GEOCHEMISTRY OF THE MISSISSIPPIAN DELLE PHOSPHATIC EVENT, EASTERN GREAT BASIN, U.S.A.

PAUL W. JEWELL[1], N.J. SILBERLING[2], AND K.M. NICHOLS[2]

[1] *Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112, U.S.A.*
e-mail: *pwjewell@mines.utah.edu*
[2] *Consulting Geologists, 1235 Estes Street, Lakewood, Colorado 80215, U.S.A.*
e-mail: *slbrlng@email.msn.com*

ABSTRACT: The Middle Mississippian Delle phosphatic event marks a significant change in depositional conditions in the Devonian–Mississippian Antler foreland basin of North America. Stratigraphic and petrographic studies show that deposition of Delle-event rocks ended a long period of open-marine carbonate sedimentation when facies shifted to phosphorites, cherts, fine-grained siliciclastics, and lime mudstones from highly productive waters that may have been episodically anoxic. This drastic change in lithology is reflected in the chemistry of the two suites of rocks. $\delta^{18}O$ values of the Delle-event lime mudstones and phosphatized wackestones–packstones affected by the Delle event are 3–5‰ lighter than underlying and overlying open marine wackestones–packstones. Sr concentrations of Delle-event lime mudstones and open marine wackestone–packstone facies are low, suggesting that both of these lithologies have undergone similar postdiagenetic alteration. The uniform Sr concentrations and variable $\delta^{18}O$ data suggest that either the younger Delle-event rocks were exposed to meteoric water during diagenesis or that the relatively light $\delta^{18}O$ values represent a primary brackish-water depositional signal. Either interpretation is consistent with sedimentological evidence of the Delle event occurring in a predominantly shallow-water setting. $\delta^{13}C$ values of Delle-event lime mudstones are also anomalously light, indicating a high input of organic carbon during their formation. Mn concentrations of the Delle-event lime mudstones and stratigraphic equivalents are highly variable, suggesting fluctuating oxygen concentrations during their deposition and diagenesis. Rare-earth-element data from phosphorites and cherts of the Delle event indicate oxic to suboxic depositional conditions.

INTRODUCTION

Phosphorous is an important link between the biogenic and nonbiogenic parts of the modern hydrosphere, and sedimentary phosphorites are important archives of a variety of processes in the geologic record (e.g., Glenn et al. 1994; Föllmi 1996). Phosphorites have been deposited in a number of depositional environments and tectonic settings, and their chemistry and sedimentology has been studied at many localities throughout the world (e.g., Coles and Varga 1988; Cook et al. 1990).

The Devonian–Mississippian Antler orogeny and development of the Antler foreland basin are important events in the geologic history of western North America (e.g., Roberts et al. 1958; Stewart 1980). Phosphatic rocks have long been known to be associated with Lower Mississippian strata in the distal part of the Antler foreland in Utah (Cheney 1957; Schell and Moore 1970; Gutschick 1976). These phosphatic rocks were originally assigned to the lowermost Brazer Dolomite, Deseret Limestone, and Woodman Formation. Subsequently, they were formally given the name Delle Phosphatic Member by Sandberg and Gutschick (1984) and recognized as the lowest member of all of these formations. This usage, however, was not followed by Silberling and Nichols (1991) and Silberling et al. (1995) because regionally there are no consistent criteria for recognizing the upper stratigraphic limit of the Delle Phosphatic Member away from its type locality in the southern Lakeside Mountains, Utah. Instead, the strata in question are characterized as those influenced by the Delle phosphatic event

(Silberling and Nichols 1990), the effects of which diminish in different ways and at different intensities both up section and from place to place.

Delle-event phosphorites consist of pelletal phosphatic crusts, pisolitic phosphates, and detrital aggregates of ooidal and other types of phosphate grains (Nichols and Silberling 1991b, 1991c). The Delle phosphorites belong to the phosphate–black shale–chert association, which also includes the Permian Phosphoria Formation of the western United States and the Cambro-Ordovician Tal deposits of India (Riggs 1986). In the sedimentological classification scheme of Föllmi (1996) the Delle is considered to be a "condensed phosphate" in which multiple stages of phosphogenesis are interrupted by one or more episodes of winnowing and reworking.

The rocks resulting from the Delle phosphatic event were originally interpreted by Sandberg and Gutschick (1980, 1984) to represent deposition in the "Deseret deep starved basin" in which water depths of at least 300 m were inferred. Subsequently, both the rocks of the Delle phosphatic event and their underlying open-marine limestones were reinterpreted as part of a relatively shallow-water shelfal succession (Nichols and Silberling 1990), leading to a debate concerning water depth and paleogeographic significance of the Delle event (Sandberg et al. 1991; Nichols and Silberling 1991a). The Sandberg–Gutschick model of the Delle implies that a relatively deep ($\sim$ 300 m) Antler foreland occupied much of what is now western Utah and that the continental shelf was considerably farther to the east. On the other hand, the Nichols–Silberling model of the Delle event implies a broad, shallow Antler foreland basin in which Delle rocks occupied a relatively shallow portion of the shelf.

More recently, the anomalous deposits of the Delle phosphatic event have been attributed to restriction in the backbulge region of the Antler foreland during an episode of active flexural loading in Osagean to Meramecian (mid-Mississippian) time (Nichols and Silberling 1993; Silberling et al. 1997). The nature of the Delle event and its associated rocks is therefore important for interpreting the overall paleoceanographic setting and paleotectonic history of the Antler foreland basin. Understanding the Delle event may also have implications for the genesis of more extensive Paleozoic phosphate deposits such as those of the Permian Phosphoria Formation (Silberling and Nichols 1989).

A potentially important tool for understanding the paleoceanographic conditions of the Delle phosphatic event is geochemical characterization of the carbonates, fine-grained siliciclastic rocks, cherts, and phosphorites that make up the depositional package. Similar geochemical studies have successfully aided in the interpretation of a variety of depositional environments (e.g., Veizer 1983). This paper presents data on stable isotopes, trace elements, and rare earth elements from carbonates, cherts, siliciclastic rocks, and phosphorites deposited before, during, and after the Delle phosphatic event in an effort to complement ongoing field and petrographic studies of these enigmatic rocks. Preliminary geochemical results are also included in Jewell et al. (1996) and Silberling et al. (1997).

SAMPLING AND ANALYTICAL METHODS

Considerable research has been directed at using stable isotopes to reconstruct the history of seawater during the Paleozoic (e.g., Popp et al. 1986; Veizer et al. 1986; Lohmann and Walker 1989; Marshall 1992). In many of these studies, the emphasis has been on microsampling specific carbonate components that have not undergone diagenetic alteration or re-

crystallization. Brachiopod shells and clear calcite cements have proven particularly useful for this work. The fine-grained nature of the lime mudstones associated with the Delle phosphatic event precluded separation of individual carbonate components for analysis in this study. Wackestones and packstones from the stratigraphic sections that immediately predate onset of the Delle event and those that postdate the event were also bulk sampled so that their isotopic signatures could be directly compared with that of the fine-grained lime mudstones of the Delle event.

Samples were collected from well-documented stratigraphic sections in northern and western Utah that have been described in detail elsewhere (Sandberg and Gutschick 1980, 1984; Nichols and Silberling 1991b, 1991c). From east to west, these are Samak in the Uinta Mountains, the Crawford Mountains, the Lakeside Mountains, Ophir Canyon, the East Tintic district, the Pahvant Mountains, the Confusion Range, and the Mountain Home Range (Fig. 1). Because the Lakeside Mountains contains the best example of Delle-event rocks, it was sampled extensively. All samples in this study were collected by the authors during 1993, 1998, and 1999 field investigations, with the exception of a small number of samples that were collected and analyzed by M.E. Henry (U.S. Geological Survey) in 1987.

After collection, the rocks were coarsely crushed and subsampled in order to exclude material containing calcite veins, weathered surfaces, or any visible alteration. Petrographic examination was used to exclude limestones that had been extensively recrystallized or that contained dolomite. The carbonate samples from 1993 were analyzed by the Krueger Enterprises, Inc. (Cambridge, Massachusetts) stable-isotope laboratories. Samples collected in 1998 and 1999 were analyzed in the stable-isotope laboratories of the University of Utah. In both cases extraction was by reaction with orthophosphatic acid and subsequent purification of the resulting CO_2 gas. Isotopic analysis was conducted using a VG Micromass mass spectrometer for the 1993 samples and a Finnigan MAT 252 mass spectrometer for the 1998 and 1999 samples. Analysis of internal standards was within 0.3‰ for oxygen and 0.1‰ for carbon. Duplicate analyses were within ± 0.1‰ for both carbon and oxygen.

Phosphorites, cherts, siliciclastic rocks, and selected carbonate rocks were analyzed by XRAL, Inc. (Ann Arbor, Michigan) for rare earth elements (REE) using neutron activation analysis. Selected samples from stratigraphic sections that had not undergone obvious weathering, metamorphism, or hydrothermal alteration were analyzed for total organic carbon (TOC) content by LECO analysis by XRAL, Inc. Analysis of internal standards was within 10% for TOC, La, Ce, and Nd, and duplicate analyses were within ± 5% for REE concentrations of > 1 ppm and ± 10% for REE concentrations < 1 ppm and for TOC measurements.

Subsets of the carbonate samples were dissolved in 0.5 N acetic acid, a procedure that has been shown to be effective for completely dissolving the carbonate fraction of rocks without leaching additional trace-element material from the siliciclastic fraction (Derry et al. 1992). The resulting solutions were analyzed for Mg, Sr, Mn, and Fe by atomic absorption at the University of Utah.

STRATIGRAPHY

Rocks of the Antler foreland basin can be conveniently discussed in the context of sequence stratigraphy. As a prelude to considering the geochemistry of the Delle phosphatic event, we provide a summary of the sequences that are contemporaneous with or bracket the Delle event (Silberling et al. 1995). For a somewhat different interpretation of the sequence stratigraphy of this part of the Mississippian section in the same general region see Giles and Dickinson (1995).

The major share of the Mississippian section of western Utah and adjoining Nevada can be treated as three successive sequences (from oldest to youngest): the Morris sequence (mainly upper Kinderhookian), the Sadlick sequence (Osagean to Meramecian), and the Maughan sequence (upper Meramecian to Chesterian) (Fig. 2, Table 1) (Silberling et al. 1995). The

systems tracts of these sequences were interpreted from the nature of genetic rock units termed lithosomes and designated by abbreviations that represent the sequence name, modifying descriptive terms, and rock type.

The Morris sequence corresponds to a single transgressive–regressive third-order depositional cycle. It is expressed by shelfal marine carbonate rocks averaging about 50 m in thickness and blanketing the region from central Utah to eastern Nevada with only gradual westward progression from more inshore to more subtidal, deep-ramp facies. The overlying third-order Sadlick sequence, by contrast, has an unusual pattern of systems tracts and records the Delle phosphatic event in its upper part. The youngest lithosome among the carbonate rocks of the Sadlick sequence transgressive systems tract is laterally extensive and apparently continuous across much of central and western Utah, having thicknesses up to a few tens of meters and forming the uppermost unit of the Gardison Limestone (Table 1). This unit of diffusely interbedded wackestone and packstone (designated lithosome SA.Di.WkPk in the nomenclature of Silberling et al. 1995) is interpreted as an open marine, above wave base, moderately deep subtidal deposit. It is the lowest stratigraphic unit geochemically sampled for the present study; samples were taken both from the main body of this unit and from its solution compacted and partly phosphatized uppermost part.

The wackestone–packstone lithosome (SA.Di.WkPk) was altered at its top, and its deposition abruptly terminated, by onset of the Delle phosphatic event, above the level for which the Sadlick sequence is quite different and interpreted as the highstand system tract of the sequence. In general, most of the upper part of the Sadlick sequence within the study region is formed of two lithosomes: laminated dolomitic siltstone (lithosome SA.LaDo.St) to the west and a lithosome of rhythmically bedded lime mudstone and wackestone (SA.Rh.LmWk) to the east.

These lithosomes intergrade laterally. Still farther east, the rhythmically bedded, deep subtidal limestone of lithosome SA.Rh.LmWk is laterally supplanted and progradationally overlain by peritidal carbonate rocks of the Brazer Dolomite. To the west and south the upper part of lithosome SA.LaDo.St is intercalated and then supplanted upwards by peritidal calcareous sandstone at the top of the highstand tract (Fig. 2).

The laminated dolomitic siltstone lithosome (SA.LaDo.St) locally exceeds 100 m in thickness and records an unusual depositional and diagenetic history. Along with its intercalated lithosomes, it corresponds to the Woodman Formation and the Needle Siltstone, which is variably treated as a formation within the Chainman Shale group or as a member of either the Chainman Shale or Woodman Formation (Table 1). Most of these rocks are carbonate-supported silt-laminated secondary dolomite, or else they are dolomitic or calcareous siltstone and fine-grained sandstone. The laminated dolomitic siltstone lithosome (SA.LaDo.St) also contains, as minor constituents, radiolarian and secondary chert, limestones, replacement and detrital phosphate, and some pelitic rocks (which may be mainly decalcified marls). Intercalated with lithosome SA.LaDo.St is evenly bedded, dense, megascopically unfossiliferous limestone, designated ostracode lime mudstone (SA.Os.Lm), forming units up to 10 m thick that are laterally persistent on a kilometer scale. Lithosome SA.Os.Lm also extends east of the limit of SA.LaDo.St as the basal unit of the highstand systems tract grading eastward into rhythmically bedded limestones having some marine fossils and bioclasts. A layer of detrital phosphate everywhere marks the base of lithosomes SA.LaDo.St and, farther eastward, SA.Os.Lm, and it signals the onset of the Delle phosphatic event. In both the more western and eastern parts of the study region, only a single phosphate layer marks the base of the highstand. In between, at localities such as the Lakeside Mountains, multiple phosphatic layers occur through the basal 20–30 m of lithosome SA.LaDo.St. At such localities parasequence successions of different rock types within SA.LaDo.St are suggested, even though exposure is generally poor. These repetitive, complete and incomplete successions appear to grade upward from phosphatic and cherty rocks at their bases to silt-laminated secondary dolomite, bioturbated silty dolomite, dolomitic or calcareous siltstone, fine-grained sandstone containing widely scattered brachio-
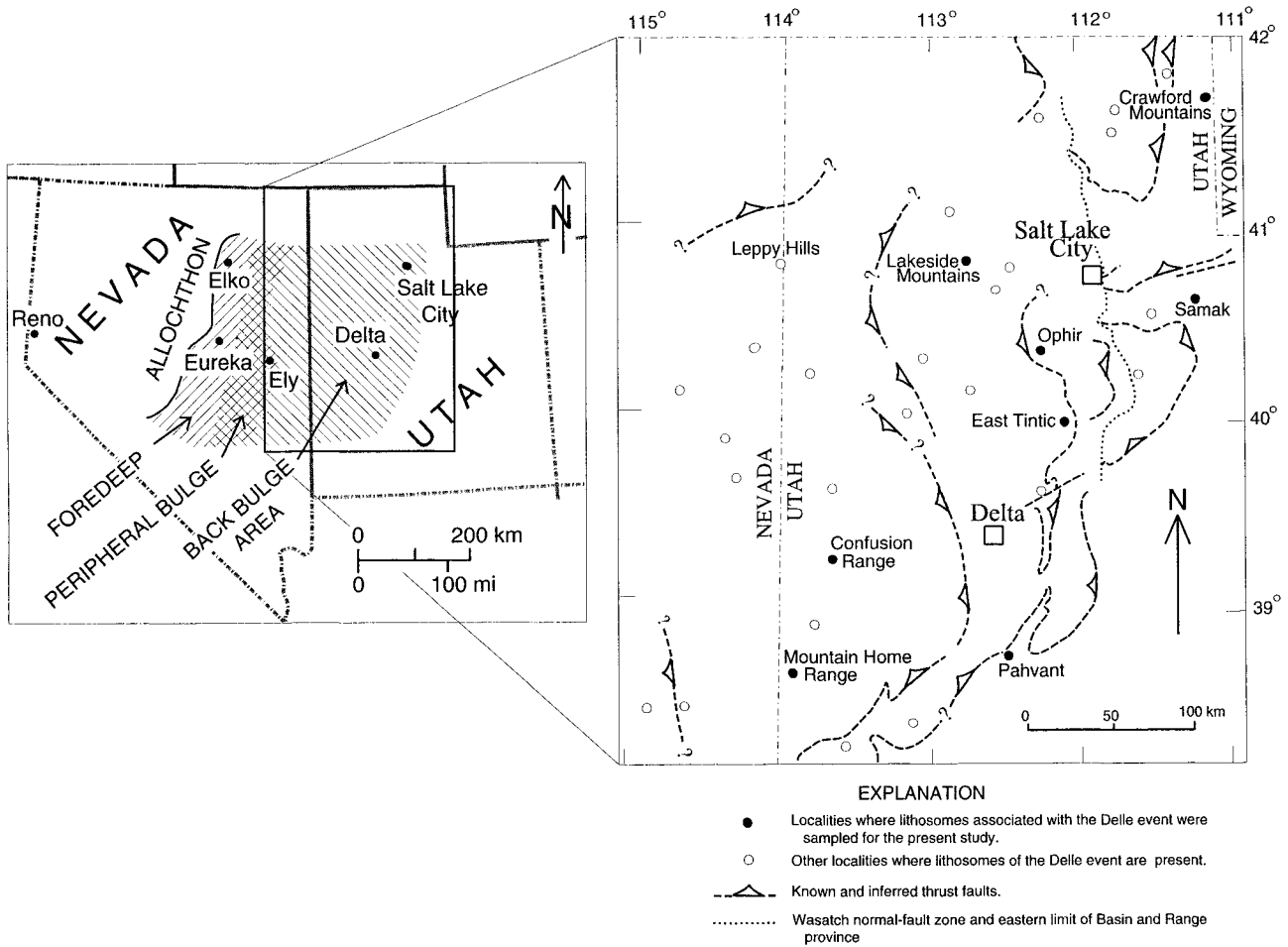
FIG. 1.—Index maps showing location of the stratigraphic sections sampled in the study area and the regional setting of this area with respect to inferred mid-Mississippian paleotectonic features of the Antler foreland. The present shape and proportions of these paleotectonic features have been strong influenced by post-Paleozoic tectonism.
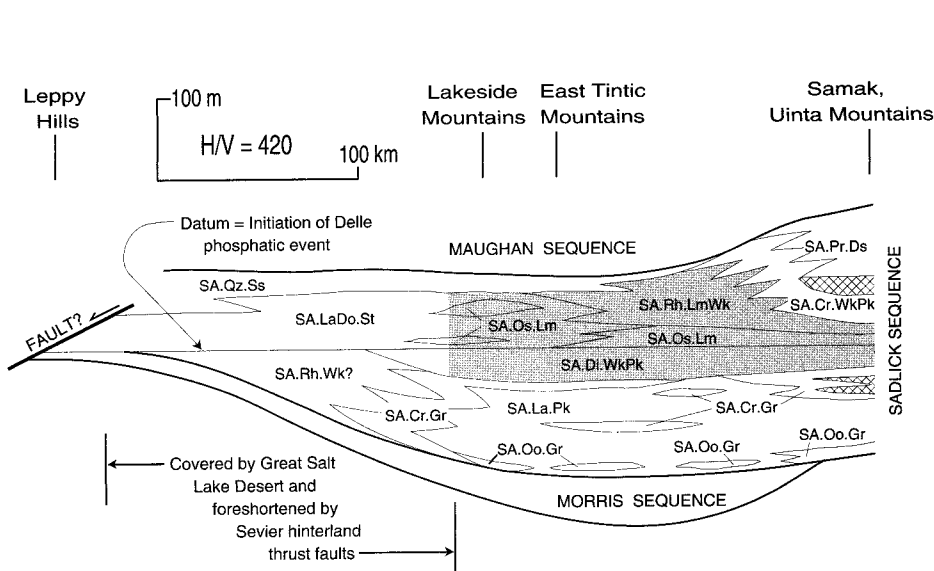

FIG. 2.—Diagrammatic cross section of the Sadlick-sequence Mississippian lithosomes sampled as part of this study. Stratigraphic data from the southern Lakeside and East Tintic Mountains are projected into the line of section, i.e., from the Leppy Hills eastward to Samak at the west end of the Uinta Mountains (Fig. 1). Palinspastically corrected for the estimated horizontal shortening across the Mesozoic Sevier thrust system. Lithosome designations for the Sadlick sequence are from Silberling et al. (1995): SA.Qz.Ss, quartzose sandstone; SA.LaDo.St, laminated dolomitic siltstone; SA.Rh.Wk, rhythmically bedded wackestone; SA.Os.Lm, ostracode lime mudstone; SA.La.Pk, laminated packstone; SA.CrGr, crinoidal grainstone; SA.Di.WkPk, diffusely interbedded wackestone and packstone: SA.Oo.Gr, oolitic grainstone; SA.Rh.LmWk, rhythmically bedded lime mudstone and wackestone; SA.Cr.WkPk, Crinoidal wackestone and packstone; SA.Pr.Ds, primary dolostone. Sampled lithosomes are shaded; cross-hatch pattern represents eogenetic secondary dolostone.

Lithosome	Description	Lithostratigraphic designation
MA.Ms	Maughan sequence black mudstone and shale; minor concretionary limestone in lower part.	Lower part of Camp Canyon Member of the Chainman Shale.
MA.Rh.Lm	Maughan sequence rhythmically bedded, featureless lime mudstone.	Skunk Spring Limestone Bed of Chainman Shale.
SA.LaDo.St	Sadlick sequence laminated dolomitic siltstone and silty secondary dolomite. Planar laminated or burrowed on stratification. Beds of radiolarian limestone, ostracode lime mudstone, and layers of phosphatic mudstone and phosphorite interbedded in lower part.	Most of Needle Siltstone or Needle Siltstone Member of Chainman Shale; most of Woodman Formation; lower part of Deseret Limestone; Delle Phosphatic Member of Woodman Formation.
SA.Rh.Lm Wk	Sadlick sequence rhythmically thin- to medium-bedded lime mudstone and spiculitic wackestone.	Lower parts of Brazer Dolomite and Deseret Limestone; Tetro Member of Deseret Limestone.
SA.Os.Lm	Sadlick sequence ostracode lime mudstone. Regularly thin- to medium-parted; megascopically featureless except for characteristic nodules of secondary wood-grained chert.	Delle Phosphatic Member of the Woodman Formation; lower parts of the Desert Limestone, Brazer Dolomite, and Needle Siltstone Member of the Chainman Shale.
SA.Di.WkPk	Sadlick sequence diffusely, irregularly, and gradationally interstratified medium to thick layers of conspicuously crinoidal packstone and pelletal wackestone. Abundantly fossiliferous. Nodules and bedding-plane stringers of secondary chert common.	Uppermost unit of Gardison Limestone, Lodgepole Limestone, and Joana Limestone.

pod shells, to units of ostracode lime mudstone at their tops. Each parasequence, if complete, indicates upward change between drastically different depositional conditions. Pinch-and-swell dissolution remnants of radiolarian- and goniatite-bearing limestone beds occur locally, as in the Lakeside Mountains, within laminated dolomitic siltstones of SA.LaDo.St. Significantly, in contrast to the limestone units of SA.Os.Lm, other limestones within lithosome SA.LaDo.St, and those immediately beneath it, strongly show the effects of dissolution, and some are preserved as only dissolution remnants. Also, some chert layers in the section may be replacements of original limestone, and the secondary dolomite of lithosome SA.LaDo.St is presumably a replacement of laminated, silty lime mud. All of these diagenetically altered carbonates that were originally limy sediments contain marine fossils and bioclasts. In SA.Os.Lm, on the other hand, necessarily open-marine fossils are generally absent, and aside from containing replacement nodules of wood-grained chert (DeCelles and Gutschick 1983), it is crisply bedded and little altered. Restriction of recognizable fossils in SA.Os.Lm, to only ostracodes indicates abnormal salinity as compared to open-marine seawater. Geochemical samples of Delle-event carbonate rocks for this study (Table 2) were taken mainly from the ostracode lime mudstone units (SA.Os.Lm) but also from the limestone pinch-and-swell bodies in SA.LaDo.St. Samples of other rock types (phosphorites, cherts, and fine-grained siliciclastics, Table 3) are mostly from lithosome SA.LaDo.St.

The youngest sequence analyzed in this study is the Maughan sequence. In the eastern part of the study region, placement of the Sadlick–Maughan sequence boundary is uncertain owing to lack of structural and stratigraphic control at critical localities (Silberling et al. 1995). Farther west the basal unit of the Maughan sequence is one or more units, up to thicknesses of several tens of meters, of rhythmically bedded dense limestone (lithosome MA.Rh.Lm), which corresponds to the Skunk Spring Limestone (member of the Chainman Shale) and the limestone of Whitehorse Pass (Table 1). In places its base bears evidence of disconformity; in the Confusion and

Needle Ranges the sequence boundary may be transitional. MA.Rh.Lm is generally unfossiliferous but does yield conodonts; it is interpreted as mainly a deep subtidal, perhaps-below-wave base, limestone. Above MA.Rh.Lm, and forming the lower part of the Camp Creek Member of the Chainman Shale, is lithosome MA.Ms. This lithosome consists mostly of black mudstone and shale but also contains sporadic concretionary limestones containing goniatites. A few geochemical samples included in the present study were obtained from the carbonate rocks of Maughan sequence lithosomes in the Confusion and Needle Ranges (Figs. 1, 2).

In an effort to understand the detailed geochemistry of Mississippian rocks in the Lakeside Mountains, formations that are stratigraphically well above the type area of the Delle event were sampled. These include a rhythmically bedded lime mudstone within the Humbug Formation (Upper Meramecian) and crinoidal limestone beds from the base of the Great Blue Limestone (Lower Chesterian). These lithosomes have yet to be placed within a formal sequence stratigraphic context.
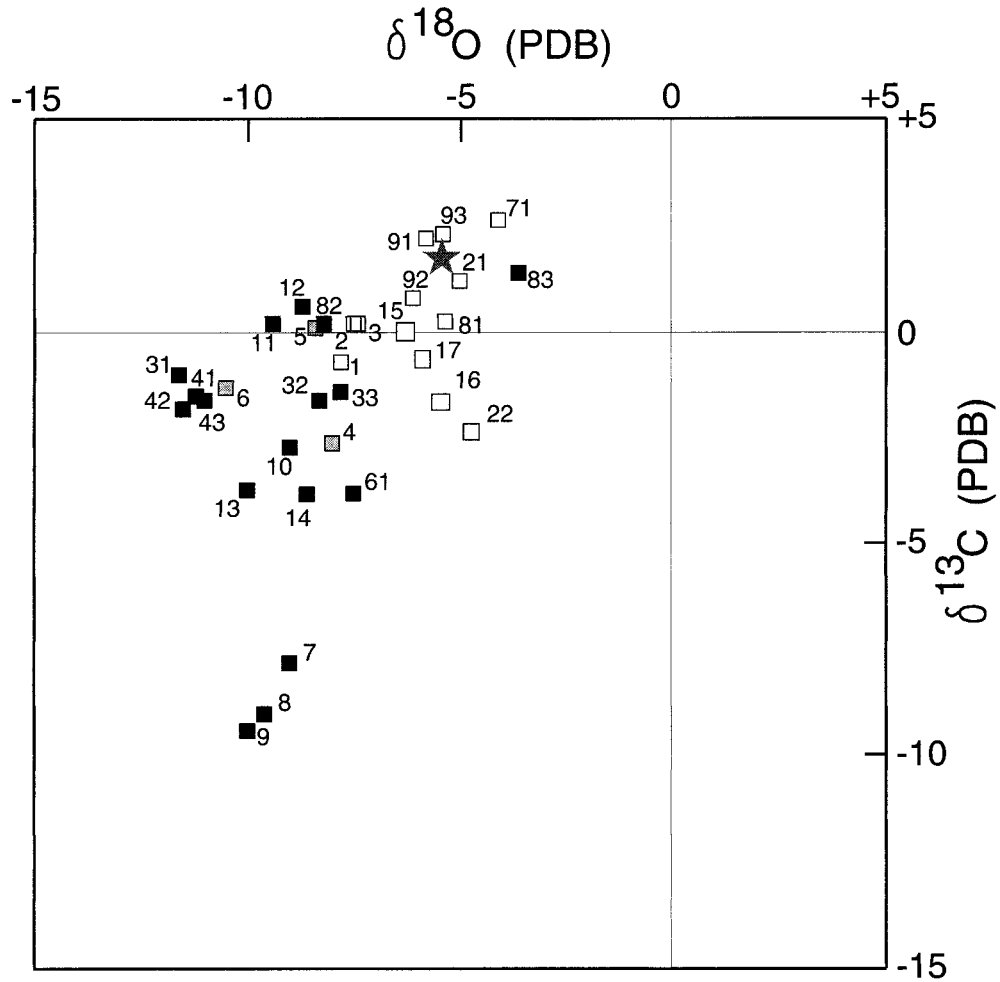
GEOCHEMISTRY

Stable-Isotope and Trace-Element Analysis

Stable isotopes for the appropriate carbonate lithosomes that bracket and include the Delle event are considered here. Particular emphasis is placed on stratigraphic and areal variations within the Sadlick sequence. In addition, trace-element analysis of the carbonate rocks permit further insight into the deposition and subsequent diagenesis of the carbonates. Sr and Mg concentrations tend to decrease, whereas the concentrations of Mn and Fe increase, during diagenetic alteration of carbonates (e.g., Veizer 1983; Morse and Mackenzie 1990). Interpretation of Mn concentrations in carbonates is complicated by the redox behavior of this element. In general, Mn concentrations are higher if lithification takes place in anoxic environments (e.g., Pratt et al. 1991; Force and Maynard 1991). Rare-earth-element analysis of phosphorites, cherts, and shales has also proved useful for interpreting the general provenance and depositional conditions of ancient marine sequences (e.g., Fleet 1984; McLennan 1989; McLennan and Murray 1999). Data presented below attempt to place the rare-earth geochemistry of the Delle event and associated lithosomes within the context of other studies of similar rocks.

Delle- and Pre-Delle-Event Carbonate Rocks.—In addition to being lithologically distinct, Delle-event limestones have chemistries markedly different from the rocks that immediately preceded them. The areally extensive wackestone–packstone lithosome of the Sadlick sequence (part of the Gardison, upper Joanna, and Lodgepole Limestones) that underlies Delle-event rocks has $\delta^{18}O$ values ranging from -4.7 to $-7.8‰$ (Table 2). A clear distinction exists between the $\delta^{18}O$ and $\delta^{13}C$ values of the open-marine wackestone–packstone (SA.Di.WkPk) lithosome and the Delle-event ostracode lime mudstone lithosome (SA.Os.Lm) (Fig. 3). The younger lime mudstones have $\delta^{18}O$ values that are considerably lighter than the underlying wackestones–packstones. Aside from one anomalously heavy sample (SA-6) in the Samak section ($-4.7‰$, Table 2), Delle-event lime mudstone $\delta^{18}O$ values range from -7.8 to $-11.5‰$. As discussed below, the depositional environment of the Samak ostracode lime mudstone in the easternmost part of the Antler foreland basin may have been different from environments to the west and could thus explain the anomalously heavy $\delta^{18}O$ value from this location.

A stratigraphic plot of carbon and oxygen isotopes from the well-documented Lakeside Mountains section (Fig. 4) provides a spatial context of stable-isotope data and previous stratigraphic and petrographic observations (Nichols and Silberling 1991c). The upper 1 m of wackestones–packstones have significant shifts toward lighter carbon and oxygen isotope values in comparison to rocks that are 1–5 m below the top of the Gardison Limestone, and this coincides with the onset of the Delle phosphatic event. This is consistent with petrographic observations showing that the upper 1 m or so of the Gardison Limestone has significant postdepositional solution com-

$\delta^{18}O$ (PDB)

-15   -10   -5   0   +5 +5
+5

93   71
91   21
92   83
12   82
15   81
11 5 2 3
17
31 41
42 6 32 33
43
16
4   22
10
13 14 61

0

-5

7

8
9

$\delta^{13}C$ (PDB)

-10

-15

Lakeside Mountains
12. 87-N-31
11. LM-16b
10. LM-16a
9. LM-15a2 ⎤ pinch & swell
8. LM-15a1 ⎦ limestones
14. LM-13b
13. LM-13a
7. LM-6f

6. LM-1c
5. LM-1b
4. LM-1a
3. 87-N-34B
2. LM-m3
1. LM-m4.5
15. LM/1-99
16. LM/2-99
17. LM/3-99

Confusion
Range

22. CR-16
21. CR-15

☐ SA.Di.WkPk   ■ SA.Os.Lm

▨ Altered top   ★ Average Mississippian
of SA.Di.WkPk   marine limestone
                         (Keith & Weber 1964)

Ophir   East Tintic
33. OP-10   43. MP-12   SA.Os.Lm
32. OP-9   42. MP-11   (Except as noted)
31. OP-1   41. MP-8

SA.Di.WkPk

Crawford Mountains
61. 87-N-202B

Pahvant
71. 87-N-271B

Needles Range   Samak
82. MH-3   94. SA-6
83. MH-2   95. SA-10   SA.Os.Lm

81. MH-1   93. SA-3   SA.Di.WkPk
                 92. SA-2
                 91. SA-1

TABLE 2.—*Summary of geochemical data for calcite from the carbonate lithosomes associated with the Delle phosphatic event.*

Sample	Formation	Lithology	Lithosome	$\delta^{13}C$(‰)	$\delta^{18}O$ (‰)	Sr (ppm)	Mn (ppm)
Pre-Delle Event							
LM-m4.5	Gardison Limestone	Wackestone	SA.Di.WkPk	−0.7	−7.8	240	116
LM-m3	Gardison Limestone	Packstone	SA.Di.WkPk	0.2	−7.5	231	107
LM/1-99	Gardison Limestone	Packstone	SA.Di.WkPk	−1.2	−5.6	216	
LM/2-99	Gardison Limestone	Packstone	SA.Di.WkPk	0.1	−6.1	222	
LM/3-99	Gardison Limestone	Wackestone	SA.Di.WkPk	−0.5	−5.8	216	
LM-87-N-34B	Gardison Limestone	Packstone	SA.Di.WkPk	0.2	−7.4		
SA-1	Lodgepole Limestone	Packstone	SA.Di.WkPk	2.2	−5.8	309	18
SA-2	Lodgepole Limestone	Packstone	SA.Di.WkPk	0.8	−6.1	223	38
SA-3	Lodgepole Limestone	Wackestone	SA.Di.WkPk	2.3	−5.4	316	20
CR-15	Joanna Limestone	Lime mudstone	SA.Di.WkPk	1.2	−5.0	423	99
CR-16	Joanna Limestone	Packstone	SA.Di.WkPk	−2.3	−4.7	374	319
MH-1	Joanna Limestone	Wackestone	SA.Di.WkPk	0.2	−5.6	388	280
PA-87-N-271-B		Wackestone	SA.Di.WkPk	2.6	−4.1		
Delle Event							
LM-1a	Gardison Limestone	Wackestone (alt)	SA.Di.WkPk	−2.6	−8.0		
LM-1b	Gardison Limestone	Packstone (alt)	SA.Di.WkPk	0.1	−8.4	254	242
LM-1c	Gardison Limestone	Wackestone (alt)	SA.Di.WkPk	−1.3	−10.5	250	273
LM-6f	Woodman Formation	Lime mudstone	SA.Os.Lm	−7.8	−9.0	332	185
LM-13a	Woodman Formation	Lime mudstone	SA.Os.Lm	−3.7	−10.0		
LM-13b	Woodman Formation	Lime mudstone	SA.Os.Lm	−3.8	−8.6	292	78
LM-15a1	Woodman Formation	Lime mudstone	SA.Os.Lm	−9.0	−9.6	339	93
LM-15a2	Woodman Formation	Lime mudstone	SA.Os.Lm	−9.4	−10.0		
LM-16a	Woodman Formation	Lime mudstone	SA.Os.Lm	−2.7	−9.0	323	78
LM-16b	Woodman Formation	Lime mudstone	SA.Os.Lm	0.2	−9.4		
87-N-31	Woodman Formation	Lime mudstone	SA.Os.Lm	0.6	−8.7		
SA-6	Brazer Dolomite	Lime mudstone	SA.Os.Lm	3.0	−4.7	564	27
SA-10	Brazer Dolomite	Lime mudstone	SA.Os.Lm	2.1	−10.0	250	49
OP-1	Deseret Limestone	Lime mudstone	SA.Os.Lm	−1.0	−11.6	309	78
OP-9	Deseret Limestone	Lime mudstone	SA.Os.Lm	−1.6	−8.3	297	87
OP-10	Deseret Limestone	Lime mudstone	SA.Os.Lm	−1.4	−7.8	305	73
MP-8	Deseret Limestone	Lime mudstone	SA.Os.Lm	−1.5	−11.2	353	218
MP-11	Deseret Limestone	Lime mudstone	SA.Os.Lm	−1.8	−11.5	239	207
MP-12	Deseret Limestone	Lime mudstone	SA.Os.Lm	−1.6	−11.0	224	147
Post-Delle Event - Lakeside Mountains (East)							
98-5-81	Humbug Formation	Lime mudstone		0.8	−8.2	452	
98-5-82	Humbug Formation	Lime mudstone		0.8	−7.6	545	
98-5-83a	Humbug Formation	Lime mudstone		0.9	−7.8	564	
98-5-83b	Humbug Formation	Lime mudstone		0.5	−7.8	607	
98-5-84	Humbug Formation	Wackestone		2.0	−7.0	275	
98-5-91	Great Blue Limestone	Wackestone		1.7	−6.1	472	
98-5-92	Great Blue Limestone	Wackestone		2.1	−7.2	330	
Post-Delle Event - Confusion/Mountain Home Ranges (West)							
CM-87-N-202B	Chainman Shale						
PA-87-N-271B	Chainman Shale	Lime mudstone	SA.Rh.LmWk	−3.8	−7.5		
CR-4	Needle Siltstone, Chainman Shale	Lime mudstone	SA.Rh.LmWk	2.6	−4.1		
MH-2	Needle Siltstone, Chainman Shale	Lime mudstone	SA.LaDo.St	−9.4	−5.4	1342	328
MH-3	Needle Siltstone, Chainman Shale	Lime mudstone	SA.LaDo.St	1.4	−3.8	563	50
CR-1	Skunk Spring Limestone, Chainman Shale	Lime mudstone	SA.LaDo.St	0.2	−8.2	351	89
CR-2	Skunk Spring Limestone, Chainman Shale	Lime mudstone	MA.Rh.Lm	−4.0	−4.7	926	90
MH-6	Skunk Spring Limestone, Chainman Shale	Lime mudstone	MA.Rh.Lm	−1.2	−7.9	3249	132
		Lime mudstone	MA.Rh.Lm	−5.8	−6.4	623	111
CR-9	Chainman Shale	Lime mudstone	MA.Ms	1.4	−5.9	2357	34
CR-10	Chainman Shale	Lime mudstone	MA.Ms	1.8	−6.1	2477	70
CR-11	Chainman Shale	Lime mudstone	MA.Ms	−11.0	−9.5	1573	86
CR-13	Chainman Shale	Lime mudstone	MA.Ms	−10.8	−4.5	883	97

Abbreviations for sections samples (Figure 1): LM = Lakeside Mountains, SA = Samak, OP = OPir, ET = East Tintic, CR = Confusion Range, MH = Mountain Home Range, TP = The Peak, PA = Pahvant, CM = Crawford Mountains.

paction and phosphatization (Nichols and Silberling 1991b, 1991c, 1993). It also suggests that the highly altered, uppermost part of the Gardison was influenced by the isotopically lighter waters associated with the Delle phosphatic event.

All ostracode lime mudstones (SA.Os.Lm) associated with the Delle Phosphatic event in the Lakeside Mountains have $\delta^{18}O$ values (−8.6 to −10.0‰) that are significantly lighter than those of unaltered or partially altered wackestone and packstones (−5.6 to −7.8‰) more than 1 m below the top of the underlying Gardison Limestone. Shifts toward lighter carbon isotopes associated with the Delle phosphatic event are more dramatic and varied than $\delta^{18}O$ shifts. Carbon isotope values of discontinuous, relatively thin radiolarian-bearing lime mudstone in Unit 6 (Fig. 4) 3 m above the Gardison–Woodman contact and pinch-and-swell limestone dissolution remnants (Unit 15, Fig. 4) about 30 m above the contact are approximately

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FIG. 3.—$\delta^{13}C$–$\delta^{18}O$ plot of rocks from the pre- and post-Delle-event wackestone and packstone and Delle-event lime mudstone lithosomes. The Mississippian limestone value of Keith and Weber (1964) is an average of bulk limestone values, which do not necessarily correspond to the isotopic composition of the oceans during that period of time.

TABLE 3.—*Summary of phosphorous and rare earth element data for the lithosomes associated with Delle Phosphatic Event.*

Sample	Formation	Lithology	P_2O_5 (%)	La (ppm)	Ce (ppm)	Nd (ppm)	Ce/Ce*
LM-1c	Gardison Limestone	Wackestone (alt.)	3.3	49	35	38	0.37
SA-4b	Brazer Dolomite	Chert	0.2	5	2	3	0.22
LM-3a	Woodman Formation	Siltstone	0.2	9	9	7	0.53
LM-6a	Woodman Formation	Chert	0.2	6.5	5	6	0.37
LM-6d	Woodman Formation	Chert	0.3	8	4	7	0.25
LM-7a	Woodman Formation	Shale	0.8	18	8	12	0.24
LM-11a	Woodman Formation	Phosphorite	30.2	114	19	64	0.09
LM-11e	Woodman Formation	Phosphorite	25	293	59	156	0.11
LM-14a	Woodman Formation	Chert	2.9	71	11	43	0.08
OP-3	Deseret Limestone	Phosphorite	22.9	137	53	110	0.21
OP-6	Deseret Limestone	Phosphorite	29	82	27	30	0.21
ET-1	Deseret Limestone	Phosphorite	34.8	125	44	110	0.18
ET-3	Deseret Limestone	Phosphorite	32.9	114	31	80	0.14
ET-6	Deseret Limestone	Phosphorite	35.7	91	18	40	0.12
CR-3	Needle Siltstone, Chainman Shale	Siltstone	0.1	31	59	22	1.01
CR-6	Needle Siltstone, Chainman Shale	Siltstone	0.1	28	53	32	0.87
CR-8	Needle Siltstone, Chainman Shale	Siltstone	0.1	16	32	13	1.02
CR-17	Chainman Shale	Shale	0.3	50	97	42	0.98
CR-18	Chainman Shale	Shale	3.5	85	151	65	0.92
MH-4	Needle Siltstone, Chainman Shale	Siltstone	0.2	13	25	12	0.94

Abbreviations for sections samples (Figure 1): LM = Lakeside Mountains, SA = Samak, OP = Ophir, ET = East Tintic, CR = Confusion Range, MH = Mountain Home Range. Ce/Ce* is calculated as 3Cen/(2Lan+Ndn) where "n" refers to concentrations normalized to the average values defined by Gromet et al. (1984).

6‰ lighter than the altered Gardison Limestone immediately below the contact. The ostracode lime mudstones (Units 13 and 16, Fig. 4) about 20 m above the Woodman–Gardison contact, on the other hand, have $\delta^{13}C$ values closer to those of the altered Gardison wackestones and packstones, although $\delta^{18}O$ values of these lime mudstones are among the lightest (-8.7 to -9.4‰). The very lightest carbon isotopes (-9.0 and -9.4‰) from the Lakeside section are found in the limestone pinch-and-swell structures (30 m above the Gardison–Woodman contact) (Unit 15, Fig. 4). Samples from the rim and interior of these pinch-and-swell structures (samples LM-15a1 and LM-15a2, respectively) have similar carbon and oxygen isotope values ($\pm$ 0.4‰ variation) (Table 2). These data are not consistent with these structures being concretions (Sandberg and Gutschick 1984), which typically have interior-rim $\delta^{18}O$ and $\delta^{13}C$ variations of 1–10‰ (Mozley and Burns 1993).

$\delta^{18}O$ values from other sections containing Delle-event ostracode lime mudstones (Ophir Canyon, East Tintic, and the Crawford Mountains) also have light $\delta^{18}O$ values (-7.5 to -11.5‰). $\delta^{13}C$ values from these sections are generally heavier than those of the Lakeside Mountains (-3.8 to

-1.0‰). The two ostracode lime mudstone samples from the Samak section have relatively heavy $\delta^{13}C$ values (2.1, 3.0‰) and variable $\delta^{18}O$ values (-10.0, -4.7 ‰).

The data thus show that, with the exception of the Samak section in the eastern part of the study area, Delle-event lime mudstones have markedly lighter oxygen and carbon isotope signatures than the open marine carbonate rocks that immediately precede them. These geochemical changes correspond to pronounced lithologic changes between Delle and pre-Delle-event rocks.

It is not appropriate to place these $\delta^{18}O$ results within the context of Early Mississippian seawater geochemistry. The most critical complication relates to these mostly fine-grained rocks being sampled in bulk in the present study rather than as individual constituent components. Furthermore, the Late Devonian–Early Mississippian ocean appears to have been characterized by significant and relatively rapid changes in oxygen and carbon isotope values (Lohmann and Walker 1989). Although the $\delta^{18}O$ values of the early wackestone–packstone lithosome (SA.Di.Wk.Pk) are similar to those reported by Lohmann and Walker for Late Devonian sea-
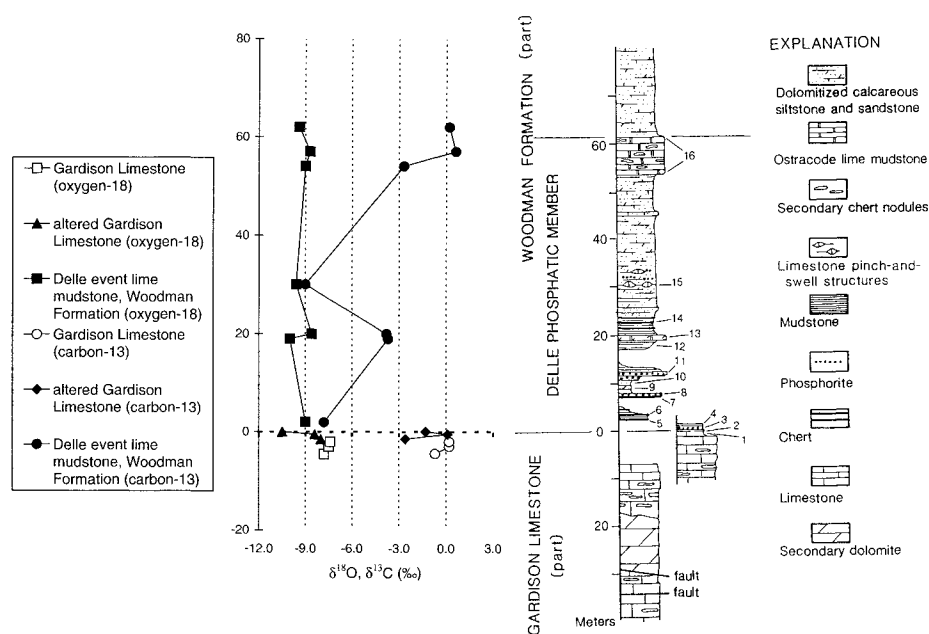

FIG. 4.—Stratigraphic plot of $\delta^{13}C$ and $\delta^{18}O$ from the Lakeside Mountains shown as meters above the Gardison–Woodman contact. Numbered units in the stratigraphic column are described in Nichols and Silberling (1990, 1991c).
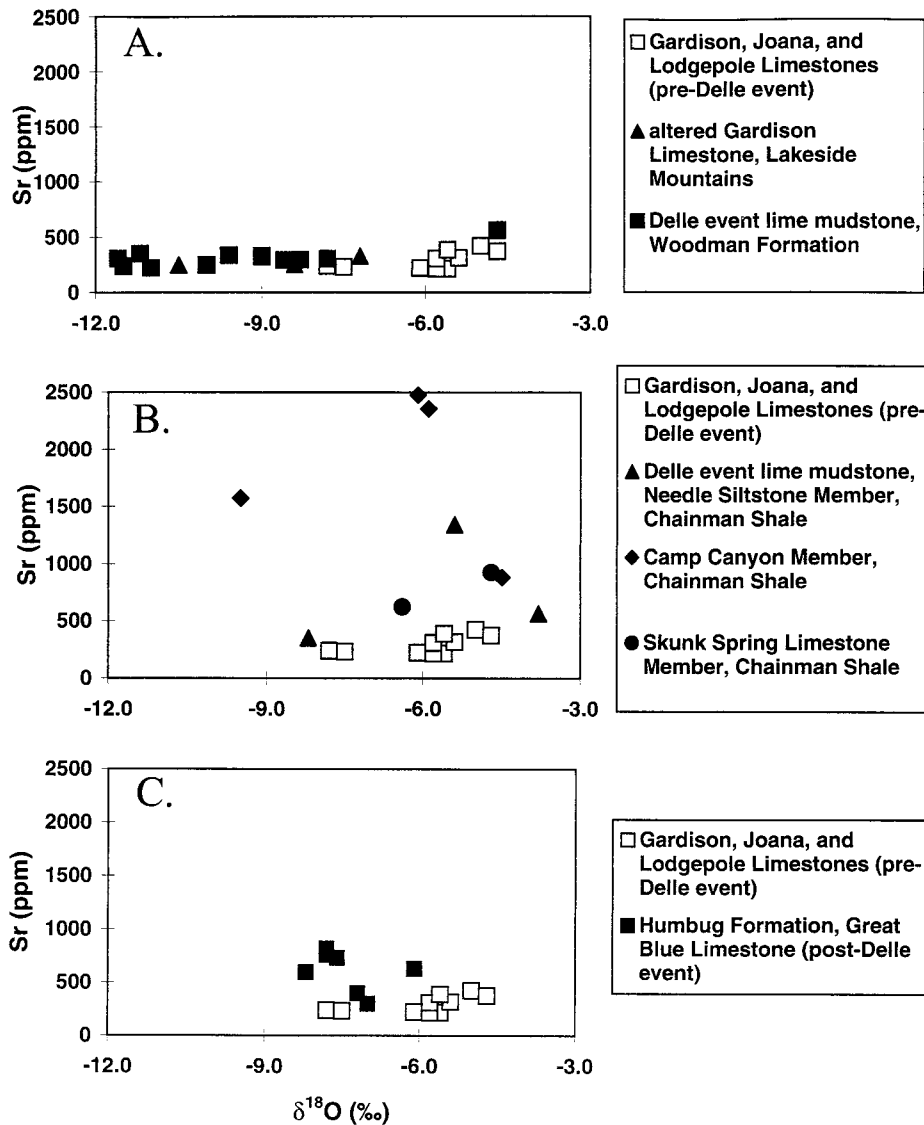
Fig. 5.—Sr–δ^{18}O data. **A)** Pre-Delle-event wackestones and packstones and Delle-event ostracode lime mudstones from the Lakeside Mountains. **B)** Pre-Delle-event wackestones and packstones and post-Delle-event limestones from the Lakeside Mountains. **C)** Pre-Delle-event wackestones and packstones and Delle-event and post-Delle-event limestones from the western part of the study area (closed symbols).

water (-5 to -7‰), they are considerably lighter than values for Early Mississippian (Osagean) seawater (-1 to -2‰). It would thus appear that these open marine carbonates have undergone a modest postdepositional oxygen isotope shift toward lighter values.

Trace-element data provide further evidence for postdepositional alteration of the carbonates. The wackestone–packstone and Delle-event ostracode lime mudstone lithosomes have similar Sr concentrations (200 to 560 ppm) (Table 2, Fig. 5A). Sr concentrations from both of these lithologies are close to the values reported for carbonate rocks that have been exposed to meteoric water during diagenesis (Land 1986). Limestones with a totally marine depositional and diagenetic history generally have Sr concentrations of $\sim$ 2000–3000 ppm (e.g., Veizer 1983; Land 1986).

Mn concentrations in carbonate rocks have been used for two different purposes. The first is to interpret the general redox state of fluids during diagenesis and lithification. Because Mn is more soluble under reducing conditions, higher Mn concentrations in rocks that have similar lithology and facies are consistent with the lower oxygen concentrations in the bottom waters in which the rocks were deposited. Also, Mn concentrations are believed to be higher in rocks exposed to meteoric water during diagenesis (just as Sr concentrations are generally believed to be lower) (Veizer 1983).

A strong correlation between Mn concentrations and δ^{13}C would be expected if Mn concentrations were controlled by the redox state of the formation waters (e.g., Pratt et al. 1991). Within the wackestone–packstone (SA.Di.WkPk) and ostracode lime mudstone (SA.Os.Lm) lithosomes, however, the correlation between these two variables is weak (Fig. 6). Furthermore, Mn concentrations from the two lithosomes are similar despite sedimentologic, petrographic, and δ^{13}C evidence that the ostracode lime mudstones were deposited in a much more productive environment. Finally, Mn concentrations of these carbonates are lower than those of carbonates believed to have been deposited under anoxic conditions (e.g., Pratt et al. 1991; Force and Maynard 1991). Therefore, although the high δ^{13}C concentrations and lack of open-marine fossils in the ostracode lime mudstones suggest deposition in a highly productive environment, it is unlikely that the bottom waters were anoxic.

Post-Delle-Event Carbonate Rocks.—In an effort to understand depositional conditions following the Delle event, two suites of samples were studied. The first is from the areally extensive exposures of Lower Meramecian to Upper Chesterian limestones (Humbug Formation and lower Great Blue Limestone) in the southern Lakeside Mountains approximately 1.5 km southeast of the type Delle section, and the second comprises a variety of lithologies that immediately postdate the Delle event elsewhere
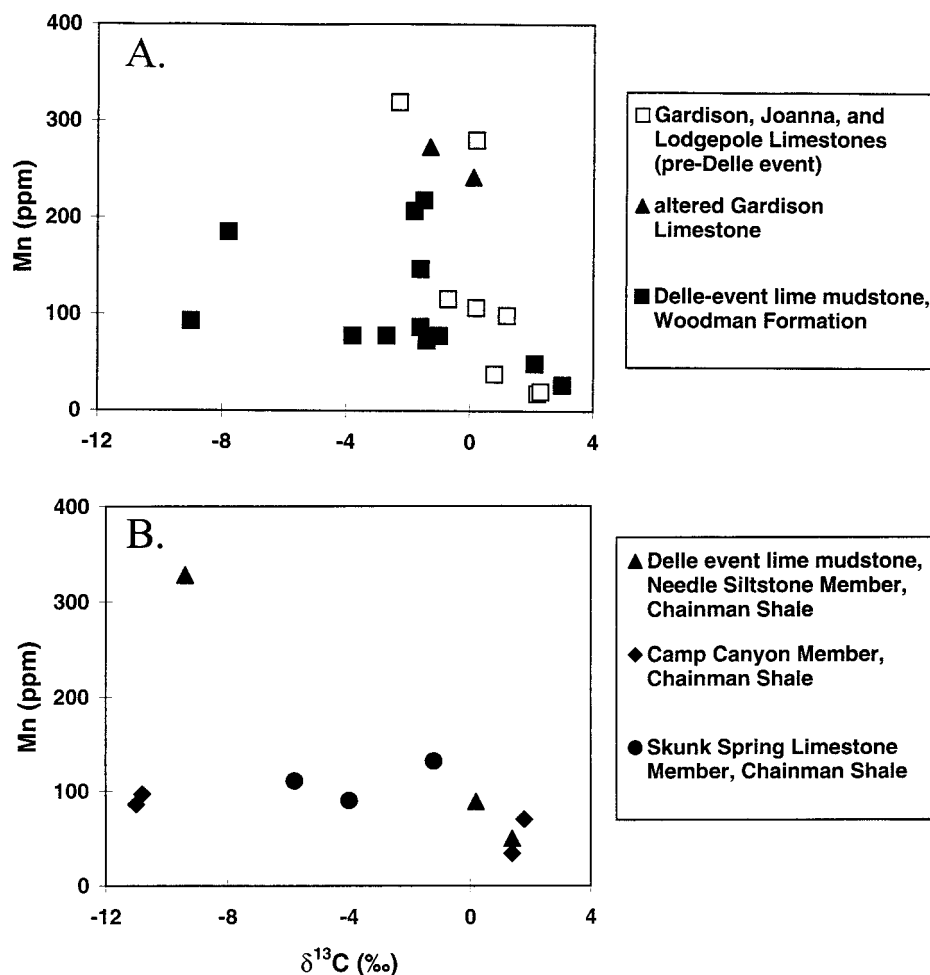
Fig. 6.—Mn–δ^{13}C data. **A)** Pre-Delle-event wackestones and packstones and Delle-event ostracode lime mudstones from the Lakeside Mountains. **B)** Delle-event and post-Delle-event limestones from the western part of the study area.

in the study area (Table 2). Post-Delle-event rocks from the Lakeside Mountains have isotopic and trace-element chemistry that is very similar to carbonates that underlie the Delle event (Gardison Limestone) (Table 2). δ^{18}O values of pre-Delle carbonates in the Lakeside Mountains ranges from −7.4 to −7.8‰ whereas post-Delle carbonate δ^{18}O varies between −6.1 and −8.7‰. Sr concentrations of pre- and post-Delle-event carbonates are also very similar (Table 2). These results suggest that although the entire Lakeside Mountains has undergone postdiagenetic geochemical alteration, the δ^{18}O signature of Delle-event lime mudstones is anomalously light relative to other carbonate units in the Lakeside Mountains section.

Lime mudstone beds within the laminated silty dolomitic siltstones (SA.LaDo.St) of the Sadlick sequence (the Needle Siltstone Member of the Chainman Shale in the western part of the foreland basin) (samples CR-4, MH-2, and MH-3, Table 2) and two samples from the approximately time-equivalent rhythmically bedded lime mudstone (SA.Rh.LmWk) of the Chainman Shale (samples CM-87-N-202B and PA-87-N-271B, Table 2) to the east (Fig. 2) produced δ^{18}O values (−3.8 to −8.2‰) that are close to those of underlying open-marine wackestones and packstones despite being lithologically more like the older ostracode lime mudstones associated with the Delle event. With the exception of one sample (CR-4) from Confusion Range, δ^{13}C values are close to those of typical open-marine carbonate rocks. Carbonates from two lithosomes of the Maughan sequence in the western part of the study area (Confusion and Needle Ranges) were analyzed (Figs. 1, 2). The first is a dense, nearly unfossiliferous lime mudstone (lithosome MA.Rh.Lm) that constitutes the Skunk Spring Limestone Bed (Meramacian) of the Chainman Shale (samples CR-1, CR-2, and NR-6) (Tables 1, 2). The second set

of samples was collected from the Camp Canyon Member of the Chainman Shale (lithosome MA.Ms), which is stratigraphically above the Skunk Spring Limestone. These latter samples include a winnowed encrinite bed (CR-9, CR-10), a black lime-mudstone concretion (CR-11), and an organic-rich lime mudstone (CR-13) (Table 2). These Maughan sequence rocks have variable isotopic compositions. With the exception of the black lime-mudstone concretion (sample CR-11) (Table 2), δ^{18}O values are close to those of the Sadlick sequence wackestones and packstones (−4.5 to −7.9‰) of lithosome SA.Di.WkPk. δ^{13}C is highly variable but in general is negatively correlated with organic carbon concentrations (Fig. 7). Sr concentrations of the Maughan sequence carbonates are generally higher than those of the wackestone–packstone and ostracode lime mudstones of the Sadlick sequence (Table 2). Maughan sequence carbonate Sr values are closer to what is typically considered to be the result of an open-marine depositional and diagenetic history (Veizer 1983; Land 1986).

Rare Earth Elements

Rare earth elements (REE) have been used to infer both sediment source and depositional environment for a variety of rocks. The REE content of siliciclastic rocks tends to reflect the character of the sedimentary sources from which they were derived. On the other hand, chemically precipitated rocks (e.g., cherts, phosphorites, and carbonates) incorporate rare earth elements from the fluids in which they formed. The REE signature of rocks is therefore dependent on both the source material and the environment of deposition as reflected by the relative amounts of detrital and chemical constituents in a given rock.
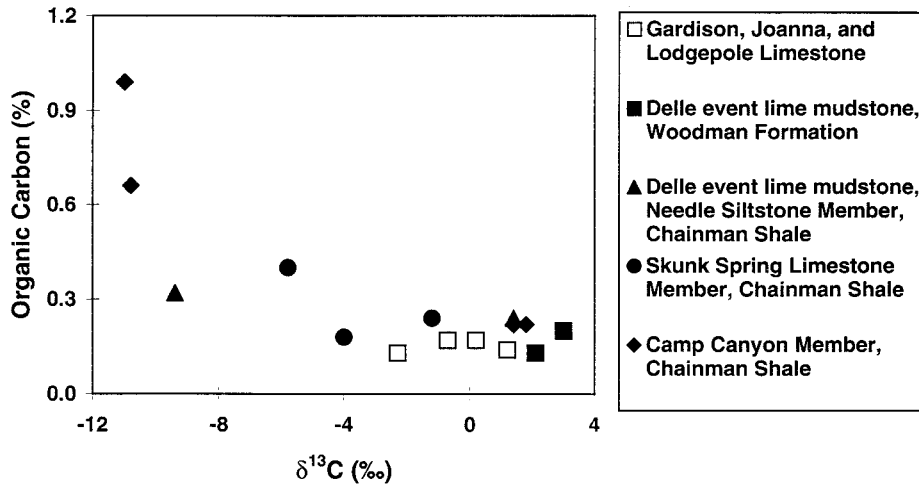
FIG. 7.—Organic carbon–δ^{13} plot of various lithosomes in the Sadlick and Maughan sequences.

Apatite is considered to be a particularly good authigenic mineral for REE studies because the two calcium sites accept a wide variety of REE cations (Wright et al. 1987; Piper 1991). REE signatures also appear to be retained during postdepositional diagenetic modification of cherts (Shimizu and Masuda 1977; Murray et al. 1990, 1991, 1992). German and Elderfield (1990) caution, however, that the REE signatures are usually acquired during lithification of the host mineral and are generally indicative of diagenetic rather than ambient seawater conditions.

The geochemistry of Ce is particularly useful in determining the redox conditions of chemical sediments because it has two oxidation states: soluble Ce(III) and insoluble Ce(IV). Elevated Ce concentrations relative to La and Nd (the two nearest elements in the periodic table measured by standard neutron activation analysis) are taken to indicate that the host mineral was formed under reducing conditions. On the other hand, oxygenated seawater is depleted in Ce because of the formation of insoluble Ce-hydroxides in coastal and estuarine environments. Chemically precipitated rocks from oxygenated open-ocean environments thus tend to be depleted in Ce.

Ensemble averages of shales, such as the North American Shale Composite (NASC) (Gromet et al. 1984), have typically been used to normalize REE concentrations in order to assess source-rock and depositional conditions (e.g., Jewell and Stallard 1991; Murray et al. 1991), and this convention is used here. The most common way to report Ce anomalies is Ce/Ce* = $3Ce_n$/ ($2La_n + Nd_n$), where the subscript ''n'' refers to shale-normalized concentrations) (de Baar et al. 1985). For this study, La, Ce, and Nd concentrations are reported for cherts, phosphorites, and shales from the Sadlick sequence in a variety of localities (Table 3). A single carbonate sample from the altered uppermost part of the Sadlick wackestone–packstone lithosome (SA.Di.PkWk) of the Gardison Formation in the Lakeside Mountains (sample LM-1c) is reported because of its relatively high P_2O_5 content. Ce/Ce* values of cherts and phosphorites from these eastern localities (Lakeside Mountain, Samak, Ophir, and East Tintic sections) (Table 3) are relatively low and would seem to indicate formation in an oxygenated environment. Similar negative Ce anomalies have been reported for other phosphogenic provinces (Coles and Varga 1988; Jewell and Stallard 1991; Piper 1991). Formation in oxygenated water is not surprising given studies of modern phosphorites that indicate formation in a low-oxygen but not anoxic environment (e.g., Föllmi 1996). Episodic anoxic diagenetic conditions during the Delle event, however, are suggested by the presence of authigenic ammonium feldspar (buddingtonite) in dolomitized calcareous mudstones of the Lakeside Mountains (Nichols and Silberling 1990, 1991b). The shales, cherts, and phosphorites of the Delle event thus appear to be characterized by deposition in productive, anoxic to suboxic water conditions.

Time-equivalent siltstones and shales from the Sadlick sequence farther

west in the Antler foreland (Confusion and Mountain Home Ranges) have Ce/Ce* values (0.87–1.02) that are close to those of the NASC. A shale Ce/Ce* value close to 1 has typically been interpreted as representing deposition close to the terrigenous sedimentary source (Murray et al. 1991). One shale sample (CR-18, Table 3) collected from the Needle Siltstone–Joana Limestone contact in the Confusion Range has high P_2O_5 and REE concentrations. The relatively high Ce/Ce* value from this sample stands in contrast to low Ce/Ce*, phosphate-rich samples from farther east in the Antler foreland and could imply diagenesis in an anoxic environment.

DISCUSSION

Insight into the depositional history of the Antler foreland rocks can be gleaned from the stable-isotope and trace-element data presented here. Overprints of meteoric water have probably changed the isotopic composition of all rocks in this study. The difference in isotopic composition between the Delle-event carbonates and those that underlie and overlie the Delle-event rocks is striking, however, and these differences occur regionally between starkly contrasting lithologies. Post-Mississippian geochemical alteration of these rocks is a virtual certainty, but it would be a monumental coincidence if, for example, this alteration selectively depleted the oxygen isotopes only in the Delle-event rocks in all of the sections that were studied.

Lime mudstones deposited during the Delle event have $\delta^{18}O$ signatures that are 3–5‰ lighter than the underlying (Fig. 4) and overlying open-marine shelf carbonates. These isotopic differences are observed in the detailed work conducted in the Lakeside Mountains as well as in all of the sections containing rocks of the Delle event that were studied (Table 1). Sr concentrations of all carbonate rocks in the eastern part of the study area are low, suggesting that both Delle and non-Delle carbonate rocks have been subjected to postdiagenetic alteration. In contrast, stable-isotope variations correspond to lithologic variations within a restricted stratigraphic interval (< 65 m) on a large regional scale (Figs. 1, 3). We therefore argue that the relatively light stable-isotope signature of Delle-event carbonates represents either a primary depositional or an early diagenetic signal caused by isotopically light water.

If the light $\delta^{18}O$ signature of the Delle-event limestones was acquired by contact with meteoric water during early diagenesis, then the Delle rocks must have been deposited in water sufficiently shallow to allow circulation of meteoric water soon after deposition. Similar oxygen isotope shifts associated with early diagenesis by meteoric water have been documented in a variety of shallow-water Pleistocene, Mesozoic, and Paleozoic limestones (e.g., Allan and Matthews 1982).

The dramatic lithologic and geochemical shifts that coincide with the
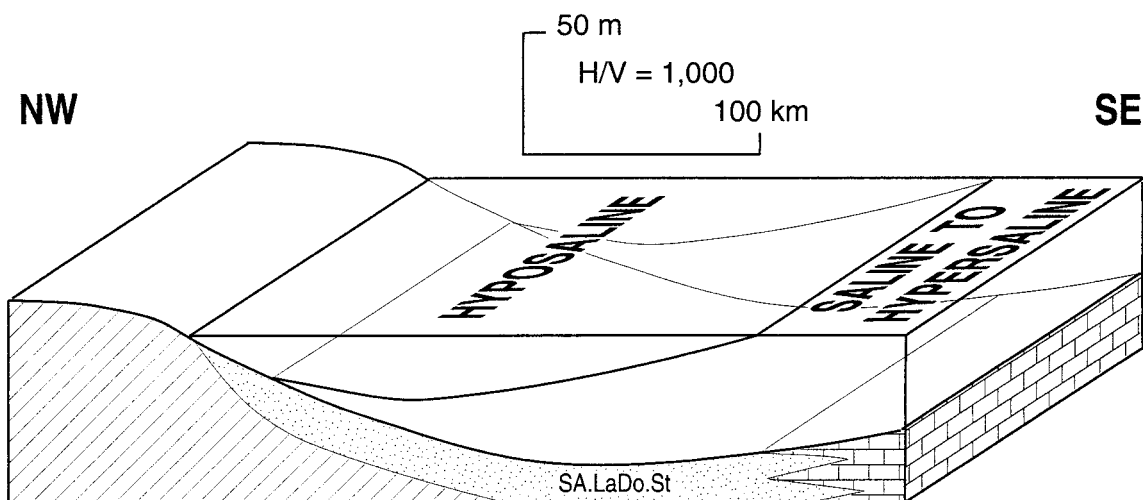
F<small>IG.</small> 8.—Diagrammatic model of depositional conditions during the Delle Phosphatic event in the distal Antler foreland. The source of both meteoric water, which formed the hyposaline upper water mass, and the fine-grained siliciclastic sediment, which characterizes lithosome SA.LaDo.St, is believed to have been from the west or north, from the peripheral bulge (Fig. 1) or its original northern extension.

contact between Delle and underlying non-Delle-event rocks over a wide geographic area suggest that the $\delta^{18}O$ shift is genetically related to depositional conditions of the Delle event itself. In this scenario, highly productive brackish water displaces nutrient-poor open-marine seawater within the Antler foreland (Fig. 8). Ostracode lime mudstones such as those found in the Lakeside Mountains (Figs. 2, 3) may have been deposited from brackish water, which was then available to diagenetically alter previously deposited, more open-marine parts of the Delle-event section and the immediately underlying carbonate rocks. This brackish water had somewhat lower pH, leading to dissolution and phosphatization of stratigraphically lower carbonate rocks (Nichols and Silberling 1991b, figs. 10, 11; Nichols and Silberling 1991c, figs. 5, 6; Nichols and Silberling 1993, fig. 21). The particularly low $\delta^{13}C$ values of radiolarian- and goniatite-bearing limestones (units 6 and 15, Fig. 3) from the Lakeside Mountains might represent episodes of enhanced circulation within the Antler foreland basin when highly productive marine water produced by upwelling in the foredeep, possibly as a result of low-latitude coastal nutrient trapping (Jewell 1995), found its way into the back-bulge region of the foreland (Fig. 1). In contrast, the ostracode lime mudstones may then relate to times of maximum restriction of the backbulge region from open marine circulation. Although such basins often have anoxic or low-oxygen bottom waters, their primary productivity tends to be modest (Jewell 1996).

Although we interpret the relatively light $\delta^{18}O$ values of Delle-event rocks of the Lakeside, Ophir, and East Tintic sections as indicating deposition under hyposaline conditions, the variable isotopic composition of the easternmost Samak section (Fig. 1) makes depositional interpretations for this locality somewhat ambiguous. The lack of siliciclastic material in this section (Nichols and Silberling 1991a) may indicate that terrigenous input from emergent parts of the Antler highland to the west was not important at this locality. If water depths at Samak were relatively shallow and the water body was isolated from the rest of the foreland (as suggested by the lack of siliciclastic material), then the water column could have shifted from hyposaline to saline or hypersaline to the east. Some modern shallow-water carbonate environments show similar widely varying salinities. For instance, the Gulf of Batabono in Cuba shows a 7‰ salinity gradient over a horizontal distance of 80 km (Hoskins 1964).

In summary, we acknowledge the possibility that the lower isotopic values in the Delle-event rocks could be a result of early diagenetic alteration by meteoric water. If so, this also supports our contention that the Delle was deposited in relatively shallow water, because this is the only way

these rocks could be exposed to meteoric water during early diagenesis. If Delle-event rocks were geochemically modified during early diagenesis, then one is still left to explain why the isotopic shift always coincides with appearance of the lithologically distinct Delle rocks.

Mn concentrations do not seem to indicate that the environment of the Delle-event lime mudstones was permanently anoxic. Low oxygen concentrations, however, may have occurred intermittently because of the high surface productivity and relatively shallow depth. Low oxygen in combination with relatively high nutrient concentrations would have stifled establishment of the diverse, warm-water benthic shelly fauna that is typical of the underlying wackestones and packstones of the Gardison Limestone. Rare-earth-element data indicate that phosphorites and cherts in the eastern localities of the laminated dolomitic siltstone lithosome were deposited under highly productive but oxic conditions with low terrigenous input.

In contrast to the wackestones, packstones, and lime mudstones of both Delle and non-Delle rocks in the eastern part of the Antler foreland, high Sr concentrations indicate that limestones within laminated dolomitic siltstones of the Sadlick sequence and limestones from the younger Maughan sequence to the west were deposited and lithified under conditions that were always open marine. Carbon isotopes suggest that surface-water productivity in these environments was variable. Mn concentrations indicate that bottom carbonate formation took place under oxic to suboxic conditions, although REE data from these rocks could be interpreted as representing formation under anoxic conditions.

These results as well as those of previous studies of Delle-event phosphorites in the Antler orogenic belt add to a growing body of literature documenting phosphorite deposition in relatively shallow water (Lucas and Prèvôt-Lucas 2000; Schwennicke et al. 2000). These results also point the way for possible additional detailed study of carbonate sequences that are succeeded by condensed phosphate sections (e.g., Föllmi et al. 1994).

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