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CONFERENCE REPORT

Measurement and Modelling of Glacial Isostatic Adjustment

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INTRODUCTION

Recent uplift and subsidence of the Earth's surface have to a large degree been driven by North American deglaciation, which accounted for over 50% of global mass redistribution since the last glacial maximum (LGM). The effect is most pronounced within the limits of glaciation. Relative sea-level in Hudson Bay, for example, has fallen >100 m, and continues to fall at a rate of >10 mm per year. There also are global effects through sea level rise and associated loading. Recovery of displaced viscous mantle is a millennial-scale process now affecting the entire surface of the Earth. These changes can be measured by relevelling or by use of the Global Positioning System (GPS) and other space-based geodetic techniques, and they also appear as sea-level change, lake-level tilting, and changes in gravity. Past change is measured from sea-level history and tilted glacial lake shorelines. These global changes are best understood, and interpolation of trends obtained, by modelling glacial isostatic adjustment (GIA).

GIA is a key source of information on earth properties, such as mantle viscosity, that is required to understand processes such as plate motion. An understanding of GIA also is required to understand shoreline erosion on large lakes, flood history of rivers, and earthquake hazard. Long-term monitoring and prediction of sea-level change are required to update navigation charts, and to calibrate satellite-based sea-level and gravity monitoring. Furthermore, sea-level is a sensitive indicator of global change, and a key agent of global change impacts such as increased coastal erosion and flooding. Discrimination of climatic and oceanographic influences on sea-level from uplift or subsidence is required to assess climate change impacts such as storm surges and coastal flooding, and there are international obligations for global change monitoring. Deformation measurements are also required for maintenance and enhancement of national survey reference systems such as the Canadian Spatial Reference System (CSRS), including corrections obtained from optimal interpolation of isolated measurements. This is best accomplished using a geophysical model that unifies water-level inferences, geodetic measurements, gravity monitoring, and an account of glacial history.

CRUSTAL MOTION AND NORTH AMERICAN ICE-SHEET RECONSTRUCTION

Scientists specializing in crustal motion, geophysical modelling, ice sheet reconstruction, sea-level change, and glacial history gathered at the **Canadian Geophysical Union (CGU) Annual Meeting, 14-17 May 2001, at the University of Ottawa**. A session on "Crustal motion: geodetic techniques, glacial isostatic adjustment, and geological evidence," and both a session and a workshop on "North American ice-sheet reconstruction," were chaired by Professor W.R. Peltier of the University of Toronto and were sponsored by the Climate System History and Dynamics program (CSHD) as well as by the Geodesy Section of CGU. Speakers represented Government of Canada labs, Canadian universities, the international community, and Canadian provincial agencies.

Lev Tarasoff of University of Toronto presented work on **dynamical ice-sheet models and their incorporation into geophysical inverse reconstructions of North American ice sheets**. The forthcoming ICE-5G geodynamic model of glacial isostatic adjustment (GIA) will include an attempt to combine geophysical constraints, relative sea-level records, and enhanced glaciological self-consistency. Using a non-linear optimization scheme, regional climate forcing, mass-balance, and basal ice sheet parameters will be adjusted to enhance the ice-sheet fit to actual geophysical and geological/ glaciological observations. Comparison of deglaciation histories between current dynamical ice sheet models and that of the earlier ICE-4G geodynamic model of GIA point to data gaps and regions of dispute where new data would be most useful.

Tony Lambert of Natural Resources Canada (NRCan), Geological Survey of Canada (GSC), presented work on **GIA in mid-continental North America**. Absolute gravity measurements made twice a year at six stations from Iowa to Churchill yield rates of change higher than expected. Ice load, mantle viscosity, timing of deglaciation, Lake Agassiz shorelines, lake gauge tilts, and anomalous relevelling results from northern Manitoba were discussed. These results are being supplemented by GPS monitoring at four of the six stations, to improve uplift estimates, thereby better understanding issues such as Lake Winnipeg shoreline erosion.

Tom James of GSC Pacific presented **postglacial rebound modelling of southwestern British Columbia (BC)**, based on sea-level, proglacial shorelines, and geodetic information, and based on a grid finer than that of global models. The maximum extent of the Cordilleran Ice Sheet was a brief event, retreat was very rapid, and the maximum glacial extent in British Columbia was similar to that of today by shortly after 10 ka BP. Rapid rebound caused sea-level retreat along most of the BC coast. The model accounts for these observations, and indicates underlying thin lithosphere as well as low and variable mantle viscosities, consistent with other tectonically active regions.

Spiros Pagiatakis of NRCan's Geodetic Survey Division (GSD) presented **a synthesis of 50 years of gravity observations in Canada**, primarily using data from 64 stations maintained since 1950. All observations were reprocessed for body tides, ocean loading effects, instrument calibration, epoch, and instrument type. Gravity difference measurements were incorporated with their associated covariance matrix, and an appropriate covariance matrix was assigned to the initial-g values in a weighted constraint least-squares adjustment. A clear outline of the post-glacial rebound signature was obtained from a least-squares solution using five weighted constraints from repeated absolute gravity observations.

Patrick Wu of University of Calgary presented **modelling of crustal motion induced by GIA in a mantle with power-law creep**. Data for sea-level, uplift, horizontal velocity, gravity, and other observations were used to infer mantle rheology and deglaciation history. Power-law creep in the lower mantle provides better prediction of sea-level in and around the former ice margin than a linear uniform 1E21 Pa-s mantle. However, sea-level data alone cannot discriminate between the stress exponents in a nonlinear lower mantle. Additional constraints could be obtained from gravity and horizontal motion if monitoring stations are appropriately positioned.

Jim Teller of University of Manitoba presented work on **Lake Agassiz as a monitor of late-glacial isostatic rebound and variations in large ice-marginal water masses**. Lake Agassiz occurred along the ice margin in central North America. Lake-level fluctuations related to ice margin position, topography, outlet elevation, and uplift are now recorded as glacial lake shorelines that now rise to the northeast. Teller showed modelling, completed with Dave Leverington and Jason Mann, of abrupt changes in area and volume of Lake Agassiz resulting from discharges from the basin, including the very large, two-step final drainage of the Agassiz-Ojibway "superlake" at about 7.6 ka BP.

André Mainville of the NRCan GSD presented **new analyses of present-day Great Lakes tilting** based on water-level gauges. Monthly mean water-levels at 45 sites around the Great Lakes were processed for the years 1860 to 2000, and rates of apparent relative vertical movement between pairs of stations were determined by a least-squares procedure. The estimated differential vertical rates were compared through correlation to the ICE-3G and ICE-4G geodynamic models of GIA. The analysis indicates vertical motion ranging from subsidence of about 30 cm per century in the south, to uplift at a rate of 30 cm per century in the north.

Detlef Wolf of GeoForschungs-Zentrum in Potsdam, Germany, described the **SEAL project, an integrated approach to quantification of sea-level change**. Sea-level is being analysed using satellite techniques, altimetry, GPS buoys, GPS control of tide gauges, high-accuracy satellite gravity measurements, and analysis of global ice volume. GPS control of tide gauges is recent and incomplete, so an estimate of vertical motion is necessary for all gauges. He also presented work by colleagues on Pleistocene and Holocene (= Recent) changes of glaciation in Svalbard, based on tide-gauge, GPS, other space geodetic techniques, and absolute gravity measurements, as well as work on incorporation of compressible viscoelasticity into elastic, spherical earth models.

Dick Peltier of University of Toronto described work towards **a new global model of deglaciation, sea-level change, and GIA, the ICE-5G geodynamic model.** Key constraints for this model include sea-level records from Barbados and the southeastern coast of the United States that have been challenged by a recent claim of higher values. Peltier suggested that this claim was based on an erroneous use of an approximate form of the theory for sea-level history that does not conserve mass, and supportive data has been reported for Sunda Shelf. Adjustments to the Laurentide component of the ICE-4G model are required to reconcile new space geodetic and other constraints, and the radial viscoelastic earth structure is in review, owing to its critical role in the inference of ice thickness from sea-level observations.

Art Dyke of GSC Ottawa presented **a synthesis of current understanding of the extent and timing of the most recent maximum advance of the North American ice sheets**. The interstadial minimum at 27-30 ka BP was near the limit of the exposed Canadian Shield, although extent was much more limited in the Cordillera and Arctic. LGM limits were reached between 24 and 20 ka BP. Unlike inferences from earlier models, ice is thought to have been extensive in the Arctic and on the Atlantic shelf. Drawdown of central ice is correlated to the Heinrich 1 iceberg event in the Atlantic at 14.5 ka BP, and this was followed by substantial ice margin recession after 14 ka BP, although retreat was delayed in the northeast and high Arctic. The maximum extent seems to have been more prolonged than is implied by marine isotopic records. A more detailed interpretation of glacial history is achievable, but will require much processing of radiocarbon databases.

Ralph Stea of the Minerals and Energy Branch, Nova Scotia Department of Natural Resources, presented **a discussion of glacial extents in Maritime Canada**, as well as a poster on sea-level history of the region. Previous models for limited ice extent, based on bulk organic ages, absence of raised shorelines, and lack of erratics in highlands, have been rejected on the basis of accelerator mass spectrometry (AMS) dates that indicate Late Wisconsinan glaciation of the shelf as well as evidence for glaciation of areas previously thought to have been nunataks. The timing of deglaciation has been delayed, the Younger Dryas cold period clarified, and a model for locally centered, highly dynamic ice masses presented. Sea-level history was controlled by rates of ice retreat and ice load, and discrepancies between model and field data were explained by isostatic recovery from thick Appalachian ice caps combined with slow rates of deglaciation.

David Scott of Dalhousie University and John Shaw of GSC Atlantic presented **a compilation of postglacial relative sea-level changes in Atlantic Canada**. The most complete record, for Halifax, shows emergence beginning about 14 ka BP, followed by submergence, with a second period of emergence at around 8 ka BP. Also noted were periods of rapid sea-level rise in the late mid-Holocene, a large range in submergence rates across Prince Edward Island, ridges of high relative sea-level values over Newfoundland and the Maritime Provinces, a re-entrant of lower levels in the Gulf of St. Lawrence, gradual submergence of large islands on the shelves, and complex changes in the Gulf of St. Lawrence.

Heiner Josenhans of GSC Atlantic described **current interpretations of Late Wisconsinan ice margins in Atlantic Canada** based on multibeam bathymetry, seismic reflection studies, cores, and radiocarbon dates. The synthesis showed extensive glaciation of the shelves at 19 ka BP, followed by phases of rapid ice margin retreat. In the Laurentian Channel, the ice margin lay south of the Cabot Strait at 14.3 ka BP, but had retreated to Anticosti Island by 13.7 ka BP, leaving ice on the outer banks. This and other areas of rapid deglaciation reorganized the ice mass, although late stage ice persisted in the southern Gulf of St. Lawrence.

Mike Lewis of GSC Atlantic presented **an evaluation of glacio-isostatic uplift inferred from tilted shoreline data from the Great Lakes basins**. Deglacial ice margins, lake outlets, and uplift amounting to 350 m since 11.3 ka BP were inferred from the Algonquin, Glenwood II, Minong, Whittlesey, and Iroquois levels of the Huron, Michigan, Superior, Erie, and Ontario basins, respectively. This information was combined with the 5 ka BP Nipissing level to define the uplift pattern as an exponential function with a relaxation time of 3700 $\pm$ 700 years. The model implies that early Holocene lake levels in the Huron-Georgian Bay basin, following cessation of meltwater inflow, were at times below their outlets, suggesting an episode of closed lakes in a dry climate.

Thane Anderson of the Canadian Museum of Nature, Ottawa, presented **a revised chronology of deglaciation of the Great Lakes region**. A key site adjacent to the North Bay outlet in the northern Huron basin, originally cored and dated using conventional radiocarbon dating of basal organic lake sediment in 1969, was resampled and re-dated using AMS analysis of terrestrial plant seeds. The re-analysis resulted in a 2 ka BP revision to more recent ages, owing to the hard-water effect in the original ^{14}C assay. Correlation of pollen profiles supports the revision, which places the drainage of Lake Algonquin and the post-Algonquin phases at 10.5-10 ka BP.

DISCUSSION

Workshop discussion initially focussed on a process co-ordinated by GSC scientists for reaching a new consensus regarding North American glacial history, at an enhanced spatial resolution of 0.5° of longitude by 0.25° latitude, and temporal increments of 500 calendar years. Ice thickness estimates initially will be based on the ICE-4G geodynamic model. The work will be co-ordinated with a global International Union for Quaternary Research (INQUA) initiative. The current revision of the model will be distributed to the North American INQUA team, such that discussion will be focussed relative to an evolving standard. The model will be drawn at the highest spatial detail possible, using radiocarbon years at 1000-year intervals. Workshops may be required to address regional issues. Much effort will be needed to process radiocarbon ages to account for new considerations such as clarified reservoir effects. A series of isobase maps will incorporate sea-level history, glacial lake shorelines, and modern observations, and future modelling will use the isobases as a constraint. A first draft of the model will be produced by autumn 2001, pending confirmation of required resources. Following iteration over ensuing months, the model will be discretized and converted to constant 500 calendar year increments by GSC scientists, in co-operation with University of Toronto.

There also was much discussion of space-based geodetic methods, which will require control for hydrological factors, and on placement of new GPS, gravity, and tide-gauge installations. In the Arctic, where the need for monitoring has been cited by the international community, there may be a limited number of satisfactory sites with respect to stability, communications, and security. Some monitoring will continue to be intermittent. There are many applications and user groups that extend beyond the range of the current discussion, such as the oceanography community. Oceanographers may prefer continental margin sites, whereas geoscientists may prefer continental interior sites. Furthermore, a key application of tide-gauge analyses, where the GIA component of sea-level change is known, is to derive a climate history from the residual sea-level data. Measurement of horizontal motion, such as along a transect from the uplift center to the East Coast, or ideally on both sides of the uplift, would be very valuable. There was general recognition that renewed commitments to monitoring by many agencies, including the international community, have presented opportunities for new data collection that hopefully will be optimized for long term needs on the basis of current and continuing discussions.

The very great importance of Hudson Bay postglacial sea-level records also was discussed, given their large amplitude and central location relative to the previous ice load. There was agreement that upgrading these sea-level records is a high priority, including detailed mapping of the synchronous marine limit in the south. Also of high priority is the mid-continent area, where trends have not previously been compiled. New GPS stations are especially important in data-poor areas. There is a need to more fully assess opportunities for analysis of lake gauge data, and to lobby for maintenance of an optimal network of gauges. There also is much potential for increased use of glacial lake shorelines as uplift monitors, although new mapping and dating are required to confirm some of the key shorelines. Future models will incorporate glacial lake water loads, and both sedimentation in deltas and possibly landscape denudation eventually will be incorporated. There is much potential to better map basal thermal regimes to aid glaciological modelling. Regional GIA modelling is likely to play an increasing role.

A key outcome of the meeting is a commitment to increased integration among fields, such that constraints from the geological, glaciological, geodetic, and geophysical fields will increasingly be brought to bear on integrated synthesis and geodynamic modelling. There may be potential for major new initiatives. Co-ordinated progress is anticipated in coming months, and an opportunity for another similar meeting will be sought.