U12A-0012 1330h POSTER

Role of CO2, Insolation and Antarctic ice Sheet on the Interglacial Marine Isotope Stage 11

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The Marine Isotopic Stage 11 (MIS 11), around 400kyr BP ago, has been suggested as an analogue for a future climate under natural forcing because of the similar conditions of orbitally driven insolation during this interglacial period and the one covering the Holocene and the near future. There are many open questions about unusual MIS 11 climatic conditions (length of the interglacial, temperature, sea level, marine carbonate system), as recorded in different marine and continental records. The Antarctic Vostok ice core provides the only atmospheric record extending back to MIS 11 and we use it to discuss the Antarctic temperature, the atmospheric CO2 concentration and the ice sheet stability in the central part of East Antarctica during this interglacial.

The unique nature of the Vostok atmospheric record leads us to use the available Vostok data to drive climate and ice sheet models for MIS 11. A model of intermediate complexity (LLN-2D model) is used to investigate the sensitivity of the simulated MIS 11 deglaciation to the interplay between insolation and CO2. It is shown that the length of the simulated interglacial depends strongly on the phasing between these two climate forcings. We also investigate the response of the Antarctic Ice Sheet to changing climate through simulations performed with the LGGE 3-D ice sheet model. The results indicate that sea level stands during MIS 11 as high as 20 m. above present level, as suggested by different elevated marine terraces, cannot be explained, except by assuming that MIS 11 was very dry over Antarctica.

U12A-0013 1330h POSTER

Reassessment of Greenhouse Gas and Temperature Covariation From Vostok Ice Core Data

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A major and widely recognized failure of the Milankovitch theory is its inability to predict the 100 kyr beat of the ice ages, and the synchroneity of major climate changes in the northern and southern hemispheres. Feedbacks between climate and biogeochemical cycling, and corresponding changes in atmospheric chemistry, have had a significant role in these aspects of ice-age climate cycling. This was first demonstrated by Barnola and colleagues using gas and water-isotope data from the Vostok ice core. We have re-evaluated the relationship between temperature and greenhouse gas forcings as revealed by Vostok ice, by using a temperature reconstruction model that incorporates deuterium excess to correct for artefactual source region climate effects. The covariance of carbon dioxide and temperature is significantly stronger in our new reconstructions than in the original analyses. Covariance of carbon dioxide and temperature is estimated to have been 89% over the last 150 kyr, and 84% over the past 350 kyr. Furthermore, much of the obliquity-period variations in temperature originally inferred from the Vostok ice core are shown to be artefacts of changes in atmospheric transport characteristics associated with changes in the meridional insolation gradient.

U12B MC: 134 Monday 1330h

Oceans Within Our Solar System and Beyond

Presiding: **T V Johnson,** Jet Propulsion Lab**; J R Delaney,** University of Washington

U12B-01 1330h INVITED

Oceans in Planetary Satellites: An Historical Overview

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Planetary astronomers have long recognized that frozen water or frost, as well as more exotic frozen volatiles, may be a major constituent of the surfaces of bodies in the cold reaches of the outer solar system. The idea of large amounts of water, possibly in liquid form, in the interiors of satellites of the giant planets first began to be seriously discussed about thirty years ago (e.g. Lewis, 1971). Since then, theoretical debates concerning the likelihood of these global subsurface oceans have continued. Data from the Voyager encounters with Jupiter, Saturn, Uranus and Neptune (1979-1989) showed the satellites of the outer solar system to be geologically diverse with some showing evidence of young, resurfaced surfaces consistent with the possibility of a subsurface liquid layer. Tidal heating as a significant energy source for these bodies was also spectacularly confirmed with the discovery of volcanoes on Io. Results from the Galileo mission (1995 present) have provided significant support for the presence of a global liquid water layer in all three of the icy Galilean satellites, Europa, Ganymede, and Callisto. The current evidence from Galileo will be reviewed as well as prospects for future exploration.

U12B-02 1345h INVITED

Frequency and Nature of Planetary Water-Dominated Oceans

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There are three kinds of planetary water-dominated oceans. The first kind is Earthlike, where the overlying atmosphere has modest optical depth. In addition to requiring sufficient water, such an ocean requires a rather narrow range of circumstances to exist (sometimes erroneously labeled "the habitable zone"). Early Mars, and early Io and Europa may have had this kind of ocean but it could be rare as a long-term stable state. The second kind of ocean is kept warm by a dense atmosphere. For example, an earth mass body that retains a kilobar hydrogen atmosphere in interstellar space can have an ocean maintained by radioactivity alone. Bodies such a Uranus and Neptune can be thought of as grossly exceeding the necessary conditions (i.e., their water component is actually too hot to produce a well-defined ocean). There is no reason to suppose that this second kind of ocean is rare; it may well be the most common kind and a common occurrence throughout the universe. I will discuss the difficulties of detecting these bodies. A solid layer of ice caps the third kind of ocean. All large satellites are thought likely to have such an ocean; in the cases of Europa and Callisto the best evidence is the magnetic fields observed by the Galileo spacecraft and attributed to the induction response of a salty water layer. These water layers can be sustained by radioactivity alone in bodies the size of about Callisto or larger, while tidal heating is probably important in Europa. The antifreeze properties of ammonia may extend the domain of ocean worlds to considerably smaller bodies, perhaps including Triton and Pluto. In summary, oceans are probably common and diverse.

U12B-03 1405h INVITED

Sources of Water for Oceans on Planets

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Studies of D/H in the H2O carried by three Oort cloud comets have shown that such comets could not have contributed all of the water in the Earth's oceans. The extent of the cometary contribution depends on the value of D/H in water brought directly to the planet as hydrous minerals or adsorbed solar nebula H2O. That some cometary water was in fact delivered to the inner planets is strongly suggested by the value of D/H in Shergottite minerals when viewed in the context of other isotope geochemistry on Mars (Owen and Bar-Nun, FARADAY DISCUSSIONS 109, 453-462 (1998)). This scenario is also consistent with noble gas and siderophile element abundances on Earth. The identification of comet-produced water vapor around the aging carbon star IRC +10216 (Melnick et al., NATURE 412, 160-163 (2001)) provides concrete support for the widely held assumption that a cometary reservoir for the irrigation of inner planets should be a common feature of planetary systems throughout the galaxy.

U12B-04 1425h

Microbial Life in the Subseafloor at Mid-Ocean Ridges: A Key to Understanding Ancient Ecosystems on Earth and Elsewhere?

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Some planets and moons in our solar system were similar to Earth in their geological properties during the first few hundred million years after accretion. This is the period when life arose and became established on Earth. It follows that understanding the geophysical and geochemical characteristics of early Earth could provide insight into life-supporting environments on other solar bodies that have not evolved "Garden of Eden" conditions. Hydrothermal systems are primordial and their emergence coincided with the accumulation of liquid water on Earth. The interactions of water and rock associated with hydrothermal systems result in predictable suites of dissolved elements and volatiles. While the concentrations of these chemicals vary at different vent locations and were certainly different during the early Archaean, the overall chemical composition of aqueous hydrothermal fluid is likely to be the same because of the basaltic nature of oceanic crust. In present-day hydrothermal systems, those environments not contaminated by electron acceptors produced from pelagic photosynthesis would most closely mimic the earliest conditions on Earth. These conditions include the subseafloor and high temperature, anaerobic environments associated with hydrothermal systems. The microorganisms associated with these environments derive energy from sulfur, iron, hydrogen and organic compounds. New seafloor eruptions and diffuse flow vents provide unprecedented access to deep subseafloor microbial communities. For example, 12 new eruptions have occurred in the past 15 years including five in the Northeast Pacific. Hyperthermophiles were isolated from 5-30°C diffuse vent fluids from new eruption sites at CoAxial within months of the June, 1993 eruption and from the 1998 eruption at Axial Volcano, and from plume fluids within days of the February, 1996 eruption at the N. Gorda Ridge. The presence of such organisms in fluids that are 20 to 50°C below their minimum growth temperature indicates that they originated from a hot subseafloor habitat. Based on the 16S rRNA sequences and the RFLP patterns of the 500 base sequence between the 16S and 23S rRNA genes (intergenic spacer region), these heterotrophic archaea represent new species, and a new genus, within the Thermococcales (Summit and Baross, 1998; 2001). These isolates grow over an unusually wide temperature range and in low levels of organic material. While Thermococcus and Methanococcus species are the most commonly isolated species of hyperthermophiles from subseafloor biotopes, preliminary phylogenetic analyses based on 16S rRNA sequences of microbial communities in the diffuse flow fluids at new eruption sites show a high diversity of archaea that are not related to cultured organisms. Results to date support the hypothesis that subseafloor microbes associated with hydrothermal systems have nutritional, physiological and bioenergetic characteristics that reflect the physical and geochemical properties of their habitat. Moreover, we propose that deep-sea subsurface environments are analogs of ecosystems on other solar bodies. Thus, by examining the chemical and microbial ecology and energetics of the subsurface, and particularly the subsurface associated with hydrothermal systems, a framework for studying the prospects of extraterrestrial life can be developed. It is predicted that if there were life on other hydrothermally active solar bodies, the same energy sources would fuel microbial metabolism even though the molecular characteristics of these life forms may not resemble Earth organisms having identical metabolisms.

U12B-05 1505h INVITED

Standing Bodies of Water on Mars: A Review of Their Mode of Emplacement, Scale, Behavior and Fate

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There is clear evidence for standing bodies of water in different places and at different times in the history of Mars. The martian outflow channels debouched into the northern lowlands primarily in the Late Hesperian Period and their characteristics suggest to many workers that a large standing body of water, or ocean, was produced as a result. Characteristics of northern lowland deposits in the Early Amazonian Period suggest that by this time such an ocean was gone. What would be the fate of such standing bodies of water under climatic conditions similar to the present? The evolution of water loaded with sediments emplaced by outflow channel formation would include three phases. (1) Violent emplacement of warm water followed by a short period of intensive evaporation and convection. Water vapor would strongly influence the climate, at least for a geologically short time; when the water reached 277 K, boiling and intensive convection ceased and sediments were deposited. (2) Geologically fast (10^4years) freezing accompanied by weak convective water movement. (3) Sublimation of the ice lasted longer than freezing, but for a geologically short period. The rate and latitudinal dependence of sublimation, and locations of water vapor condensation, crucially depend on planetary obliquity, climate, and sediment veneering of the ice. Several observations support the hypothesis that the Late Hesperian Vastitas Borealis Formation is the sublimation residue of the ocean. Geological evidence has been cited to support a warm, wet era in the earlier Noachian Period (e.g., valley networks, degradation rates, etc.) and standing bodies of water under these earlier conditions have different origins and could have significantly longer residence times. Critical assessment of this evidence leads to several scenarios for the emplacement style, location and fate of water on early Mars, and the important transition to conditions similar to those of today. Candidate early Mars emplacement styles include: 1) pluvial, 2) sapping and groundwater recharge, 3) ice sheet meltback, 4) global hydrostatic equilibrium, and 5) cryospheric seal disruption. We examine evidence for these mechanism for formation of standing bodies of water in the history of Mars, and assess their fate. Examples range in age from Noachian to Late Amazonian.

U12B-06 1525h INVITED

Europa: Divining Water from Surface Geology

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Europa's surface geology as viewed by Galileo imaging suggests a thin brittle lithosphere above a warm (potentially salt-rich) ice layer that is at least in part convecting, in turn situated above a liquid water ocean. This configuration is consistent with thermal and geochemical modeling, and with Galileo magnetometer and NIMS results, which suggest that Europa may have a salty global-scale subsurface ocean at relatively shallow depths (20-30 km). Dynamical modeling and visible crater density suggests a surface age of 50 million years, implying that Europa is probably still geologically active today. Large shallow craters and even larger multi-ringed structures imply impact into low-viscosity (warm) subsurface material. The satellite's bright plains are criss-crossed by narrow troughs and enigmatic double ridges (paired ridges separated by a medial trough); a morphological sequence (and implied evolutionary sequence) exists from isolated troughs to doublet ridges to wider and more complex ridge morphologies. Troughs are inferred as widened fractures formed though tensile and shear failure in response to global stressing of the ice shell above liquid water. Several models exist to explain ridges, but the most likely is one in which localized shear heating triggers upwelling of warm ice along fracture zones. Triple bands are ridges with diffuse ruddy margins that may have formed through thermal alteration and/or partial melting of briny ice. Wider pull-apart bands represent complete separation and spreading of the icy lithosphere, in a manner broadly analogous to terrestrial sea-floor spreading. Europa's global lineament pattern implies that nonsynchronous rotation and orbital flexing ("diurnal" stressing) have worked in tandem to deform the surface. Diurnal stressing can explain Europa's extremely enigmatic cycloid ridge and fracture patterns, and may drive rapid strike-slip faulting along ridges. Because significant tidal amplitude is necessary to produce significant diurnal stressing, this argues strongly for a subsurface liquid layer, but does not constrain its depth. Extremely slow nonsynchronous rotation of the ice shell may drive shear failure in equatorial regions, and may have opened the satellite's pull-apart bands. Mottled terrain consists of pits, domes, dark spots, patches of smooth plains, and regions of chaos terrain. Chaos is characterized by fragmented blocks of the preexisting surface, some of which have translated a few kilometers from their original positions, in a dark hummocky matrix. Mottled terrain landforms suggest vertical deformation and disruption of the surface along with localized partial melting. Their formation has been interpreted as due to diapiric upwelling–the expression of solid-state convection of warm subsurface ice–predicted to occur within an ice shell tens of kilometers thick above liquid water. Warm ice diapirs can circulate material between Europa's ocean and shallow levels within the ice shell, and can trigger local partial melting of briny ice, potentially creating near-surface biological niches. Europa's astonishing geology and its biological potential makes the satellite a high priority for future orbital and landed exploration.

U12B-07 1545h INVITED

Tidal Dissipation in the Rocky Core Drives Oceanic Processes on Europa

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Chaos-type features on the surface of Europa are interpreted as melt-through structures formed by rotationally confined, steady and/or episodic oceanic plumes that rise to the base of the ice shell from magmatically heated hydrothermal venting regions on the seafloor. The ocean is assumed to be weakly stratified due to turbulent convection generated by heating from below and cooling from above. Seafloor heating, maintained by tidal dissipation in the rocky interior, generates an estimated global heat flux of 8.7×10^12 W and limits the mean ice thickness to 2 to 5 km. For seafloor heat sources with radii, r, that are less than the ocean's deformation radius ND/f (where N is the buoyancy frequency, D is the water depth, and f is the magnitude of the Coriolis parameter), the diameters of chaos-type regions are expected to diminish from O(100 km) within equatorial regions to O(10 km) at high latitudes. Provided there is sufficient time before refreezing, ice rafts in large melt-through regions are imbedded in episodes of preferentially anticyclonic circulation, corresponding to clockwise motions in the northern hemisphere. Although the Coriolis effect may be unimportant for short-lived ice-raft displacements characteristic of most melt-through regions, rotation is of fundamental importance in determining the formation and physical dimensions of the melt regions.

Roughly 10^21 j were required to melt the ice in the 100 km diameter Conamara Chaos region. For a steady, localized heat flux of 10^11 W ($\sim$ 1% of the global heat flux), it would take about 1000 years for the initial melt-through to occur, an acceptable timescale for steady state venting systems on earth. As on Earth, the Europan ocean may also switch between weak and strong stratification modes over geological time scales. At times of strong stratification, most convective plumes would not penetrate to the base of the ice and heat would be trapped in the lower portion of the water column. Continued bottom heating and surface cooling would eventually weaken the upper ocean stratification, allowing thermal plumes to again penetrate to the base of the ice cover. The stratification-destratification cycle would be completed by the formation of low salinity, upper ocean melt-water during times of increased under-ice melting.

U12B-08 1605h INVITED

Oceans on Titan: Past, Present and Future

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Titan is Saturn's largest moon, and the second largest natural satellite in the solar system. Composed of half rock by mass, the satellite probably contains enough radiogenic material so that, when combined with accretional heating, differentiation into a rocky deep mantle and icy upper mantle is likely. Unlike its near twins in size and density, Jupiter's Ganymede and Callisto, Titan is endowed with a dense atmosphere, mostly nitrogen but with an admixture of methane. The methane is photolyzed in the upper atmosphere to make, with the participation of nitrogen, a complex mixture of hydrocarbons and nitriles. This in turn forms aerosols which descend to the surface, and have accumulated over time as solids and liquids. If photochemistry has occurred in a steady state fashion over Titan's history, perhaps hundreds of meters of liquid hydrocarbons (expressed as equivalent depth of the layer) reside in the upper crust and on the surface. The Cassini-Huygens mission will search for such liquids and assess the extent of photochemistry through time. Titan's overall history with respect to surface liquids may be complex. In the distant past accretional heating could have sustained a deep layer of mixed water-ammonia liquid as a kind of cryogenic magma ocean. Liquid hydrocarbons have come and gone on the surface through time to the present. In the distant future, when the Sun becomes a red giant star, Titan could once again possess a water-ammonia surface ocean.

U12B-09 1625h

TITAN - A NEW LABORATORY FOR OCEANOGRAPHY

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Saturn's giant moon Titan has a thick (1.5 bar) nitrogen atmosphere, and quite probably large expanses of liquid hydrocarbons on its surface. The physical processes in these lakes and seas will open new vistas on oceanography and limnology.

Although the Voyager-era paradigm of a deep, global ocean is ruled out by radar and infrared data showing that at least part of Titan's surface is icy, the photochemical arguments that originally led to the proposal of hydrocarbon oceans still apply. Even if the methane in the atmosphere is being resupplied by delivery from the interior, the ethane produced by photolysis would still accumulate to form large deposits on the surface. The near-infrared maps of Titan's surface from the Hubble Space Telescope and groundbased adaptive optics consistently show a number of dark (in fact, pitch-black!) regions that are strong candidates for hydrocarbon seas. These could be up to some 500km in extent.

Titan promises to be a new laboratory for oceanography. Like in meteorology, many ocean processes are better parameterized than they are understood, and thus the different physical circumstances on Titan may shed new light on them. Titan has a lower gravity and its ocean fluids are of lower density, perhaps of lower viscosity (depending on solutes and suspended material) and probably rather more likely to cavitate. The ratio of atmospheric density to ocean density is much larger on Titan than on Earth, suggesting that liquid motions will be well-coupled to surface winds (although the distance from the sun is such that the energy in such winds is likely to be low.)

Titan is also subject to strong tidal forces (the equilibrium tide due to Saturn's gravity is some 400x larger than that of the moon on Earth.) Although the 100m tidal bulge stays almost fixed because Titan rotates synchronously, the eccentricity of Titan's orbit leads to significant libration and variation in the tidal strength. The 500km seas allowed by the IR data may yet have a 2m tidal amplitude. The long period of tidal excitation, however, means that tidal resonances are unlikely to occur.

The NASA-ESA Cassini/Huygens mission will arrive in late 2004, and deliver the parachute-borne Huygens probe to Titan's surface in early 2005, taking images during its descent. The Cassini orbiter during its 4 year tour will fly by Titan some 45 times, taking SAR and altimeter data with a multimode radar, and observing the surface with optical and near-IR sensors. Future missions to Titan are already being contemplated, and might involve such platforms as helicopters or blimps.

U21A MC: 134 Tuesday 0830h

Plate Tectonics and Self-Organization I

Presiding: **D L Anderson,** California Institute of Technology**; D Bercovici,** Yale University

U21A-01 0830h

Plate Tectonics as a Far-From-Equilibrium Self-Organized Dissipative System

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A fluid above the critical Rayleigh number is far from equilibrium and spontaneously organizes itself into patterns involving the collective motion of large numbers of molecules which are resisted by the viscosity of the fluid. No external template is involved in forming the pattern. In 1928 Pearson showed that Bnard's experiments were driven by variations in surface tension at the top of the fluid and the surface motions drove convection in the fluid. In this case, the surface organized itself AND the underlying fluid. Both internal buoyancy driven flow and flow driven by surface forces can be far-from-equilibrium self-organized