EUG XI

Symposium CC03

From Icehouse to Greenhouse: Records, Causes and Consequences of Extreme Climatic Events in the Last 750 Ma

Convenors

Greg Price
Anne Nedelec
Gilles Ramstein
Joe Meert
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Wednesday AM Session

CC03 : WEam01 : G2
Snowball, Slushball and Oddball Glaciations: Comings and Goings of Precambrian Ice Sheets

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Some of the most bizarre climatological events in Earth history may have occurred during the Neoproterozoic interval from 750-600 Ma. It has been suggested (most recently by Hoffman et al., 1998) that the Earth endured extreme changes from icehouse to greenhouse states in a relatively short interval. These so-called Snowball Earth events are now fairly well-entrenched in the geologic literature, but their existence has not been clearly substantiated by the available data. Furthermore, although there is considerable speculation about how these events might have been triggered and how the earth may have recovered, there is considerable debate amongst those who favor low-latitude icehouse models. Paleomagnetic data are unique in that they can help distinguish between two of the models for Neoproterozoic low-latitude ice sheets. The high obliquity model (e.g. G.M. Williams et al., 1998 and D.E. Williams et al., 1998) requires that these 'oddball' glaciations are restricted to low-latitudes (less than ~45 degrees). In contrast, the Snowball Earth hypothesis is mostly untestable through paleomagnetic studies since any paleolatitude can be fit to the snowball model. Unfortunately, the current paleomagnetic arguments are not well-constrained as they are primarily derived from either post or pre-glacial rocks and the paleolatitudes of the glacial rocks are inferred. The second problem is a lack of rigid temporal constraints on the glacial deposits. A snowball earth should yield broadly similar ages for the glaciogenic units whereas a high-obliquity model would favor asynchronous glaciations. Evans (2000) provides a useful review of both the geochronologic and paleomagnetic controls on these glacial episodes, but fails to reach a decisive conclusion in favor of either model. While the snowball Earth model has enjoyed a popular revival in the past several years, the model has not been rigorously tested. This is in part due to the fact that the glacial rocks are generally poor recorders of magnetization and are seldom interbedded with dateable rocks. Of the two hypotheses (snowball versus high-obliquity), the high obliquity model is much easier to test since a single well-dated high latitude pole would falsify the hypothesis. The snowball Earth hypothesis is much more difficult to test, but one refutation of the hypothesis would be to show that the glaciations are not synchronous. Other possible tests that might invalidate the Snowball Earth hypothesis are ambiguous (e.g. lack of glacial deposits on some cratons, slow deposition of 'cap-carbonates'). Indeed, if adequate geochronologic control is not available for these glaciogenic rocks it may render the snowball hypothesis untestable.

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CC03 : WEam03 : G2
The Fundamental Proterozoic-Cambrian Transition in Earth's Icehouse Modes

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Paleomagnetic data from Phanerozoic glaciogenic rocks or time-equivalent units from the glaciated continents indicate, not surprisingly, an abundance of glacially derived deposits at high paleolatitudes. This paradigm persists from modern times back to the Paleozoic Era, when both the south pole and the glacial centers migrated in tandem across Gondwanaland (Caputo and Crowell, 1985). A diametrically different pattern is observed for Proterozoic glacial deposits: low paleolatitudes are abundant, and not a single example is identified poleward of 60 degrees (Evans, 2000). This trend, although derived from a limited number of the total glacially derived formations, is common to both Neoproterozoic and Paleoproterozoic Eras. Despite limitations in dating and regional correlations, glaciogenic rocks from the latest Neoproterozoic in near-equatorial Australia and the early Cambrian in near-polar west Africa appear to support a sharply defined Proterozoic-Phanerozoic dichotomy. Earth's geomagnetic field has been modeled as primarily dipolar and axially aligned for the entire available paleomagnetic record, extending into the Archean (Kent and Smethurst, 1998).

What happened, then, at the Proterozoic-Cambrian boundary to cause a fundamental paradigm shift in Earth's climate system? The High-Obliquity hypothesis (Williams, 1993) invokes a rapid un-tilting of the planetary orbital axis, but does not directly address how or why this may have occurred. A reincarnation of the Snowball Earth hypothesis (Hoffman et al., 1998) includes speculation that the evolutionary development of bioturbation impeded efficiency of sedimentary carbon burial, and hence drawdown of atmospheric carbon dioxide, from Cambrian times onward. An alternative, or additive, corollary of the Snowball model is that long-lived supercontinents, driven to the equator by true polar wander, may induce glaciation via their effects on planetary albedo and geochemical cycles. Intriguingly, both Paleoproterozoic and Neoproterozoic episodes of low-latitude glaciation appear to be preceded by long-lived supercontinents, and the only Phanerozoic supercontinent, Pangea, was ephemeral.

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CC03 : WEam04 : G2
From Rodinia to Gondwanaland: Growth of the Pacific Ocean and Destruction of the Mozambique and Brazilide Oceans

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We present in a series of global Mesoproterozoic to Early Palaeozoic palaeoreconstructions the history of the breakup of the Rodinia supercontinent and assembly of Gondwanaland based on palaeomagnetic information supported by geological and geochronological evidence. Australia, Antarctica, India, Kalahari and NE Madagascar are likely to have been part of West Rodinia, and Amazonia, West Africa and La Plata part of East Rodinia, adjacent to the eastern margin of Laurentia. According to available palaeomagnetic data, the Congo/Sao Francisco block may not have been part of Rodinia. Palaeomagnetic data from Australia and South China suggest that the breakup of East and West Rodinia started at ca. 780 Ma, forming the Palaeo-Pacific Ocean. Palaeomagnetic data from Laurentia suggest at least two possible interpretations of the late Neoproterozoic. In one interpretation, Laurentia underwent a rapid poleward rotation between 615 Ma and 580 Ma, which may have been associated with renewed breakup and extension along the Australian-Antarctic margin. In the other, the high-latitude palaeomagnetic data from Laurentia is regarded as suspect, and Laurentia remained at relatively low latitude throughout the Vendian.

Gondwanaland formed by the convergence of the Amazonia-West African block and Australia-Antarctica-India closing the Brazilide and Mozambique Oceans between 630 and 540 Ma. Final amalgamation of Gondwanaland may not have been completed until the earliest Cambrian, at approximately the same time as subduction was initiated along the Pacific margin of Antarctica. Current palaeomagnetic information from Laurentia permits high latitudes for eastern Laurentia at ca. 570 Ma, but low latitudes by the late Early Cambrian suggest that the early Iapetus ocean was a few thousand km wide by 530 Ma.

The earliest glaciation Neoproterozoic glaciation (ca. 750 to 720 Ma, Sturtian-Rapitan) is coeval with Rodinian breakup, but the second major glacial interval (ca. 610 to 600 Ma, Marinoan-Ice Brook) does not appear to be associated with any marked breakup of continents.

CC03 : WEam05 : G2
Paleogeography of Neoproterozoic Gondwana: Implications of Paleomagnetic Poles from South America and West Africa

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Recent works have shown that the assembly of continental landmasses forming supercontinents can promote strong changes in the global climate pattern. For instance, the hypothesis of low latitude glaciations in the end of Neoproterozoic (the icehouse) is related in time to the formation of the Gondwana supercontinent after the breakup of Rodinia (Hoffman et al., 1998). However, the configuration and the timing of supercontinent assembly, as well the hypothesis of another supercontinent (Pannotia) formed before the separation of Laurentia from Gondwana margins, are constrained by quite a few high quality paleomagnetic poles, mostly from eastern Gondwanan cratonic units (see Meert et al., 1995, 2000). In this way, we present new Neoproterozoic paleomagnetic poles obtained in granitic and volcanic rocks from South America and West Africa (Trindade, 1999; Ponte-Neto and Ernesto, 1999). These poles are analysed together with other poles for the same region in-between 750 and 500 Ma for which a rigorous selection was performed using the criteria defined by Van der Voo (1990). The best paleomagnetic poles for these areas allowed the construction of a coherent apparent polar wander path (APWP) from 600 Ma to 500 Ma after rotation of South America to Africa in a pre-drift configuration. Paleomagnetic poles older than 600 Ma are scattered suggesting that the assembly of west Gondwana was attained around 600 Ma. The APWP for South America and West Africa in-between 550 Ma and 500 Ma is in accordance with Meert's APWP for the East Gondwana, confirming that the Gonwana supercontinent was completely assembled during this time. Two poles from Africa, Dokhan volcanics and the Northern Cameroon volcanics, with ages at ca. 580 Ma, define the 600-550 Ma segment of the West Gondwana APWP. The hypothesis of Pannotia supercontinent, comprising Gondwana, Laurentia, Baltica and Siberia, is reinforced by the coincidence of these two poles and the 580 Ma mean paleomagnetic pole for Laurentia rotated to the Pannotia configuration.

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CC03 : WEam06 : G2
Paleomagnetism of Upper Riphean Rock Complexes of the Polar Urals

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Polar Urals is one of the few areas in the Uralian orogenic system with widespread pre-Paleozoic complexes. In particular, in the basin of Manyuku-Yaha R. (Engane-Pe Range), the most coherent sections of the Upper Riphean are represented by formations of island arc affinities [1]. For paleomagnetic studies we chose the Bedamel Fm., which is divided into two sequences: the lower volcanic/sedimentary and the upper volcanic/pyroclastic. The microphytological analysis reveals acritarchs of Late Riphean and Early Vendian age [data by A. Veis]. U/Pb measurements were done on plagiogranites from a block of the ophiolite affinity in the Enganepe complex. The two coarsest zircon fractions yielded concordant ages in the range of 670±5 Ma [2]. Stepwise thermal cleaning to 650°C and NRM measurements on a cryogenic magnetometer (at Munich University) reveals a complex NRM pattern. Only

10 samples of magmatic rocks out of 40 and 11 out of 43 sedimentary samples yielded meaningful high-T NRM vectors. For the whole set of samples, this high-T component shows a much greater consistency in the stratigraphic than in geographic reference frame. Sedimentary rocks yield vectors with both positive and negative inclinations. For 38 samples the NRM behaves in a rather different manner: Zijderveld's plots are incomplete (not tending to the origin of coordinates), and after each cleaning step NRM vectors plot on the great circle. In the stratigraphic reference frame the circles intersect at virtually the same point as the vectors of high-T components from the most stable samples. The high-T component (Dec=233.4°, Inc=54.4°, k=22.6, a95=6.4°, stratigraphic frame) can thus be adopted as meaningful, having close-to-original age. The computed paleomagnetic pole coordinates are: F = 19.9°, L = 20.4°, dp = 6.3°, dm = 9.0° (south pole). In constructing the polar wander path for the Eastern European continent between 700 and 600 Ma we used only those paleomagnetic measurements that passed the fold test [3, 4, 5]. At ca. 700 Ma the Eastern European continent, based on these poles, was situated at the equator, its Uralian margin facing northeast. By the Riphean/Vendian boundary, this continent had drifted into medium southern latitudes, its Uralian margin then running roughly E-W. It is around that time that along that margin, at 35±7° latitude, the Polar Urals island arc originated. Based on these data, the Late Riphean-Vendian arc may have been nearly parallel to the Uralian margin of the Eastern European continent. Considering the existence of the Circum-Siberian ophiolite belt and subduction-related rock assemblages, as well as paleomagnetic data from the Siberian craton, a major intercontinental oceanic basin at least 2,000 km wide with two active continental margins must have existed between 1 Ga and 570 Ma between Baltica and Siberia. By 600 Ma, the Baltica continent had drifted into high latitudes of the southern hemisphere. This work was supported by the RFBR, Project nos. 99-05-64857, 99-05-64050 and IGCP Project 440.

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CC03 : WEam09 : G2
Theme and Variations on Neoproterozoic Cap-Carbonate Sequences: Signatures of Snowball Earth Events

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Post-glacial cap carbonates are unique to the Proterozoic and their existence offers insight on the nature of ice ages at that time. Forming regionally continuous dolomite or limestone layers meters to tens of meters thick, they abruptly terminate glaciogenic intervals without evidence of significant hiatus. Cap carbonates have unusual primary structures and negative $\delta^{13}C$ values, consistent with a carbonate-dominated global carbon burial flux. We suggest that this was driven by alkalinity input to the ocean due to intense carbonate and silicate weathering in the transient ultra-greenhouse aftermaths of snowball events. We illustrate the intra- and interbasinal variability in thickness, lithologic sequence and isotopic profile of Neoproterozoic cap carbonates with examples from Namibia (N1-2) and Mauritania (M). The ultimate thickness of a cap-carbonate sequence is determined by water depth, after glacio-eustatic rise, which is a function of the subsidence rate and duration of the preceding snowball event. Cap-carbonate sequences are thicker in areas of active crustal stretching (N1) and young passive margins (N2) than in cratonic settings (M). Lithologic sequence depends critically on when carbonate production begins relative to glacio-eustatic rise. This in turn depends on when the surface ocean reaches critical saturation (with carbonate solubility increased by high CO_2 levels). If sedimentation began during glacio-eustatic rise, a basal transgressive sequence tract will be present (N2); if carbonate production is delayed, the transgressive tract will be absent and the sequence will be exclusively regressive (N1). Isotopic profiles ($\delta^{13}C$, $\delta^{18}O$, $\delta^{34}S$, $\delta^{44}Ca$, $^{87}Sr/^{86}Sr$) are also variably base-truncated, depending on the onset of carbonate production relative to the post-glacial history of factors like fractional carbon burial, atmospheric CO_2 drawdown, meltwater injection, water temperature, carbonate and silicate weathering fluxes, ocean mixing, etc. We interpret a marked decrease in $^{87}Sr/^{86}Sr$ and coincident increase in Sr/Ca+Mg and $\delta^{34}S$ (Hurtgen et al., 2000) 60-80 m above the base of N2 as representing the mixing of cold, saline, deep water and a warm surface layer dominated by glacial melt water. In contrast, cratonic sequences (M) are top-truncated because accommodation is limited, and the occurrence of synsedimentary barite crusts in supratidal tepee breccias may signify mixing of marine and meteoric groundwaters. High $\delta^{34}S$ in barite (Shields et al., 1999) implies that sulfate was supplied by marine waters deprived of riverine sulfate input during prolonged snowball events.

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CC03 : WEam10 : G2
The Mid Cretaceous Siberian Continental Interior Climate Paradox: Geological Facts and AGCM Results

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Middle Cretaceous palaeoclimate data were collected from the continental interior Vilui Basin, eastern Siberia. Lower Cretaceous strata are dominated by stream channel sandstones interbedded with tabular bodies of autochthonous coals, stacked palaeosols, and lacustrine shales. Middle to Upper Cretaceous successions (Timerdyakh Formation and the basal Linde Formation) show upwardly increasing channel cannibalism and reworking of floodplain and levee deposits. Bank collapses led to the inclusion, in basal channel deposits, of mud and peat balls, slumped tree bases, fossil drift wood and log jams, and reworked siderite concretions, reflecting the former interfluve conditions. Sites of plant growth are represented by rare immature palaeosols with rooting and weak destratification. Palaeobotanical remains were preserved in abandoned channels and in rhythmical low-discharge interbeds of seasonally active channels. Preservation of delicate floral components indicate limited downstream transport prior to deposition. Palaeoclimate data include qualitative palynological and clay mineralogical evidence of the general floodplain conditions, and quantitative palaeobotanical evidence of near-channel conditions. The palynoflora reflects a very high floral diversity (more than 190 taxa) which, together with presence of thermophilic taxa (probable palm pollen), indicates warm and humid climate conditions. Preliminary mudstone clay mineral analyses show domination of kaolinite, again indicating warmth and humidity. Physiognomic analysis of Timerdyakh Formation leaves using the CLAMP technique (173 site dataset) yielded a mean annual (MAT 13.2±3.4°C(2σ)), warm month mean (WMMT 21.5±3.8°C), and cold month mean (CMMT 5.7±5.2°C) temperatures, the length of the growing season (7.5±1.8 months), growing season precipitation (1033±878 mm), mean monthly growing season precipitation (151±98 mm), three consecutive wettest months precipitation (579±380 mm), three consecutive driest months precipitation (337±240 mm), mean annual relative humidity (75.9±17.6%) and enthalpy (313±7.4 kJ kg^{-1}). CLAMP data show that the most pronounced mid-Cretaceous continental interior region in the Northern Hemisphere, Vilui Basin, appears remarkably equable with CMMT well above freezing and WMMT around 22ºC. This is in marked contrast with the wide annual range of temperatures seen in continental interiors today, and with predictions of both UGAMP AGCM (MAT 4.3ºC, WMMT 34.4ºC, CMMT -17.8ºC) and Hadley Centre AGCM (MAT 0.5ºC, WMMT 27.3ºC, CMMT -20.9ºC). Another difference is that CLAMP predicts a moderately wet regime year round, whereas the AGCMs suggest a very dry regime. In conclusion, the Vilui Basin AGCM climate reconstructions clearly do not match those from foliar physiognomy, palynology and clay mineralogy, and may indicate that the mid-Cretaceous atmospheric dynamics were significantly different to those of the Present and those incorporated into AGCMs. The reasons for the model-data mismatch may be due to a lack of a dynamic ocean and appropriate vegetation feedbacks, but we must understand this paradox before we can have full confidence in future global warming predictions.

CC03 : WEam11 : G2
High Resolution Analysis of Cyclicity in Upper Triassic Lake Sediments in the UK

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Upper Triassic sediments in SW Britain exhibit cyclic alternation of red, green and grey lacustrine mudstones. Thin section fabric studies suggest that much of the brecciation and microfabric observed is consistent with a soil-zone or dry lake basin setting. Magnetostratigraphy has correlated precisely, for the first time, three sections, from the basin margin at Lavernock Point (South Glamorgan), St. Audrie's Bay (North Somerset) and the basin centre at Haven Cliff (South Devon). This detailed correlation indicates that the green/grey to red mudstone cyclicity cannot be directly matched between sections, and it is possible that the green colouration is largely diagenetically controlled. A well-defined normal polarity magnetozone at St. Audrie's Bay is now correlated with the E18n magnetozone in the Newark Basin of N. America (Kent et al., 1995), a section exhibiting sedimentary cyclicity which has been tied to climatic changes brought about by the Earth's orbital cycles. The parameters described below are being investigated to see whether a climatic signal is recorded in the UK Triassic sediments.

Magnetic parameters (NRM intensity, susceptibility, IRM acquisition) show strong cyclicity related to the red/non-red mudstone cyclicity, with the red mudstones dominated by a high abundance of coarse and fine-grained haematite. The green and grey mudstones tend to be more magnetite dominated, but still occasionally contain significant amounts of coarse-grained haematite.

Although there is no clear relationship between grain size and lithology, there is evidence of metre-scale cyclicity in silt modal grain size. This variability may be representing changes in palaeo wind strength. At St. Audrie's Bay modal silt grain size is coarsest at the top of the studied sequence where dolomite is most abundant, suggesting a possible link between substrate grain size and authigenic dolomite formation.

Stable isotope work on the St. Audries Bay samples shows that dolomite from the upper samples (see above) have $\delta^{18}O$ values around 0 to +1‰ and $\delta^{13}C$ values +1 to +2.3‰, broadly consistent with known Triassic evaporitic-continental dolomite compositions. In contrast, calcite isotopic compositions from lower in the same sequence have $\delta^{18}O$ values around -4 to -5‰, and $\delta^{13}C$ values of around +0.50‰. The offset between the dolomite and calcite $\delta^{18}O$ values could be consistent with well-known mineral dependant fractionation - assuming both minerals precipitated from the same fluid - combined with some evaporative fractionation. However, this is being followed up on mixed mineralogy samples. The difference in $\delta^{13}C$ values is more likely to be environmentally controlled and may be related to evaporative effects in the parent water. These data cast considerable doubt on the meaning of the whole rock stratigraphic trends published previously.

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CC03 : WEam12 : G2
Milankovitch Cyclicity and Sea-Level Change in the Late Eocene-Early Oligocene Interval; Evidence for Rapid and Extensive Antarctic Glaciation at 33.5 Ma?

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We have studied an expanded succession of coastal marine, estuarine and lacustrine sediments of Late Eocene-Early Oligocene age in the Isle of Wight southern England. In this succession, a strong Milankovitch signal (406, 100, 40 and weaker 20Ka) is recorded from the relative abundance of neoformed illite and illite-smectite, which formed in soils by seasonal wetting and drying. The orbital timescale is calibrated using magnetostratigraphic, and to a lesser extent, biostratigraphic data. Combined orbital calibration and sequence stratigraphic analysis allows us to identify the major control on sea-level as the 406Ka long eccentricity cycle, which caused sea-level to fluctuate by 10-15 m. These values have been determined from the amount of incision at observed at sequence boundaries on a regional scale. Minor sea-level changes of 1-3 m were controlled by obliquity. The position of the Early Oligocene heavy $\delta^{18}O$ event can be inferred in the Isle of Wight from its magnetostratigraphic proxy (base of chron 13n). We have determined the sea-level fall at this level to be approximately 12 m, close in magnitude to drops associated with the preceding 3 Late Eocene 406 Ka sequences. This evidence does not support recent estimates of a 50-90 m sea-level fall within the Early Oligocene based on the calculation that a significant part of the oxygen isotope event was caused by rapid Antarctic ice buildup. Rather, orbitally driven sea-level changes throughout the Late Eocene-Early Oligocene, although probably glacioeustatic in origin, remained of similar magnitude.

CC03 : WEam13 : G2
From Icehouse to Greenhouse: Clues from Permian Benthic Faunas of the Southwestern Tethys for the Interpretation of Extreme Climate Changes

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Carbonate-secreting Permian benthic faunas of the Sultanate of Oman reflect climate changes with a previously unknown high resolution and will help to calibrate paleoclimate studies as well as paleogeographical reconstructions.

Upon Permo-Carboniferous glaciogenic deposits (Al Khlata Formation), mixed carbonate-siliciclastic sediments of the Sakmarian (Lower Permian) Saiwan Formation display a biotic composition similar to the heterozoan association (as defined by James 1997) and are interpreted as products of a non-tropical carbonate factory. Fossiliferous float- and rudstones contain brachiopods, bivalves, gastropods, bryozoans, and crinoids indicating cold-water conditions and lack tropical skeletal grains. Cross-bedded sediments from subtidal carbonate dunes and beds with horizontal bedding, which represent tempestites, are both typical for cold-water shelves. Following an unconformity, fluviatile, lacustrine, and shallow-marine siliciclastic sediments with tree trunks (Gharif Formation) were deposited and overlain by a thick limestone-marl sequence of the Khuff Formation and the lateral equivalent Saiq Formation (Wordian-Roadian age, Middle Permian). Cold-water taxa from Gondwana represent only 12.5% Khuff brachiopod genera, while tropical Tethyan taxa make 44% (Angiolini et al. 1996). By contrast, carbonates of the Saiq Formation are dominated by tropical rugose corals, calcareous algae, large alatochonchid bivalves, and fusulinids. The Upper Permian depositional sequence of the Arabian platform is terminated by mudstones indicative of a Sabhka environment and points to an constant increase in aridity.

Reef communities rimming the margin of the Arabian platform and isolated seamounts exhibit changes with respect to reef types, framework preservation, and biotic composition. Lower Permian benthic communities are biodetrital bryozoan reefs comparable to cold-water buildups of the Northwest Pangean shelf, while Middle and Upper Permian sponge and coral communities constructed reefs resembling tropical counterparts of the equatorial Tethys. These reefbuilders and calcareous algae exhibit close biogeographic relationships with faunas from the South China block, Kitakami terrane, and Tunisia representing the optimum of Permian tropical reefs.

Sedimentological and paleontological data contradict previous interpretations of the whole depositional sequence as tropical and point to a constant change in climate from icehouse to greenhouse conditions. The mechanisms responsible for the amelioration of climate need further examination: Generally, the proposed 15° northward migration of Pangea (e.g. Ziegler & Gibbs 1996) caused during the Permian a drift of the Arabian plate in the tropical realm and increased the diversity of benthic communities. On the small scale, the contemporaneous occurrence of cold-water faunas (Khuff Formation) and tropical faunas (Saiq Formation) may result from temperature stratified carbonates on a ramp setting.

Angiolini L, Bucher H, Platel JP, Roger J, Broutin J, Baud A, Marcoux J & Al Hashmi H, *Permophiles*, **29**, 62-63, (1996).
James NP, *SEPM Spec. Publ*, **56**, 1-20, (1997).
Ziegler AM & Gibbs MT, *Permophiles*, **29**, 44-46, (1996).

CC03 : WEam14 : G2
Late Triassic-Jurassic Clay Mineral Suites of the Fennoscandian Border Zone and the East European Platform: Effects of Pangean Seasonality, Aridity and Humidity

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Late Triassic and Jurassic detrital clay mineral suites of the Fennoscandian Border Zone show high detrital smectite and/or kaolinite contents, moderate illite contents, and low chlorite contents compatible with expected mid-latitude warm equable greenhouse conditions. Norian seasonal aridity promoted the forming and preservation of haematite cemented arkoses and smectite-dominated playa lake clays (smectite >> kaolinite). The Rhaetian opening of internal seaways into Pangea triggered the transgression of the Central European basin areas. On their NE margin (the Fennoscandian Border Zone) this led to humid onshore conditions, which supported peat accumulation, meteoric flushing, palaeosol development and deep weathering of the crystalline basement. Due to stripping of the regoliths, kaolinite is a dominating detrital mineral in the receiving sedimentary basins from the Rhaetian and throughout the Jurassic (kaolinite > illite >> chlorite & smectite (I/S)). Minor clay mineralogical variations within the humid climate Rhaetian-Jurassic successions were controlled by the pronounced block-and-graben-relief hydrology, the depositional environment and the eodiagenetic conditions, rather than by climate. In deltaic and alluvial coal-bearing successions the detrital clay mineralogy is very constant (kaolinite “ illite >> chlorite). Conversely, in shallow marine deposits the quantitative variation is notable (kaolinite “ illite > variable smectite >> chlorite). The marine environments preserved the original clay mineral composition better, but was potentially subjected to influx of exotic reworked mud. Gypsum and caliche nodules associated with traces of smectite ambiguously indicate increased aridity in Late Jurassic times. Analysis of mainly marine Middle to Late Jurassic clay mineral suites of the East European Platform (Lithuania and NE Poland) clearly shows an upwards increasing smectite content at the expense of kaolinite. This implies an increasing aridity in the sediment source areas, and shows that the major arid belt to the south and west of the study region migrated north- and eastwards. The sedimentary environments of the East European Platform were better suited than those of the Fennoscandian Border Zone to preserve and homogenise the Late Jurassic arid climate signal (i.e., the smectite content), due to the passive tectonics (low relief, minimal hydrological effects), the marine depositional environments, and the extensive sediment mixing during sediment transport. However, the role of bathymetric effects, i.e., selective clay mineral sorting during marine transport due to sea level change, are not yet clear.

Wednesday PM Session

CC03 : WEpm25 : G2
Planetary Greenhouses and Icehouses: Oxygen Isotope Record

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Understanding past climatic variability is essential if we are to quantify the impact of natural vs. anthropogenic phenomena within the context of global change issues as well as the role climate may have played in extinctions, sedimentation regimes, patterns of oceanic circulation and related phenomena. The causes, onsets and recurrence of ice ages (icehouses) and warm climates (greenhouses) over the last 600 million years, with major ice ages during the Neoproterozoic, Ordovician/Silurian, Carboniferous/Permian and Cenozoic, each comprising shorter term advances and retreats (stadials/interstadials), are enigmatic. Our newly acquired $\delta^{18}O$ experimental database for Phanerozoic carbonates (Veizer et al., 2000) correlates well with the paleoclimate record, having a periodicity of 135 Ma for the apexes of icehouses. It also argues for large tropical sea surface temperature oscillations that are at odds with temperatures calculated with an energy balance model forced by paleo-CO_2. If such is the case, then atmospheric CO_2 was not the principal driving force of climate on geological timescales for at least 1/3 of Phanerozoic times and/or reconstructed paleo-CO_2 concentrations do not reflect natural levels.

Veizer J, Godderis Y & Francois LM, *Nature*, **Dec. 7**, (2000).

CC03 : WEpm26 : G2
A Major Carbon-Cycle Perturbation in the Middle Jurassic and Accompanying Climatic Change Adduced from the Land-Plant Record

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The Middle Jurassic Ravenscar Group of Yorkshire, England, yields one of the best studied Jurassic land-plant records in the world. Carbon-isotope analyses of wood fossils shows that two major atmospheric isotopic excursions occurred during deposition of these rocks, a negative excursion at about the Aalenian-Bajocian boundary and a positive excursion in the late Bajocian. The sharp negative excursion is associated with an apparently abrupt change from charcoal to coal as the dominant mode of preservation in the succession. A gradual reversion to charcoal dominance follows and is maintained through the remainder of the section. Multivariate analysis of leaf morphology in relation to climate-sensitive lithology indicates a warm period approximately coincident with the negative excursion, and analysis of leaf stomatal indices show similar evidence of high pCO_2 although the precise stratigraphic relations remain to be determined. Similarities can be seen with isotopic curves derived from European marine successions and, in common with other examples, there exists a relationship between isotopic excursion and sea-level change: the negative excursion occurred during relative sea-level rise and the positive excursion occurred during relative sea-level fall. Unlike many other prominent Phanerozoic carbon-isotopic excursions there is as yet no large igneous province reported from this time, nor significant mass extinction, and the origin of the isotopic fluctuations is not yet known.

CC03 : WEpm27 : G2
Observations of the Neoproterozoic Glaciogenic Rock Record: Implications for Palaeoclimate (Snowball Earth) Models

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Neoproterozoic Earth System changes are purportedly some of the most dramatic to have occurred during geological time. This is embodied in the present incarnation of the Snowball Earth hypothesis, which envisages a near global expanse of frozen oceans during inferred epochal-duration zeniths of frigid climatic conditions. Such extreme Neoproterozoic climates are indicated by evidence for ice sheets in low-latitudinal settings. In addition, occurrences of Neoproterozoic iron-stones and $\delta^{13}C$ excursions in marine carbonates which cap glaciogenic rocks are being utilised as verification of globally frozen oceans. But does the rock record actually provide evidence in support of the elegant, geochemical conceptual models now being advanced as confirmation of Snowball Earth conditions? Our work on the cap carbonates exposed in Namibia reveals an astonishing variability in their $\delta^{13}C$ signatures. Taken at face value, these data imply carbonate precipitation during times of oceanic dynamism rather than from a monotonously mantle-dominated and biochemically stagnant hydrosphere. Furthermore, Neoproterozoic glaciogenic rocks typically consist of many tens to several thousands of metres of glaciomarine sediments, which include repetitive ice-rafted deposits. Such facies require dynamic ice sheets and transport of glacial debris associated with surface runoff and thermo-haline circulation in (semi)open oceans. In addition, where present, the overwhelming majority of Neoproterozoic iron-stones occur interbedded in glaciogenic rocks far below the stratigraphic surface marking the inferred rapid transition from icehouse to greenhouse states. This indicates that they are products of syn-glacial, basinal conditions and thus can not be used as evidence for re-aeration of a long-lived (millions of years) globally anoxic ocean. These observations must be accounted for in any geological model offered as an explanation of Earth System conditions during the wonderfully intriguing Neoproterozoic.

CC03 : WEpm28 : G2
$\delta^{13}C$ Data from Neoproterozoic Cap and Associated Dolostones, Varanger, Finnmark, N. Norway

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A preliminary study of $\delta^{13}C$ from Neoproterozoic dolostones from Varangerhalvøya-Tanafjord, northernmost Norway, was undertaken for comparing with other regions. Varangerhalvøya is bisected by the WNW-ESE trending Trollfjorden-Komagelva Fault (TKF), with c. 200 km syn-Caledonian dextral strike-slip displacement. The zones bounding the TKF are linked stratigraphically, but detailed correlations are uncertain. South of the TKF, two diamictite horizons have been recorded - the Smalfjord (lower) and Mortensnes Formations, separated by the Nyborg Formation. Reliable age constraints are not available; c. 650 Ma presumed diagenetic ages have been proposed for Member B of the Nyborg Formation (Rb/Sr, K/Ar and Ar/Ar) whilst the earliest Ediacara fauna found in N. Norway lies c. 150 m above the Mortensnes Formation. $\delta^{13}C$ analyses of the 100 m interbedded clastic-dolostone Grasdalen Formation, the youngest unit underlying the sub-Smalfjord Formation unconformity, gave a $\delta^{13}C$ range of +0.8‰ to +6.1‰ (n=7; all data compared to PDB) and on presumed Grasdalen Formation clasts within the Smalfjord Formation a $\delta^{13}C$ range of +2.9‰ to +6.8‰ (n=6). The Smalfjord Formation (0-60 m) is overlain by a 50 m cap of stromatolitic dolostone, intraformational dolostone breccias and thinly interbedded dolostones and red shales (Member A, Nyborg Formation; $\delta^{13}C$ values of -5.7‰ to +2.0‰, n=24). This is overlain by 400 m of shales/sandstones (Members B-D) and then by 25 m of sandstone with two thin dolostones (Member E; $\delta^{13}C$ range -8.7‰ to -7.6‰, n=5). The Mortensnes Formation (0-50 m), which unconformably overlies the Nyborg Formation, has no cap-carbonate. Based on the criteria used in the `cladistic´ division of Neoproterozoic diamictites, the Smalfjord Formation cap-carbonate seems more comparable to Marinoan type cap-carbonates, with $\delta^{13}C<0‰$, a pale colour, a presumed low organic content and abundant sheet cracks (forming pseudo-stromatolitic-domes and -tepee structures), and a very small-scale crystal fan at one locality. Since it overlies the lower diamictite in Varanger, this suggests that either there were three glacial events (the Mortensnes Formation thus being the third, post-Marinoan event) or the factors used to make the `cladistic´ division are mutually inter-related, rather than mutually independent and so give spurious correlations. North of the TKF, 1.5 km of supra-/inter-tidal dolostones/limestones, with associated clastics, form the Båtsfjord Formation. Limited $\delta^{13}C$ analyses gave values of -4.2‰ to -2.0‰ (n=6). The Båtsfjord Formation, which is older than the Grasdalen Formation, overlies 2.5-3.5 km of deltaic rocks and underlies 1.5 km of shallow marine sediments, forming an apparently continuous succession, within which no diamictites or significant unconformities have been recognised. These negative $\delta^{13}C$ values (from limited data) are comparable to Neoproterozoic cap-carbonates values, although negative values are also found below the upper diamictite in several areas. Thus, in summary, the Varanger region, like so many others, has direct lithological evidence of only two diamictite (glacial) events, but indirectly suggests there may have been more.

CC03 : WEpm29 : G2
Isotopic and Stratigraphic Evidence for a Neoproterozoic Cap-Carbonate in the Grusdievbreen Formation, Norhteastern Svalbard

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Post-glacial cap-carbonate sequences sharply overlie Proterozoic glacial deposits and equivalent surfaces. Regionally continuous dolomite or limestone layers form the base of the cap-carbonate sequences and are often easily identified based on their unusual lithology and negative $\delta^{13}C$ composition. Specifically predicted by the snowball earth hypothesis to be widespread in the aftermath of ice ages, cap carbonates point to glacial events in the stratigraphic record, even where glacial deposits are absent. The isotopic character of these cap carbonates also sheds insight on the nature of the ice ages they terminate and the geochemistry of the waters immediately following glaciation.

Here we report isotopic and stratigraphic data from a ca. 35 m thick, shallowing-upward parasequence which overlies a conspicuous erosional unconformity in the Neoproterozoic Grusdievbreen Formation, northeastern Svalbard. Though no glaciogenic deposits have yet been found atop this sequence boundary, the overlying sequence may be a post-glacial cap carbonate. Not only does this parasequence stand out amidst the bracketing stratigraphy (mid-shelf limestones with rare evidence of exposure), but also $\delta^{13}C$ shows a sudden negative shift of ca. 8‰ across the sequence boundary, dropping to a nadir of -1.5‰ ca. 20 m above the base of the parasequence. Occurrence of cm-scale crystal fans (inorganic sea floor precipitates) within the parasequence further allies this “cap” to other known Neoproterozoic cap carbonates. Oxygen isotopes in the Grusdievbreen “cap” are exceptionally coherent and identical within analytical error in two sections separated by 135 km. A continuous rise in $\delta^{18}O$ from -11 to -8‰ in the lower 10 to 20 m of the parasequence is consistent with the mixing of cold, saline, deep water with an isotopically light surface water layer fed by glacial melt waters. This hypothesis can be tested using other isotopic systems (e.g. $\delta^{34}S$ and $^{87}Sr/^{86}Sr$).

Supported by the Arctic Natural Science Program (NSF) and the Astrobiology Institute (NASA)

CC03
Extreme Climatic Events in the Last 750 Ma

CC03 : WEpm30 : G2
Rapid, Orbitally Controlled Global Sea-Level Change during the Cenomanian: Evidence for Antarctic Ice during the Late Cretaceous?

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The Cenomanian Stage (100-95 Ma) provides an excellent opportunity to test the extent, synchroneity and causes of sea-level changes, on account of the very high resolution ammonite biostratigraphy (cosmopolitan taxa), the widespread onlap of marine Cenomanian deposits on continental margins, and the development of an orbitally tuned timescale for the stage. The precise synchroneity of 10 sequences and component systems tracts between the Anglo-Paris Basin (Europe) and the Cauvery Basin, SE India, can be demonstrated from detailed stratigraphic study of ammonites of the families Acanthocerataceae and Turrilitaceae, supported by inoceramid bivalves. These 3rd order sequences(sensu Vail) are precisely coincident with the 400Ka Milankovitch cycle in orbitally tuned successions. We have generated a sea-level curve for the expanded Cenomanian succession of the Cauvery Basin, based on outcrop sequence analysis. This proximal sandy succession was deposited in a coastal plain environment; during sea-level lows the plain was incised by tidal channels, and flooded by shallow coastal seas during transgressive episodes. Extensive soils developed during highstands. Relative sea-level changed by 5-20 m on the frequency of the long eccentricity (406Ka) cycle, and 1-2 m on the scale of precession (20Ka). Rates of both rise and fall are rapid (150-200 m/Ma), and suggestive of glacioeustatic control. We therefore propose that even at the time of the Cenomanian thermal maximum high level ice was present in the interior of the Antarctic continent. The area of ice needed to generate these sea-level changes was equivalent to 1-3 times that of the present Greenland ice sheet.

CC03 : WEpm33 : G2
Cretaceous Model-Data Comparisons: How Bad are the Models?

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The problem of cold winter temperatures during the Cretaceous period is one of the most serious model-data disagreements. The geological data, and especially paleobotany, indicates that continental interiors were near or above freezing even during the coldest months. Climate models do not predict this. They suggest that the coldest winter temperatures are -15ºC or colder. However, much of the discussion of this model failure has lacked scientific rigour in that there has been little to no attempt to quantify the uncertainities in the modelling procedure, or in the proxy climate data. We have performed a careful analysis of model and data estimates and conclude that for many locations, the models and data do agree within the inherent uncertainities. The major exception is in central Eurasia (the Vilui basin), where the model and data are still in serious disagreement even after taking into account the error bars. Our results highlight the importance of including a full error analysis in any rigorous model-data study.

CC03 : WEpm34 : G2
Modeling the Eocene/Oligocene "Greenhouse" to "Icehouse" Transition

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The Paleogene glaciation of East Antarctica and the associated decline in high southern latitude temperatures marks a fundamental reoganization of the global atmosphere-ocean-cryosphere system. The opening of oceanic gateways around Antarctica and declining atmopsheric CO_2 are often cited as the climatic forcings responsible for the late Eocene-early Oligocene cooling trend. However, the relative importance of these forcing factors to Paleogene climatic change are not well understood. Nor is it clear what forcing/feedback mechanisms are directly responsible for the sudden growth of East Antarctic ice around 33.7 Ma. To asses the role of atmopsheric CO_2, orbital parameters, and paleogeography in the initiation and growth of glacial ice on Antarctica, we used the GENESIS version 2 Global Climate Model (GCM), asynchronously coupled to a finer-grid 3-D dynamical ice sheet model. The model scheme was applied to a new global paleogeographic reconstruction of the earliest Oligocene, including a pre-glacial reconstruction of Antarctic topography. A suite of coupled GCM-icesheet-CO_2 sensitivity tests (ranging from 8x to 1x present values of atmospheric CO_2) and long (41,000 yr) asychronously coupled GCM-ice sheet integrations show that pCO_2 and orbital parameters may be the most important forcing factors in the rapid build up of East Antarctic ice ~33.7 Ma. Our results suggest a threshold in the long term decline of Cenozoic atmospheric CO_2 (around 2x present CO_2) was crossed near the Eocene/Oligocene boundary, at which southern polar warmth could no longer be maintained and significant permanent ice was allowed to accumulate on Antarctica. Orbital variations punctuated a growing sensitivity of high-latitude ice sheets as atmospheric CO_2 declined. These results imply that the opening of the Drake Passage and Scotia Sea region, leading to the organization of the Antarctic Circumpolar Current, may have contributed to additional Antarctic cooling in the Neogene, but may not be responsible for the initiation of widespread glacial conditions in the earliest Oligocene.

CC03 : WEpm35 : G2
The Late Devonian Faunal Crisis as Seen Through a Numerical Model of the Geochemical Cycles

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The Upper Devonian faunal crisis represents one of the most prominent mass extinction events in Earth history, particularly affecting the low latitude shallow-water ecosystems. This crisis spread over 1 to 3 million years with a major extinction pulse being identified at the Frasnian-Famennian (F-F) boundary (367 my). Coincident with this crisis are two periods of intense sedimentation of organic matter (Kellwasser horizons). Both periods of enhanced organic carbon burial correspond to major positive excursions in surface water $\delta^{13}C$ reflecting maximum amplitudes of +3 permil. The first excursion (lasting 0.5 my) coincides with a minor transgressive-regressive episode. The onset of the second excursion (lasting 1.2 to 1.8 my) is observed within the latest Frasnian and correlates as well with a sea-level rise. However, a prominent sea-level fall is observed in the earliest Famennian.

Several qualitative hypotheses have been proposed in order to integrate these observations into a unique model. Here we present quantitative results of a numerical model of the global biogeochemical cycles of carbon, oxygen and phosphorus. The model includes ten oceanic boxes divided up into two oceanic basins (Paleotethys and Panthalassa). The ocean module is coupled to an energy balance climate model. Supply of elements to the ocean by weathering of continental rocks is simulated according to the calculated climate. The sea-level is a forcing function. A simplified hypsometric model is used to estimate the change in the volume of the oceanic reservoirs together with the change in the area of surface reservoirs during sea-level fluctuations. The evaporation over each surface reservoirs is parameterized as a function of their areas and temperature, to allow calculation of their salinity content. Starting from an hypothetical steady-state, the model is run through 5 million years, covering the F-F transition.

Preliminary simulations show that the $\delta^{13}C$ excursions are related to increased deliveries of continental P to the ocean by increased runoff, itself triggered by increased evaporation over transgressive coastal reservoirs. Global burial of organic carbon increases by 45%, essentially due to increased productivity in surface waters, but also due to decreased oxygen content of bottom waters related to increased salinity. The second excursion is followed by the weathering of platform carbonates exposed during the regression phase, increasing the mean $\delta^{13}C$ of river water, and maintaining high seawater $\delta^{13}C$ values. The climatic response is a global cooling of 2ºC during the transgression phases, since exospheric carbon is buried into sediments and pCO_2 is declining. Then pCO_2 is increasing during the regression since the weathering of platform carbonates releases carbon into the exospheric system, and the global mean temperature increases by 7ºC. These climatic changes in combination with changes in surface water salinity may have especially affected the shallow water ecosystems.

CC03 : WEpm36 : G2
Simulation of the Permo-Carboniferous Glaciation with a GCM Forced by a Global Paleogeographic Reconstruction

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The climatic evolution of the Earth is punctuated by cold episodes, which may have lead to ice sheet formation. The insolation forcing factor is able to explain Quaternary glaciations. This period has been extensively studied using climate models. For the previous main glaciation, which occurred during the Permo-Carboniferous period, the causes are not so well defined. Very few climatic simulations have been performed in order to understand these causes. The other major difficulty consists in the validation of the simulated climate, data are relatively sparse in comparison with Quaternary ice age. We performed a set of simulation using an atmospheric general circulation model in order to investigate the climatic impact of a Permo-Carboniferous paleogeography (295 Ma). The simulated climate is in good agreement with data. A polar climate is simulated at high latitudes in Gondwana, which is consistent with the geologic data. Moreover, a large ice cap can be maintained if we prescribe a large ice sheet over South Gondwana. These simulations of Permo-Carboniferous climate suggest that paleogeography is a major climate forcing for this period. At last we use the outputs of the AGCM experiments to force the LGGE Ice sheet model in order to study the response of this model under such a climate. The simulated ice sheet will be compared with its extent derived from geological data.

CC03 : WEpm37 : G2
Earth's Climate and Glaciation Changes over Phanerozoic Time: Comparison of two Different Modeling Approaches

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We present two approaches to model climate variations over Phanerozoic time and compare our results to the geological evidence.

In the first model pCO_2 variations are calculated according to Freeman and Hayes (1992) using isotopic differences between marine carbonates and marine organic matter, obtaining a compilation of own measured values and further literature data. Temperatures needed for the calculations are obtained from oxygen isotopic records of marine carbonates. The record of calculated temperatures matches well to the occurrence of Phanerozoic glaciations.

The pCO_2 variations that we calculated using the first model are compared to those obtained from a geochemical model of the long-term carbon cycle. This second model is based on carbon isotope mass balance equations for marine carbonate and marine and, for the first time, also terrestrial organic matter which was measured at BGR.

Calculated pCO_2 variations agree very well between both models and show a good agreement with ancient carbonate abundance. However, pCO_2 variations do not always parallel with the temperature record. This indicates that carbon dioxide is not necessarily the driving force within the Phanerozoic climate system.

For purpose of comparison, we then reconstructed changes in the land/ocean ratio and of vegetation cover since Devonian times to calculate variations of the Earth's albedo. In geologic history, cooling took place in times when large continents were shifted to high latitudes and the Earth's albedo was high. The building of ice caps as during the Permo-Carboniferous increased the Earth's albedo and in turn cooled down the Earth. In addition, the cooling must have lowered the atmospheric content of water vapor and hence reduced the total greenhouse effect. Using an energy balance approach, we calculated changes of the Earth's temperature and deduced changes of the atmospheric water vapor content. We found that during cool periods high pCO_2 was more than compensated by low water vapor content of the atmosphere. We therefore infer from our model that over long geological periods continental drift is the driving force for climatic variations.

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CC03 : WEpm38 : G2
Is High Obliquity a Possible Mechanism to Explain Tropical Glaciation at Neoproterozoic?

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One possible mechanism that can be invoked to explain low-latitude glaciation in the Palaeoproterozoic era is an high value of the Earth obliquity. On one hand, Williams et al. (1998) have suggested that "climate friction" could have caused the obliquity to shift from high values to low values (as for present day). On the other hand, Laskar et al. (1993) have shown that for low obliquity values, the effect of the moon implies stability of the Earth obliquity in a narrow band (as for present day), but the behaviour is chaotic for high obliquity (from 60 to 90°). We have investigated using the response of an AGCM high obliquity scenarios for explaining tropical glaciation. Because high obliquity enhances seasonality, it can lead to the melting of ice cover, therefore, it is important to test the consistency between 90° obliquity scenario and Proterozoic glacial climate.

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Wednesday PO Session

CC03 : WEpo01 : PO
Astronomical Forcing in Late Eocene Sediments: Using XRF Data from ODP Leg 171B Site 1052

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Recently the astronomically calibrated geological timescale has been extended to the base of the Oligocene (Shackleton et al, 1999). Here we present a new relative age calibration of sediments of late-Middle Eocene (39.5 Ma) to Late Eocene age (35 Ma) that were obtained from deep-marine sediment cores during ODP Leg 171B from Site 1052. We analyse elemental ratios of Fe and Ca as a proxy for calcium carbonate content, obtained by using an X-ray Flourescent Scanner (XRF). Our data match very well with other proxy data (magnetic susceptibility and colour reflectance) but show a significantly higher signal-to-noise ratio and a more consistent hole-to hole agreement. The data obtained hence allow the construction of a more accurate composite depth scale.

The data display a strong orbital signal that shows variability at all major Milankovitch frequencies. We use the eccentricity driven amplitude modulation of precession to put our record onto a relative timescale, assuming that the 400 kyr eccentricity cycle has been stable at that time (Laskar, 1999). The exact nature of the orbital signal might be subject to revision pending further calculations, but the consistent relationship between the different orbital frequencies present in the data suggests new ages for Magnetochrons C16, C17, and C18 that will refine the magneto-stratigraphic timescale created by Cande and Kent (1995). Our astronomical calibration suggests that the relative durations of these magnetochrons has not changed significantly, although the absolute ages might be ~200 ky younger than on the Cande and Kent timescale. Our study should allow a better time control for high-resolution studies over the late Eocene time interval.

Shackleton NJ, Crowhurst SJ, Weedon GP & Laskar J, *Phil. Trans. R. Soc. Lond. A*, **357**, 1907-1929, (1999).
Laskar J, *Phil. Trans. R. Soc. Lond. A*, **357**, 1735-1759, (1999).
Cande SC, Kent DV, *J. Geophys. Res*, **100**, 6093-6095, (1995).

CC03 : WEpo02 : PO
Discovery of the Northernmost Gondwanian Evidence of an Upper Ordovician Glacier: Southern Turkey

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Although evidence for the latest Ordovician (Hirnantian) glaciation is well documented from western Africa to Arabia, the maximum extent of grounded ice in northern Gondwana has always been elusive. Recent investigations in the Taurus chain of southern Turkey now demonstrate that glaciers extended northwards much farther than previously expected.

The existence of glacially-related sediments in southern Turkey was suspected following the identification of conglomeratic sandstones at the Ordovician-Silurian boundary. However these conglomerates were generally considered as forming the basal part of the Silurian formations. Closer examination of several lower Palaeozoic successions in Anamur, Silifke, Adana and Mardin provinces locally demonstrates the presence of the glacier itself in late Ordovician times. The glacial nature of the deposits is shown by numerous isolated pebbles and cobbles of exotic origin (granite, orthogneiss, aplite, rhyolite, quartz) which are embedded in diamictites or sandy shales, and exhibit typical planar striated faces.

The extension of grounded ice in southern Turkey is demonstrated by a striated pavement upon structureless diamictites that contain in situ striated pebbles bearing the same orientation. In Adana province, the latest Ordovician succession suggests a prograding submarine fan in contact with ice (glacial maxima), followed by dropstone-bearing distal glaciomarine shelf deposits (deglaciation). Trilobites of early Ashgill age are present in the underlying siltstones, and overlying black shales are dated as Llandovery by means of graptolites. These relationships suggest that, in southern Turkey, only a minor (if any) sedimentary hiatus is associated with the glacio-eustatic sea level lowstand.

This sequence displays strong affinities with coeval glacial successions in North Africa (Algeria, Morocco), Iberia and Sardinia. Global reconstructions generally agree in locating southern Turkey along the Egyptian-Libyan coastline. At present, southern Turkey appears to be the northernmost part of the Gondwana platform covered by late Ordovician ice.

CC03 : WEpo03 : PO
The use of Organic Matter and Clay Minerals Study to Define the Selli Event (Konhora Fm., Western Carpathians, Slovakia)

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Lower Aptian sediments of the Konhora Formation in the Rochovica section represents an intercalation of black shales in pelagic majolica-type limestones of the Pieniny Klippen Belt. Detail C-isotope stratigraphy allows to determine the "Selli Event" in the anoxic part of the Konhora Fm (Lintnerova et al. 2000). Three transgessive/regressive cycles are recognizable in ca 6-7 meters thick sequence. Sedimentary organic matter sensitive reflects these small-scale fluctuations. Study of quantitative and qualitative distribution of organic matter in the Konhora Fm. provides the following identifications: 1. Organic matter (OM) content reaches the maximum (TOC = 0.68 - 0.71 wt%) in the initial phase of transgessive cycle. Increase of TOC content due to transgression is even more expressed under anoxic conditions of sedimentation (TOC = 1.39 - 3.23 wt%). 2. Two main types of sedimentary OM are present in shales: marine (alginite) and terrestrial kerogene derived from land vegetation (vitrinite, liptinite, fusinite, sporinite). Anoxic part of study section is markedly anomalous from other parts, having a considerably greater quantity of both OM types, smaller forms of alginites, prevalence of liptinite over vitrinite, predominance of "relative fresh" (non-oxidized particles) above oxidized terrestrial OM. 3. Lowermost OM contents occur in condensed parts of the section, linked with maximum flooding surfaces (TOC = 0.45 wt%). Characteristic feature is occurrence of pure inertinite and fusinite particles (oxidized OM). Microscopical observations fit well with the Rock-Eval pyrolysis data, giving the lower HI values in the condensed parts (44 mg HC/g Corg) and substantially higher HI values in other parts (296 mg HC/g Corg). Within the sequence studied, no systematic variations in contents of clay minerals have been observed. The clay fractions consist of discrete illite + I/S, corrensite-like mixed-layered chlorite/smectite or chlorite/vermiculite and chlorite with average ratio of 7:2:1. The more expressive change of smectite content in I/S was recorded in bed 409: an abrupt increase from 20-25% S to 40-50% S, which persists up to bed 437. This is also accompanied by a decrease of degree of ordering in the I/S from R1 to R0 or R0.5. As the burial effect is not considered here, sudden change of I/S properties might be related to the change of provenance of siliciclastic material and/or change of climatic conditions during deposition. The Konhora Formation "anoxia" gave rise due to the Lower Aptian greenhouse. During the greenhouse, the nutrification and overproduction, as well as continental runoff of terrestrial plants led to oxygene depletion and anoxicity of water mass. Therefore, the organic matter study closely correlate with positive isotope excursion within the Selli Event of the Konhora Fm.

Lintnerova O, Michalik J, Wissler L, Biron A & Kotulova J, *Slovak Geol. Mag*, **6, 2-3**, 231-233, (2000).

CC03 : WEpo04 : PO

Depositional Rate of the Cap Carbonates in Namibia Estimated with Periodicity Analysis of Rhythmites

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Carbonate that cover Neoproterozoic glacial deposites are called 'cap carbonate' and regarded as an important key in understanding the Neoproteozoic glacial event. The Neoproterozoic 'snowball' Earth hypothesis predicts that the depositional process of the post-snowball 'cap carbonate' is different from a normal postglacial carbonates. The trigger of recovering from the 'snowball' condition should be the greenhouse effect of highly concentrated carbon dioxide derived from volucanoes, which in turn was finally deposited as cap carbonate. Therefore the depositional rate of the cap carbonate in the beginning of the deposition should be very large. Previous works inferred that the rate of cap carbonates is relatively large based on the observation of fine laminatinos, crystal fan and tubular gas escape structure in cap carbonates. In this study the depositional rate is estimated by rhythm analysis of fine lamination in cap carbonate. In the Neoproterozoic Namibia sequence the glacial deposits and cap carbonate occur twice. The upper cap carbonate (Maieberg formation) has 250 m thick rhythmite part at the sampling point (platform). At the lower part of Maieberg formation facies change from stromatolitic dolomite with gas-escape structure to rhythmite. The specimen at the lowest part of the rhythmite has mm order lamina and cm order bands. Each of cm order band in turns contain around 15 bands of mm order. the thickness of cm order bands show alternation of thicker and thinner. This combination of periodicity may be interpreted as a result of sediment deposition in neap-spring cycle of tide. The depositional rate is 25 cm/year, a very large value. The value is representative of the depositional rate over the platform at the beginning. The lower cap carbonate (Rasthof formation) has 15 m thick rhythmite part at sampling point. The rhythmite part was continuously sampled. We recognised two periodicities in its chemical profiles. The simplest explanation for the occurrence of these cyclicities is that each bed is verve and the depositional rate is 1 mm/year. The reason that the depositional rate is smaller than that of upper cap carbonate may be its depositional depth. On the other hand, the estimated recovery times of the delta carbon isotope excursion in both cap carbonates show similar value (10^3-10^4 year).

CC03 : WEpo05 : PO

Palaeoclimatic Development Recorded in Palaeozoic Sediments of SW Gondwana

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The paleogeographic constellation of Southwest-Gondwana changed dramatically during the Late Palaeozoic. From Late Carboniferous to the Early Permian the region was affected by the Panafrican glaciation which is documented by widespread glacial deposits. The Upper Permian is characterised by rising temperatures. Glaciers retreated and the global sea level rose as documented by deposition of organic rich sediments (transgressive black shales) in several late Palaeozoic Basins of the world.

Permo-Carboniferous Sediments from the Karoo- (Rep. SA) and Paraná-Basin (NE Brazil) as well as from adjacent basins were sampled. Our multiproxy geochemical investigation is aimed towards a better understanding of the temporal and spatial variation of sediment and organic matter source regions, of the sedimentary environment and of the burial history of the Lower Permian glacial/postglacial transition.

Different geochemical proxies can be used to distinguish between marine/lacustrine environments or to specify the salinity or redox state of the sedimentary environment (Jones et al., 1994; Dean et al., 1989; Nesbitt et al., 1982 and Hughes et al., 1995). It has to be emphasised that no single proxy can be regarded as a definitive indicator of conditions of sedimentation. Only a combination of different independent signals can lead to sufficient reliability in the reconstruction of paleoenvironments. The independence of proxies used in this study was achieved by using sediment main and trace element composition, oxygen isotopes of silicate fractions, carbon and oxygen isotopes of sedimentary carbonate, carbon and nitrogen isotopes of organic matter, organic matter elemental analysis, organic matter Rock Eval pyrolysis and extractable biomarker composition.

First results of geochemical, O- and C- isotopic compositions as well as organic geochemical characteristics demonstrate clear time dependent variations and allow correlations between the different proxies. Climatic changes as well as variations in the depositional environment are documented by the correlated variations of Rb/K, CIA, V/Cr, $\delta^{18}O$ of the silicate fraction, $\delta^{13}C$ of organic mater and different organic geochemical parameters.

Hydrogen and oxygen indices determined by Rock-Eval pyrolysis of roughly time equivalent sediments from the Paraná-, Karoo- and Kalahari-Basin indicate accumulation of predominantly marine derived organic matter. Changes between a marine or more terrestrial affected sedimentary environment can be observed across the sampled profile of Paraná sediments by the use of different geochemical proxies.

The question still remains, whether the observed signals reflect primary conditions of sedimentation or rather modifications by postsedimentary processes? If the geochemical proxies were originally controlled by primary environmental conditions, do they represent global or regional geochemical evolution trends? Further geochemical investigations like $\delta^{13}C$ and $\delta^{15}N$ measurements of the organic matter and sampling in adjacent areas as well as comparison with equivalent profiles in other parts of the Paraná/Karoo-Basin may contribute to solve these questions.

Dean WE & Arthur MA, *Amer. J. Sci*, **289**, 708-743, (1989).
Hughes WB, Holba AG & Dzou LIP, *Geochem. Cosmochim. Acta*, **59(17)**, 3581-3598, (1995).
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CC03 : WEpo06 : PO

Early-Middle Cretaceous Equatorial Ocean Temperature Variability

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The extent to which the middle Cretaceous provides an analogue for a 'greenhouse' world warmed by elevated levels of atmospheric carbon dioxide has been widely debated. Although this time is undoubtedly punctuated by oscillations of climate, whether sufficient to lead to polar cooling and the formation of polar ice remains controversial. Our understanding of the structure and temperature of the oceans has frequently relied upon the isotopic analysis of biogenic carbonate material. Presented here are stable isotopic measurements made on well preserved planktonic and benthonic foraminifera, in addition to coccolithic-rich sediments of early-middle Cretaceous age from a number of low latitude DSDP/ODP sites. The hedbergellid foraminifera display consistently lighter oxygen and more positive carbon isotopic values than do the rotaliporid foraminifera. The benthic foraminifera yield consistently heavier oxygen and carbon isotopes in comparison with the planktonic foraminifera and hence provide isotopically derived palaeotemperatures consistent with a thermally stratified ocean. The isotopic results suggest that the temperature of bottom waters were coolest during the latest Aptian and increased gradually through the Albian and Cenomanian. Data derived from planktonic foraminifera yields a trend that shows a more rapid increase in surface temperatures through the same interval, reaching a maximum in the late Cenomanian. These isotopic data are similar to data from other early-middle Cretaceous successions. Hence the isotopic variation is thought likely to be reflecting climate change on a global scale. Furthermore, as the cool episode recorded within the latest Aptian can be correlated with a eustatic sea-level low, a link between cooling and the formation of limited polar ice is conceivable.

CC03 : WEpo07 : PO

Getting into Global Glaciation: Clues from Isotope Profiles and Stratigraphy in the Polarisbreen Group, Northeastern Svalbard

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Neoproterozoic glacial deposits are widespread on Earth and arguably represent periods of global glaciation. In addition to studying the glacial deposits themselves, an important means of understanding how these extreme ice ages initiated is to examine the sedimentary record leading up to glaciation. Isotope profiles in carbonates immediately below glacial deposits are proxies for marine chemistry leading into the ice age and may help to elucidate their ultimate cause.

Here we present sequence stratigraphic and isotopic profiles spanning the two glacial horizons in the Polarisbreen Group, northeastern Svalbard, building on published data by Knoll et al. (1986) and Kaufman et al. (1997). An important result from our study is firm documentation of a large decline in $\delta^{13}C$ preceding deposition of the Petrovbreen Member (Elbobreen Formation) diamictite, the older of the two glacial deposits. The Petrovbreen diamictite overlies a sequence boundary which has outcrop scale relief of at least 2 m and regional relief of at least 20 m. The immediately underlying stratigraphy is quite variable, with m-scale parasequences separated by flooding surfaces and capped by dolomitic grainstones and microbialaminites. $\delta^{13}C$ varies between 1 and 5‰, 30-80 m below the glacial interval, then drops to values as low as -6‰ in the upper 16 m. In conrast to these depleted isotopic compositions, the ca. 10 to 15 m of dolomitic grainstones and microbialaminites immediately below the younger Wilsonbreen Formation glacial deposits are positive ($2 < \delta^{13}C < 4‰$). Though the contact between the dolomite and overlying Wilsonbreen Fm. is brecciated and silicified, there is no evidence for erosional relief on this contact, either in outcrop or regionally. Thus, it appears that the underlying isotope signature is not truncated, signifying that the carbon isotopic composition of the oceans prior to the Wilsonbreen glaciation was very different than that prior to the Petrovbreen glaciation.

Large declines in $\delta^{13}C$ prior to Neoproterozoic glaciation have also been identified in Namibia (Ombaatjie Fm.) and the Adelaide Rift Complex of Australia (Trezona Fm.). Though the mechanism for a pre-glacial excursions remains unclear, it constrains the relative timing between the dramatic perturbation to the carbon cycle it records and the ice age it presages.

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Kaufman AH, Knoll AH & Narbonne GM, *Proc. Nat. Acad. Sci. USA*, **94**, 6600-6605, (1997).

CC03 : WEpo08 : PO
Sensitivity of Coupled Climate System to Position of Indonesian Throughflow

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The sensitivity of the coupled tropical ocean-atmosphere system to the position of the Indonesian Throughflow is investigated using the coupled ORCA/ECHAM4 model. The ORCA ocean model used in this study is well suited for studying coupled tropical climate questions, as it has high resolution (1/2 degree meridional, 2 degree zonal) in the tropics, and 31 vertical layers. The study was motivated by our interest in determining the effect on climate of the tectonic changes in the Indonesian Straits over the last 5 million years. In particular, we focus on the role of tectonic changes on the cooling of the earth's climate which occurred between 3 and 2.5 million years ago. The coupled model is run without flux corrections for 50 years. The coupled model output is analyzed for changes in the mean state of the tropics and changes in African precipitation, and the model results are discussed within the context of existing paleo data.