Biostratigraphic and chemostratigraphic correlation of Neoproterozoic sedimentary successions: Upper Tindir Group, northwestern Canada, as a test case

Alan J. Kaufman, Andrew H. Knoll
Botanical Museum, Harvard University, 26 Oxford Street, Cambridge, Massachusetts 02138
Stanley M. Awramik
Department of Geological Sciences, Preston Cloud Research Laboratory
University of California, Santa Barbara, California 93106

ABSTRACT

Recent advances in Proterozoic micropaleontology and sedimentary isotope geochemistry suggest that improved interbasinal correlation of Neoproterozoic (1000–540 Ma) successions is possible. Because widely varying interpretations of its age have been suggested and no reliable radiometric dates or paleomagnetic data are available, the upper Tindir Group of northwestern Canada provides an opportunity to test this hypothesis. The age of these strata is of paleontological importance because silicified carbonates near the top of the group contain disc-shaped-scale microfossils that may provide insights into the early evolution of biomineralization. A reinterpretation of upper Tindir microfossil assemblages suggests a late Riphean age. Although diagenesis and contact metamorphism have altered the isotopic compositions of some carbonates, least altered samples indicate that $\delta^{13}C$ of contemporaneous seawater was at least +4.7‰, typical of Neoproterozoic, but not Cambrian, carbonates. Strontium isotopic compositions of the least altered samples yield values of ~0.7065, which can be uniquely correlated with late Riphean seawater. Together, micropaleontology and the isotopic tracers of C and Sr constrain the upper Tindir carbonates and their unique fossils to be late Riphean, likely between 620 and 780 Ma.

INTRODUCTION

Our ability to interpret Earth's tectonic, biological, or environmental history depends fundamentally on stratigraphic correlation. Fossils (increasingly supplemented by paleomagnetic and chemostratigraphic data) provide an accurate and reliable means of subdividing and correlating Phanerozoic sedimentary successions. In contrast, the interbasinal correlation of Proterozoic sedimentary rocks has proven difficult because of a general lack of megascopic fossils and our limited ability to date sediments of this antiquity directly. Recent advances in Proterozoic micropaleontology and sedimentary geochemistry suggest that improved interbasinal correlation is possible for at least Neoproterozoic (1000–540 Ma) successions. During this interval, planktonic protists diversified markedly (Vidal and Knoll, 1983). This radiation included large, acanthomorphic acritarchs whose morphological complexity, broad geographical distribution, and apparently limited stratigraphic ranges make them promising candidates for biostratigraphic correlation (e.g., Knoll and Butterfield, 1989). Proliferating data on secular variations in the C- and Sr-isotopic compositions of Neoproterozoic carbonates suggest further tools for interbasinal correlation (e.g., Knoll et al., 1986; Lambert et al., 1987; Aharon et al., 1987; Derry et al., 1989; Kaufman et al., 1991; Kirschvink et al., 1991; Asmerom et al., 1991).

It is one thing to discuss potential, however, and another to demonstrate utility. To realize the promise of Neoproterozoic biostratigraphy and chemostratigraphy, we must be able to use fossils and isotopes to solve geological problems. The upper Tindir Group provides a good test case. Widely varying interpretations of its age exist in the literature. Proper age determination is paleontologically significant because silicified carbonates near the top of the group contain unique disc-shaped-scale microfossils that may provide insights into the early evolution of biomineralization (Allison and Hilgert, 1986).

LITHOSTRATIGRAPHY AND AGE CONSTRAINTS

The Tindir Group is a succession of sedimentary and volcanic rocks exposed in east-central Alaska and the adjacent Yukon Territory. Following earlier authors (Cairnes, 1914; Mertie, 1930, 1933; Brabb and Churkin, 1969), Young (1982) recognized distinctive lower and upper divisions. The upper Tindir Group is up to 2000 m thick and has been subdivided informally into five formations (units 1–5) consisting, from base to top, of (1) mafic pillow lava and volcaniclastic rock, (2) purple mudstone and diamictite, (3) diamictite with local development of iron-formation, (4) shale and turbidite, and (5) basinal shale, siliciclastic turbidite, and carbonate. The upper part of unit 5 contains the strata of principal interest here—gray to dark gray, cherty, thin-bedded, (in part) microbial-laminated limestone with a pronounced fetid odor, along with black shale and minor sandstone (Allison and Awramik, 1989).

Young (1982) proposed broad lithostratigraphic correlation of upper Tindir strata with the Neoproterozoic succession of the Mackenzie Mountains, some 500 km to the east. Upper Tindir units 1–3 were correlated with the lithologically similar Rapitan Group, known on radiometric evidence to be <778 Ma but older than sequences containing Ediacaran fossils (Armstrong et al., 1982; Hofmann et al., 1990). Upper Tindir unit 4 was likened to the Twitya Formation, and the carbonates of unit 5 were correlated with the Keele Formation. Keele strata lie beneath Mackenzie Mountain units containing diverse Ediacaran metazoans (Hofmann et al., 1990); Aitken's (1991) description of a tillite that overlies the Keele suggests that the limestone is pre-Varanger (latest Riphean) in age. Thus, if Young's correlation is correct, unit 5 carbonates of the upper Tindir Group should be older than the tillites that define the base of the Vendian system (see Fig. 3 caption for note on Neoproterozoic ages).

In some individual sections the contact between upper Tindir carbonates and overlying Cambrian strata appears conformable, but Young (1982) concurred with earlier workers (Brabb and Churkin, 1969) that a major regional unconformity separates the two successions. In contrast, Allison and Awramik (1989) suggested that, at Tindir Creek, sedimentation is continuous between the upper Tindir Group and the overlying Funnel Creek Limestone, but they disagreed on the age of unit 5. Allison favored an Early Cambrian age, on the basis of her interpretation of (1) the apparent stratigraphic continuity between unit 5 and the Funnel Creek, and (2) acicular crystals in unit 5 carbonates interpreted as sponge spicules. Awramik argued that there is no compelling paleontologic evidence for the precise age of the upper Tindir Group. Noting the similarity of unit 5 microfossils to Neoproterozoic assemblages elsewhere, he favored a Precambrian age.

TABLE 1. C AND O ISOTOPE DATA AND ELEMENTAL RATIOS FROM THE TINDIR GROUP, CANADA

Sample	Depth (m)	Lithology	$\delta^{13}C_{WR}$	$\delta^{18}O_{WR}$	$\delta^{13}C_{MS}$	$\delta^{18}O_{MS}$	$\delta^{13}C_{org}$	C (mg/g)	Mn/Sr	Mg/Ca
			‰, PDB							
Funnel Creek										
1 7-7-79	384.5	light gray dolostone	-2.26	-2.63	-2.17	-1.41	-24.14	n.d.	3.043	0.433
MM 80 107	n.a.	light gray dolostone	n.d.	n.d.	1.22	-1.12	n.d.	n.d.	8.727	0.574
Unit 5										
2 7-7-79	383.5	medium-dark gray limestone	-1.39	-10.48	-1.53	-10.67	-24.80	2.20	1.267	0.005
3 7-7-79	380.2	medium-dark gray limestone	3.66	-5.48	3.47	-6.29	-27.38	1.41	0.441	0.014
4 7-7-79	377.9	light gray limestone	4.64	-4.83	3.44	-2.91	-26.41	0.44	1.140	0.008
5 7-7-79	376.5	medium gray limestone	4.63	-4.35	4.67	-4.20	-25.10	0.13	0.934	0.009
7 7-7-79	374.7	light gray limestone	-4.22	-12.63	-4.74	-13.70	-23.04	0.17	3.998	0.013
8 7-7-79	373.9	light gray limestone	-5.67	-12.79	-4.87	-10.69	-23.73	n.d.	7.022	0.074
6b 7-7-79	373.0	light gray dolostone	-6.53	-13.20	-5.52	-11.44	-24.19	n.d.	10.244	0.418
9 7-7-79	370.8	medium-dark gray limestone	1.76	-7.37	-0.66	-9.07	-25.62	1.71	1.830	0.006
5 7-22-79	367.4	medium-dark gray limestone	1.10	-8.49	1.03	-8.22	-25.84	n.d.	2.614	0.004
2 7-22-79	365.2	medium gray limestone	2.65	-7.38	n.d.	n.d.	-22.41	0.15	0.753	0.004
2.2 7-8-79	347.8	medium gray limestone	2.58	-7.39	2.89	-7.49	-20.92	5.33	1.535	0.003
2.4 7-8-79	347.4	medium gray limestone	2.49	-7.77	1.93	-3.86	-21.76	0.63	1.376	0.002
1 7-6-79	n.a.	light gray limestone	-3.00	-8.66	-3.89	-9.50	-28.15	1.71	4.054	0.000
2 7-6-79	n.a.	gray limestone	-1.89	-7.13	-2.81	-7.41	-26.63	0.40	2.697	0.004
2b 7-6-79	n.a.	gray limestone	-2.67	-7.43	-2.25	-6.66	-26.63	0.61	3.679	0.003
3 7-6-79	n.a.	gray limestone	2.29	-6.61	2.35	-6.33	-25.21	n.d.	2.201	0.003
3a 7-6-79	n.a.	buff limestone	1.08	-5.23	1.90	-4.08	-25.51	1.60	1.799	0.002
3b 7-6-79	n.a.	buff limestone	1.53	-8.66	1.85	-8.57	-25.16	2.22	1.108	0.001

Note: n.a. = not available, n.d. = not determined.

At present, there are neither reliable radiometric dates nor paleomagnetic data that can help resolve the age of this unit. Thus, the stratigraphic problem is clear. Can microfossils and isotopic geochemistry provide an unambiguous solution?

GEOCHEMICAL METHODS

Samples for this study were collected by Awramik in 1979 and by M. S. McMenamin in 1980. The 1979 samples (see Table 1) cannot be correlated with the main suite of stratigraphic samples and may have been affected by contact metamorphism associated with the intrusion of a nearby dike. Twenty samples were chosen for elemental and isotopic analysis. A part of each was fragmented, etched, and ground for whole-rock analysis. A second part was cut to expose two mirror-image faces from which a polished thin and thick section were prepared for petrographic analysis, and for cathodoluminescence (CL) examination and detailed microsampling, respectively. Procedures for the determination of elemental and isotopic compositions are described in Kaufman et al. (1991) and Derry et al. (1992).

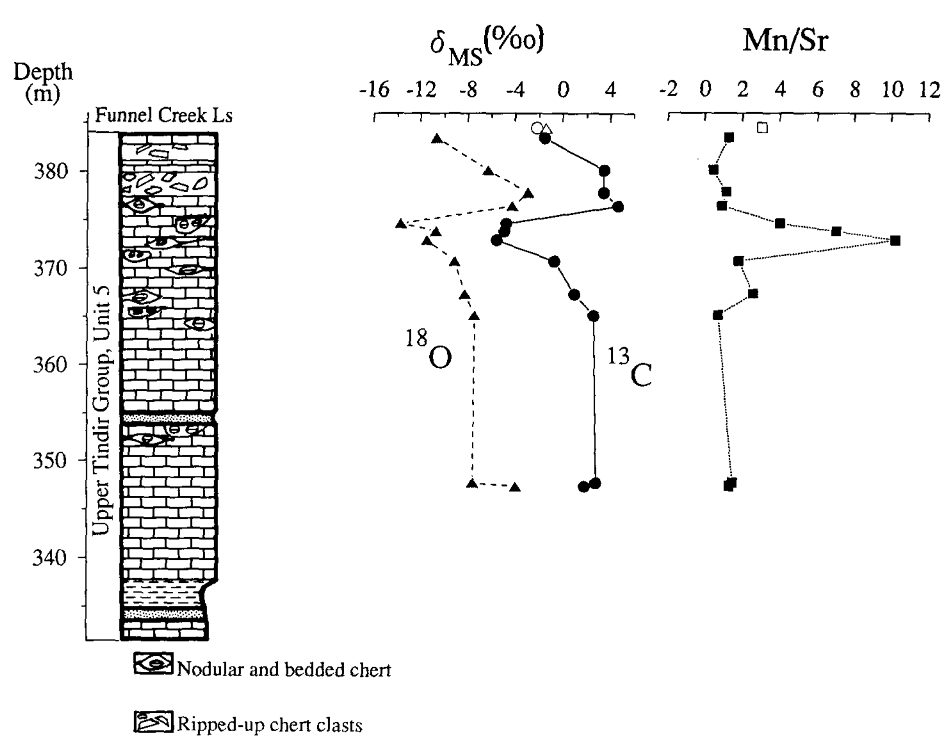

Figure 1. Detailed stratigraphic column for unit 5 of upper Tindir Group as well as C and O isotopic compositions and Mn/Sr for subsamples of microspar (MS) isolated from whole-rock samples. Solid symbols indicate upper Tindir Group samples; open symbols indicate Funnel Creek samples.

GEOCHEMICAL RESULTS AND DISCUSSION

Petrography and Cathodoluminescence

Calcite and dolomite microspars (10–20 μm) are the most abundant constituents in the thin sections (typically between 60% and 95% of the rock), with lesser amounts of sparite (crystal dimensions up to 50 μm), chert, pyrite, clays, and organic carbon. Chert is present as in situ nodules and lenses, detrital clasts, and authigenic cements; pyrite is present as small disseminated cubes. Claystone generally constitutes less than 1% of the rock. Organic C is typically light brown, indicating a mild thermal history for the rocks. The only exceptions to this are samples collected in July 6, 1976, near an igneous intrusion (Table 1, samples of 7-6-79); in these samples organic C is black and concentrated along stylolites. All microspar was either moderately or highly luminescent during CL examination; no strictly nonluminescent microspar was observed (cf. Kaufman et al., 1991). Where possible, the moderately luminescent microspar was isolated for elemental and isotopic compositions; otherwise, highly luminescent microspar was isolated.

Elemental and Stable Isotopic Compositions

Results of elemental and stable isotopic analyses are presented in Table 1 and Figure 1. Most samples are limestone with very low Mg/Ca (<0.015). The few dolomitic limestones and dolomites analyzed (Fig. 1) have high Mn/Sr (>3.000), suggesting that dolomitization occurred under the influence of meteoric fluids that removed primary Sr and added Mn. These samples and those stratigraphically adjacent to them also have the most negative $\delta^{13}C$ and $\delta^{18}O$

values measured (Table 1). Sample 2 of 7-7-79 is also depleted in ^{13}C and ^{18}O, but this result likely reflects its proximity to an exposure surface developed sometime after upper Tindir Group deposition and prior to Funnel Creek Limestone deposition (e.g., Beeunas and Knauth, 1985; Rush and Chafetz, 1990). Values for $\delta^{13}C$ and $\delta^{18}O$ of Funnel Creek dolomites are distinct from those of upper Tindir carbonates (Table 1; Fig. 2A), similarly suggesting a significant depositional hiatus between units.

We envision that sediments from unit 5 were originally organic rich and that early diagenetic oxidation or contact metamorphism of this organic C led to the formation of carbonate relatively depleted in ^{13}C. The abundant chert in these sediments supports the idea that original organic C abundances were high (e.g., Maliva et al., 1989). The spread in $\delta^{13}C$ values of the Tindir carbonates may thus be explained by the incorporation of variable amounts of secondary, isotopically light carbonate. There is, however, no apparent correlation between the present abundances of organic C in these samples and $\delta^{13}C$ values of carbonates or coexisting organic C (Table 1). The wide range in both $\delta^{13}C$ and $\delta^{18}O$ values of subsamples of microspar is also inconsistent with primary variations in the beds from which these samples were collected. The positive correlation of $\delta^{13}C$ and $\delta^{18}O$ values (Fig. 2A) and the negative correlation of $\delta^{13}C$ and Mn/Sr values (Fig. 2B) are typical of carbonates altered by meteoric fluids (Veizer, 1983; Given and Lohmann, 1986; Derry et al., 1992). These trends suggest that the least altered carbonates from upper Tindir unit 5 are those with the most enriched C and O isotopic compositions and the lowest Mn/Sr values. Accepting this logic, primary $\delta^{13}C$ and $\delta^{18}O$ values for carbonates in these beds at the top of the upper Tindir Group are estimated to have been no lower than +4.7‰ and −3.0‰, respectively. Isotopic data for coexisting organic C corroborates this interpretation. In little-altered Neoproterozoic successions $\Delta\delta^{13}C$ ($\delta^{13}C_{MS}$ − $\delta^{13}C_{org}$) is ~28.5‰ (Knoll et al., 1986). Comparably large $\Delta\delta^{13}C$ values characterize only the Tindir samples with the highest $\delta^{13}C_{MS}$ values.

Values for $\delta^{13}C$ of +5‰ and greater are typical of younger (less than ca. 850 Ma) upper Riphean marine carbonates in Svalbard and East Greenland (Knoll et al., 1986), Arctic Canada (Asmerom et al., 1991), Namibia (Kaufman et al., 1991), and India (Schidlowski et al., 1975). The ^{13}C enrichment in these carbonates is matched by that in coeval kerogens (Strauss et al., 1992). Comparable ^{13}C enrichment has also been reported for some upper Vendian carbonates from China (Lambert et al., 1987), the lesser Himalayas (Aharon et al., 1987), and Namibia (Kaufman et al., 1991). In contrast, highly enriched $\delta^{13}C$ values are not consistent with a Cambrian or earlier Proterozoic age. Therefore, C isotopic chemostratigraphy allows us to rule out Allison's interpretation of the unit 5 carbonates as Cambrian. Further, the Tindir unit 5 carbonates exposed near Tindir Creek cannot be the same age as purported Tindir outcrops in eastern Alaska that contain chancellorid spicules (Allison, 1988). Whether the Tindir Creek carbonates are late Riphean or Vendian cannot be determined by using C isotopes alone (Fig. 3B).

Secular variation in the Sr isotopic composi-

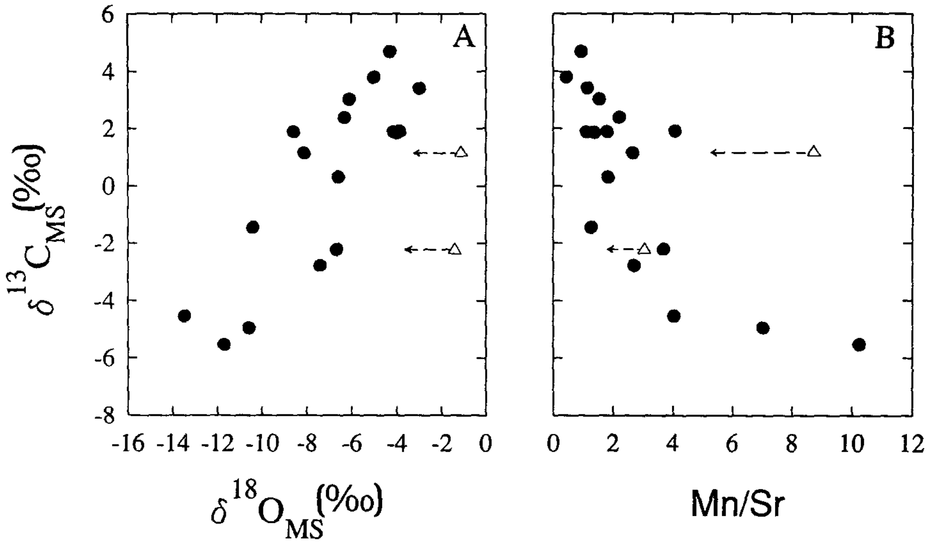

Figure 2. Crossplots of $\delta^{13}C$ vs. $\delta^{18}O$ (A) and Mn/Sr (B) of microspar (MS) subsamples. Solid circles indicate upper Tindir Group samples; open triangles indicate Funnel Creek samples. Arrows indicate direction $\delta^{18}O$ and Mn/Sr compositions of dolomites would move if corrected to compare with calcites.

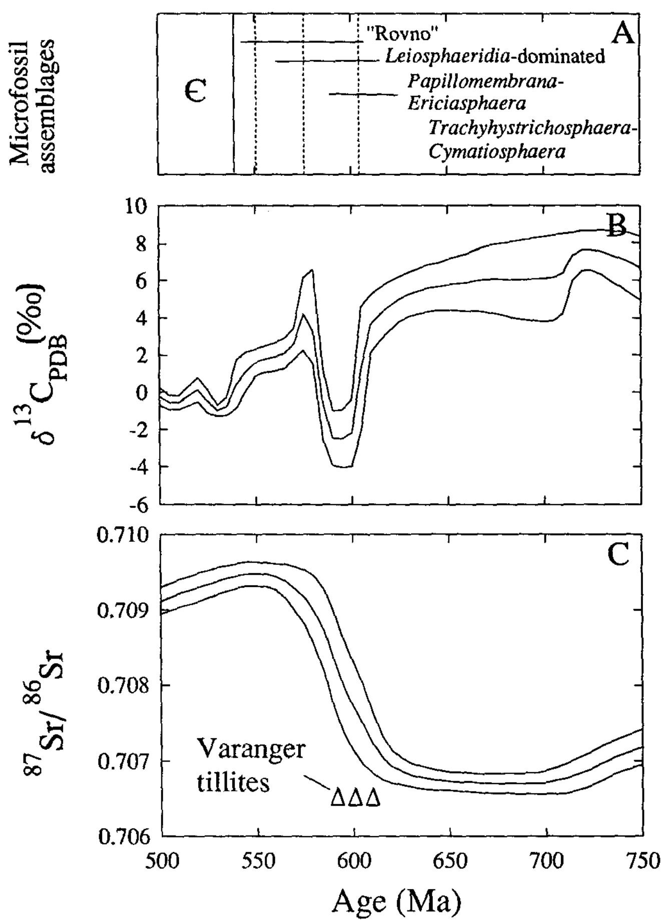

Figure 3. A: Estimated range of microfossil assemblages (Cambrian contains numerous acritarch zones, four in Lower Cambrian alone, and "Rovno" is distinctive assemblage of leiosphaerid and other acritarchs recognized in East European platform and elsewhere). B: Secular variations in $\delta^{13}C$ of marine carbonates (after Derry et al., 1992). C: Secular variations in $^{87}Sr/^{86}Sr$ of marine carbonates (after Asmerom et al., 1991). Age estimates from Conway Morris (1989).

tion of Neoproterozoic marine carbonates (Asmerom et al., 1991) provides a potential means of choosing between the stratigraphic alternatives permitted by C isotopes. Late Riphean $^{87}Sr/^{86}Sr$ values range from 0.7055 to about 0.7075, whereas published values for Vendian $^{87}Sr/^{86}Sr$ range from 0.7075 to 0.7095. A sharp rise in Sr isotopic compositions is noted to coincide with the Varangian glacial episode estimated at 590–610 Ma ago (Fig. 3C). Four whole-rock samples with the most positive $\delta^{13}C$ and $\delta^{18}O$ values and the lowest Mn/Sr were chosen for isotope dilution and Sr isotopic analysis (Table 2). Two of these samples were not analyzed for $^{87}Sr/^{86}Sr$ because they have low overall Sr abundances and high $^{87}Rb/^{86}Sr$, indicating an unacceptably large proportion of radiogenic ^{87}Sr in the sample. Strontium isotopic compositions of the two remaining Sr-rich samples are virtually identical, with an average of 0.70655, which we infer to reflect the $^{87}Sr/^{86}Sr$ of seawater during deposition. Therefore, insofar as diagenesis is likely to drive Sr isotopic ratios to higher values, the $^{87}Rb/^{86}Sr$ values for the Tindir samples indicate a late Riphean (pre-Varangian) age between 620 and 780 Ma.

BIOSTRATIGRAPHY

Allison and Hilgert (1986) described 32 taxa of disc-shaped scales from the upper Tindir unit 5 and Funnel Creek Limestone. Allison and Awramik (1989) subsequently described some 60 species of organic-walled microfossils from unit 5 chert nodules. In our view, these fossils corroborate the stratigraphic placement inferred from the geochemical data. Many of the Tindir microfossils are prokaryotic or simple problematic spheroids; others are morphologically complex but unique to the Tindir Group. Such fossils are not stratigraphically informative. Fortunately, unit 5 cherts contain at least two biostratigraphically useful acritarch taxa, *Cymatiosphaeroides kullingii* and *Trachyhystrichosphaera vidalii*.

Trachyhystrichosphaera is a genus of extremely large (100 μm to at least 2700 μm) acanthomorphic acritarchs reported from at least 14 late Riphean fossil assemblages (Timofeev et al., 1976; Knoll, 1984; Knoll et al., 1991; Pyatiletov, 1988; Jankauskas, 1989; Butterfield and Rainbird, 1988). Broadly comparable fossils have been reported from early Vendian rocks in China (Awramik et al., 1985), but these fossils and the assemblage in which they occur are distinctly different from those of the late Riphean (see below). The genus *Cymatiosphaera* is not as widely known, but this distinctive taxon occurs in several late Riphean formations from Svalbard (Knoll, 1984; Butterfield and Rainbird, 1988; Knoll et al., 1991). There is also a report from the late Riphean Chuar Group, northern Arizona (Vidal and Ford, 1985). The presence of vase-shaped microfossils in the Tindir assemblage (Allison and Awramik, 1989) is also consistent with a late Riphean age, although Vendian examples may exist (Hofmann, 1987). In contrast, the Tindir acritarchs do not closely approximate the assemblages of large, morphologically complex acritarchs reported from early Vendian (Varangian and immediately post-Varangian) rocks (Yin, 1987; Zang and Walter, 1989; Vidal, 1990; Knoll, 1992). Neither do they resemble late Vendian assemblages, which consist principally of simple leiosphaerids (Volkova, 1968), or Early Cambrian acritarchs, which include diverse acanthomorphic species that are quite distinct from the complex acritarchs of the Proterozoic (Volkova, 1969; Knoll and Butterfield, 1989; Moczydłowska, 1991).

Although continuing discoveries could increase the known ranges of Neoproterozoic acanthomorph species, our present understanding of acritarch biostratigraphy suggests that the upper Tindir unit 5 is Neoproterozoic in age and most likely predates the Varangian ice age. This corroborates the age estimate drawn from the C and Sr isotopic data, demonstrating that two independent means of correlation give the same results. Young's (1982) interpretation is strongly supported by our data.

TABLE 2. ELEMENTAL AND Sr-ISOTOPIC COMPOSITIONS FROM THE TINDIR GROUP, CANADA

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
2 7-7-79	0.183	68.094	0.0038	n.d.
3 7-7-79	0.363	824.311	0.0013	0.706583
4 7-7-79	0.143	77.744	0.0053	n.d.
5 7-7-79	0.131	177.599	0.0021	0.706509

Note: n.d. = not determined.

PALEOBIOLOGICAL IMPLICATIONS

The Tindir microbiota are among the best preserved and most diverse Proterozoic assemblages known. If our stratigraphic placement is accepted, however, these fossils cannot be interpreted as documenting the Precambrian-Cambrian biological transition (cf. Allison and Awramik, 1989)—they are simply too old for that. If anything, this greater age increases paleobiological interest in the unique scale fossils reported by Allison and Hilgert (1986). These remarkable fossils document scale-forming protists otherwise unknown from pre-Carboniferous rocks. If Allison and Hilgert (1986) are correct in that the scales were originally siliceous, these fossils augment other reports (Horodyski and Mankiewicz, 1990; Grant et al., 1991) that protistan biomineralization significantly predates the Cambrian explosion.

A second implication stems directly from Young's (1982) lithostratigraphic correlation of upper Tindir unit 5 with the Keele Formation of the Mackenzie Mountains. Keele carbonates lie beneath a recently identified glaciogenic horizon (Aitken, 1991) and above Twitya Formation sandstones and shales that contain possible metazoans (Hofmann et al., 1990). Accepting Young's correlation, our chemostratigraphic and biostratigraphic data support Hofmann et al.'s (1990) interpretation that the glaciogenic horizon is no younger than Varanger tillites in other parts of the world and that the fossils are, in consequence, older than all previously reported Ediacaran animal remains.

CONCLUSIONS

In concert, chemostratigraphy and biostratigraphy can constrain the correlation of Neoproterozoic sedimentary sequences. Documentation of a late Riphean (likely between 620 and 780 Ma) depositional age for upper Tindir unit 5 near Tindir Creek, Yukon Territory, contributes to an understanding of Neoproterozoic geologic evolution in northwestern North America and forces a reevaluation of suggested correlations between this succession and some purported upper Tindir equivalents in Alaska (Allison, 1988). It also advances our understanding of early evolution by showing that scale-forming protists diversified significantly before the Ediacaran radiation.

There is also a cautionary message. This study contributes to a growing literature that demonstrates that Proterozoic carbonates can retain near-primary C and Sr isotopic signatures; however, interpretation of the values requires a great deal more work, including the analysis of carbonate–organic C pairs (Knoll et al., 1986), trace element analysis (Asmerom et al., 1991; Derry et al., 1992), analysis of petrographically well defined microsamples (Zempolich et al., 1988; Fairchild et al., 1990; Kaufman et al., 1991), and stratigraphic attention to exposure surfaces (Rush and Chafetz, 1990). In the example here, the wide range in $\delta^{13}C$ values suggests that early diagenesis led to the oxidation of organic C and to the formation of secondary, ^{13}C-depleted carbonate. However, results of our analyses do allow us to estimate unaltered C isotopic compositions of these carbonates. Thus, our experience with the upper Tindir Group encourages us to continue efforts to improve Neoproterozoic stratigraphic correlation with both increased confidence and appropriate caution.

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ACKNOWLEDGMENTS

Supported in part by National Science Foundation (NSF) Grant BSR 90-17747 (A. H. Knoll, principal investigator). Awramik's Tindir studies were supported by NSF Grant EAR 80-15667 and, in part, National Aeronautics and Space Administration (NASA) Grant NAGW-1948. We thank John Grotzinger, Stein Jacobsen, Ron Phlaum and John Nevins for use of facilities, and Stephen Grant and Pak Choi for help in drafting and sample preparation. Nicolas Butterfield, Ian Fairchild, and reviewer Paul Aharon and Hans Hofmann suggested useful changes to the text and figures. We also acknowledge the late Carol Allison for her dedication to the stratigraphy and paleontology of these unique sediments from the late Proterozoic to Early Cambrian of Alaska and Canada.

Manuscript received June 25, 1991
Revised manuscript received November 13, 1991
Manuscript accepted November 14, 1991

 Printed in U.S.A.