Veins in the Lockport dolostone: Evidence for an Acadian fluid circulation system

Michael R. Gross
Terry Engelder
Simon R. Poulson
Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802

ABSTRACT

The orientation and spatial distribution of veins in the Lockport dolostone attest to a fluid circulation system active during the Acadian orogeny in western New York and southern Ontario. Outcrops east of the Clarendon-Linden fault zone are cut by a prominent east-northeast systematic calcite-filled vein set, whereas these systematic veins are absent west of the fault zone, except in two quarries. Systematic veins display distinct characteristics: the mean vein orientation rotates clockwise from 067° in the east to 086° farther west, veins do not propagate into the basal Lockport Group, and calcite vein $\delta^{18}O_{PDB}$ values are significantly lighter to the east of the Clarendon-Linden fault zone. Maximum horizontal stress (S_H) trend lines drawn parallel to the strike of the systematic veins are incompatible with S_H inferred from Alleghanian plateau and other post-Paleozoic structures. However, because east-west S_H trend lines are compatible with an Acadian tectonic event in western New England, our interpretation is that systematic veins in the Lockport Group are a cratonward signature of the Acadian orogeny.

INTRODUCTION

Though development of the Appalachian orogen represents a continuum process rather than a collection of individual events (Rast, 1989), local structures and thick clastic deposits correspond to major pulses in tectonic activity (Rodgers, 1967). One example is the Acadian orogeny, which started in the Early Devonian and continued into the Early Mississippian, migrating from north to south (Ferrill and Thomas, 1988). In the central Appalachians, the Acadian orogeny is manifested by the Catskill clastic wedge of the Appalachian basin (Ettensohn, 1985), the Hudson fold belt in New York (Marshak and Tabor, 1989), and a metamorphic event in western New England (Sutter et al., 1985). Herein we describe evidence for a post-Silurian tectonic event affecting the Lockport dolostone of western New York. We argue that this event is yet another manifestation of the Acadian orogeny.

The Lockport Group, situated directly above the Rochester Shale and below the Salina Group, consists of Middle Silurian dolostones cropping out in an east-west belt and dipping slightly to the south across the Appalachian plateau in western New York and southern Ontario (Brett et al., 1990) (Fig. 1). During the Alleghanian orogeny, the Salina salts acted as the decollement horizon, decoupling the Lockport Group from the overlying upper Paleozoic rocks that were subjected to a strong component of northwest-directed layer-parallel shortening (Engelder and Engelder, 1977). Alleghanian cross-fold joints, which are so prominent in the Valley and Ridge province and the Appalachian plateau thrust sheet (e.g., Engelder and Geiser, 1980), are much less prominent in the Lockport Group; in places they are absent. The most prominent structure affecting the Lockport outcrop belt is the Clarendon-Linden fault zone, which is a series of north-trending, basement-related, normal faults (Fakundiny et al., 1978). The fault zone is mapped as a horst and graben structure composed of three main normal faults (Isachsen and McKendree, 1977) that may extend under Lake Ontario (Hutchinson et al., 1979).

SYSTEMATIC VEINS IN THE LOCKPORT GROUP

Systematic calcite veins in the Lockport Group display a similar orientation, spacing distribution, morphology, and mineralization from one outcrop to the next. Upon close examination, the systematic veins in the Lockport Group appear as composite veins that form as a series

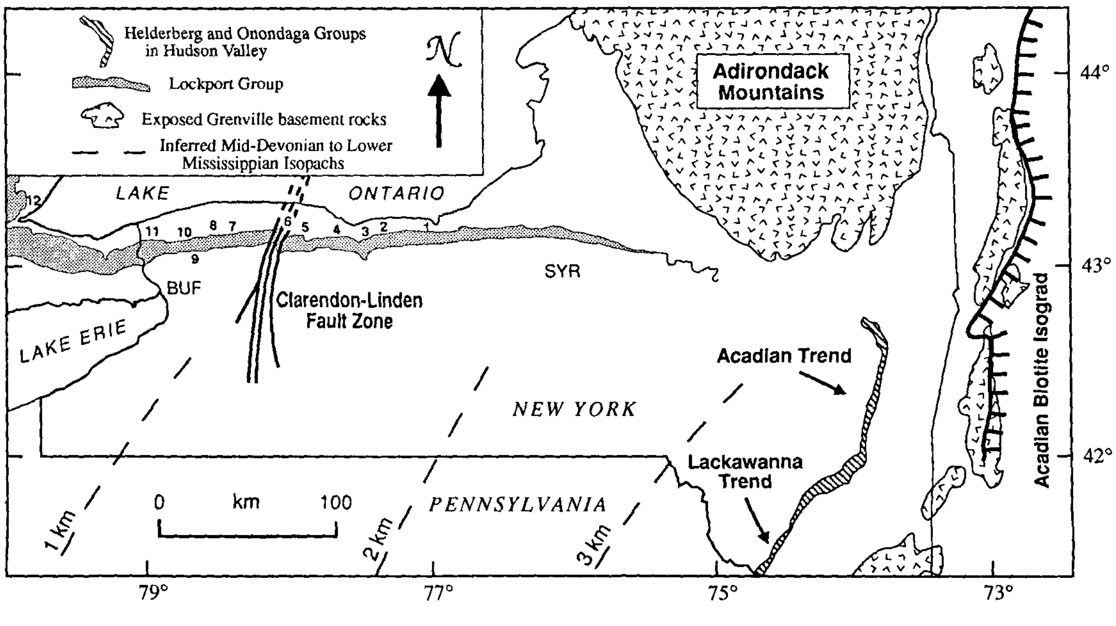

Figure 1. Map of western New York and southeastern Ontario showing Lockport Group outcrop belt and sites where fracture data were collected. Names of sites 1–12 are given in Figure 2. Other features include Clarendon-Linden fault zone (after Isachsen and McKendree, 1977), inferred Middle Devonian to Early Mississippian isopachs (after Colton, 1970), outcrop belt of Helderberg and Onondaga Groups in Hudson Valley showing what may be interpreted as Alleghanian Lackawanna trend and Acadian trend (after Marshak and Tabor, 1989), and Acadian biotite isograd (Sutter et al., 1985). BUF = Buffalo, SYR = Syracuse.

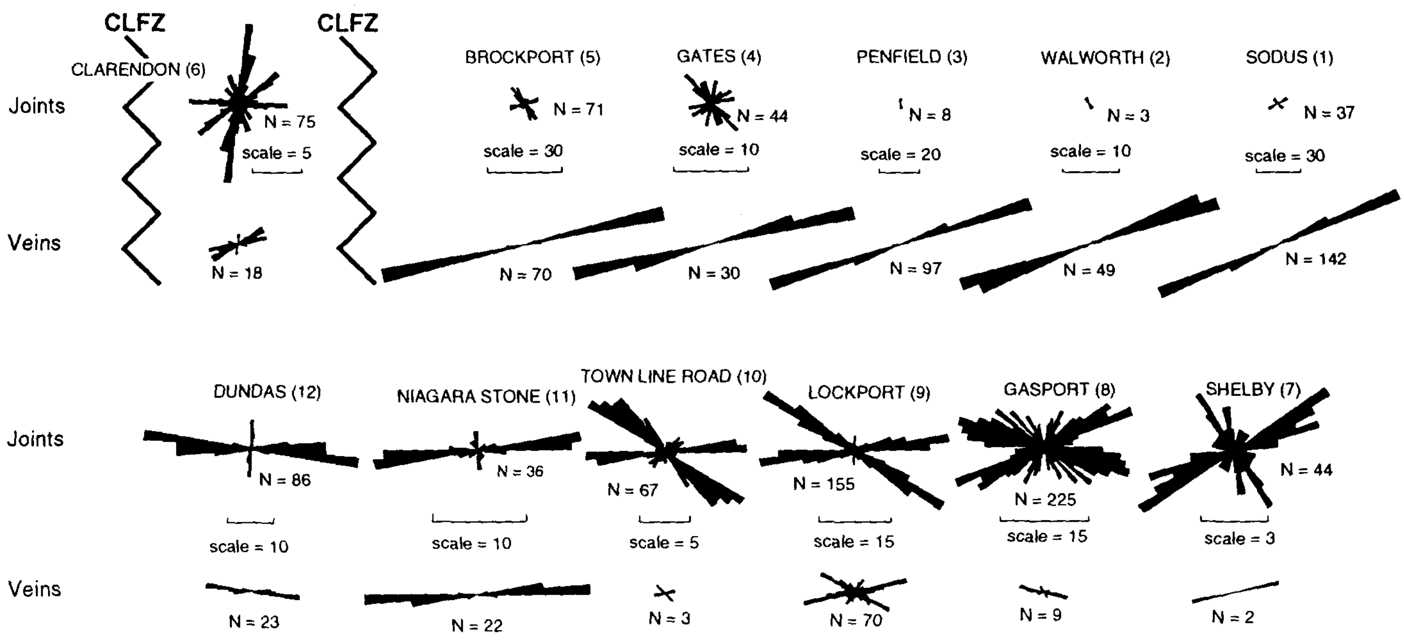

Figure 2. Rose diagrams of fracture data from 12 sites between Sodus, New York, to east, and Dundas, Ontario, to west. Data are divided into two categories: joints and veins. CLFZ = Clarendon-Linden fault zone. Rose diagrams are in 5° intervals, and there is common scale for each locality.

of individual ruptures with a steplike or en echelon geometry, suggesting that propagation may have been discontinuous. When viewed from a distance of several metres the veins appear to be a single throughgoing plane. The systematic veins in the Lockport Group cut vertically as much as 30 m and extend horizontally for distances greater than 100 m. Such veins are used by quarry operators as natural high walls, which commonly form prominent linear features on aerial photographs. In most quarries the systematic veins do not extend into the basal unit of the Lockport Group.

Major fracture sets in the Lockport Group include the east-northeast–trending systematic vein set, an east-northeast–trending joint set, and a northwest-trending joint set (Fig. 2). The systematic east-northeast–trending calcite-filled vein set is the dominant fracture set in quarries at sites 1 through 5 (Fig. 2). The systematic veins are extremely well aligned at each quarry, as indicated by the 99% confidence interval error bars (Fig. 3A). However, the systematic veins are absent at sites 6 through 10, but present at sites 11 and 12, where the vein set has a nearly due-east orientation. Between sites 6 and 11 and farther west some nonsystematic veins are found. Rose diagrams of systematic veins show an intriguing clockwise rotation in azimuth from 067° at site 1 to 087° at site 11 (Figs. 2 and 3A). The northwest-trending joint set in western parts of the field area (mainly at sites 9 and 10 and at several sites in Canada) has an orientation similar to that of the Alleghanian cross-fold joints in the Valley and Ridge and Appalachian plateau thrust sheet (Williams et al., 1985). An east-northeast–trending joint set is present in parts of the field area and is interpreted as neotectonic (Gross and Engelder, 1991).

Stable isotope analyses of vein calcite from six sites were performed using a method modified after McCrea (1950) (Table 1). Values for $\delta^{13}C$ (Peedee Belemnite [PDB]) west of the Clarendon-Linden fault zone (sites 11 and 12) are similar to those east of the zone (sites 1–4) and indicate a significant contribution of organic carbon. Analysis of multiple veins from the same site indicate large heterogeneities in $\delta^{13}C_{PDB}$. In contrast to $\delta^{13}C_{PDB}$, $\delta^{18}O_{PDB}$ values west of the fault zone are significantly heavier than for samples to the east of it, by $\sim 2‰$ (Fig. 3B). Analyses of multiple veins from the same site indicate small heterogeneities in $\delta^{18}O_{PDB}$. Measurable fluid inclusions in the vein calcite are extremely rare, although reconnaissance data from west of the fault zone indicate a mean homogenization temperature of 115 °C, which is consistent with data collected by Friedman (1987), suggesting that there once was significant overburden ($\geqslant 3$ km) above the Lockport Group.

CORRELATION WITH A TECTONIC EVENT

Systematic vein and joint sets over a large region reflect a stress field indicative of a significant tectonic event (e.g., Engelder and Geiser, 1980). Because veins in the Lockport Group show no evidence of shear movement, they are considered pure opening mode, or extension, fractures. Such veins propagated parallel to the maximum horizontal principal stress (S_H) and normal to the least horizontal principal stress (S_h). The regional trajectories of S_H are defined on a map by drawing trend lines parallel to the strike of the systematic vein at each outcrop.

S_H trend lines for cross-fold joints in forelands may converge toward a major depocenter in front of the core of an orogenic belt. For example, S_H trend lines drawn using Alleghanian cross-fold joints of the Appalachian plateau (New York and Pennsylvania) converge to the southeast near the core of the Appalachian fold-thrust belt and the site of thick Carboniferous sedimentation (Engelder and Geiser, 1980). S_H trend lines drawn from veins in the Lockport Group strike at a high angle to the S_H trend lines drawn from Alleghanian cross-fold joints of the Appalachian plateau. However, trend lines for the east-striking veins in the Lockport Group converge eastward toward New England (Gross, 1989) and are in the orientation of S_H inferred from the Hudson Valley fold-thrust belt, which has recently been interpreted as Acadian (Marshak and Tabor, 1989) (Fig. 1).

Table 2 lists a series of tectonic events that may have affected Silurian rocks in the northern Appalachian basin. Cross-fold joints formed during the Alleghanian orogeny are a manifestation of S_H oriented N10°–30°W (Engelder and Geiser, 1980). Data for stress conditions during kimberlite dike intrusions in the vicinity of Ithaca, New York (Kay and Foster, 1986), are also inconsistent with those derived from the systematic veins. Homogenization temperatures from the vein material imply that the veins formed under $\geqslant 3$ km of overburden, and therefore are unrelated to fracturing associated with uplift and erosion, such as the Early Cretaceous (120–140 Ma) uplift-cooling event in the northern Appalachian basin (Miller and Duddy,

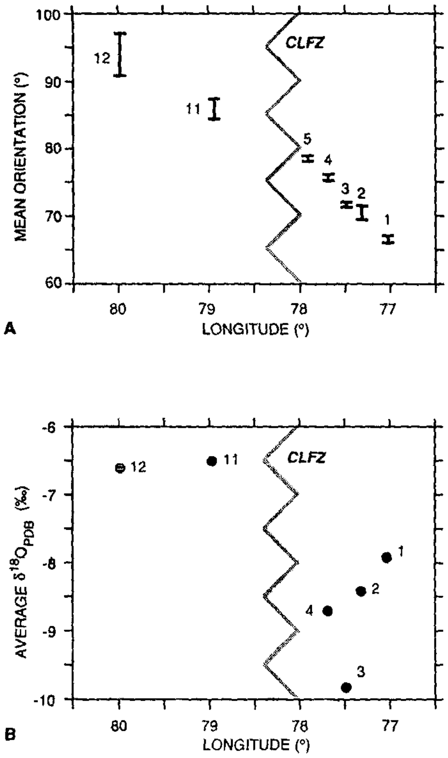

Figure 3. A: Plot of mean vein orientation vs. longitude. Error bars represent 99% confidence interval. Number adjacent to data point indicates site. B: Plot of average $\delta^{18}O_{PDB}$ of calcite vein fill vs. longitude. Number adjacent to data point indicates site. CLFZ = Clarendon-Linden fault zone.

1989) and later neotectonic joint propagation associated with recent glaciation (Gross and Engelder, 1991). Thus, it seems most likely that the systematic veins in the Lockport Group are the result of a geologic event related to the Acadian orogeny of New England and the Hudson Valley.

FLUID CIRCULATION AND THE CLARENDON-LINDEN FAULT ZONE

The presence of systematic veins to the east of the Clarendon-Linden fault zone and their absence to the west at sites 6 to 10 imply that the fault zone is a boundary with distinctly different conditions for vein development on either side. Vein propagation at a depth $\geqslant$3 km is most likely to occur under high fluid pressures. High-pressure fluids did not affect most of the dolostone west of the fault zone, as indicated by the lack of systematic veins to the west. Therefore, the fault zone appears to form a boundary between a province to the east, where crack-driving stresses in the Lockport Group were relatively high, and a province to the west (sites 6–10), where crack-driving stresses were much lower. One interpretation is that the fault zone acted as a drain, venting the fluids and relieving high fluid pressures east of the fault. Evidence for such a drain is found at site 6, which is in the middle of the Clarendon-Linden fault zone and has a fracture distribution unlike that of any other outcrop in the study area (Fig. 2). There, the dominant fracture orientation is north-south, which corresponds to the north-trending fault zone. Such pervasive fracturing could have provided a high permeability conduit for draining fluids circulating from the east. The veins at sites 11 and 12 are presumably related temporally to the veins in the eastern outcrop belt, because their orientation is consistent with a clockwise rotation from east to west. Thus, they appear to have formed within the same regional stress field, though as part of a separate fluid circulation system.

TABLE 1. $\delta^{13}C_{PDB}$ AND $\delta^{18}O_{PDB}$ OF CALCITE FROM VEIN MATERIAL

Site, no.	No. of veins sampled	$\delta^{13}C_{PDB}$ (‰)	Average $\delta^{13}C_{PDB}$ (‰)	$\delta^{18}O_{PDB}$ (‰)	Average $\delta^{18}O_{PDB}$ (‰)
Sodus, 1	1	-9.6	-9.6	-7.9	-7.9
Walworth, 2	3	-14.8, -9.8, -15.5	-13.4	-8.4, -8.4, -8.3	-8.4
Penfield, 3	3	-15.3, -10.4, -15.7	-13.8	-9.4, -10.3, -9.6	-9.8
Gates, 4	3	-7.2, -14.6, -0.8	-7.5	-9.1, -9.4, -7.7	-8.7
Niagara, 11	1	-16.3	-16.3	-6.5	-6.5
Dundas, 12	3	-9.4, -5.6, -14.3	-9.8	-6.6, -7.0, -6.2	-6.6

Note: Analyses have a standard deviation of ~0.2‰.

TABLE 2. POST-SILURIAN TECTONIC STRESS FIELDS AFFECTING WESTERN NEW YORK

Tectonic Event	Age (Ma)	Structure	S_H Orientation	Reference
Neotectonic	Recent	Topographic Linears	N62°E	Gross and Engelder (1991)
Uplift and Cooling	140-120	???	???	Miller and Duddy (1989)
Kimberlite Intrusion	140	Dikes	N10°W	Kay and Foster (1986)
Alleghanian Orogeny	300-250	Cross-fold joints	N10°-30°W	Engelder and Geiser (1980)
Acadian Orogeny	410-360	Biotite Isograd	E-W	Sutter et al. (1985)
		Hudson Valley	E-W	Marshak and Tabor (1989)

The isotopically heavier $\delta^{18}O_{PDB}$ values of samples west of the Clarendon-Linden fault zone (sites 11 and 12) indicate that these samples were precipitated at lower temperatures than the samples east of the fault zone (sites 1–4; assuming a fixed $\delta^{18}O$ value of the circulating fluid), and/or the samples west of the zone were precipitated from fluid with an isotopically heavier composition (assuming the same temperature of precipitation to the west and east of the fault zone). Using the calcite-water isotope fractionation factors from Friedman and O'Neil (1977) and a temperature of 115 °C on both sides of the fault (from the fluid-inclusion analyses), the calcite values west of the fault zone indicate calcite precipitation from a fluid with $\delta^{18}O$ (standard mean ocean water [SMOW]) ~ +8.5‰, whereas eastern samples precipitated from fluids with $\delta^{18}O_{SMOW}$ ~ +5.3‰ to +7.2‰. The isotopically heavy fluid compositions are from either tectonic-metamorphic fluids or a meteoric fluid that has undergone oxygen isotope exchange with rocks (e.g., Salina Group) during deep circulation.

A model of the geologic conditions resulting in the propagation of the systematic vein set in the Lockport Group must accommodate the following observations: (1) the presence of veins east of the Clarendon-Linden fault zone and their absence immediately to the west; (2) the clockwise swing in vein orientation from east to west; (3) homogenization temperatures of fluid-inclusions in calcite vein fill (115 °C); and (4) the significantly lighter calcite $\delta^{18}O_{PDB}$ values east of the fault zone. We propose that the Acadian Catskill delta and New England highlands provided the necessary tectonic and topographic drive for a fluid circulation system within the Lockport Group east of the fault zone. Isopachs of Devonian strata suggest that a thick sedimentary section in central New York extends over the Adirondack Mountains (Isachsen, 1975).

Figure 4 is a schematic diagram of fluid circulation during the Acadian orogeny. Calcite $\delta^{18}O_{PDB}$ values indicate an isotopically heavy fluid, such as tectonic, metamorphic, or highly evolved meteoric fluid. We suspect that high fluid pressure developed as a consequence of a significant hydraulic head to the east and was critical for crack propagation within the Lockport Group. Our model for regional flow suggests that fluids flowed down into the Lockport Group from the east and were trapped beneath the overlying impermeable Salina salt units that pinch out near Syracuse. The salt prevented fluids from circulating upward, and so high fluid pressures developed in the Lockport Group, resulting in vein propagation. The most favorable crack-driving stress conditions within the Lockport rock column existed immediately beneath the contact with the overlying salt, and therefore veins do not extend into the lower unit of the Lockport Group. As the fluids continued circulating westward, they intersected the Clarendon-Linden fault zone and drained to the surface, resulting in lower fluid pressures west of the fault and therefore no vein propagation at sites 6 to 10.

Calcite $\delta^{18}O_{PDB}$ values may be consistent

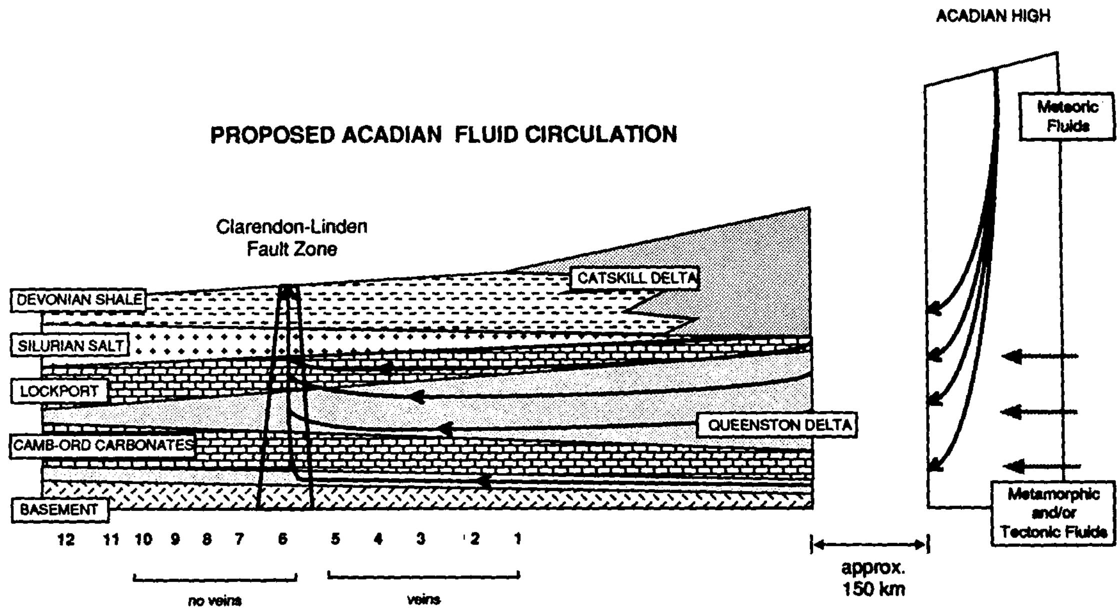

Figure 4. Schematic diagram of proposed fluid circulation during late Paleozoic that may have resulted in propagation of systematic veins in Lockport Group (not drawn to scale).

with a single east-west flow system, the fluids becoming isotopically heavier for longer flow paths, resulting in isotopically heavier calcite $\delta^{18}O_{PDB}$ values to the west. However, the general (though nonsystematic) decrease in calcite $\delta^{18}O_{PDB}$ values from east to west for samples at sites 1–4 (Fig. 3A) suggests that temperatures are also increasing along the flow path, resulting in isotopically lighter calcite $\delta^{18}O_{PDB}$ values farther along the path. If a single flow path did exist for all sites, this would suggest that calcite $\delta^{18}O_{PDB}$ values at sites 11 and 12 should be isotopically lighter than samples at sites 1–4, rather than the observed isotopically heavier values. Thus, the isotope values suggest that separate flow systems existed to the west and to the east of the Clarendon-Linden fault zone.

In summary, the east-northeast-trending systematic vein set found in the Lockport Group provides several individual pieces of evidence that together define a model for Acadian fluid circulation and allow tracking of the Acadian orogeny cratonward from New England.

ACKNOWLEDGMENTS

Supported by Electric Power Research Institute grant RP-2556-24 (Engelder), National Science Foundation grant EAR-90-03554 (Ohmoto), and the New York State Geological Survey Graduate Student Honorarium Program (Gross). We thank H. Ohmoto for use of his stable isotope laboratory at Pennsylvania State University, R. Williams of Dolomite Products, Inc., for logistical arrangements, and R. Fakundiny, D. Fisher, D. Gold, and B. van der Pluijm for helpful reviews.

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Manuscript received April 9, 1992
Revised manuscript received July 16, 1992
Manuscript accepted July 29, 1992