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Comings and Goings of Global Glaciations on a Neoproterozoic Tropical Platform in Namibia

Paul F. Hoffman, *Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA 02138*
Alan J. Kaufman, *Department of Geology, University of Maryland, College Park, MD 20742*
Galen P. Halverson, *Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA 02138*

ABSTRACT

An enduring enigma of Neoproterozoic Earth history is the intimate association of glacial diamictites with typical warm-water carbonates. Among the many hypothesized explanations for this paleoclimatic dichotomy are high orbital obliquity, true polar wander, reduced solar luminosity, snowball albedo, CO_2 drawdown, stagnant ocean overturn, and reinterpretation of diamictites as mega-impact ejecta. The Otavi carbonate platform on the Congo craton in Namibia contains two discrete intervals of diamictite and associated glaciomarine deposits, sandwiched by thick carbonates from which we have obtained detailed carbon-isotopic records. From subsidence analysis, we estimate maximum rates of shallow-water sediment accumulation. The magnitude and duration of isotopic variations permit critical assessment of the existing hypotheses.

INTRODUCTION

Louis Agassiz's (1840) apocalyptic vision of ice ages so severe that continents were glaciated in the tropics and organic activity was stilled on land and sea was overwrought for the Quaternary, but what about the extraordinary events of the late Neoproterozoic (750–543 Ma)? Brian Harland (1964) first drew attention to the global distribution of infra-Cambrian glacial deposits and postulated that they extended into the tropics. This view was not widely accepted, however, because multiple glaciogenic intervals occur in some sections, making the extent of any individual glaciation dependent on correlation. Reliable paleomagnetic tests have been difficult to perform, but there is now strong evidence for equatorial glaciation at sea level in South Australia at ~600 Ma (Schmidt and Williams, 1995; Sohl, 1997) and with less certainty in northwestern Canada at ~720 Ma (Park, 1997). Tropical glaciation has also been advocated because many Neoproterozoic glacial deposits are rich in carbonate debris and are directly overlain by carbonates containing structures indicative of sea-floor precipitates (Fig. 1)(Roberts, 1976; Fairchild, 1993; Kennedy, 1996)—a climatological or geochemical paradox, given that inorganic

Global Glaciations *continued on p. 2*

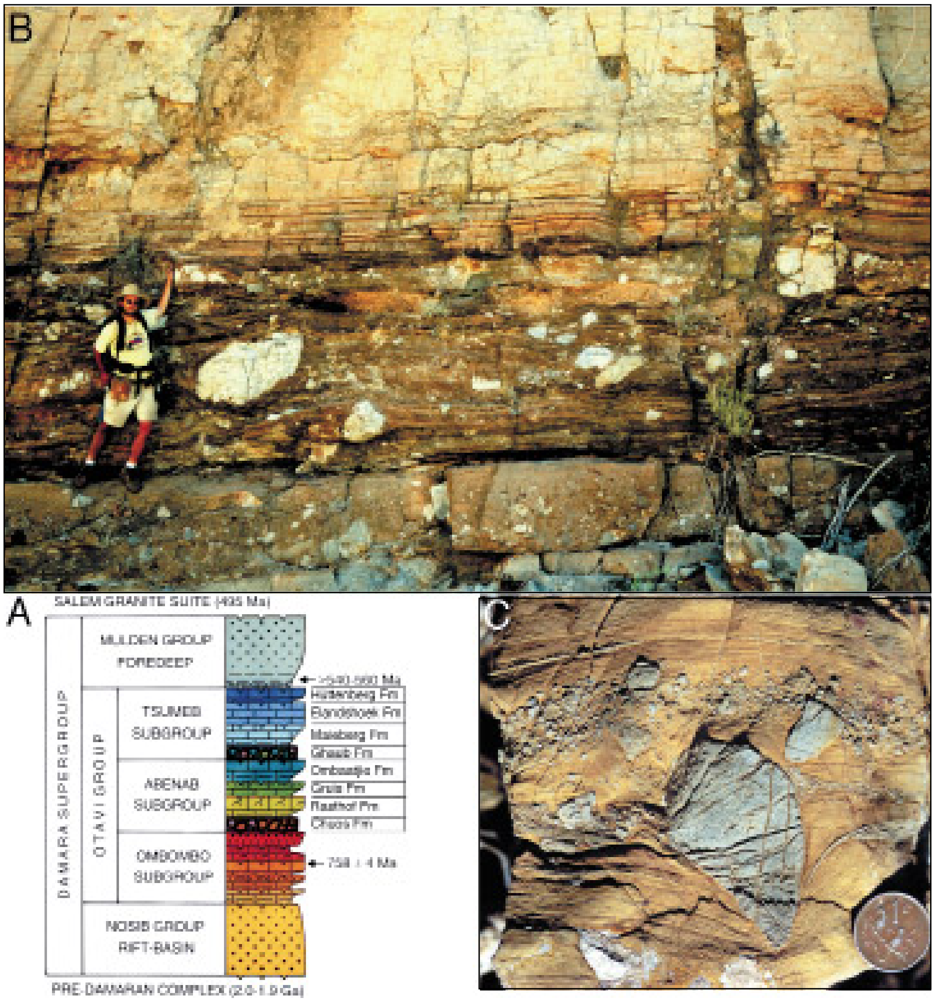

Figure 1. A: Generalized stratigraphy (Hoffmann and Prave, 1996) of Neoproterozoic cover on the Congo craton in northern Namibia, showing geochronological constaints. B: Galen Halverson points to the sharp contact between Ghuab diamictite and Maieberg cap carbonate. Below him is a graded debris flow, behind him is laminated dololutite with numerous dropstones, and above him are deep-water rhythmites with undulations due to isopachous cement sheets. All three units are composed entirely of dolomite. C: Ice-rafted dolomite dropstone pierces underlying laminae in glaciomarine Ghaub dololutite. Coin is 2 cm in diameter.

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In Memoriam

W. Hilton Johnson
Las Cruces, New Mexico
November 3, 1997

John F. Mann, Jr.
La Habra, California
March 9, 1998

Duncan A. McNaughton
Austin, Texas
January 15, 1998

Samuel P. Welles
Berkeley, California
August 6, 1997

Correction

To make housing reservations at Northern Arizona University for the Rocky Mountain Section meeting please contact Michael Ort, Dept. of Geology, Northern Arizona University, Flagstaff, AZ 86011, Michael.Ort@nau.edu, or Larry Middleton, Larry.Middleton@nau.edu, fax 520-523-9220. The final announcement for this section meeting, in the February issue of *GSA Today,* had the wrong name.

Global Glaciations *continued from p. 1*

carbonate precipitation is normally a warm-water phenomenon.

Accompanying the late Neoproterozoic ice ages are huge negative carbon-isotopic excursions, unique in the past 2 b.y. (Fig. 2). Carbonates are very strongly enriched in ^{13}C between the ice ages but plunge to extremely depleted values in lithologically distinctive transgressive carbonate units that "cap" the glacial deposits and commonly extend far beyond them, aiding regional-scale correlations (Knoll et al., 1986; Kaufman and Knoll, 1995; Kaufman et al., 1997). Such large isotopic shifts signify a combination of changes in (1) fractional organic to total carbon burial rates (Scholle and Arthur, 1980), (2) biological productivity in the surface ocean (Broecker, 1982), (3) vertical circulation rate for the whole ocean (Brass et al., 1982), (4) isotopic composition of carbon sources (Derry and France-Lanord, 1996; Dickens et al., 1997), and (5) isotopic fractionation related to carbonate ion concentration (Spero et al., 1997). All are linked to global climate change. Here we describe the stratigraphic relations of two Sturtian (750–700 Ma) glacial intervals on a carbonate-dominated platform in northern Namibia and suggest a means of estimating the time scale of their associated isotopic anomalies. Such data gain sway only in the arena of ideas; thus, we begin with a partial review of current hypotheses.

CONTENDING HYPOTHESES

A welter of hypotheses contend to shed light on the Neoproterozoic climate puzzle. Seeking primarily to explain the paleomagnetic data, Williams (1975, 1993) proposed that Earth's axial tilt (the obliquity of the ecliptic) exceeded 54° until the end of the Proterozoic, after which it stabilized at much lower values (23.5° today). Accordingly, Earth's climatic zonation would have been reversed in the Proterozoic, meaning lower insolation at low latitudes than at the poles. On the other hand, the seasonal cycle would have been greatly amplified, resulting in hot biannual summers, which do not favor glaciation. The association of carbonates and glacial deposits is not explained by this model, nor is the middle Proterozoic glacial hiatus (Fig. 2); once low obliquities were established, high obliquities should not recur (Laskar et al., 1993). The model does have the merit of a simple falsifying test—high-latitude glaciation. Only moderately high (30°–40°S) latitude glaciations have been documented paleomagnetically (Torsvik et al., 1995).

DIRECTOR — *Institute for Environmental Education*

The Geological Society of America (GSA) recognizes that earth systems science is central to environmental issues, practices, policies, and problems in society today. Thus, GSA is soliciting applications for the position of Director for the Institute of Environmental Education (IEE). Through Institute programs, GSA offers an interface between the public, business and industry, government, and the geological community on matters of earth systems science and related public policy issues. The Institute fosters communication and application of geoscience information relevant to environmental issues, education and research related to earth systems problems and public policy, and programs to facilitate professional development in the area of environmental earth science.

Responsibilities will include:

- Development of innovative Annual and Section meeting environmental forums;
- Coordination of GSA public policy activities, and enhancement of a program to involve geoscientists in issues of public policy and media outreach;
- Initiation of workshops and technical programs on environmental and earth systems science matters related to public awareness;
- Management of mentorship programs that introduce students to applied environmental geoscience career opportunities;
- Assistance in fund-raising activities and general support of the GSA education and outreach enterprise;

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➤ Catalyze cooperative interactions among Earth, Life, Planetary, and Social Science groups on earth systems science.

Desirable characteristics for the successful candidate include:

- Interest and experience in the geosciences, particularly involving earth systems science and/or applied settings;
- M.S. degree required; Ph.D. in science or engineering desirable;
- Self-starter who is organized, productive, and able to work as part of a team;
- Demonstrated interest and experience in public policy issues;
- Fund-raising abilities;
- Demonstrated ability to communicate effectively both orally and in writing;
- Ability to work effectively with diverse groups and individuals from business, government, education, media, and the general public.

The position is available July 1, 1998, and will remain open until a suitable qualified candidate has been identified. Salary will be commensurate with experience. The position will be at GSA headquarters in Boulder, Colorado. Candidates should submit a resume, a letter of interest, and the names and addresses of three professional references as soon as possible to Donald M. Davidson, Jr., Executive Director, Geological Society of America, 3300 Penrose Place, P.O. Box 9140, Boulder, Colorado 80301.

Another approach that avoids global glaciation, but which could explain rapid transitions from normal low-latitude to high-latitude conditions, is inertial-interchange true polar wander (IITPW). True polar wander refers to rotation of the entire solid shell (crust and mantle) of Earth relative to the spin axis, a special case of which involves interchange of the major and intermediate axes of Earth's nonhydrostatic moment of inertia tensor. The requisite condition arises if the geoid figure closely approximates a prolate ellipsoid: the prolate axis will stabilize in the equatorial plane to conserve angular momentum (Goldreich and Toomre, 1969), but if the other two axes are nearly equal, small changes in mass distribution may cause the globe to rotate 90° around the prolate axis in a few million years (Gold, 1955; Fisher, 1974). Consequently, continents located near the poles of the prolate axis will undergo 90° rotations, and continents located far from the axis will migrate through 90° of latitude at velocities far exceeding those due to plate tectonics. IITPW has been invoked in the interpretation of Cambrian paleomagnetic data (Kirschvink et al., 1997), and if the inferred prolate geoid figure was inherited from the former supercontinent Rodinia (1.05–0.72 Ga), then IITPW may have occurred several times in the late Neoproterozoic (Evans, 1998). This model attributes the carbonate-glacial association to rapid changes in paleolatitude; it does not explain low paleomagnetic inclinations obtained from the glacial deposits themselves (Park, 1997; Sohl, 1997). No changes in global climate are required in the model, but they would surely occur as ocean circulation patterns changed in response to migration of Earth's rotation axis. Continents moving in or out of the polar regions would experience short-term relative-sea-level falls or rises, respectively, because of their migration with respect to Earth's rotational bulge (Mound and Mitrovica, 1998). These sea-level changes would mimic those expected from glacio-eustasy.

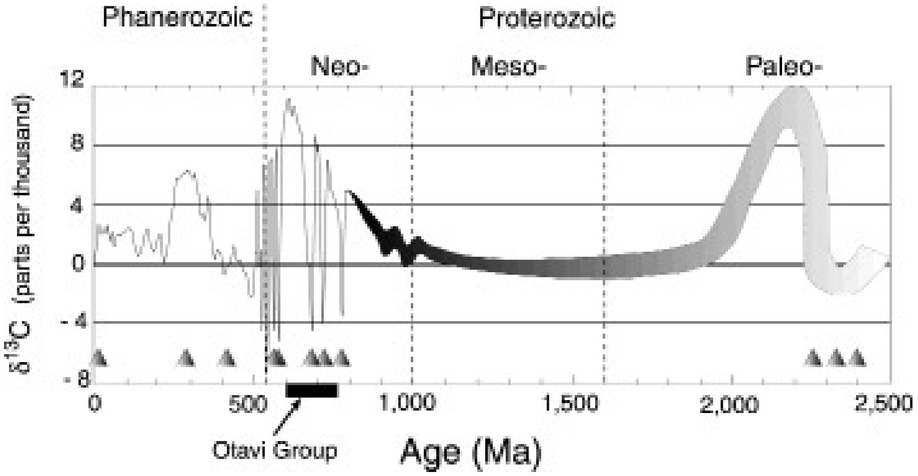

Figure 2. Secular variation in $\delta^{13}C$ (PDB) values of marine carbonates from 2.5 Ga to the present (compiled from Berner, 1989; Kaufman and Knoll, 1995; Kaufman et al., 1997, and references therein). Note enriched late Neoproterozoic isotopic values and high-amplitude negative excursions coincident with glaciations, indicated by triangles. Bar indicates inferred Otavi Group age span.

Global Glaciations *continued on p. 4*

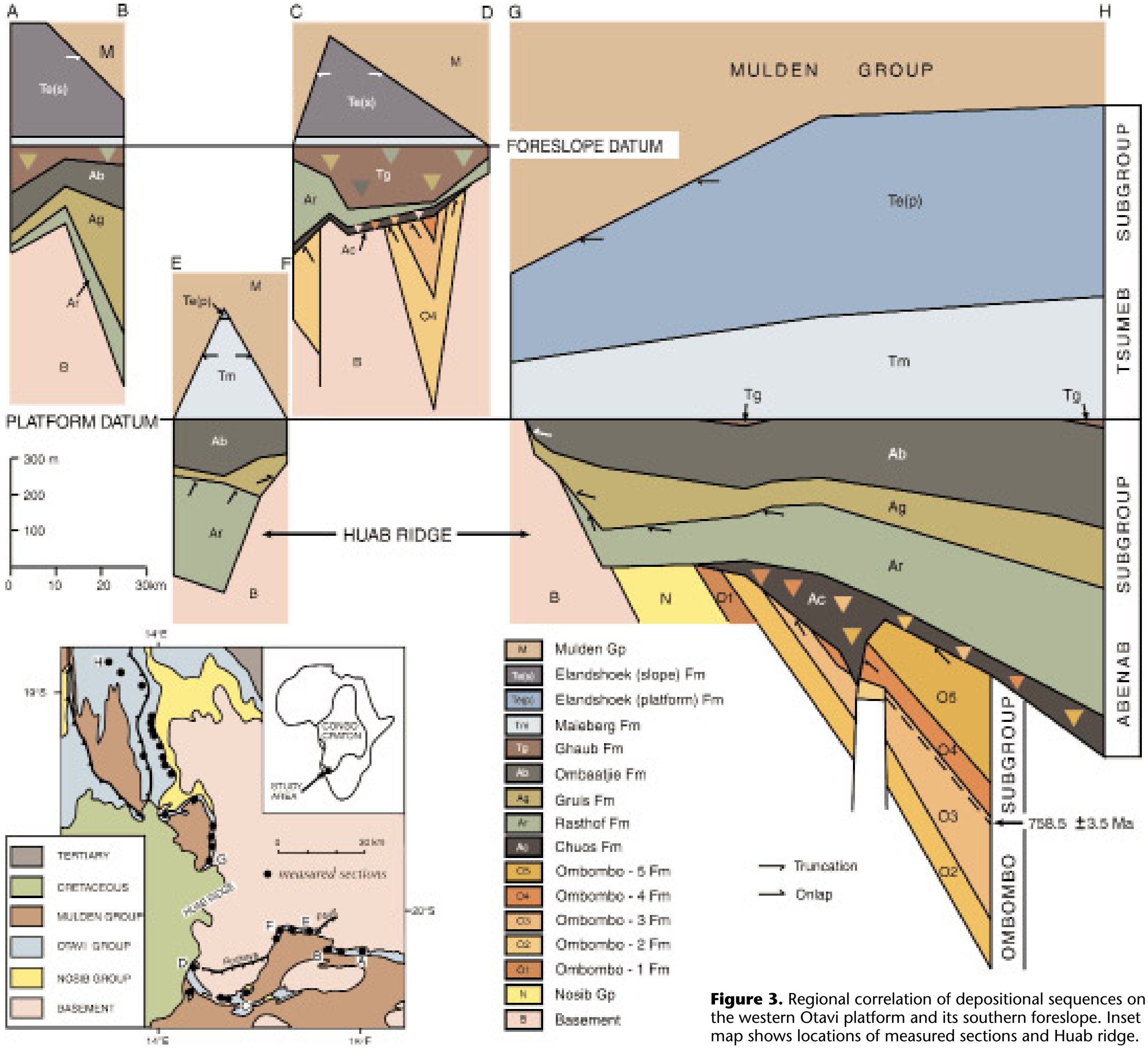

Figure 3. Regional correlation of depositional sequences on the western Otavi platform and its southern foreslope. Inset map shows locations of measured sections and Huab ridge.

Global Glaciations *continued from p. 3*

Rampino (1994) suggested that the purported glacial deposits are actually impact ejecta. His argument is that ballistic debris flows resulting from large impacts exhibit many features conventionally identified with glacial and glaciomarine deposits, including faceted and striated clasts and grooved bedrock pavements. Rampino (1994) did not discuss carbon-isotopic anomalies, but negative excursions do accompany impact-induced mass extinctions (Hsü and McKenzie, 1985; Zachos et al., 1989). Cessation of surface ocean productivity (Strangelove ocean) would cause rapid (<10^3 yr) loss of the ocean's isotopic gradient (~2‰ in the present ocean), meaning that $\delta^{13}C$ in the surface ocean would fall to whole-ocean values (Kump, 1991). Only if productivity ceased for hundreds of thousands of years would $\delta^{13}C$ approach the ocean input value of –5‰ (Kump, 1991). Barring a succession of large impacts, the isotopic excursions should strictly postdate the ballistic ejecta deposits, providing a stratigraphic test for the impact hypothesis.

The occurrence of iron-formation in several Neoproterozoic glacial deposits inspired the hypothesis that glaciation was preceded by deep ocean anoxia, favoring organic carbon burial. Invigorated thermohaline circulation during and after glaciation would result in upwelling of ferrous iron-, bicarbonate-, and CO_2-charged bottom waters, releasing CO_2 to the atmosphere and driving the precipitation of ferric oxide and isotopically depleted bicarbonate as limestone in oxic and highly oversaturated surface waters (Kaufman et al., 1991, 1997; Kaufman and Knoll, 1995; Grotzinger and Knoll, 1995). This hypothesis has been extended to account for the end-Permian mass extinction (Knoll et al., 1996), which has a carbon-isotopic signature somewhat comparable to the Neoproterozoic glacial events (Holser et al., 1989; Magaritz, 1989).

The Sun's luminosity was only 93%–94% of its present value in the late Neoproterozoic because main-sequence stars radiate more energy as their helium cores grow more massive (Gough, 1981). However, the absence of middle Proterozoic glacial deposits (Fig. 2) shows that this fact alone cannot explain late Neoproterozoic glaciations. CO_2 concentrations of 10^{-3} b (three times pre-industrial values) would have offset the reduced solar luminosity,

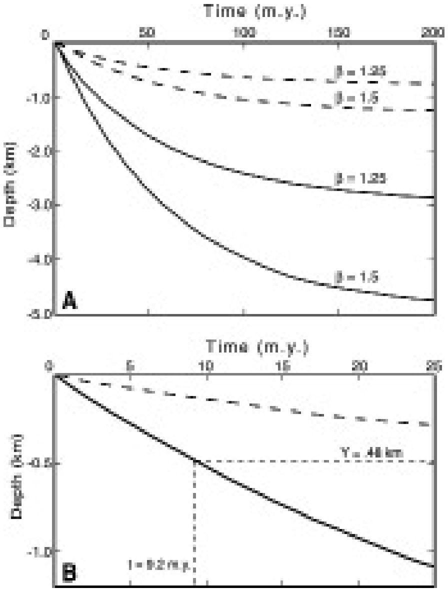

Figure 4. A: Thermal subsidence (dashed lines) and sediment accumulation (solid lines) curves generated by lithospheric stretching factors (ß) of 1.25 and 1.50. Sediment accumulation is calculated as thermal subsidence plus loading by carbonate sediment, filling available accommodation to sea level. Maximum thickness of ~2.8 km for Otavi Group after 160 m.y. implies ß ~1.25. B: Curves as above for first 25 m.y. of thermal subsidence generated by ß ~1.25. Thickness of the section (480 m) containing the negative carbon-isotopic excursion associated with Ghaub glaciation, beginning and ending with shallow-water deposits and corrected for glacial erosion, implies a duration of ~9.2 m.y.

but this dependence could have left Earth susceptible to severe chilling in event of CO_2 drawdown (Kasting, 1992). Coupled energy-balance models suggest that such scenarios are sensitive to the distribution of land masses but that CO_2 concentrations would have to fall to 10^{-4} b (0.3 times pre-industrial values) to drive tropical sea-surface temperatures to the freezing point even with reduced solar luminosity (Marshall et al., 1988; Crowley and Baum, 1993). Nevertheless, Kirschvink (1992) suggested that albedo feedback from extensive sea-ice formation on a globe with an equatorial ring of continents might lead to a "snowball Earth," in which the ocean is decoupled from the atmosphere by global pack ice, with profound implications for ocean chemistry and biological activity. For example, exchange of O_2 between the ocean and atmosphere would be inhibited, permitting ferrous iron generated at mid-ocean ridges or leached from bottom sediments to build up in solution, only to be precipitated as ferric iron-formation upon ventilation of the ocean when the ice pack receded (Kirschvink, 1992).

Global Glaciations *continued on p. 6*

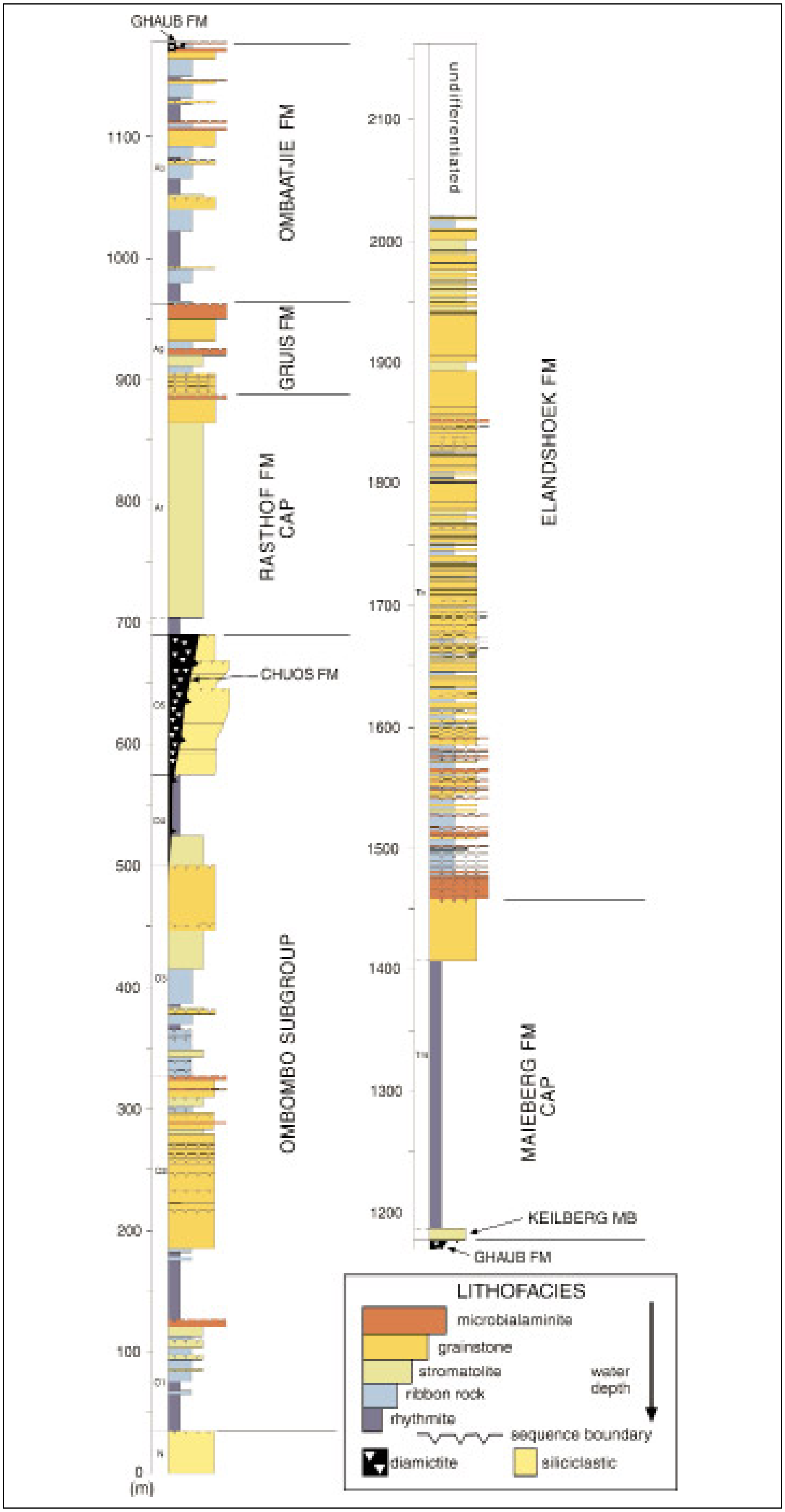

Figure 5. Representative stratigraphic section from the intra-shelf basin north of the Huab ridge (part G–H in Fig. 3). Top of left column continues at base of right column. Note anomalous thicknesses of Rasthof and Maieberg postglacial cap carbonates.

Global Glaciations *continued from p. 5*

OTAVI CARBONATE PLATFORM

In late Neoproterozoic time, the Congo craton was a low-lying platform the size of the conterminous United States. It was blanketed by carbonates and shales containing regionally mappable diamictite units of glacial origin (Hambrey and Harland, 1981). Two discrete glaciogenic intervals are contained in carbonates of the Otavi Group (Fig. 1A), which drape the southern promontory of the craton in northern Namibia (Fig. 3). We consider the Otavi Group to be entirely pre-Vendian in age (Fig. 2), on the basis of chemo- and biostratigraphic arguments. Carbon-isotopic compositions above +8‰ observed near the top of the Otavi Group (Kaufman et al., 1991) are unknown in the Vendian (Kaufman and Knoll, 1995), and Vendian fossils, abundant in the Nama Group carbonates of southern Namibia (Grotzinger et al., 1995), are absent from the Otavi Group. Paleomagnetic data from the eastern part of the Congo craton (Meert et al., 1995; Meert and Van der Voo, 1996) imply that the Otavi Group was at ~12°S paleolatitude at 743 ± 30 Ma and ~39°S at 547 ± 4 Ma (compare with age constraints in Fig. 1A).

The Otavi Group is exposed in fold belts along the southern and western borders of the cratonic promontory (Miller, 1997). The southern belt coincides with the edge of the Otavi platform, which is flanked by correlative slope and deep-sea fan deposits draped over extended Congo crust (Henry et al., 1990). A long-lived basement high, the Huab ridge (Porada et al., 1983), separates the platform margin from an intra-shelf basin to the north. The ridge was intermittently active in early and middle Otavi Group time, shedding clastic wedges bilaterally into the flanking carbonates. The western belt provides a transverse profile of the intra-shelf basin and the Huab ridge (Fig. 3), which along with the western part of the southern margin has been the focus of our field work. Another basement high occurs near the Namibia-Angola border, 300 km to the north of the Huab ridge, and the scale and structure of the intra-shelf basin and basement highs are remarkably similar to the present Namibian continental shelf (Light et al., 1993).

Regional subsidence patterns and overstepping of growth faults suggest that rifting of the western and southern margins of the Otavi platform ceased shortly before 758 Ma and shortly after 746 Ma, respectively (Fig. 1A, Hoffman et al., 1996). If carbonate sedimentation continued until the platform collided with the South American cratons at ~600 Ma (Stanistreet et al., 1991; Machado et al., 1996; Trompette, 1997), the Otavi Group represents ~160 m.y., by which time thermal subsidence would be largely complete (Fig. 4A). The maximum of 2.8 km of carbonate accumulated during thermal subsidence, after correction for sediment loading, amounts to ~0.73 km of tectonic subsidence. This amount of ultimate thermal subsidence would be induced by a uniform synrift stretching factor ß ~1.25 and would begin with tectonic subsidence rates of ~14 m/m.y., averaged over the first 10 m.y. (McKenzie, 1978). This corresponds, with sediment loading, to a carbonate accumulation rate of ~52 m/m.y. (Fig. 4B). We take this as a rough upper bound for the purpose of constraining the minimum duration of the isotopic anomalies.

GLACIAL DEPOSITS AND POSTGLACIAL CAP CARBONATES

The glacial deposits are characterized by diamictites, which are sheets of unstratified wackestone carrying outsize matrix-supported clasts of carbonate and basement rocks. Within both the Chuos and Ghaub glacial units (Fig. 3), separate diamictite sheets differ in composition, but clast and matrix compositions covary, indicating a common origin. Overall, basement debris is more abundant in the Chuos, and the Ghaub diamictites are normally dominated by debris from directly underlying carbonates. The Chuos diamictites are associated with fluvial outwash facies and fill paleovalleys with up to 180 m of local relief. Such incision is observed beneath the Ghaub diamictites only on the southern foreslope, where they are intercalated with subaqueous debris flows and topped by laminated dololutite choked with carbonate dropstones (Fig. 1, B and C). Both glacial intervals have highly complex and variable internal stratigraphies, but their external contacts are remarkably similar and consistent. On the platform, their basal contacts show intense brecciation of the underlying carbonates. Both of their upper contacts are knife-sharp and lack lag deposits or any evidence of hiatus. Where the glacial deposits are subaerial, the upper contact is a smooth flooding surface; where they are subaqueous, there is simply an abrupt cessation of ice-rafted debris.

The Rasthof and Maieberg cap carbonates (Fig. 5) directly overlie the Chuos and Ghaub glacial units, respectively, or their equivalent subglacial erosion surfaces (Fig. 3). They are single depositional sequences without internal exposure surfaces, whose average thickness of 200–300 m is an order of magnitude greater than that between successive exposure surfaces in other parts of the platformal Otavi Group. Average parasequence thickness is 20 m in the Ombombo Subgroup below the Chuos Formation and 8 m in the Gruis Formation above the Rasthof cap carbonate. It increases again to 30 m in the Ombaatjie Formation below the Ghaub glaciation, reflecting rifting at the southern margin of the platform, before declining to only 4 m in the Elandshoek Formation above the Maieberg cap carbonate. Thus, the cap carbonates require highly anomalous amounts of accommodation. From the onset of glaciation to the end of cap-carbonate deposition, the accumulated sediment must equal the sum of the tectonic subsidence, net glacial erosion/deposition, and the effect of sediment loading. Compaction is negligible in the Otavi Group carbonates and <20 m of net erosion occurred on the platform during the Ghaub glaciation. Given the average thickness of the Maieberg cap carbonate of 280 m (Fig. 3) and the maximum sediment accumulation rate of 52 m/m.y. calculated earlier, the minimum time required to create sufficient accommodation would be 5.4 m.y. Note that this is not the minimum time for cap carbonate deposition, which could be far less, but rather the total time for the glaciation as well as the cap carbonate. It is impossible to estimate the partitioning of time between the two because of transient glacio-eustatic and glacio-isostatic effects (Boulton, 1990). For example, postglacial sea-level rise can create much accommodation, but it will subsequently be eliminated by glacial rebound. Postglacial cap carbonates described elsewhere are relatively thin (Fairchild, 1993; Kennedy, 1996) but they may represent only the transgressive parts of postglacial depositional sequences. It is only from the perspective of sequence stratigraphy that the anomaly in postglacial accommodation becomes apparent, an aspect that escaped notice in the lithostratigraphic recognition of cap carbonates. Moreover, the anomaly stands out only when the cap carbonates are viewed in the sequence-stratigraphic context of the Otavi Group as a whole.

The two cap carbonates have distinctive and highly unusual lithologies (Fig. 6). The Rasthof is dark to medium gray, mostly dolomite and relatively carbonaceous (0.03–0.3 wt% C); the Maieberg is pale cream to pink, mostly limestone and extremely lean (0.001–0.02 wt% C). The complete Rasthof sequence in the intra-shelf basin consists essentially of three stratigraphic units (Fig. 5). The basal unit comprises finely and smoothly laminated micrite and varies from 5 to 60 m in thickness, dependent on the presence of centimeter-scale allodapic limestones (turbidites). The top of the flat-laminated unit is marked by profligate development of irregular domal stromatolites, the peculiar geometries of which suggest synaggradational, fault-propagation folds, verging in all directions. By implication, stromatolite development was a response to lateral growth expansion. Up-section, the stromatolite unit contains numerous coiled roll-ups (Fig. 6A), which formed while the sediment was cohesive (microbially bound?), but pliable (lightly mineralized). Also present are irregular synsedimentary collapse breccias, composed of microbialaminite blocks and void-filling thrombolite. The thick stromatolitic unit is devoid of desiccation structures and current bedforms. At its top, the lamination fades and the stromatolites pass cryptically into regressive pale gray grainstones, which coarsen upward to a sequence boundary marked by tepees and chert-breccias.

The basal transgressive unit of the Maieberg cap carbonate (Keilberg Member of Hoffmann and Prave, 1996) on the platform is an unusual stromatolitic dolomite (Fig. 6B), highly reminiscent of the postglacial Noonday dolomite (Sturtian?) in eastern California (Wright et al., 1978; Hegenberger, 1987). This pale dolomite unit consists of microbialaminite and long slender columnar stromatolites, between which are persistent synoptic depressions forming vertical sediment- and cement-filled “tubes.” The stromatolite member thickens over the Huab ridge and develops into a mounded reef complex at the platform margin. Talus blocks at the base of the reef complex are infilled by meter-scale silica fans, pseudomorphic after aragonitic sea-floor cements. The stromatolite member is overlain transgressively by marly rhythmite, followed by a thick regressive sequence of pink limestone rhythmite, pale dolomite rhythmite, and dolomite grainstone that coarsens upward to an exposure surface made prominent by downward-penetrating boxwork chert. Directly above the sequence boundary are multitudinous meter-scale parasequences with ubiquitous tepee structures, representing the basal member of the kilometer-thick Elandshoek peritidal platform. The Keilberg stromatolite member is absent on the southern foreslope, where the basal Maieberg cap carbonate consists of pale dolomite rhythmite, sheeted with early isopachous carbonate cement (Fig. 1B). Carbon-isotopic curves indicate that the Maieberg cap carbonate thins dramatically from the platform onto the foreslope, and that most of the rhythmite and rhythmite-breccia section above the Ghaub diamictite is a foreslope facies of the Elandshoek platform (Fig. 3).

CARBON-ISOTOPIC RESULTS

The carbon-isotopic composition of Phanerozoic marine carbonates is complicated by the vital effects of skeletal organisms and pervasive bioturbation. Proterozoic carbonates are not plagued with these problems. The primary Otavi Group carbonates were pure lime muds, silts, sands, and microbial micrites, most of which underwent early fabric-retentive dolomitization, rendering them relatively impermeable. Elemental ratios sensitive to diagenesis indicate minimal alteration of most samples (for details of analytical procedures used in screening for diagenetic alteration, see Kaufman et al., 1991; Kaufman and Knoll, 1995). Even the brecciated and ferruginized samples deliberately collected at exposure surfaces rarely have anomalous carbon-isotopic values, indicating that soil waters were not significantly depleted by decomposition of organic carbon. Furthermore, the carbon-isotopic trends for closely spaced samples are stratigraphically coherent and regionally reproducible.

We have obtained $\delta^{13}C$ values for ~800 samples collected through the entire Otavi Group at different locations. These data (incorporated in Fig. 2) and their interpretation have been submitted for publication elsewhere. The thick, shallow-water carbonates of the Ombombo Subgroup are strongly and uniformly enriched in ^{13}C (>+5‰), consistent with preglacial Neoproterozoic carbonates worldwide (Kaufman et al., 1997). An influx of siliciclastics (from the Huab ridge) and erosional truncation at the top of the Ombombo Subgroup create problems in obtaining data for the youngest pre-Chuos sediments. The basal Rasthof carbonates are strongly depleted in ^{13}C, beginning near –4‰ and rising to ~0‰ near the top of the flat-laminated member. At the base of the overlying stromatolitic member, $\delta^{13}C$ values rise abruptly and ultimately stabilize near +5‰ for >150 m through the remainder of the Rasthof Formation. The shift from negative to positive values is widely correlated with the onset of deep-water stromatolite development in the intra-shelf basin.

Prior to the Ghaub glaciation, $\delta^{13}C$ values through most of the Ombaatjie Formation hovered between +5‰ and +9‰, exemplifying the familiar preglacial enrichment in ^{13}C. However, the ultimate Ombaatjie shallow-water parasequence, directly beneath remnants of Ghaub diamictite or the Maieberg cap carbonate, displays a monotonic downward trend from +5‰ at the base to –3‰ at the top, reaching –5‰ in some sections. This preglacial isotopic shift occurs in at least nine sections over a north-south distance of 150 km, and Kennedy et al. (1997) reported a somewhat smaller shift beneath the Ghaub diamictite well to the east of our sections. There is little change in $\delta^{13}C$ values across the glacial interval: the basal Maieberg cap carbonate begins near –3‰ and declines gradually up-section to a nadir of –6‰ about 20 m above the zone of inferred maximum flooding. While $\delta^{13}C$ values gradually rise above this level, they remain negative through the sequence boundary at the top of the Maieberg Formation. In fact, the crossover to positive $\delta^{13}C$ values occurs ~200 m above the base of the Elandshoek Formation, which is composed of repetitious peritidal parasequences with ubiquitous subaerial exposure surfaces. Thus, the overall negative isotopic excursion begins and ends in peritidal sediments and spans a total thickness of 500 m. On the basis of previously estimated maximum thermal subsidence rates and assuming <20 m of glacial erosion beneath the Maieberg cap carbonate on the platform, the minimum duration of the negative isotopic excursion was 9.2 m.y. (480 m ÷ 52 m per m.y.; Fig. 4B). Regional sequence stratigraphic mapping provides no evidence of growth faulting coincident with the isotopic excursion, which might have produced anomalous subsidence rates, hence less time, during the interval.

DISCUSSION AND CONCLUSIONS

Let us now return to the contending hypotheses. (1) The high-obliquity hypothesis (Williams, 1975, 1993) does not account for the intimate association of glacial deposits with carbonates including inorganic sea-floor aragonite precipitates requiring warm-water conditions, exemplified by the basal Maieberg reefal cement fans. (2) The inertial-interchange true polar wander hypothesis that certain regions migrated rapidly between low and high latitudes (Kirschvink et al., 1997) does not explain the temporal association of glacial deposits with large carbon-isotopic excursions. Nor do we find transitional mid-latitude facies between the diamictites and their respective cap carbonates, as predicted by this hypothesis. (3) The suggestion that the diamictites are mega-impact ejecta (Rampino, 1994), implying that the associated isotopic excursions signify impact-induced mass extinctions, is contradicted by the onset of the negative isotopic shift, which predates the Ghaub diamictite. Moreover, we do not rely on ambiguous criteria for recognizing glacial deposits such as striated and faceted clasts, which are difficult to observe in carbonate-dominated diamictites, but on stratigraphic relations and abundant dropstones, around which only the subjacent laminations are deformed and pierced. (4) The ocean-overturn hypothesis (Kaufman et al., 1991, 1997; Kaufman and Knoll, 1995; Grotzinger and Knoll, 1995; Knoll et al., 1996) predicts that negative isotopic excursions should be short-lived, limited by the residence time for carbon in the ocean, liberally estimated at 10^5 yr (Kump, 1991). The negative excursion associated with the Ghaub glaciation, requiring an estimated minimum duration of 9.2 m.y. for 125 m of net thermal subsidence, exceeds the predicted time limit by two orders of magnitude.

So what remains? Sherlock Holmes’s dictum—that when all other hypotheses fail, the one that remains must be true—is not always appropriate in science because not all possible hypotheses are known. In this instance, however, we believe that one of the contending hypotheses, with more

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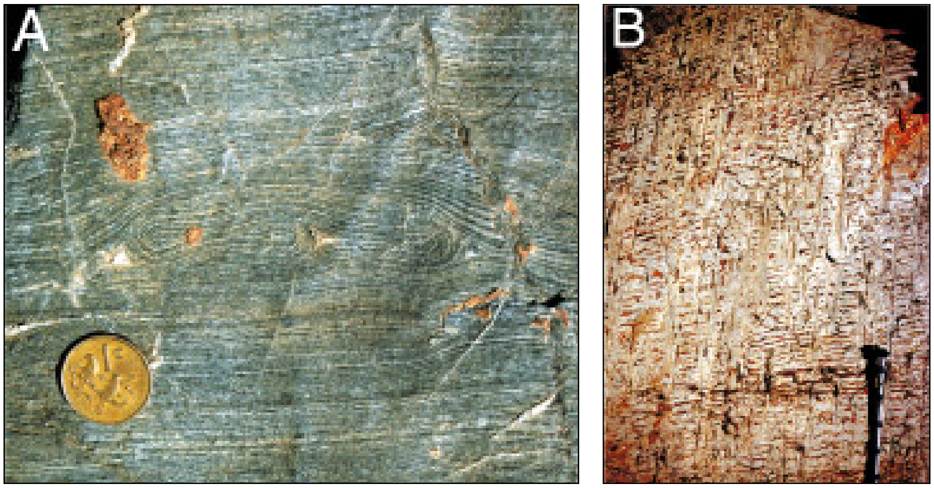

Figure 6. Unusual lithologies in postglacial cap carbonates. A: Microbial roll-ups in middle Rasthof cap carbonate (2-cm-diameter coin). B: Vertical "tubes" in basal Maieberg cap carbonate (10 cm scale divisions).

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elaboration than is possible here, provides a satisfactory explanation consistent with the data (Hoffman et al., 1998). Whether or not Agassiz's (1840) vision of panglacial catastrophes is valid for the Neoproterozoic, Namibia teaches us that Agassiz was correct when he said, "If you learn about Nature in books, when you go out of doors you cannot find Her."

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Coastal Sediments '99 Conference Calls for Abstracts

Abstracts are due *May 11, 1998*, for the Coastal Sediments '99 conference to be held June 20–24, 1999, on Long Island, New York. Scales of Coastal Sediment Motion and Geomorphic Change is the theme of the conference; GSA is a co-sponsor.

The address for submittal of abstracts (five paper copies) is: William G. McDougal, Co-Chair, Coastal Sediments '99, Dept. of Civil Engineering, Oregon State University, Corvallis, OR 97331-2302. For further information: Nicholas C. Kraus, USAE Waterways Experiment Station, Coastal & Hydraulics Lab. (CEWES-CC), 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199, or http://www.coastalsediments.org.

A GSA Committee May Need You

***Steve Stow**, Chair, 1997 Committee on Committees*

Perhaps you feel that if you nominate someone for a GSA committee, your nomination goes into a black hole, or is lost among hundreds of other nominations submitted when the Society annually calls for members to serve on committees, as it does in this issue of *GSA Today.* And if you were to volunteer for a committee assignment, your offer wouldn't be taken seriously, would it?

The reality is that there is no black hole, and every nomination for committee service is considered carefully.

The reality is also that since 1990, the number of volunteers for committee service has dropped from 50 per year to an average of 30 and that the number of members nominated for appointment has varied annually from a low of 16 in 1996 to a high of 75 in 1993; the average is 39 per year. Since 1992, the number of appointees to GSA committees has been highly variable, from zero to more than 20. The 1997 Committee on Committees, relying heavily on nominations and volunteers, selected 12 of the 29 volunteers and 12 of the 34 nominees for service on GSA committees.

For many reasons, it is not possible—or even advisable—to use only names of volunteers and nominees in making committee assignments. Many factors, including experience, geoscience discipline, geography, prior GSA experience, and minority representation, go into the selection process. The Committee on Committees draws on names of individuals considered but not selected by the previous committee, as well as its own personal knowledge of qualified candidates, in getting a slate that is truly representative of the GSA membership and qualified to perform the functions of the varied committees. It is a full day's job (after a lot of preliminary work) to arrive at the final list of candidates to be presented to the GSA Council for approval, an indication of how carefully each volunteer and each nominee are considered.

If your name, volunteered or nominated, comes before the 1998 Committee on Committees and is not selected, don't lose hope—try again next year. The simple fact that someone wants to devote some of his or her time to helping GSA, or the fact that one member feels strongly about nominating another, goes a long way in elevating that person's chance of being selected.

Graduate Students Encouraged to Volunteer!

Graduate students are now eligible to serve on GSA Committees as full members. All graduate students are encouraged to volunteer or nominate others for committee service.

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S. M. Kay, Cornell University
(607)255-4701, fax 607-254-4780
smk16@geology.cornell.edu

M. F. Miller, Vanderbilt University
(615) 322-3528, fax 615-322-2137
millermf@ctrvax.vanderbilt.edu