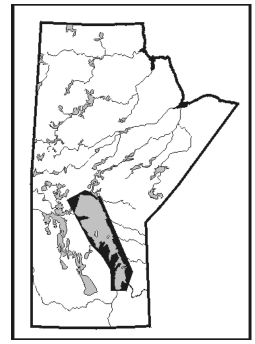
GS-31 STATUS OF THE LAKE WINNIPEG PROJECT (NTS 62I, 62P, 63A, 63B, 63G AND 63H)



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SUMMARY

The Lake Winnipeg Project was launched by the Geological Survey of Canada (GSC) and Manitoba Geological Services Branch (MGSB) in 1994, with the support of Manitoba Hydro and the Manitoba Sustainable Development Innovations Fund, in order to support management of issues such as shoreline erosion and water quality. A four-week cruise of the Canadian Coast Guard Ship (CCGS) *Namao* in 1994 was followed by a similar effort in 1996. Low frequency air gun seismic, high frequency seismic, side-scan sonar, and coring operations, guided by real-time differential global positioning system (GPS) navigation, were supplemented by limnological and biological sampling carried out in cooperation with the Freshwater Institute. A five-year program of absolute gravity measurements and GPS data collection is monitoring uplift, a key factor in shoreline erosion, along a transect from Iowa to Churchill. Accompanying research on shoreline processes has included reconnaissance surveys in 1994, targeted investigations in 1996, and a month-long intensive effort in September 1997. Previously acquired wave data have been supplemented by data from three waverider buoys deployed in 1996. Although targeted follow-up research is anticipated, final outputs from the Lake Winnipeg Project are in preparation for release in 1999. Two major questions have been addressed by this work:

What is the structure of the Lake Winnipeg basin? Results have demonstrated that the structure of sediment and rock below Lake Winnipeg dramatically differs from expectations. Prior to the 1994 cruise, it was thought that sedimentary rocks extended close to the eastern shore, and that these rocks were buried by at most 15 m of sediment. In fact, sedimentary rocks only extend 10 km east from the end of Long Point, and terminate at a buried escarpment south of Hecla Island. Beyond these Paleozoic rocks, sediments consisting almost entirely of Lake Agassiz clay reach unanticipated thicknesses of over 50 m in the South Basin and over 100 m in the North Basin. Till and other gravel-bearing glacial sediments are not extensive, but are present as formerly unrecognized major moraines at George Island and Pearson Reef. Sediments deposited by postglacial Lake Winnipeg, which rarely exceed 10 m in thickness, rest on a regionally pervasive, low-relief angular unconformity, and are ornamented by a complex array of furrows formed by the action of lake ice. Vigourous currents have stripped sediments from The Narrows and east of Black Island, producing the greatest water depths in the lake, over 60 m.

Are present-day environmental changes superimposed on long-term evolutionary trends? Without knowledge of the history of a lake, as recorded in its sediments, it is difficult to determine whether a basin was in a state of equilibrium prior to human intervention, or whether recent perturbation is only an addendum to more profound natural changes. The surveys have shown that Lake Winnipeg has, for centuries and millenia, been undergoing a steady expansion. Sediment cores from the centre of the South Basin have revealed that Lake Winnipeg offshore sediments have buried fossiliferous material that could only have been deposited at a pre-existing shoreline. Radiocarbon and paleomagnetic analysis of this material indicate that most of the South Basin was dry land at 4 ka BP (4000 radiocarbon years ago). The dominant control that has caused southward transgression is tilting, as a result of the uplift of the Hudson Bay region that resulted from melting and breakup of the continental ice sheet around 10 ka BP. The rise of the lake has been punctuated by climate change, especially the shift to cooler, moister conditions around 4 ka BP, diversion of the Saskatchewan River into the North Basin at 4.7 ka BP, switching of the Assiniboine River from a path through Lake Manitoba to the North Basin over to the Red River and the South Basin around 4 ka BP, as well as progressive merging of several sub-basins from Playgreen Lake to the South Basin into one Lake Winnipeg. Unlike other lakes, outlet downcutting has not been a significant factor on Lake Winnipeg, due to the low and easily erodable barriers that overlie resistant substrates.

INTRODUCTION

Lake Winnipeg is the eleventh largest lake in the world. With an area 25% larger than Lake Ontario, it stands as a major feature on the North American landscape. The lake is divided into two shallow basins. Depths do not exceed 19 m in the North Basin, or 13 m in the South Basin, although depths of as much as 60 m occur in the connecting narrow passages. Not only is the lake used for fisheries and recreation, it is vital to the Manitoba economy for its role in hydroelectric generation. Despite its significance, however, Lake Winnipeg had until recently been the subject of little study. Aside from hydrographic charting (Canadian Hydrographic Service 1981; 1982; 1986) and surveys on surrounding land, the only previous comprehensive scientific effort was a 1969 limnological survey, led by the Freshwater Institute, that included sampling of bottom sediments at fifty sites and collection of several short sediment cores. Knowledge of the geology of Lake Winnipeg, and hence the structure and evolution of the basin, therefore had been limited to tenuous predictions based on studies on land. An offshore survey of Lake Winnipeg therefore was proposed by the staff of GSC and MGSB in 1993, on the basis of a need for an enhanced fundamental understanding of the lake.

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PREVIOUS RESEARCH

Systematic GSC surveys of the shores of Lake Winnipeg were carried out in the 1890s by Dowling (1900) and by Tyrrell and Dowling (1900). Their reports include descriptions of the landscape and economy, to supplement description and classification of the Paleozoic sedimentary rocks along the western shore, the Precambrian rocks of the eastern shore, and the overlying Quaternary sequence. The Precambrian rocks were later analyzed in more detail by Ermanovics (1970; 1973), Bell (1978), Brown (1981), and by Weber (1990; 1996). The basal Paleozoic unit, the Winnipeg Formation sandstone, was examined by Macauley (1952), while the overlying carbonate rocks have been discussed by Baillie (1952), Stearn (1956), McCabe (1967; 1983), Bezys (1996a; 1996b), as well as by Bezys and Weber (1996). Additional work on the Quaternary geology of areas surrounding Lake Winnipeg has been reported by Antevs (1931), Klassen (1967; 1983), Tarnocai (1970), Grice (1970), Bannatyne and Jones (1979), Nielsen (1989), Henderson (1994), and McMartin (1996a; 1996b). Aggregate resources have been discussed by Groom (1985) as well as by Matile and Groom (1987), while groundwater resources around the South Basin have been addressed by Lebedin (1978) and by Betcher (1983; 1986a; 1986b). A postglacial pollen profile was obtained from a small lake on Long Point by Ritchie and Hadden (1975). These investigations of on-land Quaternary geology were summarized by Nielsen and Thorleifson (1996).

Scientific studies of the waters and biota of Lake Winnipeg were initiated in the 1920s and 1930s, including work on Red River waters by Ward (1926), on phytoplankton and other biological topics by Bajkov (1930; 1934), and on aquatic fauna by Neave (1932; 1933; 1934). Attention later shifted to engineering and development, as the prospects for lake level regulation and hydroelectric generation were defined (Lakes Winnipeg and Manitoba Board, 1958; Water Control and Conservation, Province of Manitoba, 1966; Kuiper, 1968). As decisions were made to proceed with this development, and as shoreline erosion received more attention, several University of Manitoba theses addressed shoreline processes and engineering (Buie, 1965; Veldman, 1969; Huggins and Edghill, 1969; Bray and Burgess, 1970; Cheng, 1972). Research also focussed on physical limnological topics such as wind setup and currents (Einarsson and Lowe, 1968; Hamblin, 1976; Lehn et al., 1976; Kenney, 1979). Preparation for lake level regulation included production of 1:2400 maps with a contour interval of 2 feet for areas within 3000 feet of the South Basin shore (Lockwood Survey Corporation Limited, 1972), a detailed investigation of South Basin shoreline erosion by Penner and Swedlo (1974), and publication of a shoreline erosion handbook (Manitoba Water Resources Division, 1977).

Ongoing limnological and fisheries research has been reported by Rybicki (1966), Evans and Stockner (1972), Crowe (1973), Davidoff et al. (1973), and Franzin et al. (1996). A major advance in the breadth of knowledge regarding Lake Winnipeg resulted, however, from surveys conducted by the Freshwater Institute from the CCGS Bradbury in 1969, as well as later sampling that involved other agencies. Resulting work on nutrients was reported by Brunskill (1973) and by Brunskill et al. (1980b), on lake water composition by Brunskill et al. (1979a), on attenuation of light by Lake Winnipeg waters by Brunskill et al. (1979b), on morphometry and hydrology by Brunskill (1980a), and on the bottom sediments of Lake Winnipeg by Kushnir (1971), Allan and Brunskill (1977), as well as Brunskill and Graham (1979). Later work on nutrients was reported by McCullough (1996). Research on zoobenthos has been reported by Flannagan (1979), Flannagan and Cobb (1981; 1984; 1991; 1994), and by Flannagan et al. (1994), while work on zooplankton that pre-dated the Lake Winnipeg Project was reported by Salki and Patalas (1992) and by Patalas and Salki (1992). Research based at Grand Beach, on the eastern shore of the South Basin, that was directed at use of grain size analysis in the diagnosis of depositional environments, was conducted by Solohub (1967) and by Solohub and Klovan (1970).

Much uncertainty existed about fundamental aspects of Lake Winnipeg history until recent decades. Upham (1895, p. 217) claimed that the latest and lowest Lake Agassiz shorelines are nearly horizontal over several hundred km, so uplift could not have had a significant impact on Lake Winnipeg. He also concluded that the original level of Lake Winnipeg was marked by a well-defined beach that had been reported between the mouths of the Winnipeg and Red Rivers, at 21 feet above present lake level. This was interpreted as the shoreline that had formed prior to downcutting of the outlet at Warren Landing, and he predicted with confidence that the shoreline would be found at nearly the same height around the whole lake (Upham, 1895, p. 221). Johnston (1946) later refuted this claim, by implication, by showing that late Lake Agassiz shorelines along Lake Winnipeg in fact do rise significantly, although, through miscorrelation, he implied a complex pattern of uplift. The notion of little uplift in post-Lake Agassiz time was perpetuated by Elson (1967), who again suggested that the latest Lake Agassiz beaches were only slightly uplifted. A key factor in this uncertainty likely was the long-standing debate over whether Hudson Bay is still rising; this debate was finally laid to rest in the 1960s by data from the Churchill tide gauge. Gradual recognition that uplift had caused extensive expansion of Lake Winnipeg emerged in the writings of Penner and Swedlo (1974), Ringrose (1975), Pettipas (1976), and Thorleifson (1984). Field investigations meant to test this and other hypotheses subsequently were launched by Nielsen and Conley (1994) and by Nielsen (1996a; 1996b; 1998). Major contributions to the topic also have been made by geomorphic and lake-gauge analyses by Tackman and Currey (1996a; 1996b), Tackman (1997), and Tackman et al. 1998. This research allowed predictions of Lake Winnipeg expansion to be made, but confirmation would await comprehensive offshore surveys.

PROJECT COORDINATION

The Lake Winnipeg Project was enabled by endorsements and financial support provided in 1994 by Manitoba Hydro and the Manitoba Sustainable Development Innovations Fund, whose interest in the lake was bolstered by concerns regarding shoreline erosion. With confirmation of client endorsement in hand, major commitments of funding and equipment were received from three financial and logistical sources in the GSC. Links were established with ongoing research at the Freshwater Institute, as well as with several university-based research programs. Confirmation of the availability of the CCGS *Namao* allowed a go-ahead to be declared. An organizational meeting was held in Winnipeg in May 1994, and plans were made for a scientific cruise in August 1994 and a shoreline survey in September 1994.

The 1994 cruise began with a northbound geophysical survey, followed by a gear changeover at Grand Rapids, prior to a southbound coring phase. Limnological and environmental sampling were undertaken concurrently, and a grid of bottom sediment samples, coupled with biological and water sampling, was carried out from the ship's launch during the southbound coring phase. A two-week survey of the Lake Winnipeg shoreline followed, in September 1994.

Geophysical data were processed at GSC during the winter of 1994/95. Sediment cores were thoroughly processed at GSC labs housed at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, in October 1994. Several thousand subsamples of the sediments were distributed for analysis at several laboratories across North America. Presentations summarizing the project were made at Geological Survey Open Houses in Winnipeg, in November 1994, and in Ottawa, in January 1995. A two-day scientific workshop, featuring 34 presentations, was hosted by Manitoba Energy and Mines in Winnipeg in March 1995. Support from Manitoba Hydro subsequently allowed a go-ahead for a five-year effort, co-ordinated by GSC Pacific, to use twice-annual absolute gravity measurements and two new GPS receiving stations to measure uplift. A report summarizing progress to date was submitted to Manitoba Hydro in August 1995. GSC Open File 3113, summarizing scientific results of the Project in the form of 27 chapters, was published in March 1996 (Todd et al. 1996a). A full-day session consisting of 20 presentations on project and allied activity took place at the national conference of the Geological Association of Canada in Winnipeg in May 1996.

An additional phase of work was funded in 1996, including another offshore survey and the first year of a two-year shore processes study. These efforts were funded by GSC, Manitoba Hydro, and the Panel on Energy Research and Development. Three waverider buoys were deployed to support wave research at the University of Manitoba. Shore process research intensified in 1996, followed by a major effort in September 1997. Also in 1997, display material explaining the scientific results of the project was released (Matile et al., 1996; Todd et al., 1997; http://agcwww.bio.ns.ca/pubprod/of3434/index.html). A special issue of the Journal of Paleolimnology, including eleven papers on project work, was released in March 1998 (Todd et al. 1998a). Current activity is focussed on completion of the final outputs and contemplation of targeted follow-up efforts.

NAMAO CRUISES

The central activity of the Lake Winnipeg Project has been offshore geophysical and coring operations conducted from the CCGS *Namao* in August 1994 (Todd, 1996) and August 1996. The *Namao*, built in 1975 as a navigational aids tender by Riverton Boat Works, is 33.5 m long, 8.5 m wide, and has a draft of 2.1 m. Addition of sleeping accommodation for four in a trailer on the aft upper deck permitted eleven Coast Guard staff, a scientific crew of six, as well as day visitors, to participate in offshore operations.

The 1994 cruise was designated GSC cruise Namao 94-900. Equipment was transported from Dartmouth and Ottawa to the Coast Guard base in Selkirk by tractor-trailer. Construction of a temporary laboratory in the hold of the ship, equipment set-up, and modifications to the ship's electrical system were completed from July 30 to August 3. Surveying operations began mid-day on August 4, following three hours of travel from Selkirk to the lake, and a series of geophysical survey lines, conducted as weather permitted, were completed on August 19. On August 20, the ship was changed over at Grand Rapids from geophysical surveying equipment to coring gear. The coring phase, from August 21 and 30, included a one-day visit to the ship by The Hon. Jon Gerrard, Secretary of State (Science, Research and Development), as well as visits by several additional guests. The vessel was tied up overnight each day, either at Gimli, Victoria Beach, Gull Harbour, Pine Dock, Matheson Island, Berens River, George Island, Warren Landing, or Grand Rapids. A two-day period subsequently was required to demobilize equipment.

For the geophysical survey, east-west transects, with south-north tie lines, were run in both the South and North Basins, as well as in the connecting narrows and islands area. No data were acquired in the southern part of the North Basin owing to high wind and wave conditions. Nonetheless, over 500 km of geophysical track lines were obtained. Lack of seismic penetration over broad areas, especially in the southern South Basin, was thought to be due to gas disseminated within the sediments. The low frequency seismic reflection system utilized a 24-channel seismograph, a 10 cubic inch sleeve gun operated at an air pressure of 1900 psi and fired at a 5-second interval, and an eel with 24 receivers spaced at a 5 metre interval. The Seistec high frequency (2-6 kHz) seismic system included a receiver towed from the upper deck crane to starboard from the stern. A surfboard-mounted boomer, firing at a 0.25-second interval, was towed from the starboard aft main deck. Under most weather conditions and a ship's speed of about 4 knots or 7.41 km/hr, the surfboard planed 1-2 m below water surface. Every twentieth shot was suppressed to allow the sleeve gun system to fire. The sidescan sonar towfish was towed off the port bow by a block attached to the crane. An experimental deployment of a ground penetrating radar was housed in a twin-hulled craft. A marine magnetometer was operated as well.

Coring was conducted to sample the sediments and to verify stratigraphy and features identified in the geophysical records. Navigation was by GPS with real-time differential corrections obtained from a geosynchronous satellite relaying the Duluth, Minnesota reference signal. Coring sites were determined by first inspecting high-resolution seismic records, and by interrogating stored navigation files to obtain the location. A total of 60 m of core was obtained from thirteen sites in 1994, with length ranging from 2 m to 8 m. This included one deployment of the AGC wide diameter long gravity corer, six deployments of the AGC wide diameter piston core, two deployments of the Murphy wide diameter gravity core, seven deployments of the Benthos long gravity core, and two deployments of the Benthos piston core. Two sets of piston coring gear were lost during the 1994 cruise, due to unanticipated ease of penetration of the corer into the lakefloor sediments. Excess velocity of the core head weight when the piston encountered the stop resulted in breakage of the cable and fitting. The CCGS *Namao*, being designed as a navigational aids tender, is well suited for handling large equipment on the foredeck and for deployment over the side. The vessel is equipped with a 9-m cable boom having a 5-ton primary runner. The foredeck is approximately 8.5 m by 8.5 m in size with a raised hatch cover in the centre of the deck. The AGC wide-diameter and Benthos medium-diameter piston coring systems were the primary tools used on the cruise. The apparatus was rigged diagonally across the foredeck. A maximum barrel length of 9 m was rigged due to space and handling limitations and water depth. The core liner was extruded from the core barrels, cut in 5 foot-long (1.5 m) sections, sealed at the ends, labelled and stored upright in a core cooler on the foredeck. At the conclusion of the cruise, this core cooler was transported to the core storage facility at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. Box cores were obtained at 10 sites in 1994, to obtain a high-resolution record of recent sedimentation. The apparatus recovered a cubic sample 0.5 m on each side from the lakefloor. Four 10-cm diameter tubes, aided by a vacuum pump, were used to core the sediments without disturbance.

In 1996, a second cruise was completed, in which emphasis was placed on confirmation and dating of the southward migration of the lake, and scouring of the lake bottom by ice. Outfitting of the CCGS *Namao* for the survey commenced at Selkirk on August 6, 1996. The initial portion of the cruise, from August 9-21, was devoted to geophysical surveys of ice scour features and lake bottom stratigraphy. In total, 238 km of survey lines were completed. A major innovation of the survey was the application of dual-frequency side scan sonar, which distinguished recent from buried ice-scour features. Demobilization of the geophysical instruments and mobilization of coring gear was completed August 22 at Grand Rapids. A total of 134.8 m of core subsequently was obtained from 22 sites, including excellent intersections of sand bodies buried by fine-grained sediments in the South Basin. The cruise was less experimental and diverse than the 1994 effort. No further box coring, which had been very successful in 1994, was required, and geophysical surveys were limited to low frequency seismic, high frequency seismic, and sidescan sonar. Slightly different modes of core collection, variations in corer operation, and natural variations in sediment strength lead to variations in the recovery of sediments, particularly the soft, low-strength Lake Winnipeg mud. In 1994, a long gravity corer was used after loss of two standard solid piston corers, but in 1996, a split piston corer was used.

GEOPHYSICAL SURVEYS

Seismic and sidescan sonar records obtained during the two *Namao* cruises have permitted an interpretation of the geometry of bedrock surface, of the distribution, thickness, and structure of sediments infilling the Lake Winnipeg basin, and of the nature of lake bottom morphological features (Todd and Lewis, 1996a; 1996b; Todd et al., 1998b). In most cases, a clear distinction between low relief Paleozoic carbonate rock and high relief Precambrian rocks could be made. In northern Lake Winnipeg, the eastern limit of Paleozoic rock is clearly demarcated 30 km west of the previous estimate of its position. In southern Lake Winnipeg, all or most of the Paleozoic sequence terminates at a prominent buried escarpment in the centre of the lake. This indicates that Paleozoic rock on the eastern shore, known from drilling and outcrops, is an outlier. Major moraines are apparent as abrupt, large ridges having a chaotic internal reflection pattern. These include the Pearson Reef Moraine, the George Island Moraine, and the offshore extension of The Pas Moraine. Little evidence for extensive or thick till was observed. Instead, fine-grained sediments deposited in glacial Lake Agassiz rest directly on bedrock over most of the lake basin. Hence an episode of erosion to bedrock was associated with glaciation and/or deglaciation. The "Agassiz Sequence" sediments are well stratified, drape underlying relief, and in some areas are over 100 m thick. In places, stratification in these sediments is disrupted, perhaps by dewatering. Evidence of erosion of Agassiz Sequence sediments by recent currents was observed. The contact between the Agassiz sequence and the overlying "Winnipeg Sequence" sediments is a marked angular unconformity. The Agassiz Unconformity indicates up to 10 m of erosion in places. The low-relief character of this unconformity precludes subaerial erosion and the lack of till, moraines, or extensive deformation precludes glacial erosion. Waves appear to be the most likely erosional agent, either in waning Lake Agassiz or early Lake Winnipeg time. Winnipeg Sequence sediments, in places very thin, mantle most of the lakefloor. These sediments were deposited in Lake Winnipeg and are faintly stratified to massive and reach about 10 m in thickness in deep water. On the surface of the Winnipeg Sequence, vigourous, episodic currents are thought to contribute to the construction of flow-transverse sand waves as much as 6 m high in a deep, narrow constriction in the lake.

OFFSHORE STRATIGRAPHY

Detailed interpretation of seismostratigraphy and lithostratigraphy of sediments in Lake Winnipeg has been conducted by Lewis and Todd (1996a; 1996b). This work is based on both low frequency and high frequency seismic records, and analysis of long cores obtained in 1994 and 1996. Above the "Agassiz Unconformity", the Winnipeg Sequence appears as an accoustically transparent section grading downward to weak parallel reflections, and consists of soft dark olive grey clay-silt mud, faintly banded in its lower section. In the North Basin, the underlying Agassiz Sequence mainly appears as three intervals of parallel seismic reflections of variable amplitude, and the sediments consist of silty clay rhythmites up to 5 cm thick. At one site, a grey stony diamict likely deposited as till was cored under silty clay rhythmites. In the South Basin, the Agassiz Sequence is more complex, and consists of four seismic intervals. Where cored, the upper three intervals are stiff, banded silty clay and rhythmites, stiff silty clay rhythmites, and stiff faintly banded silty clay, respectively. This stratigraphic model, when combined with other observations, has permitted an interpretation of the evolution of Lake Winnipeg to be made, providing a basis for understanding trends in water level change and shore erosion, as well as providing a basis for assessment of former lake conditions, including the distribution and history of contaminant inputs.

The work is heavily dependent on 33 long cores that recovered sediments from the two major seismic sequences. Core quality varied considerably. The quality of mud recovery was evaluated by comparing recovered sediment intervals with thicknesses determined by seismic reflection. Shortfalls in mud recovery by coring with 9-m long barrels range from zero to under 2 m most commonly, and to one extreme value of 3.4 m. The acoustic/seismic technique is favoured for determining the depth or elevation of the Agassiz Unconformity where seismic velocity has been measured in the sediment cores. Till is absent or so thin, i.e. <~1 m, beneath much of the lake that it cannot be resolved in the seismic reflection profiles. Distinctive packages of coherent, strong reflections in Seistec records give character to the Agassiz Sequence, allowing its subdivision into reflective facies intervals. Reflections show that the glaciolacustrine sediments conformably drape the underlying relief on bedrock or morainic surfaces. By comparison with core lithologies and physical properties, the coherent reflection facies are correlated to zones of silty clay rhythmites or laminated silty clay containing mm-scale silt laminae. Aggregate thicknesses of these sediments create layers >20 cm thick with differing acoustic impedances, the cross-product of sound velocity and bulk density. The boundaries between layers of differing impedance are the likely sources of the strong, coherent reflections. Within the Agassiz Sequence, these zones, with their visibly more numerous silt laminae, are thought to reflect glaciolacustrine deposition nearer an ice margin, the inferred sediment source, than sediments that produce a transparent seismic facies. The uppermost strong coherent reflection package in the North Basin correlates to interbedded sandy silt and clay and may originate by wave and current winnowing in an environment of declining lake depth.

Sediment physical properties were measured on the gravity and piston cores collected in Lake Winnipeg (Moran and Jarrett 1996b; 1996a; 1998). The measurements of bulk density, acoustic velocity, magnetic susceptibility, and colour reflectance were made using new, non-destructive methods at a 1-cm spacing. These high-resolution data have been used to construct complete composite stratigraphic sections from a series of individual, discontinuous cores. These composite sections provide a baseline depth reference for interpretation of the stratigraphy. The density and shear strength data were also used to estimate sediment stress history for each of the major lithostratigraphic units and their variations across the basin. Rack et al. (1998) have conducted experiments on magnetic resonance imaging of selected cores. Whole core gamma-ray attenuation measurements were used to calculate the bulk porosity of the sediment at 1-cm intervals for comparison with the images. Image contrast and image intensities were found to relate to local porosity and magnetic susceptibility variations. In general, regions of the core with low signal intensity contain high porosity and low magnetic susceptibility. The best contrast between sediment layers was observed from regions of the core with high magnetic susceptibility. High signal intensity was observed from regions with low porosity and/or high magnetic susceptibility.

A comprehensive program of analyses is supporting co-operative efforts to work out the stratigraphy of sediments in Lake Winnipeg. Use of macrofossils of terrestrial plants and insects to obtain radiocarbon ages for sedimentation and for the reconstruction of paleoenvironments, primarily with respect to shoreline proximity, is presently being co-ordinated by A. Telka (Vance, 1996; Vance and Telka, 1998). Paleomagnetic methods, in particular geomagnetic secular variation, are being applied by King and Gibson (1996b; 1996a). Compositional analyses are being carried out by Last (1996), Henderson (1996), and Henderson and Last (1996; 1998). Isotopic analysis of sediments and pore waters is being directed by W. Buhay and R. Betcher (Betcher and Buhay, 1996; Buhay, 1996b; 1996a; Buhay and Betcher, 1996; 1998). Palynological investigations are being conducted by T. Anderson, while ostracode micropaleontology work is being directed by Rodrigues (1996a; 1996b). Thecamoebians have been investigated by Burbidge and Schröder-Adams (1996a; 1996b; 1998), and phytoplankton by Kling (1996b; 1996a; 1998), as well as ongoing work on diatoms by J. Risberg. This array of activity is permitting a thorough investigation of the history of sedimentation in Lake Winnipeg, and hence the history of the lake itself.

A reconstruction of Lake Winnipeg lake level history, taking into account northeastward regional uptilting due to glacioisostatic recovery and diversion of the Saskatchewan River to the lake, but without consideration of climate change effects, suggests that: 1) Lake Winnipeg began after 8 ka following recession of glacial Lake Agassiz as a series of independent lakes in the North, South, and other local basins, each draining northward over a local sill; 2) local lakes transgressed southward and coalesced, with the North Basin finally controlling water level in the South Basin after about 4 ka; 3) since 5 ka, water levels throughout the basin have been augmented about 2-3 m as a result of Saskatchewan River diversion and capture of lake-level control by the more rapidly rising Whiskey Jack Narrows area 78 km north of Lake Winnipeg.

There is evidence, however, that climate played a major role in much of Lake Winnipeg history. Basal reflections within the Winnipeg Sequence provide abundant evidence of onlap. This, combined with observations of coarser basal sediments in cores and evidence of coastal onlap indicates the Winnipeg sediments were deposited in a transgressive lake with increasing water level. Basal radiocarbon ages for the Winnipeg Sequence show that the onset of sedimentation in North Basin began with the predicted isolation from Lake Agassiz about 7.7 ka, but sedimentation was suppressed at southern sites in North Basin and in the South Basin until 5-4 ka. The delay in sediment accumulation is contrary to the predictions of lake evolution based on differential postglacial rebound which assume that lakes are always open and overflowing at their outlets. Water balance computations suggest that the early history of Lake Winnipeg was influenced by closed lake conditions induced by warmer and drier climates similar to modern climates in southeastern Alberta and southwestern Saskatchewan. Under such climates, the South Basin appears to have dried up in the mid-Holocene. A lake returned and switched to open conditions after 4.5-4 ka in response to the onset of a cooler and wetter climate. A shorter and milder episode of closed lake conditions is inferred for the North Basin. Diversions of the Saskatchewan River to North Basin at about 4.7 ka, and the Assiniboine River to the Red River and the South Basin at about 4 ka (Rannie et al., 1989) are both coincident with the switch in lake status from closed to open. This study of Lake Winnipeg illustrates a general relationship between transgressive lake histories and climate. As the areas of open, overflowing lakes expanded in a suitably dry climate, for example, by transgression in a postglacial rebounding basin, they may have exceeded the capacity of the drainage basin to supply water to offset increasing losses to evaporation. Water levels were drawn down by evaporation to a smaller new steady-state area, and the lake becomes closed with a surface elevation below that of its outlet. Conversely, when climate became markedly wetter, water supply increased and evaporation decreased, so the lake would rise to its outlet and switch into an open, overflowing state.

ICE SCOUR

Sidescan sonar and high frequency seismic records obtained in Lake Winnipeg in 1994 and 1996 show numerous linear furrows in the soft sediments of the lake bottom that generally trend NNW-SSE, similar to the orientation of prevailing winds in late winter and spring (McKinnon, 1996; McKinnon et al., 1996). These features are up to 2 m in depth, 200 m in width, and several km in length, and are in many cases flanked by berms about 0.5 m in height. The furrows show crosscutting relationships, changes in orientation, and abrupt terminations. At two locations, lake bottom outcrops of Lake Agassiz sediments are heavily scoured, with a complex pattern of scour orientation, suggesting that furrows inscribed into softer Lake Winnipeg sediments are obliterated more rapidly than is the case in the harder Lake Agassiz sediments. The geometry and distribution of these features, and general knowledge of the regular formation of pressure ridges in the lake ice, indicate that wind-driven pressure ridge keels dragging on soft bottom sediment form these features. Furrows are particularly prevalent in the southern South Basin and in northwestern North Basin, where ice-accumulation conditions and water depth appear to favour scouring. Dual frequency sidescan records obtained in 1996 indicate that the majority of the scours are slightly buried, being apparent on a low-frequency record but not on the high frequency record, indicating that some years have passed since formation of most of the features.

Another type of feature on sidescan sonar records are linear features with diffuse edges, up to 15 m in width and several hundred metres in length. These features show neither trough nor berm on high frequency seismic reflection records, but a strong reflector at the lakefloor masks the record beneath the feature. Similar features observed on the Lake Ontario lakefloor have been referred to as linear acoustic backscattering anomalies (LABAs), and a pattern that radiates from the Welland Canal, combined with ash in bottom grabs, indicates that the features are ash trails associated with shipping. It is not known whether a similar genesis applies on Lake Winnipeg.

GRAVITY AND UPLIFT

North America has experienced differential crustal uplift due to the delayed response of the Earth to the surface unloading caused by the decay and collapse of the continental ice sheets. Although other factors such as climate have influenced the evolution of Lake Winnipeg, it appears that uplift has been the dominant control. Although this may have been the case in the past, a major question is whether it is the case today. Studies of the rate of coastal submergence in recent centuries (Nielsen, 1998) and lake-gauge studies (e.g. Tackman et al. 1998) have provided indications of ongoing uplift. Determining with greater confidence the past and present rate and direction of tilting will, however, assist understanding of both the history and evolution of Lake Winnipeg, and the on-going processes that will affect future evolution of the Lake. To date, the pattern of uplift due to isostatic rebound has been determined largely by measuring the elevation of relict marine and glaciolacustrine shoreline features that contain C14-datable material. These studies are continuing to provide new evidence in the form of isobase maps and regional tilt profiles that put new constraints on the history and evolution of the Laurentide sheet. Historical lake level data and repeated high-precision geodetic measurements contribute additional constraints that must be accommodated by a unified postglacial rebound model. A major initiative that will advance this topic through measurement of absolute gravity and uplift is being co-ordinated by A. Lambert, N. Courtier and T. James of GSC-Pacific (Lambert et al., 1996; Lambert, 1996; Lambert et al. 1998). This five-year project started in 1996 and is a co-operative effort by GSC, Manitoba Hydro, the US National Aeronautics and Space Administration (NASA), the US National Oceanic and Atmospheric Administration (NOAA), and Geomatics Canada.

Two new continuously-operating GPS receivers have now provided two years of GPS data recorded by GSC. In June 1996, equipment was installed at a site near Flin Flon made available by the Department of National Defence. In October 1996, another station was installed at the Underground Research Laboratory near Lac du Bonnet, a facility of the Pinawa-based Whiteshell Labs of Atomic Energy of Canada Ltd. The GPS receivers, ROGUE SNR-8000's, were obtained on long-term loan from NASA under the Solid Earth and Natural Hazards Program. Construction of buildings, antenna monuments, data communication equipment, and uninterruptible power supplies were carried out by GSC with funding from Manitoba Hydro. Data from these two stations are transmitted every four hours by automatic telephone dial-up. The data are pre-processed and archived at GSC Pacific, and are also acquired by the Geodetic Survey of Geomatics Canada, and are reformatted and retransmitted to the NASA Crustal Dynamics Data Information System. It is intended that these GPS receivers will be operated at these stations for a period of five years in conjunction with existing GPS receivers at Churchill and the North Liberty station near Iowa City, Iowa. These data will permit a joint analysis of vertical movement rates, in combination with data from Churchill, provided by Geodetic Survey of Canada, as well as from North Liberty, Iowa, provided by Jet Propulsion Laboratory, Pasadena, and other North American reference stations. Analysis of daily baselines among the four mid-continent stations and other selected GPS receivers in Canada and the USA will be carried out to determine the relative vertical and horizontal crustal velocities for comparison with theoretical model predictions. Churchill and North Liberty are stations participating in the International GPS Service for Geodynamics (IGS) program. Highly automated GPS data processing software, the Bernese processing engine, has been installed at GSC Pacific and is now being used to analyse the existing backlog of data. Initial GPS estimates of crustal movement rates should be available by mid-1999.

High-precision gravity measurements have been made by GSC and NOAA at Churchill and International Falls, Minnesota since the late 1980s and, in association with the Lake Winnipeg Project, at new stations in the intervening area since spring 1995, using FG5 absolute gravimeters. At Churchill, eight years of data indicate a steady decrease in gravity at a rate of -1.45 ± 0.19 mGal/yr. All of the gravity data collected at six high-precision stations are being re-analysed using a common data analysis protocol developed by GSC and NOAA. It has become better appreciated recently that the vertical gravity gradient at many sites departs significantly from linearity, a significant factor when measurements made by different instruments at different heights are reduced to the standard international height of 1 m. Consequently, the vertical gravity gradients at Churchill, Flin Flon, Pinawa, International Falls, Wausau (Wisconsin) and Iowa City were remeasured. The new vertical gravity profiles should keep the vertical transfer uncertainty to less than 1 mGal, the precision of the absolute measurements themselves. Care has been taken to ensure that no unexpected biases arise in the Canadian FG5-106 gravimeter with respect to the US FG5-102 instrument. Measurements are made every year with the Canadian instrument at the Table Mountain Geophysical Observatory near Boulder, Colorado, the home base for the US instrument, prior to each measurement campaign on the mid-continent line. A pattern of decreasing gravity in the north, corresponding to uplift, and increasing gravity in the south, corresponding to subsidence, is emerging from preliminary results.

By 2001, the GPS and absolute gravity data are expected to provide rates of change accurate enough to constrain postglacial rebound models significantly better than present modelling. The precision of a measurement of rate of change of height or gravity can be estimated, knowing the precision and frequency of the individual measurements. The principal assumption is that the errors on the measurements of height and gravity are 10 mm and 2 mGal, respectively, and that the errors on these measurements are normally distributed, random errors. On the basis of this statistical analysis, the daily GPS measurements are expected to yield a rate of change in height with a standard error of 1 mm/yr well within the five-year time frame. The absolute gravity measurements are expected to yield a rate of change of gravity with a standard error of 0.3 mGal in five years. To put this in perspective, the standard error on the height rate determination is 10% of the expected maximum rate at Churchill and the standard error on the gravity rate is 20% of the expected maximum rate, mainly due to the fact that gravity is measured less frequently. The ratio of the rate of change of gravity to the rate of change of height varies significantly from one process to another. For postglacial rebound, the ratio is predicted by theoretical models to be about -0.15 mGal/mm. The role of repeated absolute gravity measurements is to verify that the vertical movement detected by the GPS measurements is the result of postglacial rebound and that the observed GPS rates are not contaminated by unexpected biases. If the GPS and absolute gravity measurements are shown to be consistent with theory, absolute gravity measurements may be used as a proxy for height change observations.

The new data are also expected to be crucial to development of an improved model of the Laurentide ice sheet and better determination of Earth rheology. This will be done by combining the new geodetic data with geomorphological data on Holocene vertical crustal movements to produce a best estimate of present and recent tilt rate and direction. As a pilot exercise, two available sources of information, geometry of the 9.5 ka BP Campbell strandline of Lake Agassiz, and the rate of decrease in absolute gravity values measured from 1987 to 1995 at Churchill, Manitoba, have been examined (Lambert et al., 1998). These observations were compared to theoretical predictions based on the published ICE-3G loading history and on a model of Earth rheology characterized by a 1066B elastic structure, an upper-mantle viscosity of

10^{21} Pa s, a lower-mantle viscosity of $2x10^{21}$ Pa s, and a lithosphere thickness of 120 km. This model predicts significantly more tilt than the observed tilt of the Campbell strandline, whereas it predicts a significantly lower rate of decrease of gravity at Churchill than is observed. By varying key parameters to produce an iterated model, it was shown that, taken together, these data are consistent with a thinner Laurentide ice-sheet over the Prairies, and an increased value for lower mantle viscosity, relative to ICE-3G. The present data do not, however, appear to constrain lithosphere thickness very well. In comparing predicted rates of crustal motion and gravity for the ICE-3G and the iterated model, it is apparent that, while the rate of change of height and gravity at Churchill is not very different for the two models, there is a marked difference to the south. For the ICE-3G model, the change from uplift to subsidence occurs somewhere between International Falls and Wausau, while for the iterated model, the zero line has shifted north to lie between Pinawa and Flin Flon. The height rate differences between the two models in the vicinity of the zero line are around 2.5 mm/yr and, therefore, should be resolvable at the individual stations by GPS measurements. The corresponding rate difference in gravity is smaller compared to the precision of the rate estimates but should be resolvable over the five-year period by combining measurements at two or more stations. A new model, ICE-4G, fits the gravity change data better than the earlier ICE-3G model. Adjustment of model parameters, supplemented by the new mid-continent data, will lead to better understanding of the trade-offs between earth rheology and ice sheet history, and hence to an improved Laurentide postglacial rebound model. An improved tilt model in Manitoba is expected to influence Lake Winnipeg reconstructions and forecasts of shoreline inundation.

SHORE PROCESSES

Research on shore processes is being directed by D. Forbes of GSC Atlantic (Forbes and Frobel, 1996; Forbes 1996). The work has included reconnaissance surveys in 1994, targeted investigations in 1996, and a month-long intensive effort in September 1997. Basic information on many aspects of Lake Winnipeg shoreline processes was unavailable when this new program of co-operative research was launched. Little was known of shore-zone characteristics and processes in the North Basin and central lake, while only limited information was available for the South Basin. This lack of data fostered public misapprehension concerning the effects of lake-level regulation on shoreline stability, and compromised efforts to identify the causes of shoreline erosion. A general understanding of shore system processes is required in order to ensure effective and integrated shore-zone and lake basin management.

The lakeshore can be described in terms of seven shore-type associations: 1) marsh and deltaic shores; 2) low-energy Precambrian bedrock outcrop with discontinuous marsh; 3) sand-dominated beaches, spits and barriers; 4) heterogeneous sequences of sand or gravel beaches, low scarps, and rock or boulder-lag headlands; 5) gravel beaches and barriers associated with sedimentary rock cliffs; 6) unlithified bluffs or unstable slopes with associated mixed beaches; and 7) artificially modified shores. Shore type is a function of substrate geology, basin morphology, lake level, wave climate, sediment supply, and the action of various shore-zone processes over time. Resistant Precambrian rocks with limited sediment cover dominate the eastern lakeshore. Ordovician sedimentary rocks outcrop along the western and south-eastern shores, with a variable cover of glacial, glaciofluvial, and glaciolacustrine sediments.

The major achievements of the 1994 shoreline survey include: 1) twelve hours of low-level oblique video imagery covering most of the mainland lakeshore and major islands; 2) voice commentary describing visual observations and oblique air photos supplementing the video; 3) shore surveys and sampling carried out at 12 sites around the lake; 4) development of a shore-type classification for Lake Winnipeg; 5) the first comprehensive mapping of physical shore-zone characteristics for the entire Lake Winnipeg shoreline; 6) preliminary interpretations of lake-level history from geological evidence in the shore zone; 7) an informal presentation to Manitoba Hydro in September 1994; 8) a presentation of preliminary results at the Coastal Zone Canada conference in Halifax in September 1994; 9) summary results presented at the Lake Winnipeg workshop in March 1995; 10) a report to Manitoba Hydro in August 1995; 11) a chapter in a GSC Open File report summarizing results of the project; and 12) a presentation on shoreline indicators of lake-level history at the Geological Association of Canada conference in Winnipeg in May 1996.

A number of major questions concerning lakeshore processes in Lake Winnipeg remained after or grew out of the 1994 reconnaissance, including: 1) the origin and evolution of large lakeshore deposits; 2) sediment transport rates alongshore and offshore in relation to shore erosion and shoreface profile adjustment; 3) the role of frazil-, slush-, and anchor-ice sediment transport during freeze-up, of ice piling and of lake-bottom scour during winter and spring, and the time-variability of these processes; 4) the character of waves on Lake Winnipeg and their relationship to meteorology and basin geometry; 5) the role of wind-driven water level fluctuations in erosion and cross-shore transport; 6) shoreline erosion rates; 7) the influence of shore structures on erosion, including worsening of erosion at some sites; 8) long-term variability of storminess, lake levels, and wave energy, including evidence for extreme lake level events; and 9) evidence for long-term lake level change, both basin-wide and tilting, and the shoreline response as a function of shore type, shoreface morphology, geology, and exposure.

These issues were pursued in association with the *Namao* cruise of summer 1996. Because a full understanding of shoreline processes requires knowledge of shoreface sediments extending out into the basins, close collaboration was maintained on the planning of geophysical survey lines and coring targets for the offshore survey, to address objectives of both programs. Extension of the CCGS *Namao* cruise by one week enabled nearshore surveys directly serving shoreline process research to be carried out. The shore-zone surveys were conducted from a 20-foot aluminum work boat capable of a speed of 33 knots under ideal conditions, but slow and exposed in rough weather. The work boat operations were highly successful, completing 128 geophysical survey lines at 17 sites, producing 19 rolls of bathymetry and sub-bottom reflection data and 21 rolls of sidescan imagery. Onshore surveys were completed at 11 new sites and 14 benchmarks were installed. In total, 27 grab samples of lake-floor sediments were obtained from the work boat and 33 samples of beach, dune, and cliff deposits were collected onshore.

Key information on shoreface profiles and sediments also was obtained by sounding and coring through the ice in early 1997. This program targeted a number of profiles previously surveyed in the 1970's as well as other sites where boat or ship support was not available to extend shore-based surveys offshore. Ice-based coring was also undertaken in marshes and other sites not readily accessible for coring during the summer season. The winter program provided an opportunity to observe surface features of the lake ice cover, including pressure ridges, shore-ice rideup or pileup. Ice cores were examined for evidence of sediment inclusion by frazil or other processes. Radarsat and other satellite imagery is also being used to analyse lake ice processes.

Field effort in September 1997 had two major components, one consisting of detailed lakebed surveys, and the other focusing on nearshore dynamics and erosion processes. The combined program operated from the Coast Guard search-and-rescue (SAR) base in Gimli and used two work barges supplied from Coast Guard base Selkirk, the *Namao* landing barge and the Selkirk base barge. For the survey program, a geophysical lab was constructed to fit inside the *Namao* barge, from which bathymetric, sidescan sonar, and high-resolution seismic reflection surveys were carried out in the western South Basin. This part of the project replicated many components of the ship-based geophysical surveys of 1994 and 1996, but provided a means of carrying the lakebed mapping into very shallow water. The survey also covered areas of the central basin where ice ridging was observed the previous winter, as well as regions of known ice pileup in the shore zone during the 1996-1997 ice season. Extensive scouring of the lakebed was recorded in previously unsurveyed areas and work is in progress to determine whether any of the newly documented scours correlate with observed ice features. Sidescan sonar mosaics were completed over the shoreface off Willow Point, the site of a nearshore dynamics and erosion study, and north of Gimli. The surveys also documented outcrops of erosion-resistant glacial deposits and helped to correlate different parts of the lakebed sediment sequence to sections in the shore cliffs. This provided a basis for analysis of shore erosion as a function of nearshore sediment type and stratigraphy.

The nearshore dynamics and erosion process study used the Selkirk base barge, modified to carry a small Hyab crane. This provided support for deployment of two recording InterOcean S4A wave and current meters, and a custom-built instrumented tripod known as Ralph. The latter carried four EM current meters providing current velocity profiles, a pressure transducer for wave and water level measurements, and an acoustic backscatter sensor for measurement of bottom scour and suspended sediment profiles. These instruments were in place for 2 weeks and recorded three moderate storms. Complementing the moored instruments, numerous drops of a rotating sonar head were completed, giving high-resolution images of the lakebed before and after storm events. This revealed the formation and reworking of sand and gravel ripples over parts of the clay erosion surface, demonstrating that abrasion by coarse sediment under moderate storms is a factor in the shoreface erosion process. The sonar surveys also revealed a hummocky, pitted, and scoured clay surface, consistent with earlier sidescan and bathymetric data and with SCUBA observations. The SCUBA program was also intended to provide geotechnical data on shear strength, compressive strength, bulk density, fracture characteristics, and microtopography, as well as direct measurements of erosion. These efforts largely failed because of very low visibility in the lake. In addition, plans to deploy an instrument package called Sea Carrousel to make direct measurements of critical shear stress for erosion were thwarted as it became apparent that the lake bottom is too rough to provide the necessary seal around the skirt of this in-situ flume. Despite these problems, valuable and previously non-existent data on wave dynamics, sediment transport, erosional morphology, and fracturing characteristics in the nearshore were obtained. These provide a basis for establishing erosion thresholds related to abrasion and entrainment of fractured clay on the shoreface.

Thus the following objectives were accomplished during the 1997 work: 1) additional lakebed surveys in the South Basin to fill gaps in our knowledge of shore-zone bathymetry, nearshore sand and gravel distribution, limits of exposed Lake Agassiz clays, and shoreward limits of Lake Winnipeg basin muds; 2) preliminary study of erosion processes on nearshore profiles cut into relict Lake Agassiz clays, including quantitative data on shoaling waves, nearshore currents, bottom boundary dynamics, nearshore lakebed morphology and roughness, sediment transport, and lakebed erosion; 3) further investigation of shoreline deposits recording environmental changes on Lake Winnipeg; 4) further analysis of survey data and imagery for formation, location, and dynamics of ice ridging; and 5) lakebed surveys of previous survey lines and areas of observed pressure ridges and shore ice pileups in winter 96-97 to estimate frequency of new ice scours.

Lake-level variation at time scales of greater than one year can be divided into tilting due to differential uplift, with lake level stable at the outlet and rising at a rate increasing with distance south of the outlet, and basin-wide adjustments of climatic and hydrologic origin. Lake level rise is clearly indicated by transgressive beaches and barriers in the South Basin, such as Willow Point, Netley Marsh, Grand Marais, and Grand Beach, among other evidence. Along the north shore of the lake near the outlet, a well-developed arc extending from feeder bluffs in the east to the 20 km Limestone Point spit in the west reflects prolonged exposure to long-fetch southerly waves at relatively constant effective lake level. However, submerged ridges behind Limestone Point, transgressive sandy barriers with dunes along the eastern shore of the North Basin, transgressive gravel structures along the western shore, washover deposits in Sturgeon Bay and Fisher Bay, complex structures of the large Sandy Bar spit near Berens River, and other indicators, imply a component of medium- to long-term basin-wide submergence. Weathered high-level beaches at sites such as Selkirk Island and along the western shore of Sturgeon Bay, suggest water levels above that of the present, due either to major storms, or sustained higher water levels. These observations clearly support the notion that Lake Winnipeg is expanding, but it is important to note that erosion is not only active in the South Basin, it also is active at the north end of the lake.

WAVES

An adequate account of deep water and nearshore wave climate is fundamental to offshore and coastal engineering. It commonly is not, however, cost effective or practical to obtain wave data for each application. Long-term statistics are required for structural design, so short-term observations are of limited use. Wave climates therefore tend to be modelled using meteorological data. These models require calibration and testing, however, and an opportunity to do so was presented by the Lake Winnipeg Project. During summer 1996, under the direction of J. Doering and D. Fuchs of the University of Manitoba, a north-south array of three waverider buoys was deployed in the South Basin. Two 0.7-m nondirectional waveriders were deployed from June 13 to October 27, inclusive, although several weeks are missing from the north buoy due to malfunction. One 0.9-m directional waverider was deployed from September 13 to October 27, inclusive. Data were transmitted to a shore station at Grand Beach. A north-south arrangement was chosen because storm winds over Lake Winnipeg tend to come from the north. The synoptic array has allowed comparison of predicted and observed wave conditions, including examination of wave growth to the extent that the frequency response of the buoys allows.

Meteorological data, including wind speed, direction, and maximum gust, water and air temperature, and barometric pressure, have been obtained from the Environment Canada buoy near the northern waverider buoy, from Gimli, and also from Victoria Beach. Energetic conditions occurred at the meteorological buoy on 13 of the 62 days of record, when wind speed exceeded 40 km/h, and 55 days had wind speeds over 30 km/h. For the Gimli station, 9 days had wind speeds over 40 km/h and 41 days had wind speeds exceeding 30 km/h. For the Victoria Beach station it was found that 34 days had wind speeds readings that were in excess of 40 km/h and 65 days had readings exceeding 30 km/h.

The model SWAN (Simulation of WAves in the Nearshore) developed by Holthuijden is currently being used to construct a model for significant wave height, peak period, and wave direction that will then be compared to the observed values at the three buoys. Variance density and directional spectra are also being compared at each buoy. A comparison of Gimli weather data with Victoria Beach is being used to examine the effect of spatial variance on the wind field during storms. The model will then be applied to hindcasting wave climate on the lake for selected storms, as well as modelling wind conditions at various lake elevations. Future work may involve the measurement and modelling of nearshore wave conditions, and use of SWAN model output to develop a sediment transport model for the South Basin. Over water meteorological measurements will also be used to examine, and remove if necessary, the influence of atmospheric stability on wave growth. Meteorological data will be used to predict deep-water wave height, periods and direction. A model developed for a previous Lake Winnipeg project, based on the wave, height, period, and direction, will also be used to predict deep-water conditions.

LIMNOLOGY

In order to map the texture and composition of bottom sediments, in particular the analysis of several variables not addressed by the 1969 Freshwater Institute survey, a systematic set of bottom sediment samples was collected in 1994. Prior to the cruise, 50 evenly spaced target sites were designated, with a more dense sampling grid in the South Basin. A total of 33 of the stations were occupied from the ship's launch. Positioning was determined using a portable GPS unit. An intact bottom sediment sample was recovered using a Ponar dredge or, in a few cases, an Eckman dredge. Opening of the dredge permitted the intact sample to be placed in a plastic pan in the boat. A one-litre sample was recovered from sediments within 5 cm of the sediment-water interface. This activity was assigned the lowest priority of the geological objectives. No samples were obtained at times when wave conditions prevented safe use of the launch. No sampling was done from the ship, in order to avoid interference with coring operations. Although 33 sampling stations were occupied, only 31 bottom sediment samples were obtained. At two stations, a hard lake bottom was encountered, and no sediment was recovered. Air temperature, surface water temperature, and a Secchi disk measurement were recorded at all 33 sampling sites. Conductivity-temperature-depth (CTD) profiles, including data from below the sediment-water interface where bottom sediments were soft, were only taken at 24 of the sites, due to the necessity that the equipment be transferred to another Freshwater Institute project prior to the last two days of sampling. CTD profiles were also taken during the 1996 cruise, using GSC equipment.

During both cruises, phytoplankton samples, consisting of 0.25 litre of surface water treated with a preservative, were regularly collected. Zooplankton net hauls also were obtained, and results were reported by Salki (1996). Excess dredged sediment remaining after bottom sediment samples were taken in 1994 was screened in order to recover benthic organisms, which were preserved in formaldehyde. Time constraints prevented quantitative recovery, although qualitative analyses were reported by Cobb (1996). A few trawls to net pelagic fish along offshore transects were attempted, but were unsuccessful.

Water samples were taken during both the 1994 and 1996 cruises. Subsamples, collected for dissolved silicon and dissolved organic carbon analyses, were placed in 100 ml jars containing a preservative. Additional subsamples were filtered on board for the determination of chlorophyll and particulate silicon, carbon, nitrogen, and phosphorus. Samples were also taken for measurement of CO_2, and an instrument that allowed continuous monitoring of CO_2 was operated for a portion of the 1996 cruise. Results are on file at the Freshwater Institute, under the direction of M. Stainton.

CONTAMINANTS

A program of contaminants research based on analysis of bottom sediment samples, box cores, and long cores collected from the CCGS *Namao* during the 1994 cruise is being conducted at the Freshwater Institute (Lockhart, 1996; Lockhart et al., 1996). The principal topics are radiochemical dating of recent sedimentation rates, and the concentrations of metals in the sediments. The work is being co-ordinated with similar work on the Red River by the United States Geological Survey (Brigham, 1996), and work on organic contaminants at the University of Winnipeg (Fisher-Smith and Friesen, 1996).

Box core subsampling was conducted on board the *Namao* in 1994 by L. Lockhart. When a filled box corer was returned to the deck of the ship, the top of the apparatus was removed to expose the surface of the sediment. Cores 10 cm in diameter and 30-50 cm in length were then taken by pushing core tubes into the top of the sediment column with gentle vacuum to minimize compression of the sediment. The cores were extruded using a Teflon plunger and sliced into 1 cm thick samples. As sediment emerged from the tube into a clear plastic ring made of the same material as the core tube, slices were cut off with a stainless steel slicer. The samples were placed in Whirlpak bags and refrigerated until transferred to the Freshwater Institute. Samples were then stored in a cold room at 4°C prior to subsampling and freeze drying. Subsamples were supplied to a number of other investigators, notably W. Last, W. Buhay, H. Kling and S. Burbidge. The sediment samples were freeze dried, subsampled, and digested with nitric, perchloric, hydrofluoric and sulfuric acids in Teflon beakers. Final volumes were adjusted to 25 ml. Several metals were analysed by flame atomic absorption spectroscopy. Cadmium was analysed by graphite furnace atomic absorption and mercury by cold vapour atomic absorption. Samples analysed for mercury required a separate digestion with aqua regia. Standard reference materials were analysed concurrently as a measure of analytical quality.

The distribution of metals in the Lake Winnipeg sediments showed higher levels of mercury, cadmium and lead in the South Basin than in the North Basin. This may result from the different geological settings of the two basins, and/or anthropogenic input to the South Basin from the Red River and Assiniboine River may be responsible. Among the bottom grabs collected in 1994, mercury levels in the nine samples from the North Basin ranged from 28 to 70 ng/g dry wt with a mean of 52 ng/g, those for the narrow, central part of the lake ranged from 34 to 100 ng/g with a mean of 63 ng/g, and mercury levels in the South Basin were generally higher, the range being from 75 to 161 ng/g dry wt with a mean of 126 ng/g (Lockhart et al., 1996). Statistically, the South Basin mercury levels exceeded those in both the central and north parts of lake ($p < 0.001$). Given the higher levels in the South Basin, the question is whether the difference is caused by pollution or by the geology of the basins. A long core was taken west of Gimli (site 122) and a short box core was taken nearby (site 116). Taken together, these two cores appear to offer an historical record of mercury concentrations starting from the present time at the top and extending back several thousand years. Mercury was analyzed in 10-cm segments of the long core and values for all segments below 30 cm fell in the range of 29-61 ng/g dry wt. The top three segments showed striking elevations with mercury levels increasing to 116 ng/g at the top. The short core from the location nearby was analyzed for lead-210 and cesium-137 activities that permitted calculation of a sedimentation rate of 1000 $g/m^2/yr$. Mercury at the top of this core was 129 ng/g, which yields a flux of 129 $mg/m^2/yr$. If the sedimentation rate calculated for the short core is applied to the long core, then the flux at the base of the long core would be about 33 $mg/m^2/yr$. This approach suggests that mercury inputs to the South Basin have increased about 4-fold over several thousand years.

Work on application of stable lead isotope analysis to determination of the source of lead in Lake Winnipeg sediments is being conducted by S. Burbidge. Stable lead isotope compositions were determined for nitric acid-soluble and residual sediment fractions of sediment samples from a north-south transect. Results show that lead in Lake Winnipeg sediment is derived from natural as well as anthropogenic sources and both interbasinal and vertical variations in source material can be distinguished. The natural source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province, on the basis of a model age of 2.5 Ga. North Basin sediment is characterized by highly radiogenic acid-soluble lead and relatively non-radiogenic residual lead derived from high radiogenic lead/common lead Archean granitic rocks of the Superior Province. Lead in South Basin sediments is largely derived from Paleozoic and Mesozoic sedimentary rocks, which have a more radiogenic common lead component originally derived from the Superior Province. Vertical variations in lead isotope composition indicate three phases of lead input in Lake Winnipeg: 1) highly radiogenic Lake Agassiz sedimentation; 2) relatively constant isotopic compositions of natural Lake Winnipeg sources, and 3) reduced isotopic ratios of acid-soluble anthropogenic lead. Specific sources of anthropogenic lead for Lake Winnipeg cannot be determined with the present data since the anthropogenic isotopic composition is unknown.

During the 1994 cruise, ten air sample transects were taken using a Grasby GMW high-volume air sampler mounted at the bow of the *Namao*, and 20-litre water samples were taken for the investigation of trace organic contaminants (Fisher-Smith and Friesen, 1996). The air sampler was fitted with a glass-sampling head consisting of two filters in series, a glass fibre filter with a pore size of 1 mm followed by a three-inch long plug of polyurethane foam. The glass fibre filter was used to trap persistent organic contaminants that are sorbed to particulate matter with a diameter of 1 mm. The polyurethane foam provided a trap for volatile and semivolatile organic contaminants that exist in the vapour phase. Due to the low concentrations of the target organic contaminants in the air and water, it was necessary to sample large volumes of both matrices to ensure sufficient material for detection. The high-volume air sampler was, therefore, in use for as long as possible during each day of the cruise. Sampling was restricted to slow cruising speed and to times when prevailing winds carried the ship's exhaust away from the air sampler. During air sampling, wind speed and direction, air temperature, and atmospheric pressure were recorded at regular intervals. At the end of a sampling period, the filter and foam plug were placed in cleaned glass containers and frozen. A total of twelve samples were pumped into pre-cleaned stainless steel transfer tanks using a submersible pump. The tanks were stored in a cooler on board to maintain a temperature of 2-8° C to preserve sample integrity.

FUTURE PLANS

Although targeted follow-up research is anticipated, final outputs from the Lake Winnipeg Project are now in preparation. An open file that includes a report on the 1996 cruise, as well as data acquired since release of the earlier open file, is nearing completion for an anticipated early 1999 release. A separate open file will assemble descriptive information and data from the 1997 shore processes field work. Major scientific results will be presented at the annual meetings of the Geological Society of America (Lewis et al., 1998b; Thorleifson et al.; 1998) and the American Geophysical Union (Lewis et al., 1998a). Additional scientific papers that may form the basis of another special edition of a journal will then be the priority activity. Opportunities for integration of the offshore work with mapping presently being conducted on land are being pursued. Plans also call for the possible acquisition of a core through the thick Lake Agassiz sequence and underlying bedrock in the South Basin.

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