GP21A-07 0830h POSTER

Study on Seismomagnetism in Taiwan

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Since Taiwan is located in high seismicity zone, seismic hazard mitigation is extremely needed. In order to find out any potential precursors before large earthquakes, geomagnetic transfer functions and demodulates are calculated using the geomagnetic data with a sampling interval of one minute at Lunping, Taiwan, Geomagnetic Observatory from 1988 to 2000. These results were correlated to earthquake occurrences. First, traditional transfer functions for the frequencies from 0.1 to 10 cycles/hour are calculated day by day. Monthly means are statistically obtained from these daily values of transfer functions. All the transfer functions show the significant anomalous frequencies at 2, 3, 4, and 6 cycles/hour. Some remarkable changes of transfer function Au, possibly related to the earthquakes which occurred near the Lunping Observatory are found. Second, the Complex demodulation method (CDM) is applied to (1) study the background of the geomagnetic field; (2) set up the method on extraction seismomagnetic signals from the geomagnetic data; and (3) study the characteristics of the seismomagnetic precursory. The results show that the 'demodulate' of 1 cycle/day decrease significantly 30 days before high seismicity and retrace to normal value after main shock.

GP23A CC: 519 B Tuesday 1330h

Endings and Beginnings: Paleogeography, Life, and Climate of the Terminal Neoproterozoic Through Cambrian Time I *(joint with U, B, T, C)*

Presiding: **P J McCausland,** University of Michigan**; B Murphy,** St. Francis Xavier University

GP23A-01 1330h

Mexican data indicating ca.700 Ma breakup of Rodinia and ca.550 Ma separation of Avalonia: analogous to events in western Laurentia

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The supercontinent, Rodinia, appears to have been amalgamated by ca.1 Ga, however, its breakup in Laurentia appears to have occurred in two stages. Current hypotheses suggest that East Gondwana or Siberia separated from western Laurentia at ca.700 Ma followed by separation of (?) South China at ca.550 Ma producing two superposed passive margin sequences. Although prevailing wisdom suggests that the birth of Iapetus between North and South America occurred at ca.550 Ma, a similar 2-stage process is evident in both eastern Laurentia and Mexico. At ca.1 Ga, Mexico appears to have been located in or close to the North-South America suture and so provides crucial data. Geochronological data indicate that cooling following ca.1 Ga granulite facies orogenesis in Mexico followed two different paths. In southern Mexico the rocks initially cooled through ca.450°C at a rate of ca.8°C/my between 978 Ma and 945 Ma related to flat-slab subduction, followed by a cooling rate of ca.2°C/my through ca.150°C. In northern Mexico the rocks cooled at a steady rate of ca.1.8°C/my through ca.300°C and are cut by plume-related mafic dykes. Extrapolating these cooling paths to the surface indicates that southern Mexico reached the surface between 710 and 760 Ma, whereas northern Mexico reached the surface by 550 Ma. This may be partly explained by different depths of exhumation: 30 versus 37 km for southern and northern Mexico, respectively. On the other hand, the oldest rocks resting on the ca.1 Ga basement are Tremadocian (ca.490-480 Ma) in southern Mexico and Middle Silurian (ca.430-425 Ma) in northern Mexico. Thus it would appear that Mexico records two breakup stages: (1) at ca.700 Ma possibly related to the breakup of Rodinia; (2) at ca.550 Ma possibly related to the transcurrent separation of Avalonia followed by thermal equilibration at ca.500 Ma leading to subsidence and development of a passive margin. These data suggest that the breakup of Rodinia occurred at ca.700 Ma and was followed at ca.550 Ma by separation of large terranes from the cratonic margins. If so, the Neoproterozoic supercontinent, Pannotia, may never have existed as a single coherent landmass.

GP23A-02 1345h

Preliminary Paleomagnetic Results From the Late Neoproterozoic of Eastern Greenland: A low-latitude Sturtian Glaciation?

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The coastal successions of Eastern Greenland present one of the most complete Late-Neoproterozoic to early Paleozoic sedimentary successions in the world. These successions contain abundant evidence for glacial deposition, with at least two major tillite horizons, the Upper and Lower Tillites, present. The Lower Tillite immediately overlies Late Riphean and Sturtian deposits of the Upper Eleonore Bay Group. We have carried out detailed paleomagnetic analyses of some 86 specimens, from 62 samples collected through the top of the Upper Eleonore Bay Group in Ella Ø, principally from Bedgroups 18 and 19. These comprise dark grey to black limestones, with occasional dolomitic shales. Progressive demagnetization uncovered a multi-component remanence structure, with AF demagnetization generally providing cleaner data than thermal techniques. The majority of samples carry a low-stability (generally $<$20mT, though occasionally persisting to 40mT) component of magnetization directed steeply down to the North, close to the present Earth's field. At higher demagnetizing fields a high-stability (generally removed by 60-90mT) component was uncovered in 28 samples, with a mean direction pointing down to the southeast in geographic coordinates (D=154°, I=61°). As these results come from one limb of a fold, tectonic correction for Ordovician-aged folding does not yield any constraints on the timing of magnetization. We note, however, that the mean declination and inclination in geographic coordinates do not resemble any younger direction. The mean direction in stratigraphic coordinates (D=148°, I=17°, k=19, a95=6°) yields a paleopole at 007°E, 6°S, and would indicate a paleolatitude of 9°. If this component of magnetization is primary it would indicate that eastern Greenland was in the tropics immediately prior to deposition of the Lower Tillite Group.

GP23A-03 1400h

Modelling a Neoproterozoic Snowball Earth

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Low-latitude sea level glacial deposits suggest the existence of snowball Earth' conditions in the Neoproterozoic. Previous modelling studies have offered conflicting support for the snowball hypothesis. We use a climate model of intermediate complexity, including an ocean GCM and a sophisticated thermodynamic/dynamic sea ice component, to conduct a suite of experiments with different orbital/paleogeographical configurations and atmospheric CO2 levels. We show that depending on the orbital configuration and paleogeography, snowball conditions prevail even with atmospheric CO2 levels up to 1800 ppmv. We demonstrate the importance of using an energy conserving thermodynamic sea ice component and suggest that the inability of some previous models to enter global glaciations may be largely a consequence of using a physically incomplete representation of sea ice. Overall our modelling paradigm is consistent with the original snowball hypothesis in which an ice covered ocean surrounds a largely snow and ice free barren land, with some coastal regions permitting the growth of thick glaciers.

GP23A-04 1415h INVITED

Geochemical Constraints on Paleoenvironments During the Neoproterozoic

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During the Neoproterozoic Era, sedimentological features such as glacigenic rocks overlain by cap carbonates indicate glaciation and cool climates were extensive, but also that there was the continued presence of organisms and equatorial ice-free open areas. Most paleoclimate inferences have relied on geochemical proxies such as carbon and sulfur isotopic compositions of carbonate rocks, but the degree to which these reliably reflect specific conditions is contentious. The Windermere Supergroup in NW Canada is a succession of shallow shelf to continental-slope deposits in which two major Neoproterozoic glaciations occurred, represented by the Rapitan and the Ice Brook glacial deposits, which correlate with the Australian Sturtian and Marinoan glacial deposits. Neoproterozoic carbonates from the Windermere have superb physical and sedimentological preservation that rival the best-preserved carbonates of this age anywhere. Despite this preservation, the cap and intervening carbonates, which were originally aragonite based on petrography and high Sr contents up to 3700 ppm, have undergone complete recrystallization to low-Mg calcite or dolomite, phases that typify carbonates in coeval sections around the world. Virtually all the geochemical markers have been variably disturbed or reset, depending on the relative level of concentrations in the carbonates and later diagenetic fluids. Most $\delta^{18}O$ values are near -10 permil, indicating resetting and other geochemical tracers such as Sr, Ba, Mn and Fe indicate resetting of primary values by later diagenesis. Carbon isotopic compositions, which can be shown to be near primary in many, but not all, samples, display large variations from slightly negative values in cap carbonates and carbonates deposited just prior to the younger glaciation to anomalously positive values in the intervening Keele Formation carbonates between the glaciations. These variations in $\delta^{13}C$ values result from sequestering of a major source of organic carbon in the deep ocean, implying that deep ocean venting had ceased prior to glaciation. Although Sr isotopic compositions have been altered more significantly than carbon isotopic compositions, initial isotopic compositions vary little throughout the section, implying that the relative flux of Sr from continents and ocean-ridge hydrothermal inputs before and after global glaciations must have been constant. Hence, models for Neoproterozoic paleoclimatic conditions must account for the sedimentology, C isotopic composition of carbonates and organic matter and constant Sr isotope ratios in carbonates as these are currently the only reliable proxies for the Neoproterozoic atmosphere-hydrosphere system.

GP23A-05 1430h INVITED

Neoproterozoic Glaciations and the Early Evolution of Animals

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The intense climatic changes that characterized the Neoproterozoic world were marked by equally profound evolutionary changes that ultimately led to the Cambrian Explosion. Early and Middle Neoproterozoic oceans contained prokaryotes and diverse eukaryotic lineages, including crown-group red, green, and heterokont algae. The survival of diverse eukaryotic lineages through the Sturtian, Marinoan, and Gaskiers glaciations implies that, although these were among the most extreme glaciations Earth has ever experienced, sea ice was not as thick or pervasive as required by earlier "hard Snowball" models. Most molecular clocks predict the existence of animals well before 600 Ma and a few tantalizing hints have been found, but the oldest definite evidence of animal life are phosphatized eggs and embryos overlying Marinoan glacial deposits in China. The subsequent Late Neoproterozoic is characterized by the global occurrence of the Ediacara biota, an assemblage of cm- to m-scale fossils of soft-bodied organisms that probably represent a mixture of stem groups of modern phyla and "failed experiments" in evolution. The oldest Ediacaran fossils occur in eastern Newfoundland, and postdate the glacial diamictites and cap carbonate of the Gaskiers Formation (580 Ma) by only 5 million years, implying a causal relationship between the end of the Neoproterozoic glaciations and the proliferation of animal life. These fossils include architecturally complex fronds up to two metres long, implying either extremely rapid rates of evolution or a pre-glacial origin of the Ediacara biota. Fossils of the Mistaken Point biota (575-560 Ma) were completely sessile and show a similar fractal architecture that is difficult to relate to any existing life forms. Some of these taxa persisted into the White Sea biota (560-550 Ma), which also contains trace fossils and metameric fossils that confirm the evolution of mobile bilaterians. The youngest Ediacaran fossils (550-543 Ma) exhibit the first evidence of calcified animals and macrophagous predation. The abrupt disappearance of the Ediacara biota 543 million years ago corresponds to both oceanographic changes and the appearance of the skeletal predators that mark the beginning of the Cambrian Explosion.

GP23A-06 1450h INVITED

Why is construction of an Ediacaran-Cambrian global paleogeography so difficult?

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The foremost answer to the above question is that high-precision global biostratigraphy extends only to Early Cambrian time. A more challenging issue concerns paleomagnetic data from the Ediacaran (proposed terminal Proterozoic period) and earliest Cambrian intervals: each paleocontinent's apparent polar wander path shows a large spread in poles, intriguingly distributed around a great circle (excepting Baltica, see below), and implying rates of paleolatitude translation or rotation far exceeding typical values from the Cenozoic. Oscillatory true polar wander (TPW) has been proposed to explain these great-circle distributions, but as more data are gathered the number of required episodes increases steadily. Another mechanism to explain such jumpy datasets is a persistently nonaxial geomagnetic field, with greatly amplified paleosecular variation; however, such an interpretation is unattractive to many geodynamicists. A third approach to explain the anomalous data is to discount them altogether; this is unsatisfactory because some of the most reliable results (e.g., Grenville dykes B component and Bunyeroo Formation pole) must be discarded in order to simplify the paths. We propose a new technique for Ediacaran-Cambrian continental reconstruction, which uses these intriguing great circle pole paths regardless of how they were generated. Each paleocontinent's path yields a best-fit great circle and corresponding pole. In the TPW interpretation, that pole describes the long-lived, common (equatorial) axis to the oscillatory rotations. Given that age constraints on the poles is generally so poor, we may reconstruct each continent to this axis with azimuthal freedom. This is topologically identical to the longitudinal degeneracy of standard paleomagnetic reconstructions, but in the case of TPW uncertainties in positions along the great circle represent uncertainties in paleolatitudes, hence climate zones. Analysis of the global Ediacaran-Cambrian paleomagnetic database indicates that all reconstructed Gondwanaland fragments share the same great circle except Arabia, whose circle is offset slightly indicating late rotations during Pan-African accretion. Iapetus can be made wide or narrow, but the latter paleogeography is preferred according to the age of Appalachian rift successions. Siberia remains on the equator, near the pole to its great circle of paleomagnetic results. Baltica is the poorest constrained of any Ediacaran-Cambrian continent: no existing paleogeographic model, with or without TPW, can readily explain its highly divergent paleomagnetic poles.

GP24A CC: 519 B Tuesday 1530h

Endings and Beginnings: Paleogeography, Life, and Climate of the Terminal Neoproterozoic Through Cambrian Time II *(joint with U, T, C)*

Presiding: **P J McCausland,** University of Michigan**; C Mac Niocaill,** University of Oxford

GP24A-01 1530h INVITED

BALTICA FROM THE LATE PRECAMBRIAN TO THE EARLY ORDOVICIAN

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Current thinking supports the existence of the Rodinia supercontinent which consolidated at perhaps 1100 to 1000 million years ago and most probably disintegrated somewhere before 800 Ma. Within the Rodinian collage, Baltica was adjacent to, and probably welded to, Laurentia, with the modern eastern (Uralian) part of Baltica conjugate with the north of Laurentia. Laurentia was in turn attached to the South American terranes of Rio Plata and Amazonia, and possibly also West Africa. Baltica became an independent terrane when it split off from Laurentia, leaving a widening Iapetus Ocean between the two. When this rifting actually commenced is a matter of dispute due to very conflicting palaeomagnetic data from both Laurentia and Baltica; however, we favor that the southern part of the Iapetus, between Laurentia and South America, opened first at about 570 Ma and that this rifting spread gradually northwards until Baltica separated from Laurentia at approximately 550 Ma, near the end of Precambrian time at 543 Ma. New palaeomagnetic and geochronological data from the 616-610 Ma Egersund Dykes (SW Baltica) place Baltica at the south pole whereas subsequent Late Precambrian to Early Cambrian poles places Baltica at lower latitudes. During the late and middle Vendian, the NW margin of Baltica changed from an extensional tectonic regime to an active margin (Timanian Orogeny) in which microcontinental blocks in the Timan-Pechora, northern Ural and Novaya Zemlya areas were united with Baltica at 550-560 Ma. Largely between Middle Cambrian and Middle Ordovician times, the whole large terrane of Baltica underwent a very substantial rotation of about 120°, and the maximum rate of this rotation occurred in late Cambrian and early Ordovician times. Much of the craton of Baltica appears to have been submerged under shelf seas for long parts of this time, which lasted from 544 to 490 Ma. As a consequence the olenid trilobite fauna represent a fauna living largely in niches which were probably relatively deep on the shelf and in which the aeration was below normal, and thus similar animals are also found in comparable conditions in other terranes, such as Laurentia and Siberia. The Iapetus Ocean was at its widest at about Cambro-Ordovician boundary times, and thus Baltica was at its most isolated. The benthic invertebrate faunas of the shelf seas therefore underwent independent evolution, and the most abundant macrofauna, the trilobites and the brachiopods, were represented in Baltica not just by different species and genera but even families which were endemic to that terrane. Thus it can be safely inferred that both the Iapetus Ocean and also Tornquist's Ocean, which lay between Baltica and Gondwana, were wide enough in the early Ordovician to prevent the successful passage of larvae for a substantial proportion of the benthos.

GP24A-02 1550h

Paleomagnetism of the Grenville diabase dyke swarm and implications for the mid Vendian paleolatitude of Laurentia

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The Vendian-early Cambrian drift of Laurentia is important for theories of Snowball Earth' and the continental breakup that formed the Iapetus Ocean. However, estimates of Laurentia's paleolatitude in this period differ widely. Some authors have proposed that Laurentia remained in low latitude throughout this period, whereas others have supported rapid drift of the continent from low to high and back to low latitude. To assist in evaluating these models, a paleomagnetic study was conducted on the mid Vendian Grenville dyke swarm of southeastern Laurentia. This 700 km long swarm was emplaced along the Ottawa graben, an aulacogen associated with rifting that preceded the opening of the Iapetus Ocean. The swarm was the subject of an early paleomagnetic study by Murthy (1971). More recently, U-Pb baddeleyite and zircon ages of ca. 590 Ma have been described for three Grenville dykes (Kamo et al. 1995). At one of these sites, on the Mattawa' dyke, a positive paleomagnetic baked contact test was also reported (Hyodo and Dunlop 1993). In that detailed test thermoremanent overprinting in the zone of hybrid magnetization was shown to match that expected from heat conduction for a cooling dyke. Nevertheless, Hyodo and Dunlop suggested that the steep down remanence in the dyke, although primary, was likely acquired during a geomagnetic excursion because it did not appear to fit the then-available polar wander path. In our study, paleomagnetic sampling was carried out at 36 sites, including all three dated locations. A detailed analysis has been completed for the dated sites and preliminary analysis for the remaining sites. A stable steep down remanence was obtained for all samples in the Mattawa dyke, and in most samples from a second dated site. The third dated site is less stably magnetized and has not yielded a usable remanence direction. Ten additional sites yield stable steep down or occasionally steep up remanences. The presence of a steep remanence in two dated dykes and several others demonstrates that the remanence was not simply acquired during a short-term geomagnetic excursion. The positive baked contact test suggests that it is a primary remanence. If so, this would indicate that Laurentia was at high latitude 590 Ma ago. This would correspond to interpretations of steep magnetizations in the 577 Ma Callander Complex of the Ottawa graben (Symons and Chiasson 1991). However, other dykes in our study do not carry the steep down remanence. Six have an intermediate up WNW magnetization (or its reversal to the SE), suggesting that these dykes may not be 590 Ma in age. The WNW remanence is similar to that reported for the poorly-dated Buckingham volcanics of the Ottawa graben (Dankers and Lapointe 1981). Five additional sites carry other SE directions (both up and down) that are scattered along or near a great circle through the Mattawa and Buckingham volcanic directions, indicating that unresolved overprinting may have smeared the site directions. Therefore, caution should be exercised in interpreting the overall paleomagnetic data set until further U-Pb dating and paleomagnetic analysis have clarified whether more than one age of dyke swarm is present and whether significant overprinting has occurred. References: Dankers and Lapointe, 1981, Can. J. Earth Sci. 18: 1174; Hyodo and Dunlop, 1993, J. Geophys. Res. 98: 7997; Kamo, Krogh, and Kumarapeli, 1995, Can. J. Earth Sci. 32: 273; Murthy, 1971, Can. J. Earth Sci. 8: 802; Symons and Chiasson, 1991, Can. J. Earth Sci. 28: 355.

GP24A-03 1605h

Paleomagnetic confirmation of a low-latitude Laurentia by 534 Ma

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The paleogeography of the Precambrian-Cambrian transition is still poorly known, but is fundamental for understanding Late Neoproterozoic climate extremes and the spatial associations of the rapidly-evolving Ediacaran and Cambrian fauna. This period has also been proposed to host unusual geodynamic events such as rapid plate motions and/or the bulk tumbling of the Earth with respect to its spin axis, called true polar wander (TPW). New paleomagnetic and Ar-Ar hornblende results have been obtained from a pair of shallowly-emplaced syenitic intrusions in western Quebec, the Mont Rigaud and the Chatham-Grenville stocks, which are related to the development of the Laurentian failed rift arm during the opening of the Iapetus Ocean. Both intrusions bear hornblende which provides overlapping Ar-Ar plateau ages of 534.3±1.2 (Mont Rigaud) and 533.0±1.0 Ma (Chatham-Grenville), corresponding to