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INSIDE

Evolution of the Sr and C Isotope Composition of Cambrian Oceans

Isabel P. Montañez, *montanez@geology.ucdavis.edu,* ***David A. Osleger,*** *osleger@geology.ucdavis.edu, Department of Geology, University of California, Davis, CA 95616, USA*
Jay L Banner, *banner@mail.utexas.edu,* ***Larry E. Mack,*** *b.sambuco@mail.utexas.edu,* ***MaryLynn Musgrove,*** *mlm@mail.utexas.edu, Department of Geological Sciences, University of Texas, Austin, TX 78712, USA*

ABSTRACT

The recent proliferation of chemostratigraphic studies has clearly documented that systematic fluctuations in the strontium and carbon isotope composition of seawater have occurred throughout Earth history across a range of temporal scales. In particular, significant isotopic variation during key intervals of geologic time has provided unprecedented quantitative constraints on crustal and surficial processes, and enhanced chronostratigraphic resolution for intrabasinal and interbasinal correlations. We present the first set of high-resolution, seawater Sr and C isotope curves for the late Early through early Late Cambrian. These curves are defined in continuous exposures of marine carbonates in the Great Basin and southern Canadian Rockies, and they are used to better constrain primary variations in ocean chemistry during this time period. The Sr curve documents a rapid rate of increase through this period that is comparable to that recorded by the late Cenozoic seawater Sr proxy record of uplift and attendant weathering of the Himalaya-Tibetan Plateau. The Cambrian rise in Sr values is interpreted to record Pan-African–Brasiliano orogenesis, and reaches $^{87}Sr/^{86}Sr$ values that are higher than at any other time in Earth history. Numerous superimposed, smaller-scale oscillations may constrain the timing of individual short-term tectonic events. The C isotope curve for the same time interval reveals several previously unrecognized short-term fluctuations of up to 4‰. A sharp shift in $\delta^{13}C$ values near the Early-Middle Cambrian boundary indicates major paleoceanographic and climatic change associated with a trilobite mass extinction event. Used in concert, this set of high-resolution $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ records provides complementary quantitative constraints for the chronology of Cambrian tectonic, paleoceanographic, paleoecologic, and biogeochemical events.

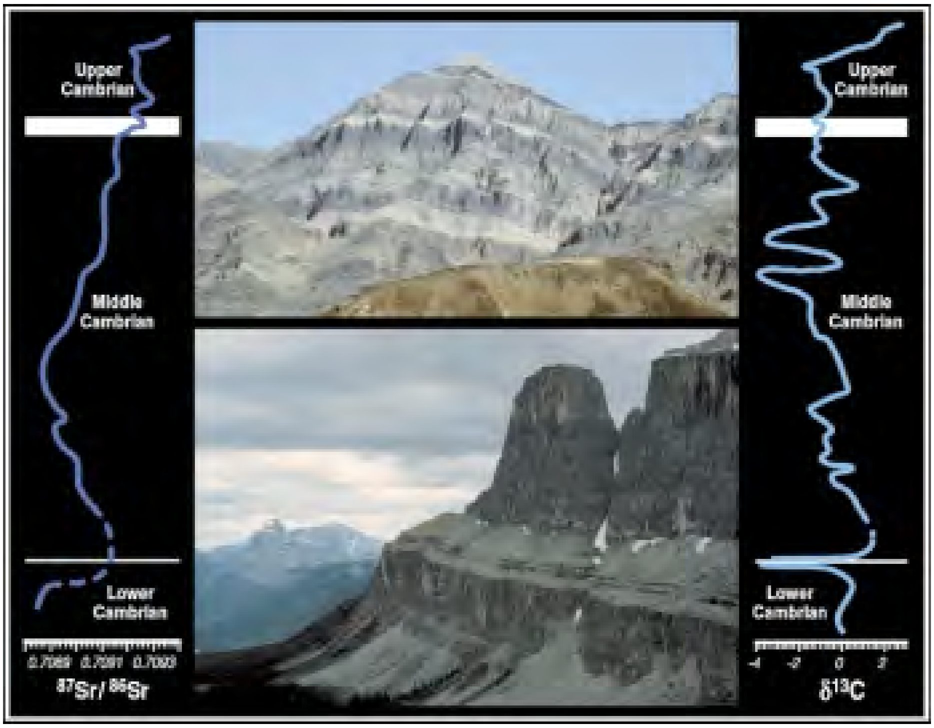

Figure 1. Representative mountain-front exposures of Middle to Upper Cambrian carbonates paired with Sr and C isotope stratigraphic variations through the study interval. Lower photo of Middle Cambrian Mount Whyte, Cathedral, Stephens, and Eldon formations exposed at Castle Mountain, southern Canadian Rockies. Upper photo of Middle to Upper Cambrian Bonanza King, Dunderberg, and Nopah formations exposed at Pyramid Peak, southern Great Basin, United States.

INTRODUCTION

Systematic variations in the Sr ($^{87}Sr/^{86}Sr$) and C ($\delta^{13}C$) isotopic composition of seawater have been documented by numerous chemostratigraphic studies across a range of temporal scales (e.g., Burke et al., 1982; Jacobsen and Kaufman, 1999; Hayes et al., 1999; Veizer et al., 1999). These "secular" isotopic variations are valuable proxies of paleoenvironmental change and paleotectonic events. They also provide valuable means of chronostratigraphic correlation in intervals plagued by a paucity of age-diagnostic biostratigraphic markers. The utility of $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ values in well-preserved carbonate rocks as proxies resides in the processes that they record. Temporal variation in seawater $^{87}Sr/^{86}Sr$ is governed mainly by changes in the balance between Sr fluxes to the ocean from continental weathering and hydrothermal fluid-rock interaction at mid-ocean ridges (Palmer and Edmond, 1989). The $^{87}Sr/^{86}Sr$ composition of the volumetrically smaller seafloor hydrothermal flux is buffered at low values of ~0.703–0.705. Conversely, continental weathering, via riverine and groundwater fluxes, contributes Sr with high $^{87}Sr/^{86}Sr$ values (0.709–0.730) to the ocean. It is primarily the variation in the larger continental flux and its isotopic composition that has affected secular change in seawater

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January 26, 2000

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^{87}Sr/^{86}Sr values. The ^{87}Sr/^{86}Sr values of unaltered marine carbonate minerals directly record seawater ^{87}Sr/^{86}Sr values, given the negligible fractionation of Sr isotopes (Banner and Kaufman, 1994) and the homogeneity of Sr in seawater (DePaolo and Ingram, 1985).

Ocean-scale variation in the δ^{13}C composition of surface seawater on time scales of $>10^5$ yr primarily arises from changes in the long-term throughput of carbon in the ocean and the isotopic fractionation associated with partitioning of carbon into reduced and oxidized reservoirs (Kump, 1991; Kump and Arthur, 1999). These mechanisms are driven by continental weathering, global sedimentation rates, primary productivity, organic carbon burial, and ocean circulation mode, all of which in turn modulate atmospheric $p\mathrm{CO}_2$ and hence climate. Thus, ^{87}Sr/^{86}Sr and δ^{13}C records are highly complementary proxies of surficial and crustal cycling as well as paleoclimate and paleoecologic change.

Seawater ^{87}Sr/^{86}Sr and δ^{13}C records for a number of important intervals of pre-Cretaceous time are of relatively low resolution, thus compromising their utility as paleoenvironmental proxies. The low resolution of these curves primarily reflects significant age uncertainties and the difficulty of obtaining a reliable marine signal due to diagenetic effects. In particular, the existing isotope curves for the late Early through early Late Cambrian need to be significantly refined, given that this was a time of dramatic change in Earth systems. Large-scale continental reorganization associated with the amalgamation of Gondwana (Unrug, 1997) and anomalously fast rotation (up to 90°) and latitudinal drift of continents (>30 cm/yr), driven by an inertial interchange true polar wander event (Kirschvink et al.,

Dialogue

Sara Foland, CEO

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At the Flatirons near Boulder, Colorado.

> "Prudence and good stewardship for the living world dictate that we start to chart our future soon, and in rather specific terms. We may or may not yet have the knowledge or wisdom to make all the right choices, but do we at least have the sense of purpose to begin?"
>
> —E-an Zen, GSA President, 1992–1993, in *The Earth Around Us: Maintaining a Livable Planet*

Stewardship: Finding a Balance

For several months, we have been discussing the values that guide our actions in GSA: science, stewardship, and service. These values are recognized in GSA's strategic plan, which focuses our actions over the next three to five years.

In the past two issues of *GSA Today,* we explored earth scientists' natural role as stewards of Earth. We also discussed our collective stewardship of earth science information, as members of a scientific society engaged in member research, publications, and programs. To expand our dialogue on stewardship, I want to share some thoughts with you now about stewardship for applied geologists. I feel particularly well qualified to do so, after spending nearly 20 years in the petroleum industry and in oil and gas exploration.

Who and What Are Applied Geologists? And Why Should We Talk About This?

The term "applied geologist" refers to those who directly apply their geoscience expertise in business and industry. Over one-third (36%) of GSA members fit this description; they work in petroleum geology, mineral or economic geology, environmental geoscience, and engineering. Many are employed by government and corporations, while others work as independent consultants.

It's important for GSA as a society to encourage dialogue and improve our overall understanding of the world of applied geology, because of the changing mix of employment opportunities we see in our field. The number of jobs in academia is shrinking, while demand for geoscience expertise in government and industry is increasing.

It's been my experience that applied geologists care about the environment, quality of life, and sustainability. The question is, how do we balance environmental awareness, resource demand and exploitation, and the economics of doing business in a commodity-based industry? From my perspective, it's all about balancing one's personal values on stewardship with those of the company and/or industry in which one works.

Pursuing a Career in Applied Geology

When interviewing for applied geoscience jobs, one is confronted with opportunities that may appear to be in conflict with our role as stewards of Earth. Here are suggestions for members who find themselves in this situation.

In order to make a values-based decision on a job offer, you must have credible information about the company. If possible, seek out information during the interview concerning how the company acted when faced with environmental challenges. Review the corporate record on past actions; this is a key to how the company may behave in the future.

Check to see if internship opportunities exist. Three- to six-month internships are a great way to get an insider's perspective on a company. You can see the corporate values in action and validate alignment with your personal values. You can also investigate how business decisions are made—who is involved and who is accountable for the results. In 17 years in the petroleum industry, my personal values never clashed with company action, as I felt I had a voice in setting and defining the corporate values.

GSA as a Forum for Debate

GSA holds a unique position and provides a focal point for members to discuss stewardship in all its aspects. We allow seemingly opposed groups—everyone from energy and mineral resource managers to environmental advocates—to meet in an open forum and explore tough issues without censorship. We intend to do this in an environment of mutual respect and joint problem solving, de-politicizing the term "stewardship."

1997), characterize this time interval. This tectonic forcing likely generated major changes in oceanic circulation, geochemistry, and primary productivity, as well as enhanced rates of continental weathering and organic carbon burial. Thus, accurate isotope curves are imperative for interpreting such significant environmental change.

To that end, we present detailed $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ curves derived from continuous exposures of marine carbonate strata in the Great Basin and southern Canadian Rockies that significantly refine the resolution of existing Cambrian trends (Fig. 1). These newly defined seawater curves document previously unrecognized fluctuations, revealing a more dynamic evolution of Cambrian ocean chemistry than defined to date. Used in concert, these high-resolution $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ records offer an unprecedented level of chronostratigraphic resolution for intrabasinal and interbasinal correlation and refined paleogeographic reconstructions, as well as provide quantitative geochemical constraints on paleoenvironment and paleoclimate change during the Cambrian.

CONSTRUCTION OF SEAWATER ISOTOPE CURVES

Cambrian carbonates in the Great Basin and southern Canadian Rockies have a complex burial history and hence potential for postdepositional chemical alteration. Thus, all samples in this study were petrographically and geochemically evaluated using previously defined criteria (Banner and Kaufman, 1994; Montañez et al., 1996) believed to be most effective in identifying components with the highest potential for yielding primary marine values. All samples were pretreated using ultrapure ammonium acetate, a cation exchange solution that preferentially removes readily leachable Sr from the surfaces, lattice, or fluid inclusions of Rb-rich clays and oxides, which are commonly associated in trace amounts with marine carbonates (description of methods available from Montañez et al. on request). Penecontemporaneous marine cements in algal bioherms and grainstones, and secondarily, very finely crystalline micrites were found to yield a best estimate of seawater $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ values.

Relative age assignment of data in this study is based on the stratigraphic position of samples relative to one another within thick continuous sections. Constrained by all available biostratigraphy, samples were merged into a composite stratigraphic section constructed from ten sections in the southern Canadian Rockies and five sections in the Great Basin. The composite section was proportioned along a linear time axis by stratigraphic position

Cambrian Oceans *continued on p. 4*

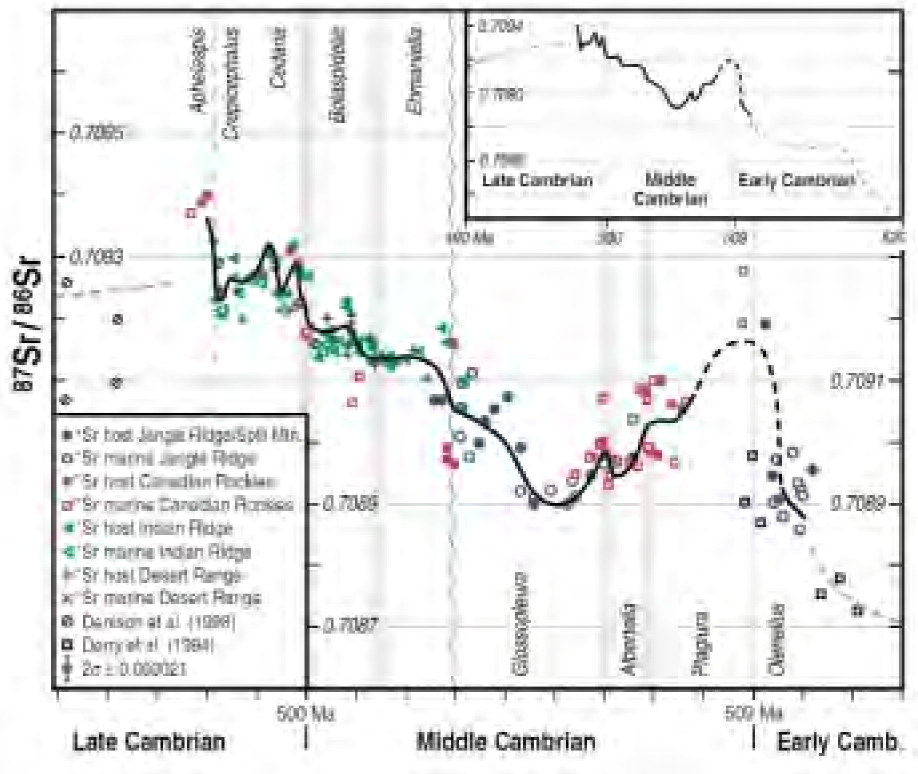

Figure 2. Temporal variations in $^{87}Sr/^{86}Sr$ values of samples determined to provide best estimate of primary marine isotope composition. Selected published Cambrian data for comparison. To facilitate comparison of $^{87}Sr/^{86}Sr$ results with published data, all $^{87}Sr/^{86}Sr$ values have been normalized to $^{87}Sr/^{86}Sr$ value of 0.710250 for NBS-SRM 987. Analysis of diagenetic calcite cements indicates that $^{87}Sr/^{86}Sr$ compositions of postdepositional waters ranged from less to more radiogenic than estimates of primary marine $^{87}Sr/^{86}Sr$ values and showed no systematic trends through the study interval. We present a five-point running average (black curve) through the data to show predominant isotopic trends. Inset shows best estimate of seawater secular Sr isotope curve for Cambrian Period (<520 Ma) based on compilation of data from this study (bold curve) and data presented in Derry et al. (1994) and Denison et al. (1998). Shaded bands separating trilobite biozones reflect uncertainty in absolute stratigraphic position of each biozonal transition. Representative analytical uncertainty for all $^{87}Sr/^{86}Sr$ values is based on replicate analyses of samples (avg. 2 $\sigma_m = 21 \times 10^{-6}$, $n = 19$) and the NBS-SRM 987 standard ($^{87}Sr/^{86}Sr$ = 0.710260; 2 $\sigma = 18 \times 10^{-6}$, $n = 94$). Strontium isotope analyses were conducted at University of Texas at Austin following procedures in Banner and Kaufman (1994). Procedural blanks for Sr (5 to 26 pg) were negligible for samples analyzed.

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of the chronometrically defined Lower to Middle Cambrian (509 Ma) and Middle to Upper Cambrian (500 Ma) boundaries (Bowring and Erwin, 1998; Davidek et al., 1998).

SECULAR Sr ISOTOPE CURVE

The temporal variation in the Sr isotope composition of late Early through early Late Cambrian oceans is defined by the $^{87}Sr/^{86}Sr$ values of best-preserved calcite marine components plotted on the most recent Cambrian time scale (Fig. 2). Our interpretation of the isotope trend as "secular" (i.e., recording temporal variation in the isotopic composition of the global oceans) is supported by the consistency of isotope trends between the two passive-margin–setting study areas separated by ~1600 km. The temporal resolution of the curves is optimized by the extraordinary stratigraphic continuity of the sampled sections (hundreds to thousands of meters; Fig. 1). Hence, this is the first continental-scale correlation of such temporally extensive and continuous Paleozoic Sr isotope trends and, as such, provides the most rigorous assessment of the global nature of the seawater Sr isotope curve. Further confidence for the veracity of the curve is provided by multiple sets of contemporaneous samples that have overlapping $^{87}Sr/^{86}Sr$ values (Fig. 2).

Seawater $^{87}Sr/^{86}Sr$ values through the late Early to early Late Cambrian define a non-monotonic rise, the values varying between a minimum of ~0.7089 and a maximum of ~0.7094 (Fig. 2). In this study, minimum $^{87}Sr/^{86}Sr$ values (0.70886–0.70895) characterize the latest Early Cambrian, and overlap with $^{87}Sr/^{86}Sr$ values previously defined from latest Early Cambrian carbonates of the Siberian platform (Derry et al., 1994). Seawater $^{87}Sr/^{86}Sr$ values may have risen rapidly to peak values of 0.70918–0.70927 coincident with the Early-Middle Cambrian transition. This short-term rise is defined tenuously, given the paucity of reliable samples available in this interval. This proposed rise in $^{87}Sr/^{86}Sr$ values warrants further evaluation, given that elevated $^{87}Sr/^{86}Sr$ values define this interval in several sections throughout the Cordilleran margin (this study; E. Fermann, 1999, personal commun.).

In the early Middle Cambrian, $^{87}Sr/^{86}Sr$ values decrease to a low point of ~0.7089 (mid-*Glossopleura* biozone), and then progressively increase through the latter half of the Middle Cambrian to a maximum of ~0.70925–0.70930 in the Late Cambrian *Cedaria* biozone. These maximum $^{87}Sr/^{86}Sr$ values are followed by a rapid decline to ~0.70920 before rising again to the highest recorded seawater values (ca. 0.70940) around 498 Ma. Notably, this maximum value is 0.00023 higher than that of present-day seawater ($^{87}Sr/^{86}Sr$ = 0.709174, adjusted to a NBS-SRM 987 value of 0.710250; DePaolo and Ingram, 1985).

TECTONIC AND CLIMATIC IMPLICATIONS OF CAMBRIAN SEAWATER $^{87}Sr/^{86}Sr$

The latest Early to early Late Cambrian seawater Sr isotope curve presented here is the continuation of a previously defined long-term rise in seawater $^{87}Sr/^{86}Sr$ values that began around 0.7063 in the late Neoproterozoic and continued through the Early Cambrian (Kaufman et al., 1993, 1996; Derry et al., 1994; Jacobsen and Kaufman, 1999). This rise (rate of 0.00002/m.y.) is interpreted to record uplift and attendant increased weathering associated with the Pan-African–Brasiliano orogeny (Edmond, 1992; Richter et al., 1992; Kaufman et al., 1993; Derry et al., 1994). The overall rate of rise in the newly defined part of the Cambrian seawater $^{87}Sr/^{86}Sr$ curve (0.00004/m.y.; Fig. 2) exceeds that of the preceding interval and is comparable to the Cenozoic rate over the past 23 m.y. (Fig. 3). The rapid rise in seawater $^{87}Sr/^{86}Sr$ values over the late Cenozoic is interpreted to record the cumulative effects of uplift of the Himalaya-Tibetan Plateau on erosion rate, climate, and continental weathering (Hodell et al., 1990; Richter et al., 1992). By analogy, the rapid Cambrian trend suggests that tectonic control on riverine Sr flux and its isotopic composition was the dominant driving mechanism. Increased erosion and silicate weathering associated with the Himalayan-scale, Pan-African–Brasiliano orogeny would have significantly increased the flux of radiogenic ^{87}Sr to the oceans.

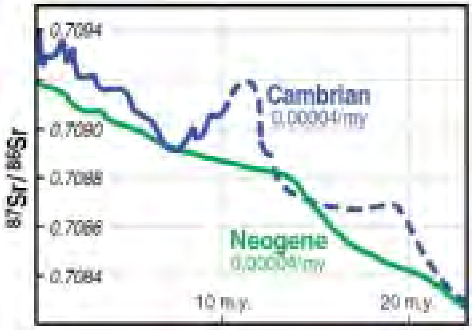

Figure 3. Comparison of seawater Sr isotope curves for latest Early through early Late Cambrian time with the late Cenozoic Sr curve (DePaolo and Ingram, 1985). Long-term rates of rise through ~23 m.y. period are comparable, but Cambrian rise is characterized by superimposed shorter term $^{87}Sr/^{86}Sr$ fluctuations, and reaches peak $^{87}Sr/^{86}Sr$ values that are unmatched in Phanerozoic time.

Our quantitative modeling suggests that an increase in the $^{87}Sr/^{86}Sr$ composition, rather than the magnitude of the riverine Sr flux, would have been required to maintain the estimated rate of rise and to attain the very high $^{87}Sr/^{86}Sr$ values observed for the early Late Cambrian. The Pan-African–Brasiliano orogeny, of late Neoproterozoic through Cambrian age, resulted in convergence and metamorphism of previously rifted Archean-Mesoproterozoic craton margins (Unrug, 1997). Uplift would have resulted in deep exhumation and erosion of these strongly metamorphosed mobile belts. The Sr released during weathering of these highly metamorphosed cratonal rocks would have been significantly more radiogenic than Sr released by weathering of average global continental rocks (cf. Edmond, 1992; Harris, 1995), and could have rapidly increased the $^{87}Sr/^{86}Sr$ composition of the riverine flux.

The evolutionary trend in Cambrian seawater $^{87}Sr/^{86}Sr$ values differs from the late Cenozoic in that the Cambrian curve exhibits considerable variability (Fig. 3). It is possible that recognizable Sr isotope fluctuations superimposed on the longer-term trend may provide constraints for the timing of discrete tectonic phases of the Pan-African–Brasiliano orogeny, for which considerable uncertainty exists. A tentatively defined short period of increased rate of rise (≥0.0002 in ~1 m.y.) across the Early-Middle Cambrian transition is followed by a progressive fall in $^{87}Sr/^{86}Sr$ values over ~4 m.y. of early Middle Cambrian time. This decrease in seawater $^{87}Sr/^{86}Sr$ values is possibly coincident with an episode of widespread rifting along the Weddell Sea–South African sector of the paleo-Pacific margin of Gondwana and the western margin of Laurentia (Grunow et al., 1996; Barnett et al., 1997; Curtis et al., 1999). Continental rifting and associated mafic to alkaline magmatism began during the latest Early Cambrian and extended into the Middle Cambrian. During this period, we infer a decrease in the $^{87}Sr/^{86}Sr$ composition of the continental Sr flux to the ocean, due to weathering of these young mantle-derived mafic rocks, coupled with an increase in the hydrothermal Sr flux, due to seawater interaction with MORB-like basalts at the subaqueous rift axes. Both processes would have driven seawater $^{87}Sr/^{86}Sr$ values downward.

The subsequent rapid rise during the latter half of the Middle Cambrian to peak values in the early Late Cambrian is interpreted to record the large magnitude of coeval orogenic events in Antarctica and Australia (Goodge et al., 1993; Curtis and Storey, 1996; Encarnacion and Grunow, 1996). If these proposed relationships can be further documented, then the shift from low seawater $^{87}Sr/^{86}Sr$ values to increasing values during the middle Middle Cambrian could place constraints on the timing of changing tectonic styles along the margins of Gondwana. Finally, the relatively short time span of the Cambrian radiogenic extreme (~497–500 Ma) may constrain the timing of the terminal phase of Pan-African orogenesis to the latest Cambrian (cf. Encarnacion and Grunow, 1996; Barnett et al., 1997).

INTEGRATION OF Sr AND C ISOTOPE CURVES

The $\delta^{13}C$ values of least-altered carbonate components define the first high-resolution, seawater secular C isotope curve for Middle Cambrian time (Fig. 4). Seawater $\delta^{13}C$ values through this time interval exhibit high-frequency fluctuations (shifts of up to >4‰) around a mean value of −0.5‰. Although the precise form of the long-term $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ trends differ, both curves define a broadly similar progressive fall in values during the early Middle Cambrian that reach minima at different times in the middle Middle Cambrian (*Glossopleura*) (Fig. 4). A rapid increase in $\delta^{13}C$ values at the youngest part of the curve (*Crepicephalus-Aphelaspis* biozones) marks the initiation of a globally recognized positive C isotope excursion (inset, Fig. 4) (Brasier, 1992; Saltzman et al., 1998). This rapid rise in seawater $\delta^{13}C$ values is matched by a coincident rise in $^{87}Sr/^{86}Sr$ values.

Our secular C isotope curve defines a previously undocumented, rapid (~100 k.y.), large-magnitude shift (≥4‰) to negative $\delta^{13}C$ values in the terminal Early

Cambrian Oceans *continued on p. 6*

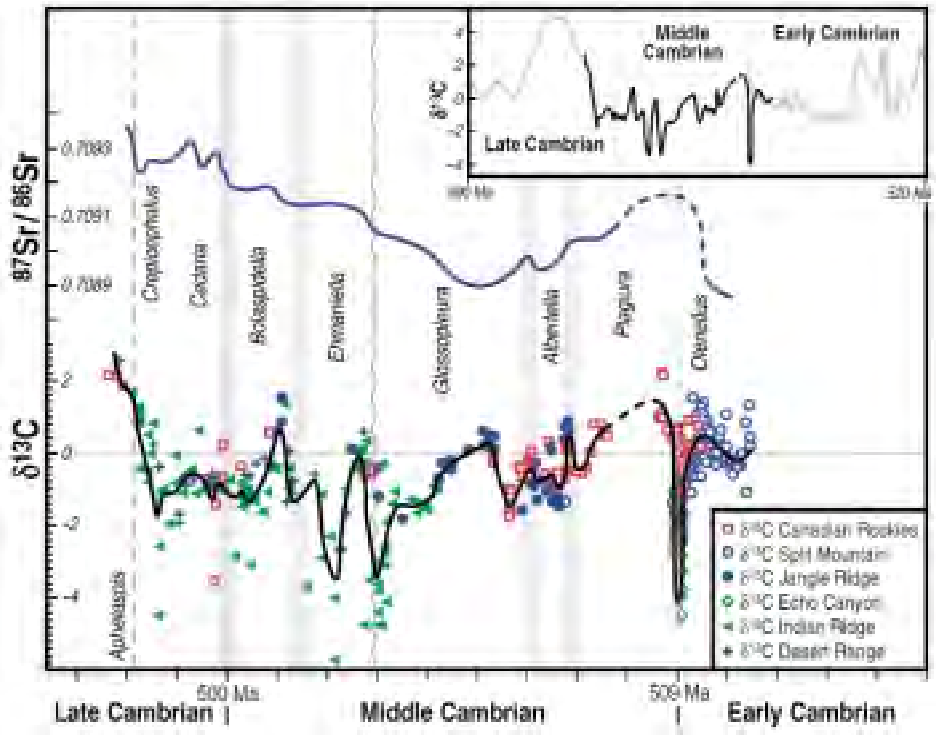

Figure 4. Secular variation in $\delta^{13}C$ values of samples used for Sr isotope analysis, as well as additional samples, that passed our petrographic and geochemical screening criteria for retaining primary marine $\delta^{13}C$ values but did not pass the criteria for Sr isotope analysis. Black curve is a five-point running average of $\delta^{13}C$ values; blue curve is five-point running average of $^{87}Sr/^{86}Sr$ values. Inset curve shows best estimate of seawater secular C isotope curve for Cambrian Period based on compilation of data from this study (bold) and data presented in Brasier and Sukhov (1998). Carbon isotope analyses were conducted at University of Southern California, University of Texas at Austin, and University of California, Davis. External precision (1 σ) for $\delta^{13}C$ was ±0.05‰.

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Cambrian. This negative C isotope excursion begins just prior to the oldest known mass extinction of trilobites and other less common community elements recorded at the Lower-Middle Cambrian boundary (Palmer, 1998). It is possible that the negative C isotope excursion is of even higher magnitude than currently defined, given that the Lower-Middle Cambrian boundary in our sampled sections is underlain by several meters of shale with few intercalated carbonates. This interval is being further evaluated by C isotope analyses of organic matter in shales and carbonates. The temporal relationship of the negative C isotope excursion to the tentatively defined rapid rise in seawater $^{87}Sr/^{86}Sr$ values during the terminal Early Cambrian cannot be clearly resolved, given that the C isotope trend was defined, in part, by marine components that were not suitable for Sr isotope analysis.

In the Great Basin sections (Split Mountain and Echo Canyon) where the C isotope anomaly is best defined, the Early to Middle Cambrian transition is considered relatively conformable, on the basis of preservation of all trilobite zones and lack of evidence of erosion. Erosion of time-equivalent successions worldwide during an early Middle Cambrian regression explains why this negative C isotope excursion has not been previously recognized despite it being among the largest magnitude Phanerozoic excursions. This isotope excursion is recorded in the Great Basin by the topmost few meters of thick (60–250 m) carbonate successions and sharply overlying, highly condensed shales with thin intercalated carbonate beds that extend across the Early to Middle Cambrian boundary. The carbonate-shale stratigraphic relationship records a rapid rise in relative sea level, which was previously recognized in other Laurentian and Siberian sections (Brasier and Sukhov, 1998; Landing and Bartowski, 1996). Evidence of prolonged environmental stress during the negative C isotope excursion is indicated by the lack of bioturbation in shales and the occurrence of carbonate shell beds that are interpreted to record episodic deposition of trilobite death assemblages (L. and M. McCollum, personal commun., 2000).

The negative C isotope excursion indicates that major paleoceanographic changes, and probably climatic changes, preceded the mass extinction at the end of the Early Cambrian. The negative C isotope excursion is interpreted as recording (1) the introduction of ^{13}C-depleted, anoxic waters onto shallow-water carbonate platforms during the latest Early Cambrian transgression, and (2) the associated decrease in organic C burial due to major biomass reduction (cf. Wilde and Berry, 1984; Kajiwara et al., 1994). An anoxic water column below the surface mixed layer may have developed in Early Cambrian oceans during the transgression, accompanied by sluggish circulation and strong stratification. These oceanic conditions would be favored by the low-latitude continentality and depressed meridional temperature gradients that likely characterized Early Cambrian greenhouse time (Railsback et al., 1990). In order to sustain the negative isotope excursion and prolong exposure of shallow-marine organisms to environmental stress, transgression may have occurred in a pattern of stepwise onlap, thus episodically introducing pulses of toxic waters from the anoxic layer onto normally ventilated parts of the platforms (cf. Wilde and Berry, 1984).

Carbonate $\delta^{13}C$ values at the peak of the negative isotope excursion (<-4‰) suggest that the ocean's isotopic composition ultimately approached that of the weathering input to the oceans ($\delta^{13}C$ of ~–5‰; Kump, 1991). This proposed increased influence of the riverine flux on the ocean's isotopic composition may reflect greatly reduced primary productivity and organic C burial rates in response to building environmental stress prior to the mass extinction. The subsequent shift to more positive $\delta^{13}C$ values in the earliest Middle Cambrian likely records the effects of (1) contraction of the oxygen-minimum zone during the subsequent early Middle Cambrian sea-level fall and attendant enhanced oceanic circulation, and (2) recovery of surface water productivity levels after environmental conditions improved sufficiently.

Superimposed on the long-term C and Sr trends are other short-term (±1 m.y.) fluctuations that are interpreted to record high-frequency changes in seawater $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values, given that they are defined in several sections throughout the Cordilleran passive margin (Fig. 4). Some of the short-term $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ fluctuations (e.g., *Bolaspidella* and *Cedaria* biozones) exhibit similar but out-of-phase trends. The short-term increases in seawater $^{87}Sr/^{86}Sr$ values during this interval could reflect the influence of increased continental flux to the ocean. In turn, the associated short-term increases in $\delta^{13}C$ values may record increased oceanic nutrient levels, primary productivity, and organic C burial driven by increased continental flux and associated oceanic sedimentation. Conversely, periods of dampened surface water fluxes to the ocean and lowered global oceanic sedimentation rates could result in decreased seawater $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values. The mechanism linking these processes could have been short-term Cambrian sea-level oscillations (Montañez et al., 1996) or short-lived tectonic events and their effect on paleoceanographic conditions and organic carbon burial.

SUMMARY

The high-resolution Sr and C isotope curves presented in this paper significantly refine our understanding of the isotopic evolution of Cambrian seawater. These isotope curves document previously unrecognized fluctuations that strongly suggest periods of significant perturbation to the global Sr and C cycles during the late Early through early Late Cambrian. We suggest that future studies of Cambrian successions focus on certain biostratigraphically constrained intervals in order to (1) better define these short-term events in other basins as a test of their validity, (2) test the proposed relationships between observed changes in seawater $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ values and crustal and surficial processes, and (3) refine the structure of less well-defined portions of the curves. Future radiometric studies are likely to elucidate the timing of discrete tectonic phases and the temporal relationships between these events and variations in seawater $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ values. In turn, the new Sr and C isotope curves may clarify the mechanistic links between tectonic events, oceanic processes, and paleoclimatic conditions, and allow for determination of their rates of change.

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NAS-NRC Committee Seeks Advice on International Geoscience Projects

Revitalization of the U.S. National Committee on Geological Sciences (USNC/GS) offers opportunities to raise the profile of geoscience internationally. Committee members note that because scientific communities are increasingly global, not national, more U.S. geoscientists are working on joint projects with foreign colleagues. These interactions are especially vital in geoscience, which requires work across international borders.

USNC/GS members recognize that many avenues already exist for international cooperation in the earth sciences, including the International Union of Geological Sciences (IUGS). However, other sciences, such as biology, astronomy, and physics, have gained more recognition than has geoscience for organized international ventures, not only with the general public but also with policymakers at home and abroad.

WHERE ARE THE OPPORTUNITIES?

The USNC/GS mission statement calls for the committee to advise the president of the National Academy of Sciences (NAS) on issues related to both the U.S. and international geoscience communities. The committee, working under the aegis of the NAS–National Research Council, will seek advice from the U.S. geoscience community, including those in industry, academia, and government. The committee needs to know of opportunities for U.S. geoscientists in the international geoscience community. Ensuring participation and representation in the International Union of Geological Sciences (IUGS) and its affiliated organizations, as well as the International Geological Congress, are priorities.

PEOPLE TO CONTACT

The USNC/GS includes scientists from government, industry, and universities; many of them are GSA members. Current committee members are Robin Brett, Farouk El-Baz, Mark Cloos, Ian Dalziel, Barbara John, Suzanne Kay, Patrick Leahy, Eldridge Moores, Richard Stegemeir, Larry Woodfork, and Peter Wyllie. The committee invites all geoscientists to participate in identifying opportunities for international efforts. Ideas that the committee should consider and requests for further information can be directed through Scott Spaulding, National Academy of Sciences staff member, at sspauldi@nas.edu. ■

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