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ABSTRACT — Limnological conditions were studied in two abandoned granite quarries in George Friedrich Park, St. Cloud, Minn. These quarries were excavated from 1886 to 1890 and left shallow due to inadequate water pumping systems at the time. The quarries were less than one hectare in area and had mean depths of 7.3 and 8.2 m. The annual heat budget was about the same for both quarries, 10,535 gm. cal/cm². Concentrations of H_2S, $Fe^{+2,+3}$, Ca^{+2}, Mg^{+2}, Cl^{-1}, SO_4^{-2}, PO_4^{-3}, $CO_3^{\div 2}$, CO_2, O_2, SiO_2, NO_2^{-1}, NH_3, and $-\log [H^{+1}]$ were determined. Very low concentrations of nitrate nitrogen were found (<0.02 mg/1 N-NO_3—). The hypolimnia of both quarries contained hydrogen sulfide throughout the study. Data show West Quarry to be meromictic while East Quarry was holomictic. With no outlet, except seepage, salts accumulated through the years, partially accounting for the eutrophic nature and chemical concentration of the quarries. Eutrophication was essentially artificial, from the addition of debris.

To this date no descriptive limnological work has been done on granite quarries in central Minnesota, one of the world's large granite-producing areas. The area contains numerous abandoned quarries which are in effect granite basins that eventually fill with water from seepage and runoff. The purpose of this study was to make a seasonal survey of aquatic environmental conditions in two apparently different abandoned quarries by determining: (1) the physical conditions and (2) the qualitative and quantitative chemical characteristics in each.

The two quarries, located in George Friedrich Park, St. Cloud, Minn. (Sec. 6, T 35N. R 30W. Sherburne County), were the largest of the Hilder Quarries, named for the original owner, G. J. Hilder. Their local names are Horseshoe Quarry and Dodd No. 20, but they are identified in this study as East Quarry (EQ) and West Quarry (WQ). They were excavated from 1886 until 1890, when lack of adequate water pumping systems necessitated their abandonment, leaving them shallower than quarries excavated after more efficient pumping equipment became available. They are within 200 m of the site of the first Minnesota granite quarry, where the State Reformatory now stands.

Materials and Methods

The investigation was conducted from September 1, 1966, to August 15, 1967. One sampling station was established for each quarry at the site of greatest depth. Temperatures were taken with a YSI Model 425C thermistor. Bottom samples were taken with a 14.8 x 14.8 cm Ekman dredge. Water transparency was measured by a Secchi disc, 20 cm in diameter. A Beckman RB3 Solu-Bridge conductivity meter was used to obtain specific conductance. A Kemmerer water sampler was used for chemical and oxygen analysis. Dissolved oxygen was determined by the Winkler method, using 0.025 N phenylarsene oxide (PAO) rather than thiosulfate as the titrant. All chemical procedures were according to Standard Methods (1965) and Hach (1966a, 1966b). With pH readings (Beckman Model 180) and bicarbonate alkalinity values, the nomogram of Theroux, Eldridge, and Mallmann (1943) was used to estimate free carbon dioxide.

Results: Basin Morphology

EQ had a maximum depth of 20 m and mean depth of 8.2 m. The total surface area was 5,162.6 m² (1.27 acres). The shoreline was smooth, taking the shape of a *horseshoe*, with vertical granite walls (Fig. 1). The shoreline development value of 1.09 indicates that EQ approaches a circle, while WQ (1.35) was more irregular. Other physical parameters are included in Table 1. The littoral zone was confined to several small granite shelves around the quarry. In each quarry, the bottom was rough and consisted of irregularly placed granite chunks with large, ooze-filled crevices, no surface outlet or inlet was observed, and seepage was the only means of loss or addition of water other than evaporation and precipitation.

WQ had a maximum depth of 15 m and mean depth

TABLE 1. Basin morphology of two granite quarries.

Parameter	East Quarry	West Quarry
Volume (V)	42,201 m³	61,249 m³
Area (A)	5,162 m²	8,312 m²
Maximum Depth (z_m)	20 m	15 m
Mean Depth ($\bar{z}$)	8.2 m	7.3 m
Shoreline Perimeter (L)	273 m	429 m
Length (l)	110 m	141 m
Breadth (b_x)	63 m	92 m
Shoreline Development (D_L)	1.09	1.35
Volume Development ($\bar{z}:z_m$)	0.41	0.49
Elevation (EL)	327 m	327 m

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Hydrologic maps, with depths in meter

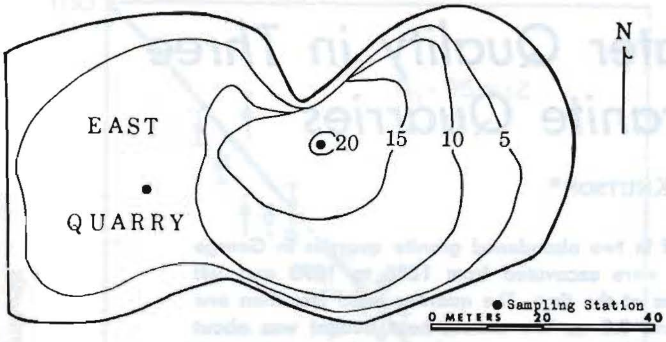

FIGURE 1. East Quarry.

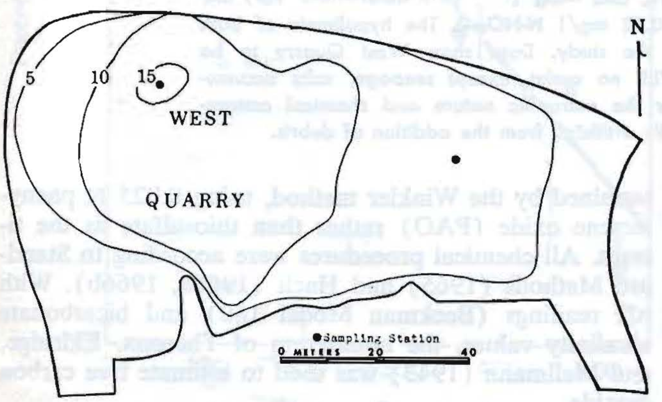

FIGURE 2. West Quarry.

of 7.3 m. The total surface area was 8,312.2 m^2 (2.05 acres). The shoreline was irregular, shaped somewhat like the *United States* (Fig. 2). The littoral zone was confined to one large granite shelf in the southwest corner, and a small shelf in the northeast corner. WQ decreases in area faster than EQ, which was also indicated by WQ volume development value of 0.49 (Table 2).

Results: Physical Characteristics

The surface temperature of both quarries ranged from 0.0 to 25.0 C. The bottom temperature of WQ fluctuated between 4.8 and 6.1 C, and EQ ranged from 3.2 to 5.5 C. Both quarries developed a thermocline in a band of 2 to 9 m. The seasonal cycles of temperatures are shown in Figs. 3 and 4. Ice ½ inch thick covered both quarries on November 23, 1966. Ice thickness was greatest in March (EQ, 22 inches; WQ, 19 inches), and melted completely on both quarries by April 8, after 132 days of ice cover.

Bottom ooze samples from both quarries indicate similar watershed types and organic sediments. The ash-free dry weight of mud in EQ was 24.9% and in WQ 23.6%. The sediments were black, organically rich, and sapropel-like.

EQ was most transparent, reaching a maximum Secchi disc reading of 9 m 23 November. WQ Secchi disc maximum was 5.6 m 22 September. Light penetration was measured through ice holes during the winter months, and both quarries reached their lowest values during this period. Secchi disc values with respect to the thermocline are shown in Figs. 5 and 6.

Results: Water Quality

Both quarries contained moderate concentrations of electrolytes. The waters were hard and quite alkaline. Throughout the investigation, surface pH values never dropped below 7.2 and averaged about 8.0. WQ developed a tremendous amount of free carbon dioxide at the bottom in late November and December; values greater than 100 mg/1 were recorded. At this time the bottom water pH dropped to 6.4.

WQ maintained dissolved oxygen throughout the season and reached a low 20 March with a surface value of 1.4 mg/1, and 0.3 mg/1 at 6 m. EQ had 0.5 mg/1 from top to bottom 20 December and 0.0 mg/1 in March (Fig. 5). Clinograde oxygen curves were shown for both quarries before fall circulation.

During the autumn overturn, dissolved oxygen in EQ gradually moved to the bottom with the more dense water, and vertical circulation was complete (Figs. 3 and 5). WQ did not circulate completely (Fig 4). Dissolved oxygen did not penetrate below 12 m nor did the temperature of the bottom waters change to the temperature of the dense vertical mixing water. Neither quarry experienced a complete spring overturn, just thorough mixing of surface water. This was determined by observing the gradual movement of dissolved oxygen from the high oxygen-saturated surface to lower depths. As water beneath the ice warmed to about 4 C, it sank to the depth of equal density. For EQ this depth was about 2 m and for WQ about 5 m (Figs. 3 and 4). The greatest oxygen concentration, in surface water, occurred April 15 with saturation values of 11.6 and 15.1 mg/1 in EQ and WQ respectively.

Seasonal temperature cycles

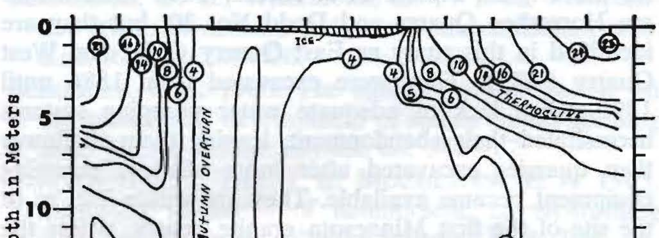

FIGURE 3. East Quarry.

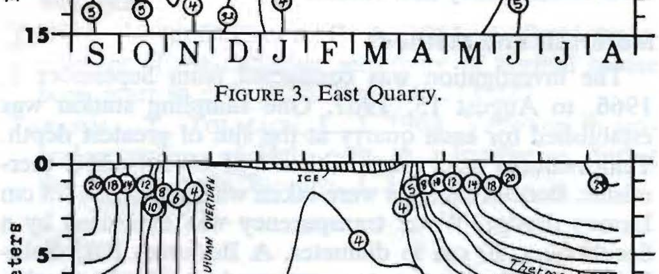

FIGURE 4. West Quarry.

TABLE 2. Morphometric features of two granite quarries.

Quarry	Depth (m)	Area Acres	Area % of Total	Stratum m	Area-Depth Decrease* (Acres)	Volume m³	Volume % of Total
East	0	1.270	100.00	0-5	0.353	22,036.09	52.23
	5	0.917	72.20	5-10	0.496	13,216.67	31.38
	10	0.421	33.14	10-15	0.268	5,615.38	13.18
	15	0.152	11.96	15-20	0.144	1,333.63	3.20
	20	0.083	6.53		Total	42,201.78	100.00
West	0	2.054	100.00	0-5	0.608	35,220.16	57.45
	5	1.445	70.35	5-10	0.802	20,590.83	33.40
	10	0.643	31.30	10-15	0.616	5,438.07	9.10
	15	0.268	13.04		Total	61,249.07	100.00

* Area decrease between 5 m contours.

The most striking chemical feature of both quarries was the low concentration of nitrates. None were detected with the method used, which had a lower limit of 0.02 mg/1 nitrate nitrogen. The presence of many autotrophic species clearly indicated existence of a usable concentration of nitrates. Ammonia was qualitatively detected below the thermocline in both quarries. WQ was very high in sulfates (157 mg/1) and deviated considerably from the lower central Minnesota surface lake water values (Moyle, 1945). EQ averaged 44 mg/1 sulfates, about ¼ the concentration of WQ. Silica was detected in both quarries at the concentration of about 1.0 mg/1 SiO_2 (August sample).

No hydrogen sulfide was detected in surface waters in WQ, but predominated throughout the survey at lower depths (Fig. 6). When EQ "froze out" in January, values of 0.5 mg/1 hydrogen sulfide were detected under the ice and lasted until March (Fig. 5). Calcium and magnesium cations were the major ions responsible for water hardness. The calcium to magnesium ratio was 5:1 for both quarries. Surface total hardness averaged 225 mg/1 as $CaCO_3$ in WQ; 140 mg/1 as $CaCO_3$ in EQ. Other water quality values can be found in Table 4.

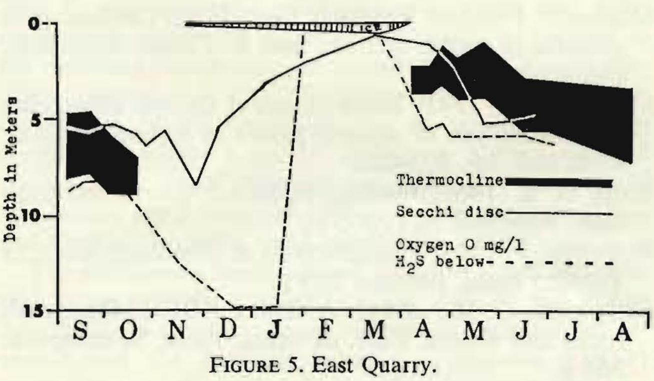

FIGURE 5. East Quarry.

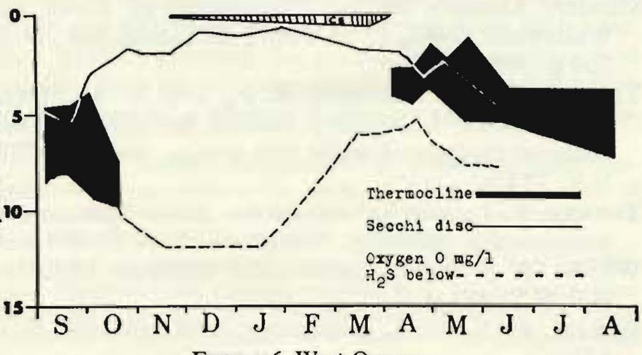

FIGURE 6. West Quarry.

Discussion

Although granite quarries are man-made, they are still open to classification except for basin origin. Eutrophication is the aging of a body of water by natural or unnatural processes (Welch, 1952). The quarries are roughly only 75 years old, yet they have aged more rapidly than most other water bodies. Natural allochthonous material was very limited because a small watershed exists, however campers and visitors have used WQ as a waste receptacle for many years, and many loads of raw manure were dumped into EQ from Great Northern Railroad stock cars. Thus, eutrophication has been rapid and artificially stimulated for these bodies of water.

An interesting difference between the quarries was that EQ was holomictic and WQ appeared to be meromictic. EQ circulated completely during the autumnal overturn, and on December 20 dissolved oxygen was detected on the bottom. Several important factors contributed to the meromictic state of WQ. No dissolved oxygen was present near the bottom; nor water at the temperature of vertical mixing water during or after the autumnal circulation period. Sulfates in excess of 200 mg/1 and total alkalinity values of 320 mg/1 were recorded near the bottom.

In August 1967 conductivity from the 12 and 13 m depths abruptly increased, presumably from the effects of summer stagnation. But the possibility of mineral springs or trapped nutrients in a monomolimnion contributing to this increase in conductivity cannot be ignored (Hutchinson, 1957). Shoreline trees at all but its east end gave WQ greater wind protection than EQ, whose west and northwest sections were nearly treeless. The small surface areas and vertical granite walls gave

TABLE 3. Energy budgets of two granite quarries for 1967.

Quarry	Area (ha)	z_m	$\bar{z}$	Heat Income gm cal/cm² Summer	Winter	Annual
East	0.51	20	8.2	8,475	2,067	10,542
West	0.83	15	7.3	8,579	1,949	10,528

both quarries additional wind protection not generally found in lakes. Wind-initiated horizontal circulation was also hindered by the vertical granite walls.

Wind protection and the combination of high biological activity (biogenic) and mineral springs (crenogenic), were considered the major reasons for the accumulation of compounds and electrolytes in this highly reductive anaerobic profundal region. More data are needed to show that the meromictic nature of WQ was not just temporary.

The igneous granite rocks in the St. Cloud area are the result of eroded mountain tops (Schwartz and Thiel, 1963). The weathering of granite rocks contributes no sulfate compounds (Turner and Verhoogen, 1960), and the high concentration of sulfates in WQ (lower in EQ) resulted from mineral springs and leaching of watershed soil. The action of sulfur-oxidizing bacteria on allochthonous organic matter also must be considered.

The low concentration of nitrate nitrogen in both quarries may be attributed to the fact that the small patches of soil around the perimeter became eroded and leached of soluble nitrates during rainfall and runoff, thus eliminating the nitrogen source. The greatest nitrate sources are the watershed and inflowing water (Hutchinson, 1957) This low concentration of nitrogen could be considered a *limiting* factor in the two quarries studied, and possibly in most granite quarries with reduced watersheds.

With no outlet except seepage, salts accumulated through the years, partially accounting for the eutrophic nature and chemical concentration of the quarries. Plankton populations of EQ and WQ will be considered in another study.

Acknowledgments

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National Conference On Advanced Placement In Chemistry in June

A three-day national Advanced Placement Conference to promote college-level courses in high schools will be held June 26-28 at Hamline University, St. Paul, Minn. The conference director is Olaf Runquist of the Chemistry department at Hamline.

The Advanced Placement Program has two goals: to make it possible for capable students to complete college-level courses while they are still in secondary school and to help participating colleges to encourage and recognize such achievement.

Course descriptions and the assistance of professional consultants to help high schools establish the advanced courses are provided by the program. It prepares, administers, and grades examinations based on these courses and communicates grades and other supporting materials to the colleges for appropriate placement and credit.

The program is in its fourteenth year as an activity of the College Entrance Examination Board, aided by Educational Testing Service of Princeton, N.J.

This year Advanced Placement Examinations are to be given in 11 subjects, including chemistry. Course descriptions and examinations are prepared by examining committees of five or more teachers.

The examinations are to be administered during the third week of May. Each is three hours in length, and essay questions predominate.

Advanced Placement Conferences in biology, mathematics, and physics are projected for 1970.