of the plasmas in the magnetosphere, the dynamics of the energetic particle populations in the magnetosphere, the amount of magnetic flux reconnected in the magnetotail, the highly structured nature of plasma flows in the Earth's magnetotail, the voltage patterns and plasma flow patterns in the polar ionosphere, and the detailed properties of the solar wind that drive the magnetosphere into sawtooth oscillations.

Two students in attendance gave presentations about their research on sawtooth oscillations: T. Gomez (University of Maryland) showed a superposed epoch study of energetic particle measurements in the magnetosphere during sawtooth oscillations, and X. Cia (University of Michigan) presented an extensive statistical survey of the properties of sawtooth oscillations and the solar wind that drives them.

Highlights of the Taos Workshop

At the workshop, several accomplishments were achieved, several new controversies were identified, and several older controversies continued.

Four immediate accomplishments of the workshop were the following:

(1) A criterion for determining whether a magnetospheric disturbance should be called a sawtooth (as opposed to an ordinary substorm) was agreed upon, with that criterion being the sighting of a dispersionless energetic particle injection at geosynchronous orbit that extends sunward of the dawn or dusk terminators.

(2) The quoted 2–4 hour recurrence period of sawtooth oscillations was deemed to be a real period of the magnetosphere and not a selection effect or a period inherent in the solar wind driver.

(3) The hot plasma in the magnetosphere was found to be very oxygen rich during eras of sawtooth oscillations.

(4) Oxygen ions were found to be suddenly energized in a broad local time range during each new sawtooth event.

Several new controversies and open problems were identified at the workshop. Three of these dealt with (1) the role of reconnection in the magnetotail at the time of sawtooth crash and during the sawtooth stretching phase, (2) why the polar cap index reacts only to some sawtooth crashes, and (3) whether the multiple onsets of a sawtooth crash are aspects of the same event or are separate events.

Workshop participants noted a dilemma between two concepts that are thought to apply during sawtooth oscillation time intervals: (1) the notion that the convection in the ionosphere is anomalously low because the cross-polar-cap potential becomes saturated during the times of sawtooth oscillations, and (2) the notion that there needs to be anomalously high levels of convection in the inner magnetosphere to account for the strength of the ring current. Both of these concepts are argued to come into play owing to the unusual conditions of the solar wind during sawtooth times.

Ongoing controversies that were not settled include: (1) whether sawtooth oscillations are merely giant substorms, or whether they have physical processes ongoing that make them unique from substorms; (2) whether the energetic particles of the Earth's outer radiation belts periodically migrate in and out within the magnetosphere during a sawtooth oscillation or whether they are repeatedly lost and replaced with new particles; (3) whether or not there are anomalously high levels of convection in the inner magnetosphere during sawtooth times; (4) whether or not sawtooth crashes of the magnetosphere are triggered by sudden increases in the ram pressure (the pressure caused by a flow velocity impinging on an obstacle in the flow) of the solar wind; and (5) the nature of the instability that leads to the sawtooth crash after the magnetic field of the inner magnetosphere stretches.

A question about the connection between steady magnetospheric convection intervals and sawtooth oscillations (which are both driven by solar wind with steady, southward magnetic fields) was posed: when the strength of the solar wind; magnetic field increases, why does the magnetosphere prefer the sawtooth oscillation mode rather than the steady magnetospheric convection mode?

After extensive discussion, it was noted that a coherent model for the evolution of the magnetosphere through the sawtooth cycle does not yet exist. What causes the extreme stretching? What causes the crash? What are the consequences of this cycle?

During most of the workshop, participants were involved with research collaborations.

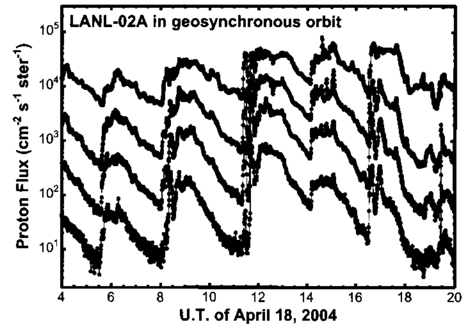

Fig. 1. A sawtooth oscillation of the magnetosphere as seen in energetic-proton measurements by the satellite LANL (Los Alamos National Laboratory)-01A in geosynchronous orbit. Sixteen hours of measurements from the synchronous orbit particle analyzer (SOPA) instrument are shown.

Three research efforts were organized and will continue beyond the workshop. A multiple-author write-up describing "the state of the magnetosphere during global sawtooth oscillations" was initiated (led by M. Thomsen). A study to determine whether sawtooth oscillations can be triggered by solar wind pressure increases is under way (led by L. Lyons). And, the creation of a large catalog of sawtooth crash times meeting the above-mentioned criterion is nearing completion (led by B. McPherron).

Progress at the workshop toward advancing the understanding of sawtooth oscillations was significant. Most of the researchers who study sawtooth events were in attendance, most attendees walked away with research ideas and research guidance, and significant collaborations were organized. Depending on the progress of these research efforts, a decision will be made in the future about a third IGPP-sponsored workshop on global sawtooth oscillations.

The Workshop on Global Sawtooth Oscillations of the Magnetosphere was held in Taos, New Mexico, 13–16 September 2004.

—JOE BOROVSKY, Los Alamos National Laboratory, New Mex.

Global Impact of the Panamanian Seaway Closure

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Closure of the Isthmus of Panama about 3 million years ago (Ma) was accompanied by dramatic changes in Earth's climate and biosphere. The Greenland ice sheet grew to continental extent and the great cycles of ice ages commenced dominating climate variability henceforth. Disruption of water mass exchange between the Atlantic and the Pacific Oceans led to different evolution of marine species on either side of the land bridge, while land-based organisms including mammals and other animals took the advantage to colonize an entire subcontinent.

A 2-day workshop at the University of Kiel (Germany) summarized our current knowledge of this time period and identified areas for new research. The workshop's main questions were:

1. What was the timing of events associated with the restriction of the seaway?

2. How did changed ocean circulation patterns affect climate, marine productivity, and evolution?

3. Did the closure of the seaway trigger the intensification of Northern Hemisphere glaciation?

Timing of the Closure

Marine carbon isotope records (δ^{13}C) from Atlantic and Pacific sediments below 1000-m depth show parallel variability until 14–11 Ma. Subsequent divergence indicates shoaling of the deep-ocean passage around that time, as reported by T. Bickert (Bremen). Between 10.5 and 9 Ma, the carbonate content in sediments from the eastern tropical Pacific began to decline dramatically. This is generally ascribed to reduced inflow of less corrosive North Atlantic Deep Water (NADW) through the seaway into the Pacific. After ~7 Ma, the modern distribution of deep-water masses with NADW advection into the South Atlantic seems to be established. Indeed, ocean-climate models in which the sill depth becomes shallower than the depth of NADW flow (1–3 km) demonstrate that NADW no longer escapes westward through the gateway into the Pacific, but floods the South Atlantic.

Restricted surface water exchange through the gateway marks the time interval from 4.7 to 4.2 Ma. Comparisons of planktonic $\delta^{18}O$ records (S. Steph, Kiel) demonstrate the establishment of the modern Pacific-Caribbean salinity contrast and the formation of the Caribbean Warm Pool. The general increase in Caribbean sea surface temperature (SST) (3°C) and salinity (up to 3 permil) was associated with pronounced variations on precessional periodicities. In the eastern tropical Pacific, a southeastward shift in the locus of maximum opal accumulation and a decrease in thermocline depth suggest intensified upwelling between 5 and 4 Ma.

Evidence of further shoaling of the seaway is provided by Mg/Ca-derived Pacific-Caribbean SST reconstructions of shallow-dwelling foraminifers (J. Groeneveld, Kiel). Similar fluctuations persisted on both sides until ~2.8 Ma. Subsequently, sea level variations of the order of 50–70 m became important in response to the amplification of Northern Hemisphere glaciation. Glacial stages (low sea level) are associated with minima in Pacific SST and maxima in Caribbean SST, indicating cessation of cold Pacific water throughflow into the Caribbean. Precise timing of the ebbing of interglacial throughflow remains unclear since presently available records end at 2.5 Ma.

The final closure of the gateway coincides with massive increases in ice-rafted detritus in Northern Hemisphere high-latitude ocean sediments. This event documents intensification of Northern Hemisphere glaciation with large continental-size ice sheets crossing the shoreline. Supporting this interpretation is a drop in sea level at 2.95–2.75 Ma as indicated by benthic $\delta^{18}O$. Subsequently, changes in Earth's orbit around the Sun, and associated variations in the seasonal cycle of insolation controlled the waxing and waning of these ice sheets.

Impact on Marine Productivity

Sediments from the subarctic North Pacific show gradually increasing opal accumulation followed by an abrupt collapse at 2.75 Ma. This is interpreted as a decline in productivity associated with the inception of the halocline (strong vertical stratification). While some researchers believe that this increase in stratification was due to a reduction in upwelling in the North Pacific, others think it might have been caused by decreased downwelling and lower rates of intermediate water formation, accompanied by a shutdown of a meridional overturning in the North Pacific. Decreased northward heat transport is supported by $\delta^{18}O$ records from the northeastern Pacific, suggesting SSTs dropped by 7°C at 2.75 Ma. Nevertheless, a consistent and unambiguous explanation of these records remains one of the major open questions concerning the closure of the Panamanian seaway.

In the North Atlantic, productivity appears to have been decreasing during the final closure, as suggested by changes in benthic foraminiferal species composition. At Ocean Drilling Program (ODP) Site 984 south of Iceland, *Bolivina pacifica*, a high-carbon flux indicator species which is common prior to 2.75 Ma, disappears completely thereafter (M. Weinelt, Kiel). This is consistent with model simulations showing that reduced inflow of nutrient-rich Pacific surface water into the North Atlantic decreases productivity there, while productivity increases in the eastern equatorial Pacific due to intensified upwelling after the closure of the seaway (B. Schneider, Kiel).

Impact on Evolution of Marine Organisms

The closure led to the separation of marine organisms, providing classic textbook examples for allopatric speciation (speciation through geographical separation). Since most of these examples come from benthic shallow-water organisms (e.g., corals), the exact timing of the separation remains uncertain. Planktonic microfossils are more suitable, since they can be examined in well-dated, high-resolution sediment cores. Occurrence of the eutrophic coccoliths *Pseudoemiliania* and *Gephyrocapsa*, and the successive disappearance of a set of oligotrophic higher taxa (e.g., Sphenoliths) represent prominent evolutionary events in the Pliocene. Possibly, the originations have been triggered by the initiation of Northern Hemisphere glaciation. The first occurrence of small *Gephyrocapsa* (4.35 Ma) is almost synchronous in the Pacific and Caribbean as at other Atlantic sites. Shoaling of the nutricline in the Caribbean basin, signaled by the decrease in relative abundance of *Florispheara profunda* after ~4.2–4.0 Ma, suggests that increased surface water nutrient supply represented a major ecological factor in sustaining a small *Gephyrocapsa* population here (D. Crudeli, Kiel). However, the evolutionary steps as a result of the final gateway closure at 2.7 Ma remain unknown.

Also unresolved is the precise timing of first and last appearances of planktonic organisms commonly used for biostratigraphy in ODP cores. The data available so far indicate no major differences in timing before and after the closure, as pointed out by D. Schmidt (London) and H. Kinkel (Kiel), except for the first occurrence of *G. truncatulinoides* (2.5–2 Ma) in the South Pacific, which gradually spread westward into the Atlantic. Present uncertainties may derive from biostratigraphy and age models that have too coarse of a resolution, but this will improve with new high-resolution sediment cores now available from both sides of the gateway (ODP Leg 202). A previously unknown biodiversity among selected coccolithophores has been shown for the early Pliocene, which supports classical biostratigraphy.

Impact on Ocean Circulation

How did the closure of this tropical seaway affect global ocean circulation patterns and heat transport? The use of climate models shows that the main water mass transport in the upper ocean has been directed from the Pacific into the Atlantic despite trade winds blowing in the opposite direction (U. Mikolajewicz, Hamburg). The reason for this unexpected behavior lies in the different sea surface elevations. Because of the density contrast of the underlying water column, the Pacific sea surface is 10–20 cm higher than the Atlantic. The resulting pressure gradient induces "downhill" flow. Flow rates depend on the sill depth with >10 Sv ($=10^6 m^3/s$) for a 700-m-deep passage reducing to ~5 Sv for a sill depth of 100 m (A. Schmittner, Kiel). New model results with higher vertical resolution suggest that in a shallow surface layer (10 m) the transport may have been seasonally reversed (from the Atlantic into the Pacific; M. Prange, Bremen).

Reduced inflow of fresher Pacific waters leads to increasing salinities in the North Atlantic, higher surface water densities, and increased formation of NADW. This implies that the closure intensified northward heat transport. Indeed, epibenthic $\delta^{13}C$ records and better carbonate preservation in the Atlantic after 4.6 Ma indicate increasing influence of NADW. A mega-hiatus (lack of sediments) in the eastern low-latitude Atlantic (ODP Leg 108) around the same time (4.5–3.8 Ma) has been interpreted as a superconveyor (stronger NADW or Antarctic Bottom Water (AABW) incursion than today) with strong bottom currents (M. Sarnthein, Kiel). New reconstructions from the North Atlantic reported by G. Bartoli, M. Sarnthein, and M. Weinelt (Kiel) show warmer interglacials by 2–3°C and increased NADW flow after 2.85 Ma, just prior to the final closure, confirming increasing ocean heat transport.

The regime of deep-water formation, however, was probably different from today. In the Nordic and Labrador Seas, where today freshly ventilated deep water leads to good carbonate preservation, carbonate concentrations were much lower throughout the Pliocene. Thus, the formation rates and fate of deep water during the seaway closure remain to be quantified in future studies combining proxy records with ocean-climate models.

Impact on Northern Hemisphere Glaciation

How could a warmer North Atlantic trigger the glaciation? At first glance, this seems to be a paradox. However, warmer temperatures will also lead to increased snowfall at high altitudes. So far, though, no model could simulate glacial inception due to changes in ocean heat transport triggered by the closure of Panama alone.

Another hypothesis suggests that intensified moisture supply to high latitudes increases Siberian river runoff, Arctic stratification, sea ice, and albedo, eventually leading to cooling and glacial inception. However, climate models suggest a small effect of increased NADW on high-latitude precipitation (U. Mikolajewicz), and so far there are no proxy records for the evolution of salinity in the Arctic. However, this issue will be addressed with new sediment cores from the ongoing IODP Arctic Coring Expedition (ACEX) 302.

Other forcing mechanisms invoked for the glacial inception are changes in orbital parameters and atmospheric CO_2 concentrations. Increasing amplitude variations of Earth's axis tilt with respect to the ecliptic led to enhanced maxima and minima in the seasonal insolation. In fact, changes in orbital parameters have a much larger effect on the perennial snow cover distribution than changes in ocean heat transport in models of intermediate complexity (A. Klocker, Bremen).

However, similar configurations of Earth's orbit also occurred well before and well after 2.7 Ma. This suggests that the climate system must have been preconditioned by some other process. Experiments with a zonally averaged atmosphere-ice sheet model forced with varying orbital parameters simulate the inception of glaciation around the correct time only if atmospheric CO_2 is decreasing, as reported by M. Crucifix (Exeter, U.K.). Reconstructions of past CO_2 levels, however, do not support this theory, indicating relatively stable CO_2 concentrations between 200 and 400 ppmv (parts per million by volume) back to the Oligocene (25 Ma), although the uncertainty leaves some room for speculations.

How did the reorganization of the ocean circulation associated with the gateway closure influence the carbon cycle and hence atmospheric CO_2? This was identified as another pressing issue that needs to be addressed with future modeling of the coupled climate-carbon cycle system.

The Pliocene Closure of the Panama Gateway and its Effect on Ocean Circulation, Climate and Evolution workshop was held 11–12 June 2004, in Kiel, Germany.

Acknowledgments

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—A. SCHMITTNER, M. SARNTHEIN, H. KINKEL, G. BARTOLI, T. BICKERT, M. CRUCIFIX, D. CRUDELI, J. GROENEVELD, F. KÖSTERS, U. MIKOLAJEWICZ, C. MILLO, J. REIJMER, P. SCHÄFER, D. SCHMIDT, B. SCHNEIDER, M. SCHULZ, S. STEPH, R. TIEDEMANN, M. WEINELT, AND M. ZUVELA

Education and Outreach for the International Polar Year

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If the 65 educators, scientists, and media specialists who gathered at the "Bridging the Poles" workshop in Washington, D.C. last June have their way, a semitrailer truck labeled "Got Snow?" would traverse the country during the International Polar Year (IPY) of 2007–2009 loaded with polar gear, interactive activities, and a snowmaker.

We would significantly increase the number of Arctic residents—especially indigenous Alaskans—with Ph.Ds. We would build exchange programs between inner city youths and polar residents. Polar exhibitions would open at natural history and art museums and zoos. And polar postage stamps, interactive polar computer games, national polar book-of-the-month recommendations, made-for-TV polar documentaries, and a polar youth forum would bring the poles front and center to the public's attention.

The goals of the U.S. National Science Foundation-sponsored workshop were to define strategies that will engage the next generation of polar scientists, engineers, and leaders, and inspire the general public. Through a series of plenary talks and roundtable discussions, the workshop focused on opportunities and needs for different education and interest levels, engaging diverse communities, leveraging the importance and excitement of polar science, and programs that could be featured nationally and internationally over the next 5 years. This was the first effort to develop an integrated education and outreach program that would maximize the potential of the International Polar Year.

Addressing All Levels of Education and Interest

Discussions about opportunities and models for engaging different education and interest levels emphasized capitalizing on the ability of polar themes to attract attention and the need for a broad, interdisciplinary approach. Levels considered included grades K–5, 6–12, undergraduate nonscience, undergraduate and graduate science majors, and the general public.

The poles can encompass multiple content areas ranging from science to culture and heritage. Workshop participants advocated capturing student interest and increasing science literacy in the general public by linking fascination with polar environments to improving science, math, reading, and other skills, while integrating polar themes into state and national standards. Polar science can engage diverse groups of learners in science as a human endeavor, the history and nature of science, science as inquiry, and science and technology. For advanced students, there are exciting opportunities in circumpolar distance learning with Web course delivery, as well as other programs such as the University of the Arctic's Ph.D. networks and collaborative field courses.

Beyond curricula, the use of polar themes in major competitions, such as the annual National History Day contest for middle and high school students, the National Ocean Sciences Bowl, and the Intel Science Talent Search Competitions for high school students, is a powerful way to expand attention on, and interest in, polar subjects. Other imaginative polar education and outreach ideas discussed at the workshop include polar-themed fast food restaurant meals, following people and animals as they go about "A Day in their Life at the Poles," and junior Arctic and Antarctic councils focusing on resolving international issues.

Engaging More Diverse Participation

Participants articulated the need of the polar science community to fully engage more diverse participation, including Arctic peoples and communities, underrepresented minorities, and women, as well as to broaden economic and geographic involvement. Communication with Arctic indigenous people must extend beyond the simple transmittal of science results. Programs must advance the next generation of researchers from the Arctic who will investigate and communicate northern issues to global populations and decision makers.

This theme of building capacity within communities, together with providing opportunities for personal contact and field experiences, making polar issues relevant at the community level, and developing mentoring and support systems, was articulated by workshop participants for each target group. Common interests can bring diverse communities together. For example, Matthew Hensen, the African American explorer who went to the North Pole with Robert E. Peary in 1909, played a crucial role in polar exploration at the turn of the last century. Yet, since his time, minorities have remained underrepresented in polar science. A first step toward making connections was taken at the workshop when the leader of the Earth Conservation Corps' Matthew Henson Center in Washington, D.C. established contact with Native Alaskans and together they began to plan exchange programs.

Unlike many of the other sciences, polar themes draw a nearly gender balanced audience, according to user data collected through the San Francisco Exploratorium's Web-based Live@Exploratorium, including "Science Live from Antarctica." Polar education efforts should build on this latent interest to develop a more gender-diverse community.

Just as it is important to engage diverse audiences, establishing connections among local scientists, educators, and informal outreach venues also can have long-lasting impacts. These connections build a network that sustains and encourages further engagement on all sides. Especially important is providing opportunities for field experiences for students, teachers, and the media; that can build life-long advocates of the poles.

Leveraging the Importance and Excitement of Polar Science

The workshop identified ways to leverage the importance and excitement of polar science, starting with what people think they know about polar organisms, and then moving beyond the charismatic megafauna of polar bears, penguins, and whales to look at the diversity of adaptations to life in extreme environments. Participants discussed ways in which major emerging science programs can be connected with meaningful education and outreach programming, and presented to the public as media events. Examples include the Antarctic Drilling Initiative (ANDRILL) in the