic Bedrock, Uinta Mountains, Utah

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ABSTRACT

A small watershed which includes several small lakes in the Uinta Mountains of northern Utah is underlain by monolithologic Precambrian siliciclastic rock with extremely limited buffering capacity. In spite of this, systematic spatial and temporal variations in alkalinity, pH, and major elements occur in springs, small streams, and one lake within the watershed. Alkalinity changes by 3-fold over 1 km of vertical elevation within the watershed. Cations and silica show similar although less dramatic changes with respect to elevation. Silicate weathering seems to constitute the dominant mechanism of alkalinity generation. The water column in Marshall Lake shows significant seasonal stratification of temperature and chemical constituents. Vertical variation of alkalinity in the lake during the summer is related to the input of geochemically distinct water sources in the watershed. Vertical pH variations in Marshall Lake do not match alkalinity variations but instead are related to photosynthesis in the upper and middle portions of the water column. Thermal and chemical stratification is greater in the lake than in well-studied alpine lakes of the Sierra Nevada. Numerical hydrodynamic models suggest that temperature and chemical stratification of this Uinta Mountain lake can be attributed to lake depth (13 m vs. more shallow depths of the Sierra lakes) or relatively weak wind shear stress. The combined watershed/lake study demonstrates the need for complete vertical water sampling in order to accurately characterize the geochemistry of deep (> 10 m) alpine lakes.

INTRODUCTION

Alpine lakes and watersheds represent important scientific and recreational resources in many western states and provinces of North America. These lakes are typically located at the head of drainages in high remote mountain regions. Although generally not impacted by human activity in the winter, alpine lakes and their surrounding watersheds have considerable summer recreational value and are often important parts of designated wilderness areas or national parks. In recent years considerable concern has been raised concerning the susceptibility of alpine lakes in the western U.S. to inputs of anthropogenic acidity (e.g., Lewis and Grant, 1980; Lewis and others., 1984).

A variety of field studies have been undertaken to understand the weathering and geochemistry of alpine

lakes and watersheds. Summaries for alpine lakes and their surrounding watersheds throughout the western United States can be found in Melack and Stoddard (1991), Turk and Spahr (1991), and the references therein. Detailed work on the chemistry of alpine watersheds has focused on mechanisms which generate alkalinity (Drever and Hurcomb, 1986; Stoddard, 1987; Mast and others., 1990; Drever and Zobrist, 1992). These studies demonstrate that bedrock weathering is the primary control of alkalinity generation although other mechanisms may also be operative. In some cases, calcite derived from the deuteric alteration of plagioclase feldspar and other reactive mineral phases (e.g., amphibole) generates a large fraction of the alkalinity in alpine watersheds (Drever and Hurcomb, 1986; Mast and others, 1990) while other studies point to silicate weathering (Stoddard, 1987; Melack and Stoddard, 1991).

The geochemistry of lakes and surrounding streams and groundwater are often related. Some researchers have noted the close correspondence between snow runoff chemistry and the seasonal

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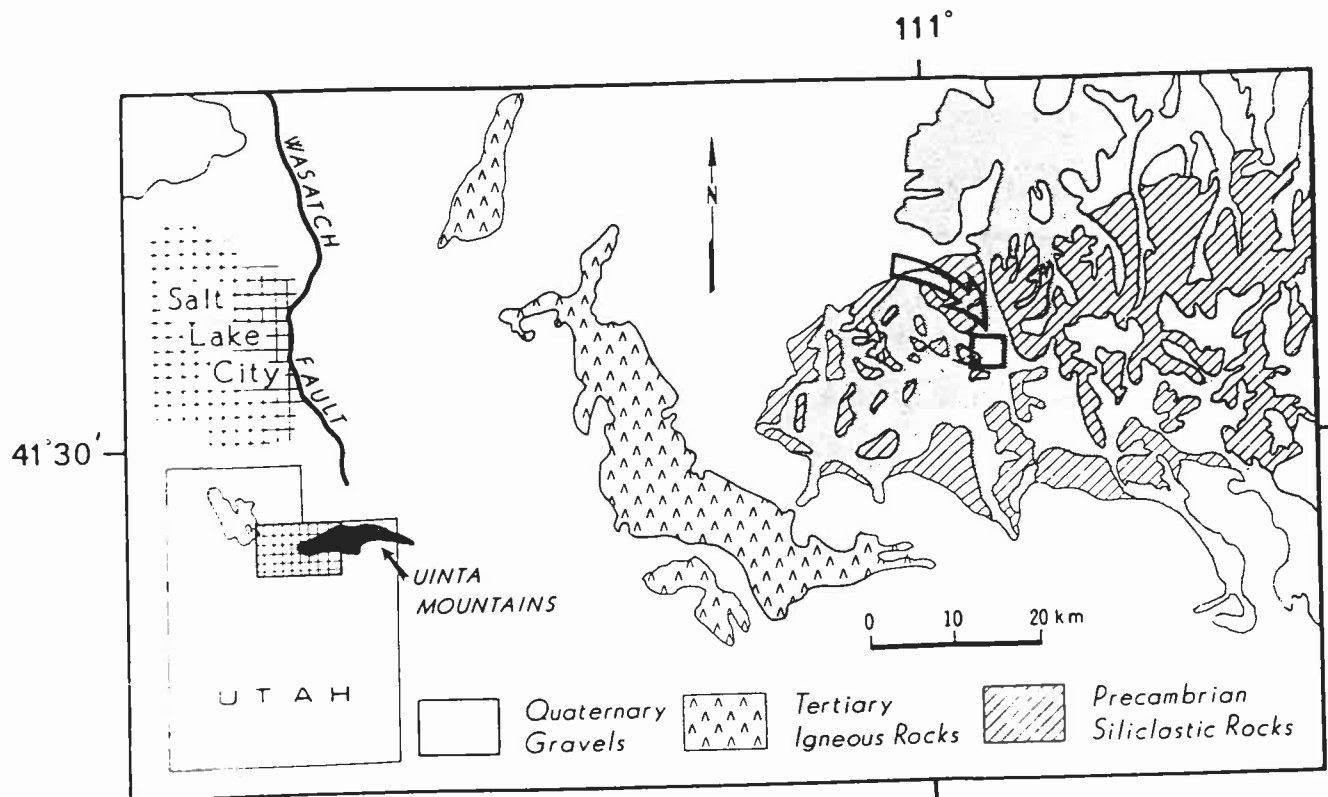


Figure 1. Generalized geologic map of north-central Utah showing the location of Marshall Lake and the Murdock basin in the western Uinta Mountains. Arrow points to the area shown in figure 2.

chemical evolution of lakes (e.g., Stoddard, 1987). Subsurface fluid flow modeling suggests that groundwater should enter the edges of lakes (e.g., Winter, 1976). However, studies which document this phenomenon are uncommon due to the well mixed nature of the water column in most alpine lakes.

This paper presents the chemical characterization of a small alpine lake and watershed in the Uinta Mountains of Utah. The study was originally undertaken because the Uinta Mountains are downwind from major metropolitan sources of atmospheric pollution (the Wasatch front of Utah) and may therefore be susceptible to acid deposition (Revelt, 1990). Furthermore, the bedrock geology of the Uintas is dominantly Precambrian quartzites and arkoses with extremely limited buffering capacity. Significant vertical variations in pH and alkalinity were discovered during investigation of the thermal and chemical structure of Marshall Lake in the high Uinta Mountains (Christensen, 1994). A survey of an adjacent watershed which had a large number of springs and streams was therefore undertaken in order to relate the chemistry of the lake with weathering chemistry.

SETTING AND METHODOLOGY

The Murdock Basin is located in the western portion of the Uinta Mountains of Utah along the border

of the Hayden Peak and Mirror Lake 7.5' U.S. Geological Survey quadrangles (figure 1). The basin encompasses a cirque of approximately 3 km² (1.2 mi²) area and several smaller drainage areas (figure 2). Marshall Lake is one of the largest of several lakes in the basin with a surface area of approximately 10 hectares (0.04 mi²) and maximum depth of approximately 13 m (34 ft). The Murdock basin watershed and its associated lakes were selected for this baseline study because of the relatively small area underlain by homogeneous, nearly monolithologic bedrock (quartzite with minor arkose and siltstone), and access via an unimproved dirt road with relatively minor anthropogenic disturbances.

The geology of the Uinta Mountains is dominated by Late Precambrian orthoquartzite, arkose, argillite, shale, and siltstone of the Uinta Mountain Group (Wallace and Crittenden, 1969). Geologic mapping shows the area around the Murdock Basin consists of the quartzite-dominated Bald Mountain Formation (Larsen, 1954). Field examination of rocks in the Murdock Basin during this study showed only massively-bedded quartzites and minor arkoses cut by high-angle faults with minor displacement. Talus slopes are abundant and soil development is minimal. No primary or secondary carbonate minerals were identified in any rocks or faults near the Murdock Basin through field, petrographic, or cathodoluminescent

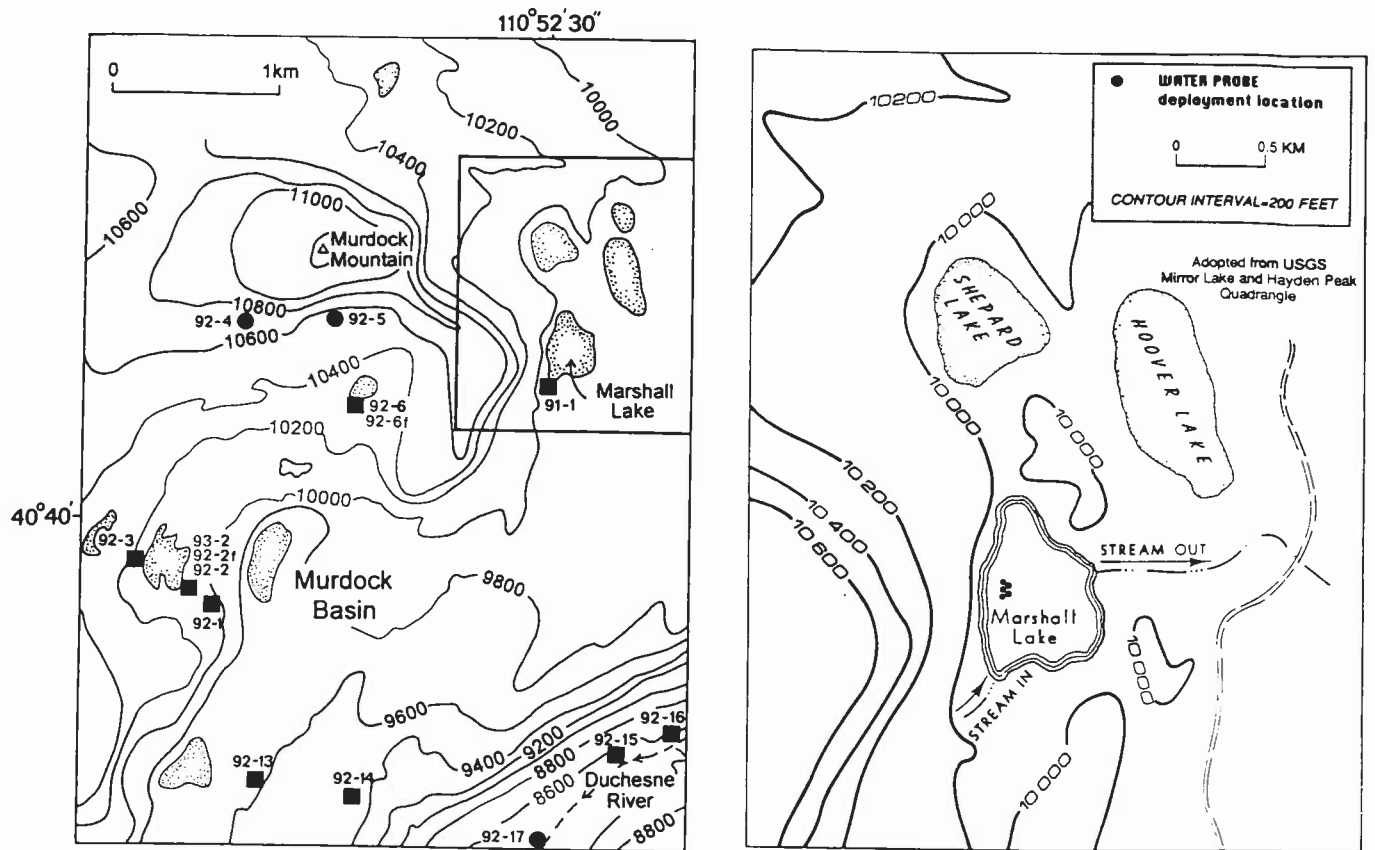


Figure 2. Topographic maps of Murdock basin and Marshall Lake, Uinta Mountains, Utah (adapted from the U. S. Geological Survey Mirror Lake and Hayden Peak 7.5' quadrangles). Dots refer to sampling location of springs and squares refer to location of streams in the watershed. Right hand map (shown as solid line insert on the left hand map) shows details around Marshall Lake.

examination. This is in contrast to studies in the Cascade Mountains (Drever and Hurcomb, 1986) and Rocky Mountain National Park (Mast and others, 1990) where trace amounts of calcite associated with the alteration of plagioclase feldspar have been identified microscopically and are believed to make significant contributions to the watershed geochemistry.

In situ measurements of temperature, pH, and water depth of Marshall Lake were made between June 22 and October 5, 1991 with an internally-recording Aquamate 1000 water quality probe manufactured by Applied Microsystems, Ltd. A total of eight probe deployments were conducted. During each deployment, the probe was allowed to equilibrate in lake water at approximately 6 m (20 ft) for 15-30 minutes. The probe was then raised to within 10 cm (4 inches) of the water surface and again lowered at 0.33 m (1 ft) intervals. It remained at each depth between 1 to 4 minutes which was sufficient time for the temperature and pH sensors to equilibrate. The probe was programmed to record pH, depth, and temperature every 10 seconds, resulting in 6-24 recordings per depth. Water samples were collected from Marshall Lake in acid-washed bottles at approximately 1 m (3 ft) intervals with a peristaltic pump.

Surface water samples from several streams and three springs within the Murdock Basin watershed were collected in May and October, 1992 and July, 1993 (figure 2). Two of the three springs were located at very high elevations (figure 2) meaning that the water flow paths were probably short and their chemistry not much different from those of the streams samples.

Alkalinity for all samples was analyzed using the method of Fishman and Friedman (1985). Cation concentration of samples from Murdock Basin were determined with atomic absorption spectrophotometry. The samples and standards were spiked with lanthium chloride in order to enhance the determination of Ca and Mg. Anion analysis was accomplished with ion chromatography. Silica was measured colorimetrically. Charge balances for the water samples averaged $\pm 7\%$.

FIELD AND ANALYTIC RESULTS

Watershed Geochemistry

A summary of major element concentration for the Murdock basin watershed and Marshall Lake is given in Table 1. Total concentrations of cations and

Table 1. Chemical analyses of water samples from the murdock Basin, Uinta Mountains, Utah. Unites are $\mu\text{eq/L}$ for ions and $\mu\text{mol/L}$ for silica. Dashes indicate that the analysis was not performed.

Sample	Elev.(m)	pH	Alk	Ca	Mg	Na	K	Cl	SO ₄	SiO ₂
92-4	3,262	5.8	85	60	24	14	4	7	19	42
92-5	3,207	6.3	81	71	26	14	5	7	17	38
92-6	3,122	5.7	77	72	28	19	5	10	20	37
92-6f	3,122	—	98	80	34	36	8	21	36	—
92-3	3,098	6	85	62	24	14	5	10	18	37
92-2	3,067	5.8	85	68	28	16	6	12	18	30
92-2f	3,067	—	110	65	29	23	8	8	19	—
93-2	3,067	6.5	63	49	22	19	6	5	16	—
92-1	3,055	7.4	85	80	35	20	8	9	27	63
91-1	3,020	6.1	110	59	39	24	9	10	10	—
92-13	2,932	6	116	85	55	22	10	10	31	27
92-14	2,887	6	99	77	38	18	8	9	24	35
92-16	2,537	6.7	107	95	49	27	9	8	41	48
92-15	2,550	6.9	210	142	13	43	13	42	15	78
92-17	2,550	7.1	197	123	119	38	17	11	52	80

anions are 100-250 μeq and thus are within the typical range of many other alpine lakes and watersheds (e.g., Melack and others, 1985; Turk and Spahr, 1991; Melack and Stoddard, 1991). The waters from the Uinta Mountains are dominantly calcium-bicarbonate which is also typical of many alpine settings of the western United States (Turk and Spahr, 1991; Melack and Stoddard, 1991).

The concentration of all ions generally increases with decreasing elevation in the watershed. Alkalinity increases of 2-3 fold over a 1 km decrease in elevation (figure 3) demonstrate that the weathering of bedrock and soils is contributing to the dissolved load of the waters. Ca, Mg, Na, and K also increase with decreasing elevation (table 1, figure 4), although changes are not as great as those of alkalinity. Similar changes in alkalinity with elevation have been documented in a watershed of the Swiss Alps (Drever and Zobrist, 1992).

A critical question is what weathering reaction generates alkalinity within the watershed. As mentioned previously, other watershed studies suggest that calcite weathering is the dominant alkalinity generation mechanism in watersheds underlain by igneous rocks (Drever and Hurcomb, 1986; Mast and others, 1990). Although no calcite was observed in bedrock of the Uinta Mountains, studies of other alpine settings have documented aeolian calcite input to mountain soils (e.g., Litaor, 1987; Giovanoli and others, 1988). Similar aeolian input to soils might logically be expected in the Uinta Mountains since they are downwind from modern evaporite basins of the Great

Basin to the west. If calcite weathering were the dominant method of alkalinity generation, then Ca/Na ratios would be expected to increase with decreasing elevation. However, Ca/Na ratios show no systematic relation to elevation in the Murdock Basin (figure 5).

An alternative to alkalinity generation by aeolian calcite would be weathering of feldspars found in the minor arkoses of the basin bedrock. Weathering of plagioclase feldspar would produce a relatively constant Ca/Na ratio with change in elevation (figure 5). Positive correlations between (Ca + Na) and alkalinity have been noted in the Sierra Nevada (Garrels and Mackenzie, 1967; Melack and Stoddard, 1991) and attributed to plagioclase feldspar weathering. Further evidence for weathering of plagioclase and a potassium-bearing mineral (either muscovite or alkali feldspar) in the Uinta Mountains comes from the positive correlation between Na-SiO₂ ($r=0.83$) and K-SiO₂ ($r=0.75$) in the waters of the Murdock Basin (figure 6).

Lake Temperature and Geochemistry

Considerable spatial and temporal variation of temperature and geochemistry were recorded in Marshall Lake. Temperature-depth profiles of Marshall Lake are typical of temperate-latitude, dimictic lakes (figure 7). Spring overturn occurred in mid-June, shortly after the melting of the lake icepack (Christensen, 1994). A gradual deepening of the thermocline was observed as the summer progressed. Maximum surface temperature was approximately 16°C (61°F) while bottom temperature never exceeded

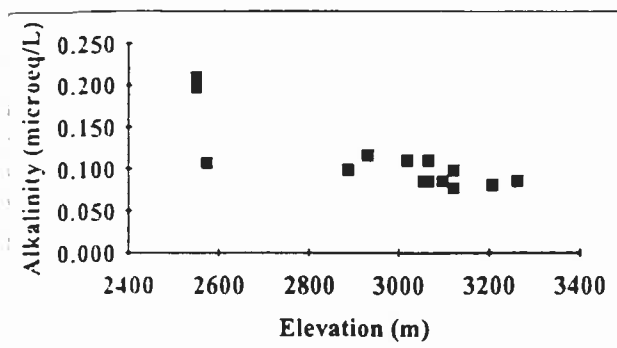


Figure 3. Alkalinity-elevation plot of waters in the Murdock basin.

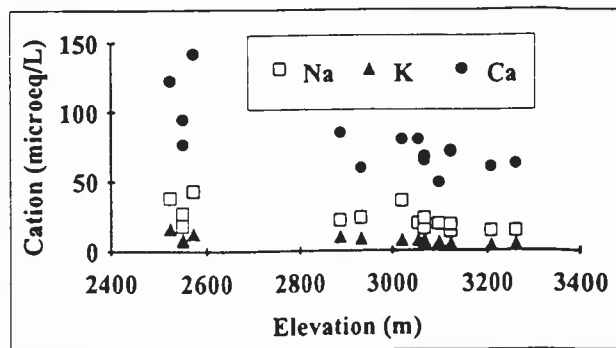


Figure 4. Cation (Ca, Na, K)-elevation plot of waters in the Murdock basin.

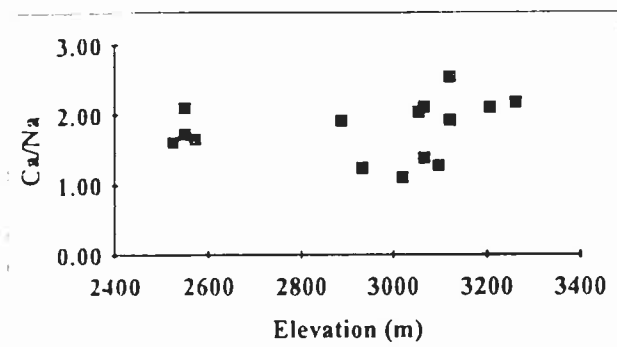


Figure 5. Ca/Na-elevation plot of waters in the Murdock basin.

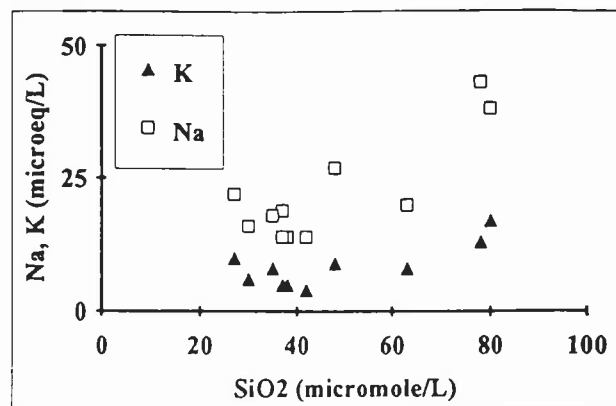


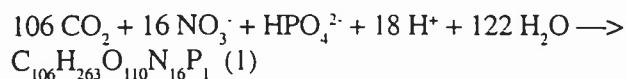
Figure 6. Na, K-SiO₂ plot of Murdock Basin waters.

5°C (41°F). Fall overturn was complete by early October. Temperature profiles of Marshall Lake also showed diurnal variability. The epilimnion was warm and relatively shallow in the August 2 evening profile (figure 8a). By the following morning, the epilimnion temperature decreased slightly and the thermocline deepened significantly as a result of night-time cooling.

Measured alkalinity in Marshall Lake during the summer season varied between 100 and 260 µeq/L (figure 9). Alkalinity at the lake bottom is significantly higher than surface alkalinity during summer stratification. The most likely explanation of the increase in bottom water alkalinity is influx of groundwater which has undergone geochemical weathering in the surrounding watershed. Springs were observed and in the area surrounding Marshall Lake throughout the year. Year-round seepages might therefore be expected to exist at the lake bottom, which would constitute the lowest hydraulic heads of the groundwater system within the catchment basin of the lake.

Seasonal pH profiles were considerably different than those of alkalinity (figure 10). Surface pH remained relatively constant at approximately 6.5 throughout the warm season. Below the surface (1-4 m or 3-13 ft), pH was considerably higher (7.2-7.3)

throughout the summer. This elevated pH is most likely the result of photosynthesis as can be seen conceptually with the reaction of Redfield and others (1963):



The effect of photosynthetic activity becomes more pronounced as the season progresses (figure 10). pH is sharply reduced at depths of 4-7 m (13-23 ft), and probably reflects the influence of the respiration of organic matter produced in the epilimnion (reverse of Equation 1).

An additional interesting feature of the pH profiles is the diurnal pH variations (figure 8B). The pH maximum due to photosynthesis is relatively close to the surface in the morning profile, but shifts approximately 1-2 m (3-6 ft) deeper into the water column in the evening profile. This deepening is approximately the same as the observed temperature, although it could be a response of photosynthetic algae to increased light intensity during the day, a phenomenon well-documented in limnologic and oceanographic textbooks (e.g., Parsons and others, 1984).

In most water column profiles, there is a noticeable increase in pH near the bottom of the lake (figure

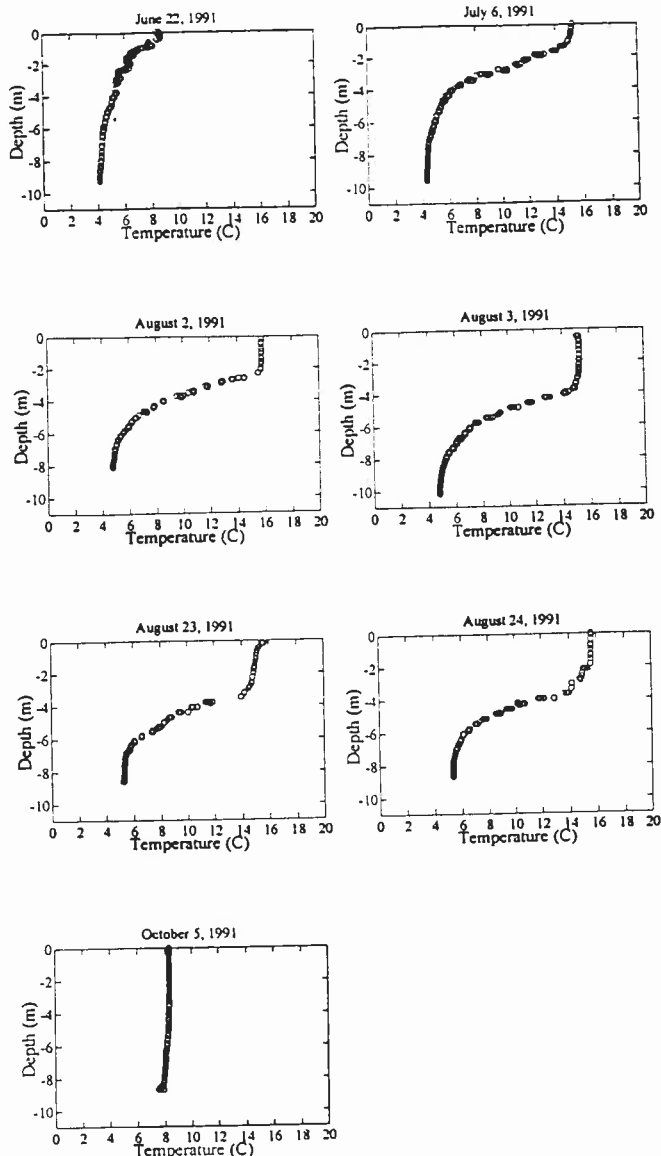


Figure 7. Temperature-depth profiles of Marshall Lake through the summer, 1991 season.

10). There are several possible explanations for this feature. Although oxidation of organic matter by nitrate and sulfate can raise the pH of natural waters when dissolved oxygen is low, the amount of SO_4^{2-} and NO_3^- in Marshall Lake is relatively small (approximately 28 $\mu\text{eq/L}$ and 8 $\mu\text{eq/L}$, respectively) (Christensen, 1994). Furthermore, the smell of H_2S in sediment core samples collected from the lake bottom was not noticed and the sediments were not laminated, indicating an oxygenated, bioturbated bottom sediment environment. The increase in bottom pH occurs at approximately the same depth as the increase in bottom alkalinity noted previously. Bottom waters with a relatively high pH in Marshall Lake lend further support to the idea that subsurface springs are entering the lower part of the lake water column.

DISCUSSION

The analytic and field measurements of a lake and watershed located in a siliciclastic terrain allow comparisons to be drawn with similar studies conducted in other settings of the western United States. Virtually all of these studies have been conducted in areas underlain by igneous rocks and most do not consider the relationship between watershed geochemistry and the internal chemical dynamics of associated lakes.

Relationship of Lake and Watershed Geochemistry

The input of geochemically evolved water to the bottom of Marshall Lake can be explained within the context of a regional groundwater scenario of the watershed. Water which enters the regional groundwater system of the watershed can follow a number of flow paths. Surface flow or shallow groundwater flow would be expected to have a geochemical signature close to that of local precipitation (Stoddard, 1987; Loranger and Brakke, 1988). Water which has longer, deeper subsurface flow paths would tend to enter lake bottom waters or bypass the local groundwater flow system of the lake basin altogether (figure 11). In either case, the water has longer residence time in the bedrock and thus acquires higher solute concentrations. In this manner, the water in the bottom of Marshall Lake (Path A in figure 11) appears geochemically similar to waters at the lower elevations of the watershed (Path B in figure 11) (table 1).

Controls of Lake Stratification

The thermal and chemical stratification observed in Marshall Lake stands in contrast to relatively weak stratification observed in detailed studies of other alpine lakes (e.g., Stoddard, 1987; Melack and Stoddard, 1991). For instance, surface-to-bottom temperature differences in Marshall Lake exceeded 11-12°C (52-54°F) (figure 12) whereas maximum surface-to-bottom temperature differences in Gem Lake of the Sierra Nevada is 1-2°C (2-3°F) (Stoddard, 1987).

The degree of stratification in lakes is a function of the counteracting effects solar heat flux and surface wind shear stress. Elevated heat flux or weak winds tend to increase stratification. Relatively shallow water bodies tend to be vertically homogeneous because of the ability of turbulent mixing caused by winds to reach the lake bottom. Deep water bodies are more likely to display thermal and chemical stratification.

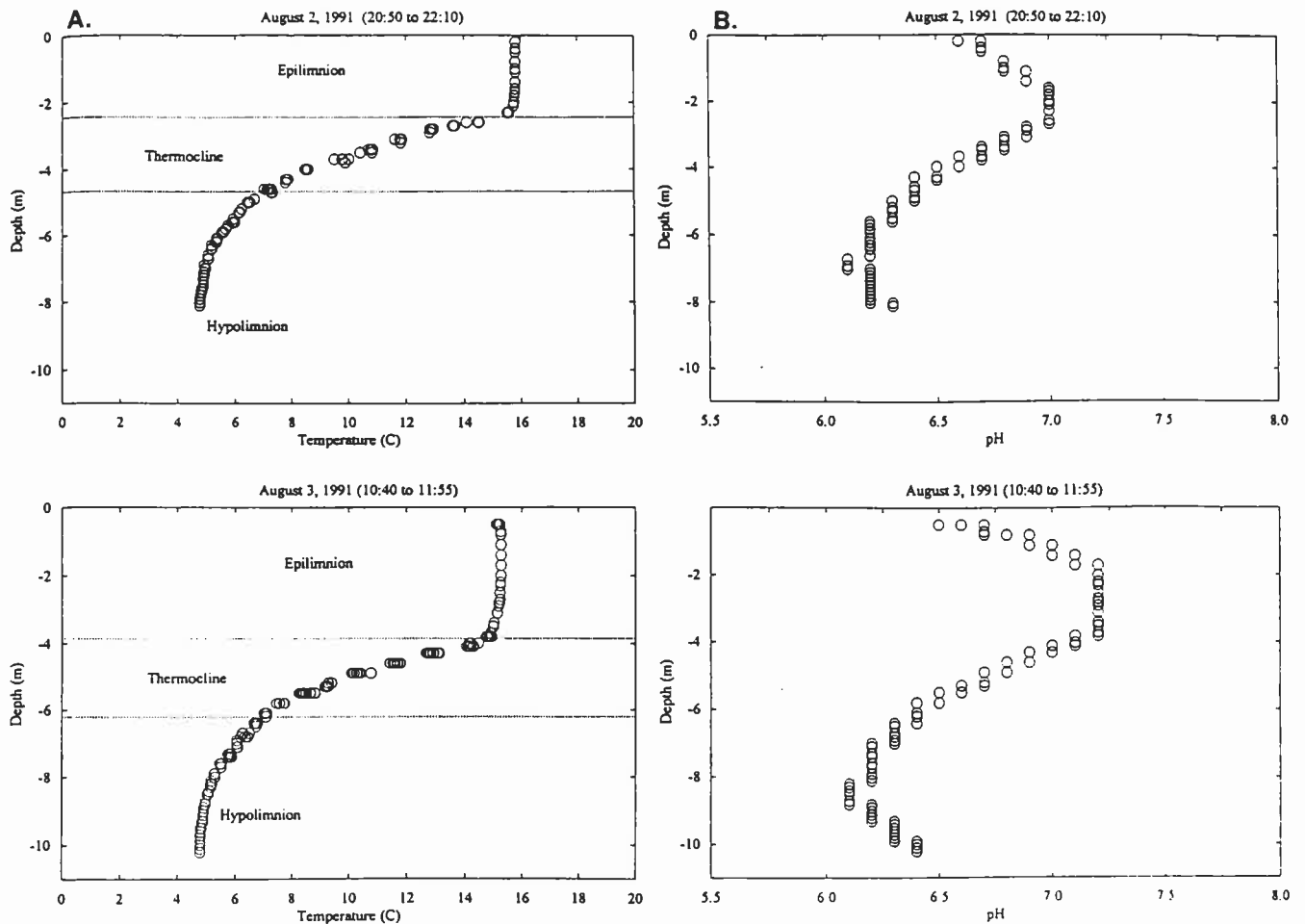


Figure 8. (a) Temperature-depth and (b) pH-depth measurement illustrating diurnal changes in properties at Marshall Lake.

Carefully constructed numerical experiments represent one way to examine the complex relationships between the degree of stratification, water depth, solar heat flux, and surface wind shear. A 1-dimensional turbulence-closure model described in detail elsewhere (Mellor and Durbin, 1975; Jewell, 1992; Jewell, 1995a) has been used to examine these relationships in two idealized lake settings. The first is meant to approximate Marshall Lake (maximum depth of 13 m or 43 ft) while the second approximates Gem Lake in the Sierra Nevada (maximum depth of 6 m or 20 ft). The use of a 1-dimensional model is considered appropriate for relatively small lakes since vertical mixing in these settings is many orders of magnitude smaller than lateral mixing (e.g., Gatcher and Imboden, 1985).

The boundary and initial conditions used in these idealized simulations are very similar to those described in Jewell (1995a, b). Briefly, measured surface temperatures are used as fixed boundary conditions for the entire seasonal simulation. Surface momentum boundary conditions employ a diurnally varying sine wave of the form:

$$(-\overline{w\bar{u}}, -\overline{w\bar{v}})_{z=0} = A(\sin \frac{2\pi t}{T}, \sin \frac{2\pi t}{T}) \quad (2)$$

where $\overline{w\bar{u}}, \overline{w\bar{v}}$ are surface Reynolds shear stress, t is time, T is 1 day, and A is maximum daily wind stress. Conservation equations for momentum, temperature, turbulent kinetic energy, and turbulent macroscale are solved with an implicit finite difference scheme in the vertical dimension and a leapfrog time differencing scheme (Mellor and Durbin, 1975). The model uses 40 vertical grid points which have a logarithmic spacing in the upper three grid points in order to provide resolution at the air-water interface. The time step is 30 minutes.

The model was used to determine the degree of temperature stratification in lakes as a function of two depths (13 and 6 m) (43 and 20 ft) and two maximum wind velocities (4.25 and 5.0 m/s) (9.5 mi/hr and 11.2 mi/hr). For a 13 m (43 ft) deep lake, significant vertical stratification of temperature is computed for both wind speeds (figure 13a). The degree of stratification is typical of that observed in Marshall Lake (figure

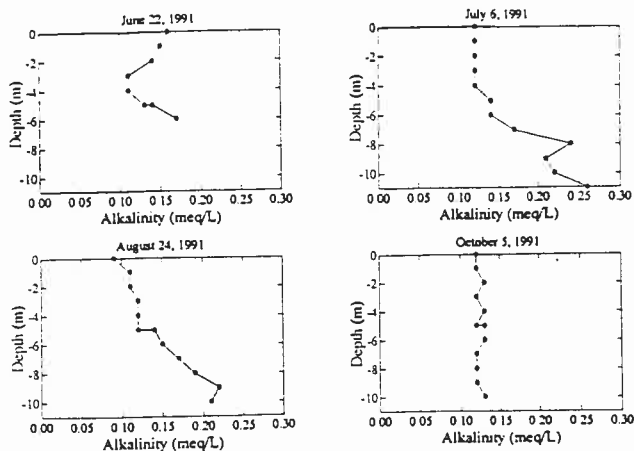


Figure 9. Alkalinity-depth profiles at Marshall Lake.

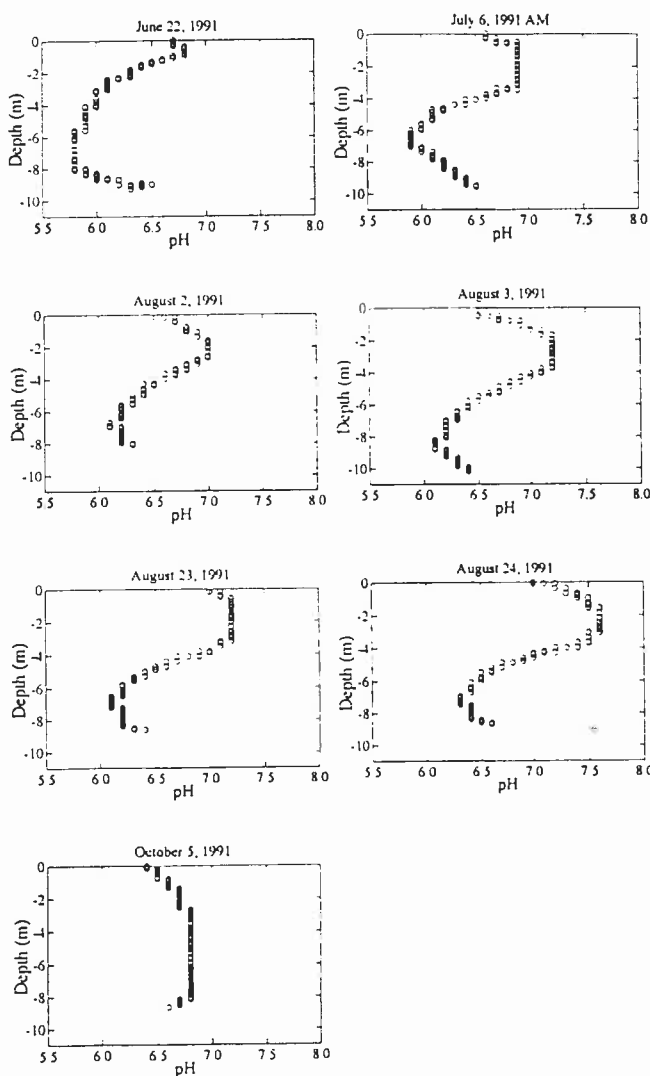


Figure 10. pH-depth profiles of Marshall Lake through the summer, 1991 season.

8). In the more shallow (6 m or 20 ft deep) lake, 5 m/s (11.2 mi/hr) maximum wind effectively mixes the entire water column (figure 13b). The relatively small

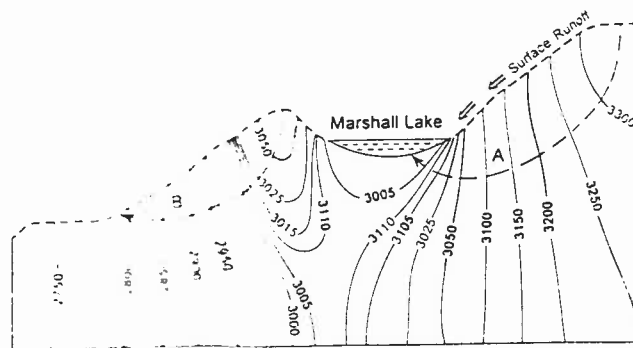


Figure 11. Idealized cross section of the Murdock Basin-Marshall Lake area showing possible heads and flowlines of groundwater. Path A represents precipitation from high elevation which enters the bottom waters of Marshall Lake as water with relatively high alkalinity. Water from Path B has a path length which is similar to that of Path A and therefore acquires a similar geochemical signature despite discharging at a lower elevation.

vertical stratification is close to that documented in the relatively shallow Gem Lake (Stoddard, 1987).

These model results illustrate the importance that depth has on maintaining thermal and chemical stratification in small lakes. Obviously, completely realistic simulations of the temperature profiles in Marshall and Gem Lakes are constrained by the lack of published wind records for both sites. It is interesting to note, however, that maximum summer winds at Emerald Lake in the Sierra Nevada range from 6-8 m/s (13.4-17.9 mi/hr) (Dozier and others, 1989). Wind speeds of this magnitude are probably sufficient to completely mix shallow lakes while deeper water bodies such as Marshall Lake would remain stratified.

CONCLUSIONS

The field observations and numerical modeling of Marshall Lake and the surrounding watershed in the Uinta Mountains have implications for the hydrology and geochemistry of alpine lakes and watersheds in other localities.

1. The significant vertical variations in temperature, pH, and alkalinity in Marshall Lake are in contrast to very small vertical variations in Gem Lake and Emerald Lake of the Sierra Nevada mountains (Stoddard, 1987; Melack and Stoddard, 1991). These latter two lakes exhibit nearly homogeneous vertical pH values. The difference between the geochemical profiles of Marshall Lake and those of the more homogeneous Sierra Nevada lakes is probably related to the relative degree of mixing in these lakes. Mixing, in turn, is controlled by the intensity of surface wind shear stress. Shallow lakes subjected to moderate wind shear stress can mix all the way to the bottom, while

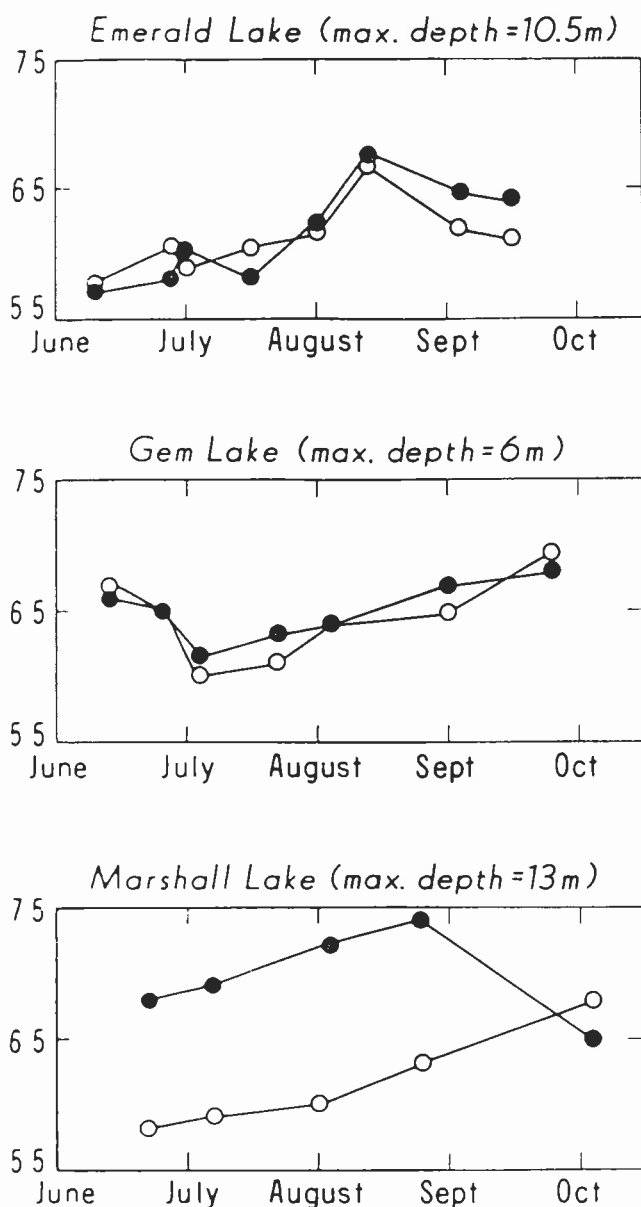


Figure 12. Maximum vertical pH differences in Gem Lake (Sierra Nevada), Emerald Lake (Sierra Nevada), and Marshall Lake (Uinta Mountains). Closed circles are surface pH measurements and open circles are bottom pH. Gem and Emerald Lake data are from Melack and Stoddard (1991). Marshall Lake data is the maximum observed difference observed in the hypolimnion and epilimnion (figure 10).

deeper lakes, or those which do not experience as much wind shear stress become stratified.

A strategy of using a single surface water sample to characterize the geochemistry of a lake has been used in several survey-type studies of alpine lakes elsewhere in the western United States (e.g., Melack and others, 1985). The idealized, comparative modeling of two lakes (6 m and 13 m or 20 and 43 ft maximum depth) presented here suggests that relatively deep (> 10 m) alpine lakes are more likely to stratify during the summer. Surface or near surface sampling of such

lakes may therefore not be representative of their overall thermal and chemical characteristics.

2. In spite of the nearly monolithologic (quartzite with minor arkose) character of the bedrock surrounding Marshall Lake and the Murdock Basin, systematic spatial variations in alkalinity, cations, and silica with elevation are observed. These suggest that silicate weathering is generating alkalinity, despite the lack of significant amounts of an obvious mineral phase which could be buffering the waters. Na/Ca ratios of surface water runoff and the lack of calcite in any of the bedrock in the watershed suggest that calcite is not contributing to alkalinity generation within the watershed.

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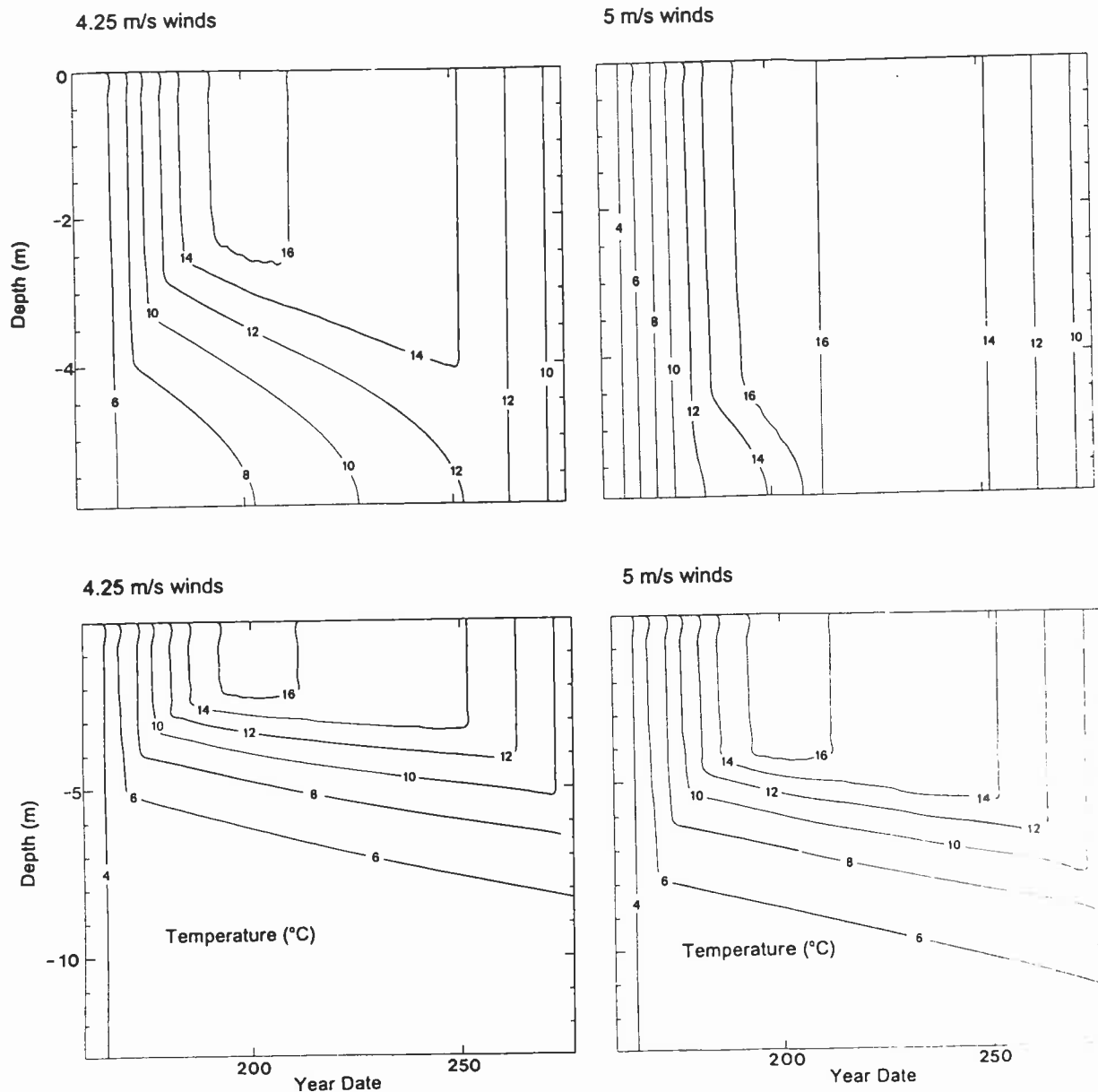


Figure 13. Comparative numerical simulations of vertical temperature in (a) a moderately deep (13 m) lake and (b) a shallow (6 m deep) lake over a season. Both lakes were subjected to wind shear stresses of 4.25 and 5.0 m/s.

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