

## Lacustrine ostracodes as hydrochemical indicators in lakes of the north-central United States

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### Abstract

The modern ostracode distribution in lakes of the north-central United States shows how ostracode abundances are related to concentrations of major ions such as calcium, sulfate, and bicarbonate. These relationships are quantified for species living in lakes that range from fresh water ( $200 \mu\text{S cm}^{-1}$ ) to saline water ( $17000 \mu\text{S cm}^{-1}$ ). Lakes located in the Minnesota forests have different ostracode assemblages and different water chemistry than lakes located on the prairie of North Dakota and South Dakota. These differences are attributed to differences in precipitation and rock-water interactions. Multivariate analyses of the ostracode and water chemistry data set indicate that different ostracode species are associated with different water types. For example, *Limnocythere sappaensis* and *Heterocypris glaucus* are found in bicarbonate-enriched sulfate-dominated waters, whereas *Limnocythere staplini* is found in bicarbonate-depleted sulfate-dominated waters. *Candona ohioensis* and *Limnocythere itasca* are found in fresh water, and *Candona rawsoni* is eurytopic and found in both bicarbonate-enriched and bicarbonate-depleted sulfate-dominated waters. Ostracodes can be used to identify changes in both ionic composition (solutes) and ionic concentration.

### Introduction

Lacustrine ostracodes are environmentally sensitive organisms, and many studies link them to hydrologic and climatic factors (Delorme, 1969; Forester & Brouwers, 1985; Forester, 1983, 1987; Carbonel & Peypouquet, 1983; Delorme, 1989). Recent studies have also shown the value of iso-

tope and trace metal content of ostracode shells for paleoenvironmental reconstruction (Lister, 1988; Chivas *et al.*, 1986; Engstrom & Nelson, 1991). Although isotope and trace metal studies offer quantitative environmental data, the paleoecologic studies have remained largely qualitative. Quantitative reconstruction of past environments from ecological data requires that environmental tolerances of taxa be expressed in hydrologic or climatic terms, which demands modern baseline data. Such reconstructions have been accomplished for pollen (Bartlein *et al.*, 1984; Webb *et al.*, 1987), diatoms (Brugam, 1983), and foraminifers (Imbrie & Kipp, 1971) for

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the late Quaternary. Under appropriate assumptions about a species' environmental tolerances, such reconstructions should be possible for ostracodes. A first step towards environmental reconstructions using ostracodes has been made by Delorme *et al.* (1977).

The purpose of this paper is to show that modern lacustrine ostracode distributions may be expressed in hydrochemical terms. This relationship is determined by constructing a set of modern data composed of samples of lacustrine ostracodes and major ion water chemistry. These samples are from 38 lakes in eastern Minnesota and western North Dakota and South Dakota and are located along a climate gradient that offers the opportunity to collect a wide spectrum of environments in a short geographic distance. The 38 lakes are representative of the water types in the region (Smith, 1991).

### Study area

The northern Midwest of the United States is an ideal location for testing the hypothesis that lacustrine ostracodes can be used in a quantitative way as hydrochemical indicators. The large number of lakes, distributed over a hydrologically and climatically diverse area (Winter & Woo, 1990), provide excellent ostracode collection sites. The climatic gradients in the region include a north-south trending temperature gradient, and an east-west trending precipitation-evaporation gradient. The zone of annual precipitation equal to evaporation traverses the region roughly parallel to the prairie-forest border (Fig. 1). Lakes to the east in the study area are located in carbonate-rich glacial drift, whereas those in the west are located in sulfate-rich glacial drift.

The lakes sampled lie along a transect from the forested area of central Minnesota to the prairies of western Minnesota and eastern North Dakota and South Dakota. The lakes to the east are in a region where precipitation is greater than evaporation, and so remain fresh because the solute residence time is short. Within the freshwater lakes of the forest, the most common dissolved

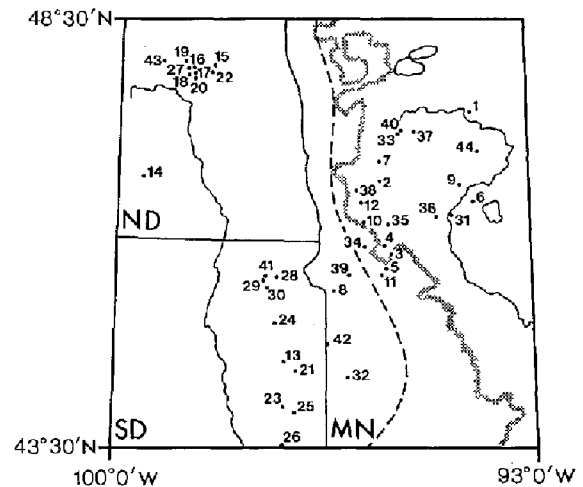


Fig. 1. The study area with the lakes sampled for lacustrine ostracodes and major ion chemistry. The dashed line indicates where annual precipitation equals evaporation. The stippled line indicates the present position of the prairie-forest border. (See Table 2 for lake identification numbers.)

major ions are calcium and bicarbonate, which are supplied from the dissolution of carbonates and the dissociation of carbonic acid (Kelts & Hsu, 1978). To the west, the lakes become progressively more saline, because solute residence time increases as precipitation declines and evaporation increases. The chemistry of these lakes is thus coupled to climate, and should change with climate (Forester, 1987; Forester *et al.*, 1987).

### Methods

#### Lake selection

The lakes in this study were selected from the Gorham *et al.* (1982) data set of 217 lakes located in Wisconsin, Minnesota, North Dakota and South Dakota. The principal criteria for lake selection were 1) geographic position, 2) published hydrochemical analysis, 3) basin morphometry, and 4) public access. A total of 43 lakes were sampled initially for water and ostracodes (Fig. 1), of which 38 were retained in the data set. Fifteen of these lakes were sampled over at least 2 seasons.

### *Ostracode collection*

Many techniques and strategies have been described for collection of nektonic (swimming) fauna and benthonic (bottom dwelling) fauna with patchy distributions and a seasonal or yearly life cycle (Goldman & Horne, 1983). I collected samples in the littoral and sublittoral zones of each of the lakes studied. These samples were collected at different depths where possible (some shallow lakes or 'sloughs' did not show much variation in depth), and also along the same isobath. On average, four samples were taken from each lake. Sampling was done in the first two weeks of June, (1988) and in mid-September (1987, 1988). In this way, a data matrix could be constructed that contained samples from different depths as well as different seasons.

I chose to collect samples using a Hongve sediment sampler (Wright, 1980), which produces a relatively uniform sample that is comparable to a coretop sample, in that it recovers a disk of sediment 5 cm in diameter and 3 cm in height. Each sample had a wet volume of approximately 60 cc.

### *Ostracode sample processing*

I used a modified version (Smith, 1991) of the processing technique developed by Forester (1988). Modern samples were gently washed with warm water through a set of three sieves (20, 100, 230 mesh). Each size-fraction was then washed from the sieve into a Whirlpac<sup>®</sup> bag and frozen. The frozen samples in the Whirlpac<sup>®</sup> bags were then freeze-dried. Following freeze-drying, each size fraction was dry-sieved and examined under a reflected light microscope.

The species identifications were based on the taxonomic publications of Delorme (1969, 1970a, 1970b, 1970c, 1971), on my previous taxonomic study of lacustrine ostracodes (Smith, 1987), and on the results of comparisons with the lacustrine ostracode collection of Forester (pers. commun.).

The final data set consists of 27 species from 71 samples collected in 38 lakes. The 27 species include only those species found living in the lakes

(Smith, 1991). Species represented only by empty shells were not included in the data set. Although each sample represented an equal wet volume of sediment, the numbers of ostracodes varied considerably, ranging from tens to hundreds of ostracodes. Within a single lake, where numbers of ostracode shells were low, I chose to pool the samples and refer to them collectively as a single sample (Smith, 1991). Therefore, 17 of the 38 lakes are represented by pooled samples that contain up to six samples from each lake. In this way I was able to determine the environmental range of each taxon in the study region. I chose to use percentages of the total counts in order to standardize the data (Smith, 1991).

The 27 species include 8 major species (mean in the data set of greater than or equal to 3%), and 19 minor species (mean in the data set of less than 3%, maximum greater than 5%) (Table 1). The eight major species include *Cypridopsis vidua* Muller, *Physocypria globula* Furtos, *Candona ohioensis* Furtos, *C. rawsoni* Tressler, *Limnocythere ceriotuberosa* Delorme, *Limnocythere itasca* Cole, *Limnocythere staplini* Gutentag & Benson, and *L. sappaensis* Staplin.

### *Water sample collecting*

Surface water samples were collected when ostracode samples were taken, following standard methods (Hem, 1989). Polypropylene bottles were rinsed with acid and distilled water, and soaked for one week in distilled water prior to water sample collection. The purpose of collecting the water samples was to measure the concentrations of the major dissolved ions that generally characterized a lake relative to other lakes in the study set. Minor ions, trace elements, and nutrients were not measured. In order to standardize the hydrochemical samples as much as possible, each sample was taken from the epilimnion, away from the littoral zone. Specific conductance, pH, and temperature were measured in the field. Specific conductance measurements were made using a YSI Model 33 salinity-conductivity-temperature meter. The conductivity measurements were

Table 1. Ostracode species present in data set.

Species name	2 letter code	Water type	Specific conductance $\mu\text{S cm}^{-1}$	Collection localities Lake ID No.s shown
<i>Candona punctata</i> <sup>^</sup>	AW	1, 2	235–340	1, 12, 33, 36, 37, 40
<i>Candona decora</i> <sup>^</sup>	AD	1, 2	210–450	1, 3, 4, 12, 28, 31, 33, 40
<i>Candona inopinata</i> <sup>^</sup>	AN	1, 2	225–450	1, 3, 4, 6, 12, 33, 37, 40
<i>Cyclocypris ampla</i>	CA	1, 2	225–750	1–6, 10–12, 15, 33, 36, 37, 40
<i>Cyclocypris ovum</i>	CO	1, 2	225–750	1, 3, 4, 6, 10–12, 28, 33, 37, 40
<i>Cyclocypris sharpei</i>	CS	1, 2	210–750	1–4, 6, 10, 12, 31, 33, 36, 37, 40
<i>Candona albicans</i> <sup>^</sup>	AL	1, 2	225–750	1–6, 10, 12, 33, 36, 37, 40
<i>Candona elliptica</i> <sup>^</sup>	AE	1, 2	210–750	1, 3, 4–6, 10–12, 33, 36, 37, 40
<i>Candona paraohioensis</i> <sup>^</sup>	AP	1, 2	210–750	1, 3, 4, 6, 10–12, 31, 33, 36, 37, 40
<i>Darwinula stephensoni</i> <sup>^</sup>	DS	1, 2	210–925	1, 3–6, 10, 12, 28, 31, 33, 34, 36–38, 40
<i>Candona ohioensis</i> <sup>^*</sup>	AO	1, 2	210–925	1–6, 10–12, 28, 31, 33, 34, 36, 37, 40
<i>Physocypris pustulosa</i>	PP	1, 2	225–295	2, 4–6, 12, 34, 40
<i>Candona stagnalis</i> <sup>^</sup>	AS	1, 2	235–1250	1, 12, 15, 40
<i>Cypridopsis vidua</i> <sup>*</sup>	CV	1, 2, 3	210–1350	1–6, 10–12, 15, 21, 23, 25, 26, 28–31, 33, 34, 36–38, 40, 43
<i>Candona acuta</i> <sup>^</sup>	AA	1, 2, 3	210–1400	4, 5, 11, 21, 23, 26, 28, 31, 32, 33, 37, 40
<i>Potamocypris smaragdina</i>	PO	1, 2, 3	305–1400	5, 10, 13, 15, 21, 23, 25, 26, 28, 32, 34, 38, 40, 43
<i>Limnocythere itasca</i> <sup>^*</sup>	LI	1, 2, 3	225–1400	1–6, 10, 13, 21, 23, 25, 26, 28, 32–34, 36, 37, 40
<i>Physocypris globula</i> <sup>*</sup>	ZA	1, 2, 3	225–6850	1–6, 10–12, 18, 21, 25, 28, 30, 33, 36–38, 40
<i>Candona caudata</i> <sup>^</sup>	AU	2, 3	450–1400	5, 23, 28
<i>Potamocypris unicaudata</i>	PX	2, 3	440–12500	4, 5, 13, 15–18, 21, 22, 27–30, 32, 33, 40, 41, 43
<i>Candona rawsoni</i> <sup>^*</sup>	AR	2, 3	450–16500	3, 10, 13–27, 29, 30, 32, 34, 41, 43
<i>Limnocythere staplini</i> <sup>^*</sup>	LS	2, 3	4220–16500	19, 22, 24, 27, 30, 41
<i>Heterocypris glaucus</i>	CX	2	3000–6850	14, 16–19, 27, 30, 41
<i>Limnocythere certionuberosa</i> <sup>^*</sup>	LC	2	1350–7550	16, 17, 18, 19, 22, 27, 43
<i>Limnocythere sappaensis</i> <sup>^*</sup>	LA	2	2590–6850	14, 17, 18, 20
<i>Cypridopsis aculeata</i>	ZC	2	7550–12000	22

\* = major species

<sup>^</sup> = benthonic

checked against standards of known specific conductance. The pH data were collected with a Markson Model 88 pH meter and combination electrode. The pH meter was calibrated with two pH standards at each sampling site.

#### Water sample processing

Magnesium, calcium, sodium, potassium, sulfate, chloride and total inorganic carbon were measured by the laboratory at the University of Minnesota's Limnological Research Center. Alkalinity as a sum of bicarbonate and carbonate was calculated from total inorganic carbon and pH using standard procedures (Mackereth *et al.*, 1978). The amount of total dissolved solids was

calculated as the summed total in  $\text{mg l}^{-1}$  of the major ions measured. In general, the results obtained at the University of Minnesota laboratory are comparable to the results of Gorham *et al.* (1982).

#### Numerical methods

Several multivariate ordination techniques were applied to both the water chemistry data and the ostracode data. The term ordination refers to the ordering of observations according to shared similarities (Davis, 1986). Different ordination techniques will emphasize different aspects of the structure in the data. In this study, principal components analysis (PCA) and detrended corre-

spondence analysis (DCA) were used to explore and characterize the structure in the data set. A detailed discussion of these methods can be found in Davis (1986) and Gauch (1982).

## Results

### *Classification of water types*

Water types can be defined in a number of ways. In this study, the lake waters are classified into

three general types based on the classification scheme of Eugster & Jones (1979). There are three major types of water represented in the lakes of the study set (Table 2). Lakes with water type one are characterized by low conductivity, primary solutes of calcium, magnesium and bicarbonate, and are located in the forest. Lakes with water type two are characterized by having specific conductance values over  $400 \mu\text{S cm}^{-1}$ , bicarbonate greater than and in some cases enriched relative to calcium, and are located from the prairie-forest border to the prairie. Lakes with water type two

Table 2. Lakes Sampled for Water Chemistry and Ostracodes, Showing Lake I.D. Numbers. Lakes listed by Name, County, and State (M = Minnesota, S = S. Dakota, and N = N. Dakota).

Water Type 1	Water Type 2	Water Type 3
Calcium approx. equals Bicarbonate. Specific Conductance less than or equal to $350 \mu\text{S cm}^{-1}$	Bicarbonate enriched relative to Calcium. Sulfate Enrichment or Dominance	Calcium enriched relative to Bicarbonate. Sulfate Dominance.
Ca-Mg-HCO <sub>3</sub> & Mg-Ca-HCO <sub>3</sub>	Mg-Ca-HCO <sub>3</sub>	Mg-Ca-SO <sub>4</sub>
Elk/Clearwater/M (33) Nokay/CrowWing/M (6) Itasca/Clearwater/M (40) Pelican/CrowWing/M (9) L. Thunder/Cass/M (44) Grass/Ottertail/M (38) Fish Trap/Todd/M (36) George/Hubbard/M (37) L. Ball Club/Itasca/M (1) Crow Wing/CrowWing/M (31) North Twin/Becker/M (7) Signalness/Pope/M (11)	Elk/Grant/M (34) Minnewaska/Pope/M (5) Mina/Douglas/M (4) Otric/Big Stone/M (8) Sewell/Ottertail/M (10) L. Pine/Ottertail/M (2) Maple/Douglas/M (3) Pickerel/Day/S (28) Coon/Nelson/N (15)	Dead Coon/Lincoln/M (32) Hattie/Stevens/M (39) Albert/Kingsbury/S (13) Herman/Lake/S (23) Norden/Lake/S (26) Oakwood/Brookings/S (21)
	Mg-Ca-SO <sub>4</sub> Madison/Lake/S (25)	Mg-Na-SO <sub>4</sub> Horseshoe/Codington/S (24) Hazeldon/Day/S (41)
	Mg-Na-SO <sub>4</sub> Waubay/Day/S (30) Round/Benson/S (43)	
	Na-Mg-SO <sub>4</sub> W. Stump/Nelson/N (22) E. Devils/Ramsey/N (16) Spring/Benson/N (27) Roslyn/Day/S (29) Devils (Mission Bay)/Benson/N (19) Alkaline/Kidder/N (14) Horseshoe/Ed/N (18)	
	Na-HCO <sub>3</sub> Elbow/Benson/N (17) Shinbone/Benson/N (20)	

include both fresh and saline lakes. Consequently, they show a progressive shift of solute composition from east to west, from calcium-magnesium-bicarbonate waters to sodium or magnesium-sulfate waters enriched or dominated in bicarbonate (relative to calcium). Lakes with water type three are characterized by high specific conductance, enrichment of calcium relative to bicarbonate, primary solutes of sodium or magnesium sulfate, and location on the prairie.

### Principal components analysis

#### Water chemistry

A principal components analysis (PCA) (Davis, 1986) of the water chemistry data shows that most of the variance (88%) in the water chemistry is explained by two factors, sulfate and alkalinity. The sulfate factor represents the gradient in sulfate concentrations and the alkalinity factor represents the gradient in alkalinity (alkalinity here is the sum of bicarbonate and carbonate) (Fig. 2a). The major ions magnesium, sodium, potassium, and sulfate are strongly positively correlated with total ionic concentration (TDS), and so act as a proxy for the total concentration variable. Calcium is weakly correlated with total concentration and sulfate, and alkalinity (the sum of bicarbonate and carbonate) is independent of total

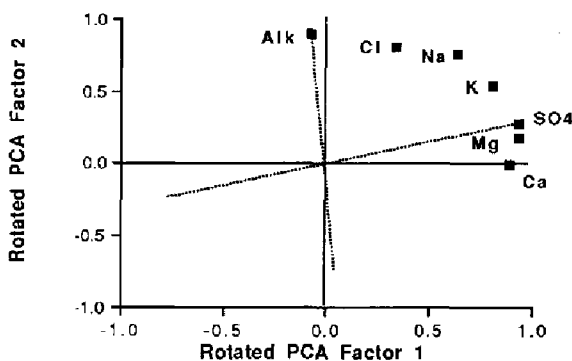


Fig. 2a. Rotated (Varimax) Principal Components 1 and 2 of the major ion chemistry data from the lakes sampled in the study region. Major ions are shown plotted on the two axes. Dotted lines indicate the relative positions of axes for sulfate and alkalinity concentrations.

concentration and sulfate in this data set. The initial use of PCA demonstrated the potential importance of sulfate as an indicator of a concentration gradient, and of alkalinity as an indicator of compositional differences (bicarbonate enrichment versus bicarbonate depletion).

The independence of sulfate and alkalinity is due to the roles these ions play in mineral saturation and precipitation. Alkalinity does not increase steadily with increasing ionic concentration because the carbonate anions are lost to carbonate minerals (typically calcite). Once the waters are depleted in either calcium or bicarbonate, whichever of the two ions are not depleted will increase with increasing total ionic concentration. Sulfate, however, increases with increasing ionic concentration within the range of ionic concentrations of the data set. The conservative nature of sulfate (*sensu* Eugster & Jones, 1979), and the nonconservative nature of alkalinity in this concentration range is the underlying reason why these two axes appear as independent principal components.

#### Ostracodes

Principal components analysis of the ostracodes and the water chemistry together indicate a difference between the nektonic and benthonic ostracodes. Most of the nektonic species are associated with fresh water. In contrast, different species of benthonic ostracodes occupy different ranges of total ionic concentrations in the data

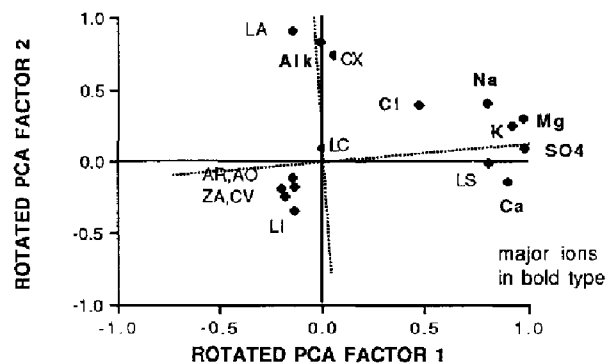


Fig. 2b. Rotated (Varimax) Principal Components 1 and 2 of the major ion water chemistry and 9 ostracode species from the lakes. (See Table 1 for species code identifications.)

set. I found that the most variance was explained by using the major species plus one minor species, *Heterocypris glaucus*, with the water chemistry variables (Fig. 2b). Also, certain benthonic species are strongly correlated with certain major ions in the correlation matrix (Smith, 1991) and are subsequently represented in the first and second principal components. In particular, *Limnocythere sappaensis* is positively correlated with high alkalinity values, whereas *Limnocythere staplini* is positively correlated with high sulfate values. *Limnocythere itasca*, *Candona ohioensis*, and several other benthonic species are correlated with low sulfate values. *Limnocythere ceriotuberosa* and the nektonic species *Heterocypris glaucus* are associated with sulfate-dominated waters enriched in bicarbonate. These relationships indicate that the benthonic ostracodes are generally more useful than the nektonic ostracodes as indicators of ranges of total concentrations and compositions of lake waters.

#### Detrended correspondence analysis

##### Ostracodes

Detrended correspondence analysis (DCA) (Gauch, 1982) of the ostracode species shows that the ostracodes also identify types of water (Fig. 3a). In this analysis, the initial matrix con-

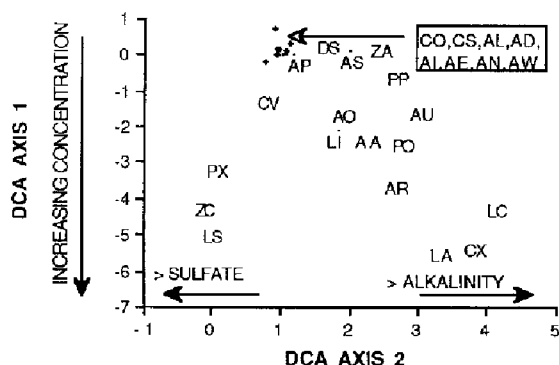


Fig. 3a. First and second axes of detrended correspondence analysis of the 27 major and minor ostracode species in the lake samples shown as ostracode scores. (See Table 1 for species code identifications.)

tains the 27 species of ostracodes as variables, and the 71 samples from 38 lakes as cases. In DCA, the species scores and the sample scores are scaled equally, so that they may be directly compared. The first two axes separate the ostracode scores into two groups that branch outward from a central cluster of points. Examination of the central cluster shows that the ostracodes represented in that cluster are all found in the very dilute waters of the forest lakes and in the lakes along the forest-prairie border (lakes with low total concentrations). One group of ostracodes that branches outward from the central cluster contains *Limnocythere ceriotuberosa* (LC), *Limnocythere sappaensis* (LA), and *Heterocypris glaucus* (CX), species already shown in PCA to be associated with high alkalinity values and lakes in which alkalinity exceeds calcium. The other group of ostracodes that branches outward from the central cluster contains, among others, *Limnocythere staplini* (LS), a species already shown in PCA to be associated with high sulfate values and lakes in which calcium exceeds alkalinity.

The three water types can be identified by comparing the distribution of the ostracode scores to the distribution of the lake sample scores (Fig. 3b). Based on the ostracode assemblages alone, the lake samples are shown to fall roughly into the grouping of fresh water (water type one), and the two types of saline water (water type two, and water type three). The first axis distributes

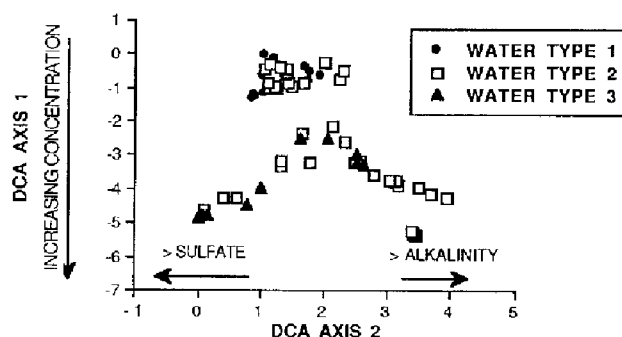


Fig. 3b. First and second axes of detrended correspondence analysis of the lake samples from which the ostracodes were taken shown as sample scores. See text for explanation of water types.

the lake samples along a concentration gradient. The second axis separates the lake samples into two groups that branch outward from a central cluster. The central cluster represents the samples from dilute lakes. One group branching outward from the central cluster consists of samples from lakes that are alkaline-enriched or alkaline-dominated. The other group branching outward from the central cluster consists of samples from lakes in which calcium is enriched relative to alkalinity, and the concentrated lakes are sulfate-dominated and alkaline-depleted. The merging of the two saline water types near the central cluster is caused by the distribution of *Candona rawsoni*. *Candona rawsoni* is eurytopic. Although *C. rawsoni* is most abundant in lakes that are alkaline-enriched relative to calcium, it is also found in small abundances in lakes that are enriched in calcium relative to alkalinity. However, the general groupings are present, indicating once again the importance of sulfate as an indicator of concentration, and alkalinity as an indicator of composition.

The PCA and DCA results, based on water chemistry and ostracodes respectively, share the same features. I can compare these results to each other directly by overlaying the DCA results

(Fig. 3a) on the PCA results (Fig. 2b). I did this by rescaling and translating the DCA axes, and applying a rigid rotation through 145 degrees, which changed the position and orientation of the DCA axes, but retained the original multivariate distances and relationships (Fig. 4). Direct comparison of the results of the two independent analyses shows how the major ion chemistry and the ostracode species are linked together. Further multivariate analysis with a technique such as canonical correspondence analysis (ter Braak, 1989) will show the same relationships that have emerged independently in these two analyses (Smith, in prep.). However, for the purposes of this study, canonical correspondence analysis is not necessary because the ostracode-water chemistry relationship is clearly demonstrated by two independent multivariate analyses.

#### Hydrochemical axes

Based on the results of these two multivariate analyses, I decided to show the ostracode species distributions on two water chemistry axes: sulfate and alkalinity, as defined by PCA (Fig. 2a, b). The sulfate axis serves as a concentration axis

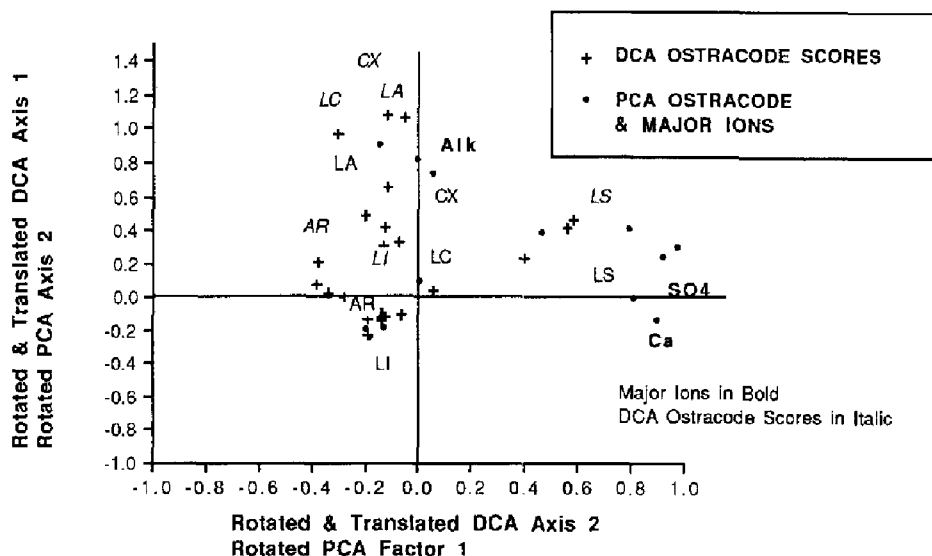


Fig. 4. First two axes of DCA superimposed on first two axes of PCA, after translation and rotation of DCA axes.



because sulfate is conservative (*sensu* Eugster and Jones, 1979) in this range of concentrations, along with magnesium, sodium, potassium, chloride, and to a lesser extent, calcium. Alkalinity (bicarbonate and carbonate) acts as a compositional axis, and is independent of sulfate in this data set because it is not conservative in this range of concentrations. Although magnesium and sodium behave in a conservative fashion, and could be used in place of the sulfate axis, the evidence from PCA and DCA indicate that the ostracode distributions are not cation sensitive, but that they are anion sensitive.

### Solute space

When values for sulfate and alkalinity concentrations from water samples of the 38 lakes are plotted on the two orthogonal axes of alkalinity and sulfate, the lakes are no longer represented in geographic space, but in solute space (Fig. 5). The boundary of this space is defined by the regions where no water types exist in the data set, and by the limits of my sampling. There are two compositional extremes represented in the prairie lakes within this data set. The first extreme includes saline lakes with high alkalinity; that is, those lakes with water type two. These are sulfate-

dominated or bicarbonate-dominated lakes, in which alkalinity (sum of bicarbonate and carbonate) is enriched relative to calcium. The second extreme includes saline lakes with high sulfate, type three waters, in which calcium is enriched relative to alkalinity. These lakes are all sulfate-dominated lakes. In terms of total concentration or specific conductance, both extremes of type two and three are similar in that they represent saline lakes. In terms of composition, the two extremes are quite different.

### Contoured surfaces

Contoured surfaces provide a three-dimensional view of the distribution of ostracode species. The major and minor species are listed in Table 1 with the corresponding water type, specific conductance range, and locality. All species were plotted in percent abundance (Z axis) within a lake sample *versus* the alkalinity and sulfate axes (X and Y axes). Distributions of a selected number of species are shown here (Fig. 6a–f), and plots of all species can be found in Smith (1991). I have chosen to discuss these few in detail because they span the entire range of water types in the data set.

*Candona ohioensis* and *Limnocythere itasca* (Figs 6a, f) are characteristic of the lakes with water type one. They are also found in the dilute lakes with water type two and three, with total concentration values below  $900 \text{ mg l}^{-1}$  ( $1000 \mu\text{S cm}^{-1}$ ). *Candona ohioensis* and *Limnocythere itasca* have overlapping distributions. *Candona ohioensis* appears to be less tolerant of sulfate than is *Limnocythere itasca*. *Candona ohioensis* is found in dilute waters with slightly higher bicarbonate concentrations than sulfate concentrations. The reverse is true of *Limnocythere itasca*.

*Candona rawsoni* is eurytopic in its distribution (Fig. 6b). Although it is found in lakes with both water type two and three, it is most abundant in lakes with water type two. *Candona rawsoni* is not found in the lakes with water type one, and is therefore a good indicator species of increasing ionic concentration in the data set.

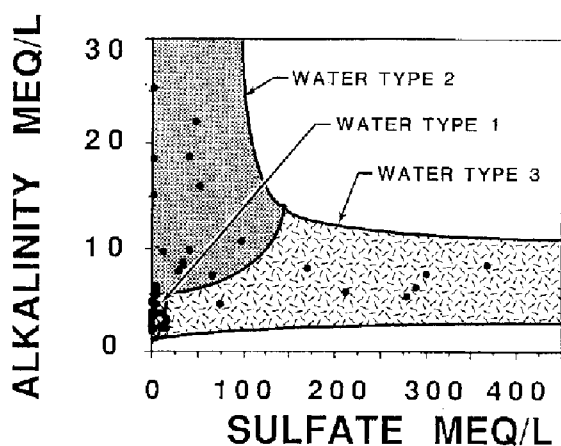


Fig. 5. Water chemistry samples from 38 lakes in the data set plotted on a sulfate axis ( $\text{meq l}^{-1}$ ) and an alkalinity axis (sum of carbonate and bicarbonate in  $\text{meq l}^{-1}$ ).

*Heterocypris glaucus* and *Limnocythere sappaensis* are both indicators of type two waters (Figs 6c, d), in which bicarbonate exceeds calcium. *Heterocypris glaucus*, a nektonic species, is found in small abundances in lakes with water type two that have total concentration values above 3000 mg l<sup>-1</sup>. *Limnocythere sappaensis* is exclusively found in the type two waters in the data set with extreme total ionic concentrations, typically with *Candona rawsoni*.

*Limnocythere ceriotuberosa* is found in both water type two and water type three (Fig. 6e). It is most abundant in lakes with with type two, in which total ionic concentrations range between 1000 mg l<sup>-1</sup> and 6500 mg l<sup>-1</sup>. *Limnocythere ceriotuberosa* overlaps slightly with *Limnocythere staplini*, which is almost exclusively found in the lakes of water type three with high total concentrations (Fig. 6g). *Limnocythere ceriotuberosa* is found commonly with *Heterocypris glaucus* and *Candona rawsoni*.

*Limnocythere sappaensis* and *Limnocythere staplini* occupy different water types at high total ionic concentrations. These two species never occur together in lakes in this data set, yet both are found in saline prairie lakes (Figs. 6d, g).

The distributions plotted on these two axes can be used to define assemblages characteristic of water type and total concentration (Fig. 7). I did this by overlaying the distributions of each species located in solute space. I then drew a contour at the 20% abundance when possible, although some species are present in low percentages, therefore requiring only a 5% or 10% contour. For the most part, there is very little overlap between assemblages. *Candona rawsoni* is notable in that its eurytopic distribution gives the species a significant occurrence in water types two and three, although it is highly abundant in only one region of the solute space, within type two waters. Another species that shows some overlap is *Limnocythere ceriotuberosa*, which occurs in type two saline waters of moderate bicarbonate and sulfate concentrations. *L. ceriotuberosa* overlaps with *L. sappaensis* when the waters are enriched in bicarbonate, or with *L. staplini* when the waters are enriched in calcium.

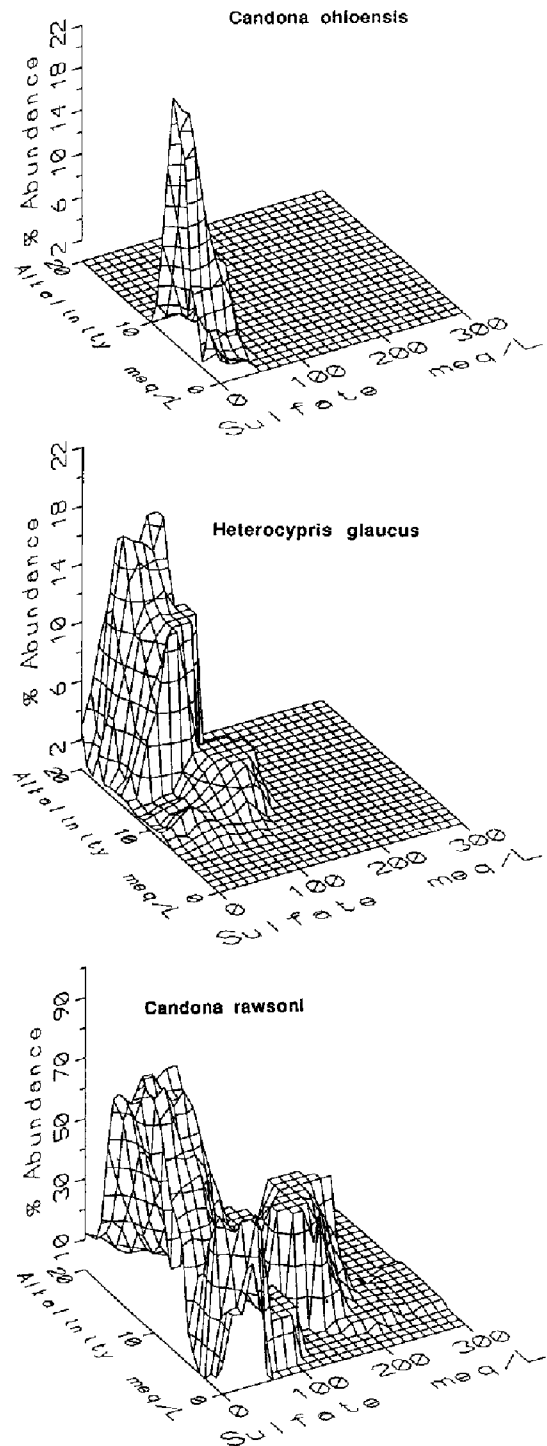


Fig. 6a–6c. Contoured surfaces of *Candona ohioensis*, *Candona rawsoni*, and *Heterocypris glaucus* showing distribution in samples from 38 lakes. Samples are plotted on sulfate and alkalinity axes (meq l<sup>-1</sup>). The Z axis is percent abundance in sample.

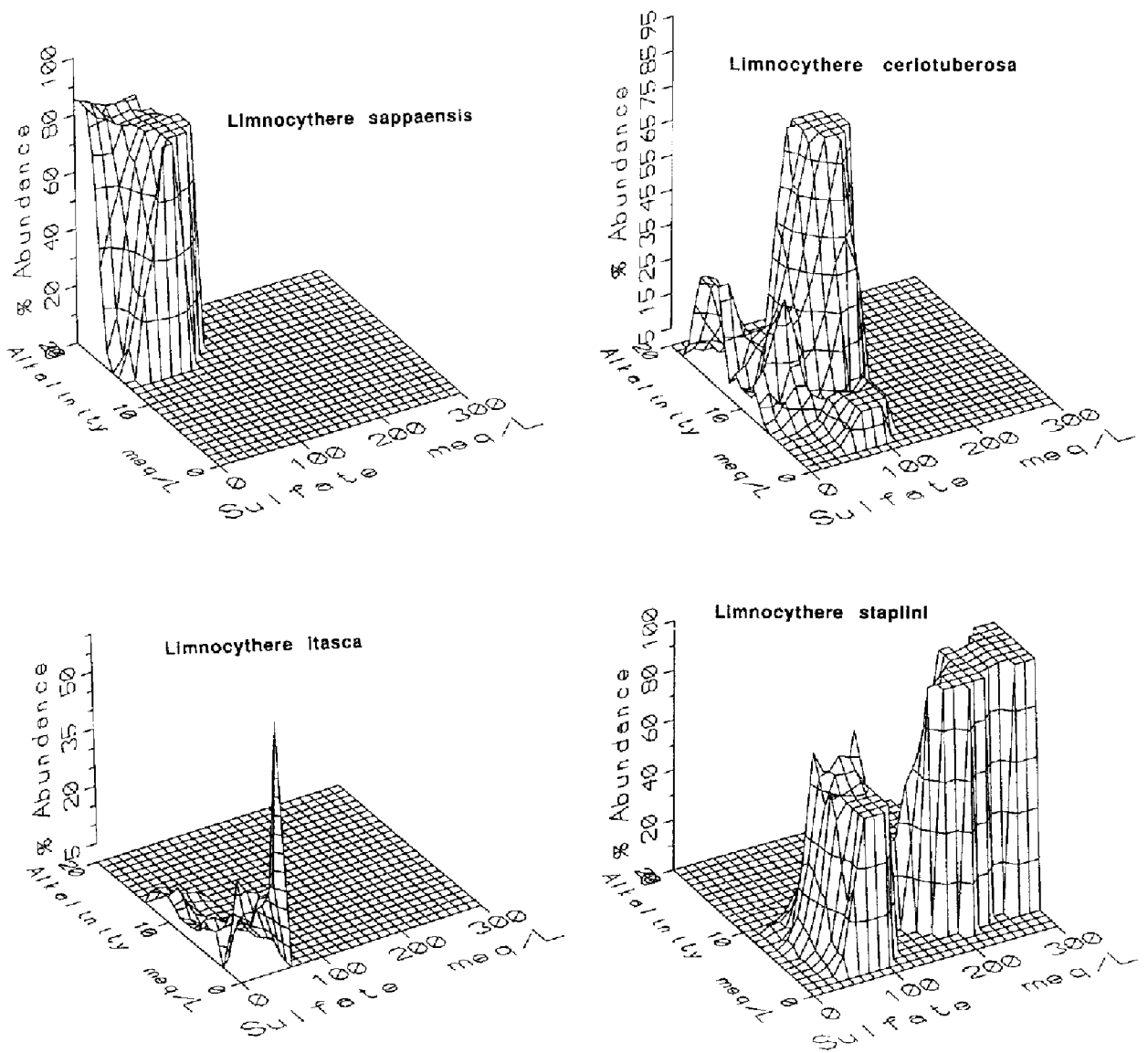


Fig. 6d-g. Contoured surfaces of *Limnocythere sappaensis*, *Limnocythere ceriotuberosa*, *Limnocythere itasca*, and *Limnocythere staplini* showing distribution in samples from 38 lakes. Samples are plotted on sulfate and alkalinity axes ( $\text{meq l}^{-1}$ ). The Z axis is percent abundance in sample.

## Discussion

Modern ostracode distributions are indicators of the present hydrochemical condition of lakes in the Midwest. Distinct assemblages of ostracode species are associated with different water types. The results of the detrended correspondence analysis show that the ostracode species alone can identify the three types of water present in the

data set. The two types of saline water are distinguishable by the distribution of *Limnocythere sappaensis*, *L. ceriotuberosa*, *L. staplini*, and *Heterocypris glaucus*. The fresh water lakes are distinguishable by the distribution of *Candona ohioensis*, *Limnocythere itasca*, and other minor species.

There are many potential applications of the relationships between ostracode distributions

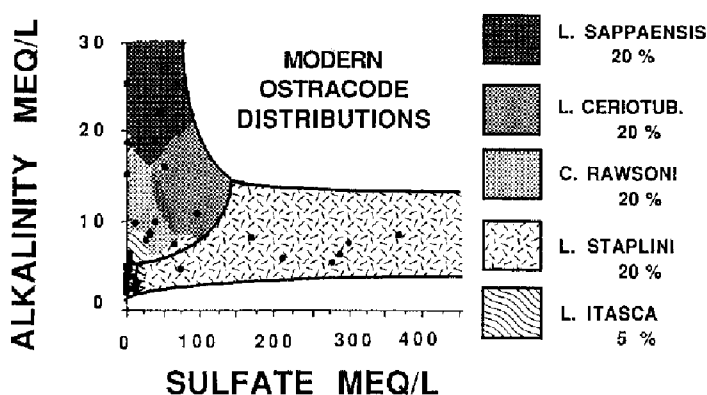


Fig. 7. Ostracode assemblages from the 38 lakes superimposed on the water samples from the 38 lakes, plotted on sulfate and alkalinity axes. Shading indicates the ostracode assemblages. For consideration of space, only one species for each field is listed. See text for explanation.

and lacustrine hydrochemistry to paleolimnology, climatology, and hydrology. For hydrology, ostracode assemblages can act as indicators of different hydrologic flow systems, and these relationships can be applied to fossil assemblages to determine changes in groundwater composition. For paleolimnology and climatology, these relationships can be used to reconstruct changes in the hydrochemistry of lakes. If used regionally, these relationships can be linked to climate changes that affect surficial hydrology, such as changing precipitation and temperature. Ostracodes provide not only a record of salinity changes, but a record of the solute changes as well. Thus they may supply an additional dimension in the form of solute history to paleolimnologic reconstructions, as well as provide an independent record of paleolimnologic changes recorded by diatoms, pollen, and other biota.

## Conclusion

Different modern ostracode assemblages are associated with different water types in lakes of the northern Midwest of the United States. Multivariate statistical analysis shows that the distribution of an ostracode species is influenced by the major ion chemistry, particularly the anionic composition. The total ionic concentration of the lake water may control the number of species that

can survive and be productive in a lake at a particular time, but the ionic composition determines which species will be present. This conclusion is drawn from the results of the ordination techniques applied to the water chemistry data and the ostracode data. Furthermore, the ostracodes themselves can be used to express hydrochemical variability, and therefore past hydrochemistry can be quantitatively estimated with fossil ostracodes. Because hydrochemistry plays a central role in the dynamics of hydrogeology, limnology and climate, ostracode-based hydrochemical reconstructions may ultimately be used to infer changes in past and future hydrologic and climatic systems. Such an application of ostracode-based reconstructions closely parallels the use of pollen and diatoms in paleoecology.

Other workers (Delorme, 1969; Forester 1983; Forester & Brouwers, 1985) have demonstrated ostracode hydrochemical sensitivity. Their qualitative studies indicate that many ostracode species are temperature and anion sensitive. The results of this study differ from previous studies by showing, in a quantitative way, that ostracode distributions correspond to the chemical properties of the lake waters in which they live. The next step is to apply these relationships to the geologic record in order to reconstruct temporal changes in lacustrine hydrochemistry, and thus temporal changes in climate (Smith, 1991; Smith *et al.*, 1992).

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