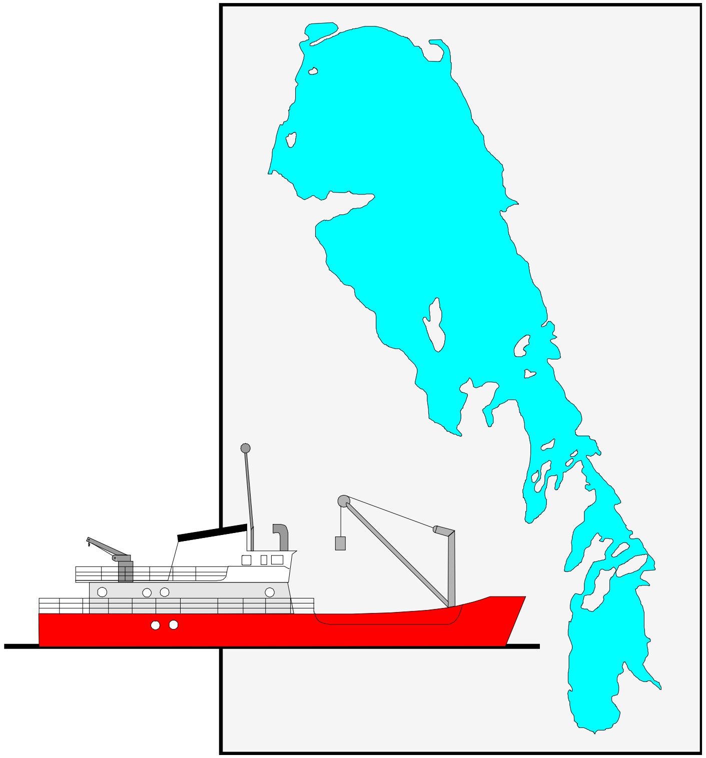
Influence of isostatic rebound on Lake Winnipeg



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2003 – present – State Geologist of Minnesota

1986 – 2003 – Geological Survey of Canada

1989 – Ph.D. – University of Colorado

1983 – M.Sc. – University of Manitoba

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My expertise regarding Lake Winnipeg

- My Masters thesis research on Lake Agassiz required an understanding of Lake Winnipeg evolution
- I first spoke on the influence of isostatic rebound on Lake Winnipeg at a Geological Society of America convention in Nevada in 1985
- I was a member of a team that coordinated comprehensive geological research on Lake Winnipeg, with Manitoba Hydro support, in the 1990s
- Results of this research are published in the peer-reviewed literature
- I wrote a plain language summary of the influence of isostatic rebound on Lake Winnipeg in 1998
- My presentation today is largely based on my 1998 summary
- I continue to have a role in related research across the region

Summary

- During the Ice Age, Canada was covered by a continental ice sheet
- Removal of the ice sheet resulted in isostatic rebound of the land
- This uplift, which is ongoing, is greatest in and around Hudson Bay
- Uplift rate diminishes in all directions from Hudson Bay
- The Lake Winnipeg outlet is thus rising relative to the rest of the basin
- Lake Winnipeg therefore is expanding due to isostatic rebound
- Ongoing shoreline erosion on Lake Winnipeg is natural

Bedrock geology

- Lake Winnipeg lies at the interface between granites and related rocks to the east, and sedimentary rocks such as limestones to the west
- The granites formed 2 to 3 billion years ago
- The limestones formed about a half billion years ago, when central North America was covered by a shallow tropical sea in which debris such as shells and corals accumulated, including the fossils we see in Tyndall Stone
- The processes that formed these rocks no longer play a role in the evolution of Lake Winnipeg

The Ice Age

- The Ice Age, also known as the Pleistocene, is geologically very recent
- During the peak of the most recent glacial cycle, between 10,000 and 20,000 years ago, Canada was covered by a glacier similar to the continental ice sheets that presently cover Greenland and Antarctica
- Ice flow radiated from the Hudson Bay region, and this ice flow scoured out the Lake Winnipeg basin as we know it

Lake Agassiz

As the continental ice sheet was reduced in size by climatic change at the end of the Ice Age, the land that slopes toward Hudson Bay in the Red River Valley filled with water due to the presence of the ice barrier to the north

This formed Lake Agassiz, which was in existence in an ever-evolving form between about 11,000 and 8000 years ago

It was in Lake Agassiz that the clay soils of the Winnipeg region were deposited

When the glacier finally was split into two remnants that both soon melted, by the formation of icebergs in Hudson Bay, Lake Agassiz drained

Isostatic rebound

- The continental ice sheet was about 4 km thick over Hudson Bay
- The surface of the earth basically floats on the interior of the earth, so accumulation of this ice mass depressed the surface of the earth by about a km
- As the glacier began to wane due to a shift from a positive to a negative balance between snow accumulation and loss due to melting and formation of icebergs, its mass was reduced and eventually removed
- Removal of this much weight is like taking a load out of a boat, and the surface of the earth rose
- Much of the uplift took place under the glacier, or soon after its withdrawal

Duration of the uplift

- Several observations indicate that the 8000-year period since deglaciation has not been enough time for the earth to adjust to removal of the glacier
- Around Hudson Bay, there are many marine shorelines that have been left behind by retreat of the bay due to uplift
- The age of these shorelines can be determined by radiocarbon dating of shells found in the gravels of these fossil beaches, and in other deposits
- The highest shoreline around Hudson Bay dates to about 8000 years, but those closer to the bay date to about 1000 years and younger
- This indicates that retreat of the bay has continued in recent centuries

Duration of the uplift

The fact that the uplift continues today is indicated by observations such as results from the Churchill tide gauge, where high-quality data collected since 1940 indicates that sea level at that site is retreating at a rate of about 0.7 m/century

Allowing for global sea level rise of about 20 cm/century in recent decades, this allows the uplift rate to be rounded off to about a m per century

The pattern of subtle trends in the strength of gravity across Canada supports these conclusions and indicates, along with information from the Great Lakes, that the general trend in uplift is for rates to diminish inland from Hudson Bay in all directions.

Differential uplift

Because the rate of uplift diminishes inland from Hudson Bay, a tilting action results

We know that the Lake Winnipeg region was tilted after the retreat of Lake Agassiz, because the shorelines of Lake Agassiz, which would have been horizontal at the time of their formation, now rise in elevation toward the northeast

Hence for at least much of its history, the Lake Winnipeg basin has been rising, and the north end has been rising more rapidly than the south end

Hydrological budgets

- A clear discussion of the influence of tilting on a large lake requires a review of the natural mechanisms that control lake level
- An open container of water such as a lake undergoes fluctuations in its level as water is gained and lost
- The volume of a lake does not determine lake level; volume is a result of lake level
- Input of water to a lake occurs in the form of river inflow, direct precipitation, and groundwater discharge from underwater springs
- Losses include river outflow, evaporation, and groundwater recharge as seepage into the lake bottom
- If inflow is greater than losses due to evaporation and groundwater recharge, the lake has a water surplus, and excess water is evacuated by outflow at the outlet(s)
- If evaporation and groundwater recharge together exceed inflow, the lake has a water deficit, and no outflow will occur

Hydrological budgets

- Hence the water budget of a lake is dictated chiefly by climate, with secondary effects related to groundwater
- In the case of a lake with no outflow, a closed basin with a negative water budget, lake level is purely a result of climate
- Examples of closed lakes are Great Salt Lake in Utah and Devil's Lake in North Dakota
- At present, however, Lake Winnipeg has a large water surplus. Water primarily derived from the Winnipeg and Saskatchewan Rivers is evacuated by the Nelson River at a rate of about 60 cubic km per year, a large flux compared to the small volume stored in the lake, about 300 cubic km
- Lake Winnipeg therefore is governed by processes related to a positive water budget. Secondary, short-term effects on lake level are caused by wind setup, and to a lesser extent, barometric pressure.

Lake level controls

- In the case of an outflowing lake with a positive water budget, lake level is controlled by the combination of climate and outlet geometry
- Climate over the drainage basin determines how much excess water there is to be evacuated
- Lake level has to reach at least the elevation of the lowest point on the topographic barrier around the lake, hence the bed of the outlet stream
- Above this level, an additional depth is required for outflow to be adequate to evacuate the surplus water
- A narrow outlet channel requires more depth than a broad outflow to achieve a given flow rate
- This is called the stage (water level) vs. discharge (volumetric rate of flow) relationship for the outlet.

Lake level controls

- Lake Winnipeg has, at least in recent millennia, been an outflowing lake
- The mean lake level therefore is constant at the outlet relative to mean climate of the time, given that a certain depth is required to evacuate excess water
- Tilting of a lake basin causes mean lake level to pivot at the outlet
- Because the outlet of Lake Winnipeg is in the north, uplift of the north end of the lake progressing at a rate more rapid than the basin to the south has meant lake level rise over the entire basin, with the rate increasing southward

Importance of outlet position relative to pattern of uplift

Not all lakes rise and expand due to tilting, however

Lake Nipigon has its outlet in the south, so it is contracting. Lake Superior has its outlet in the middle relative to the pattern of uplift, so it is rising in the south and falling in the north

Lake Winnipeg expansion

- We have collected cores from the bottom sediments of Lake Winnipeg that allow us to sample the entire sequence of sediments deposited since Lake Agassiz, including the first layer of Lake Winnipeg sediments that buried the older Lake Agassiz deposits
- We have obtained radiocarbon ages from this procedure that indicate that much of the South Basin of Lake Winnipeg was dry land 4000 years ago, while Netley Marsh was dry land about 1500 years ago
- We also have radiocarbon dates from rooted tree stumps just below lake level that suggest gradual rise in lake level over recent centuries
- These observations indicate that gradual expansion of Lake Winnipeg in response to tilting has been continuous throughout post-Lake Agassiz time.

Controls on long term lake level trends

While we place our emphasis on uplift, which has been the dominant influence, at least in the south, four other process should be mentioned as secondary factors affecting Lake Winnipeg lake level over the long term: climate, river diversions, basin merging, and outlet downcutting

Climate

- Our radiocarbon dating of basal Lake Winnipeg sediments in cores indicates that, unlike the gradual inundation of the rest of the lake, the inundation of the central South Basin was not gradual
- It seems to have occurred rapidly, as basal ages across this area cluster around 4000 years
- This is the time when climate changed rather abruptly from warmer and drier to cooler and moister, probably raising lake level a few metres

Climate

Climate of the Lake Winnipeg region has been relatively stable in the past 4000 years, however, so the impact of this climate change would have been applied rapidly, with control of lake level evolution to the present day returning to uplift dominance

Diversions

- Another factor in Lake Winnipeg lake level history was diversion of the Saskatchewan River, which formerly bypassed Lake Winnipeg in the channel now occupied by the Minago River
- Between 4000 and 5000 years ago, uplift caused diversion of the Saskatchewan River to Lake Winnipeg
- This would have raised lake level on a one-time basis by about a half metre

Basins merging

- At present, Playgreen Lake and Lake Winnipeg are almost functioning as one lake
- Strong northward currents typically flow through Warren Landing, in what could almost be considered a Narrows rather than a river, feeding the Nelson River to the north
- When strong north winds blow, however, flow at Warren Landing can be to the south. But for a few millennia after Lake Agassiz, however, what is now Lake Winnipeg was three or more lakes, a South Basin lake draining through a river in the Narrows to a North Basin Lake, which in turn drained to a completely separate Playgreen Lake

Basins merging

- All of these lakes expanded in response to tilting, and eventually the North Basin and South Basin lakes merged
- Relocation of the outlet for the South Basin Lake to a point farther north, where uplift is more rapid, would have accelerated lake level rise in the south
- More recently, perhaps about 2000 years ago, Playgreen Lake merged with Lake Winnipeg, again increasing the rate of lake level rise and lake expansion in the South Basin, once again renewing the otherwise gradually diminishing rate of rise

Outlet downcutting

Outlet down-cutting is a factor that seems not to be a significant control on Lake Winnipeg

Whereas this was the dominant factor in controlling the early history of Lake Superior, the outlet of Lake Winnipeg at Warren Landing is shallow and broad, and would have been rapidly eroded to resistant bedrock

Therefore while this could have been a compensating factor offsetting the rise due to uplift, it seems not to have played a role

Pattern of uplift

Maps showing the pattern of present uplift on the world and continental scales may be seen on p. 117 of the March 1997 issue of Scientific American, and on the cover of the 4 December 1997 issue of Nature

General models such as these, based to varying degrees on continent-wide syntheses of radiocarbon-dated marine shorelines, tide gauge trends, lake gauge trends, and gravity, give a rough estimate for uplift rates of 0.4 m/century at the north end, and 0.2 m/century at the south end of Lake Winnipeg

The difference between these two values implies a 20 cm/century rise in lake level at the south end of Lake Winnipeg

Comparison of inferred uplift pattern and Lake Winnipeg data

- This prediction can be tested by comparison to available data from Lake Winnipeg
- Offshore from Gimli, at our site 122, the pre-Lake Winnipeg surface lies under 10 m of water and 4 m of sediment
- We have dated the initiation of Lake Winnipeg sedimentation at this site at about 4000 years
- A rise of the lake to its present level over the past 4000 years implies a rate averaging 35 cm/century (1400 cm/40 centuries)
- This would be an average of higher rates earlier in the period in question, and lower rates at present, perhaps comparable to the current estimate of 20 cm/century

Comparison of inferred uplift pattern and Lake Winnipeg data

- According to Penner and Swedlo, a 40-cm-thick peat bed found 3 m below lake level near Elk Island was dated at 1060 years for the upper part of the bed and 1660 years for the lower part
- Interpolating between the upper date and present lake level gives an estimate of 28 cm/century (300 cm/10.6 centuries) for lake level rise over the past millennium
- Work by Dr. Erik Nielsen, of the Manitoba Geological Services Branch, on the radiocarbon age of drowned stumps in the Lake Winnipeg shoreface also indicates a submergence rate of about 20 cm/century over the past 300 years
- Hence available data are strongly supportive of the lake level rise predicted by uplift models

Water level trend based on regional geology

- Even without this sort of data, the experienced eye can quickly see that water levels are rising on Lake Winnipeg
- For example, geologists now agree that barrier islands are a sign of water level rise
- The sandy beach that separates the south end of the lake from Netley Marsh is a barrier island
- Other good examples can be seen on Lake Manitoba, the east coast of the US, Duluth, Hamilton, and northwestern Europe
- The geological model for how barrier islands work is for there to be erosion on the basin side, and accretion on the lagoon side. In other words, the natural behaviour for a barrier island is for it to migrate landward like a conveyor belt
- One can also recognize water level rise on Lake Winnipeg in the form of drowned valleys, also known as estuaries, such as lower Netley Creek and lower Icelandic River

Confirmation of present uplift trend

- Even if Hudson Bay is still being uplifted and the Great Lakes are still being tilted, and even if there is evidence for Lake Winnipeg having expanded in recent millennia, centuries, and decades, this does not prove that Lake Winnipeg is presently still being tilted
- Complexities in the uplift pattern could have formed in recent time. Lake gauge data, however, have provided indications of present-day uplift
- This takes the form of a gradual increase in the difference between southern gauges and northern gauges over several decades

Confirmation of present uplift trend

We also are investigating this topic with new approaches. In cooperation with NASA, we have installed two new Global Positioning System satellite receiving stations at Pinawa and Flin Flon, that will, in combination with existing stations in Iowa and Churchill, give us measurements of uplift rates

In cooperation with the US government, we also are doing very sensitive measurements of gravity along a transect of sites from Iowa to Churchill that will give us an independent check on uplift or subsidence rates

Reconciliation of uplift and shoreline recession trends

- The 1974 Penner and Swedlo report supplemented existing knowledge of shoreline erosion rates with information from surveys done at intervals of one to a few decades from the 1870s to the late 1960s
- It was found that the shoreline of the South Basin retreated over this period at rates typically of 0.5 to 5 m per year
- An average rate of, for example, 1 m per year could, of course, represent 10 m in one year and no recession for 9 years
- Can this steady rate of shoreline erosion be explained by a 20 cm/century rise in lake level?
- Let's relate the 20 cm/century rise to regional topographic gradients

Reconciliation of uplift and shoreline recession trends

At Gimli, the land rises about 25 m within 10 km inland, a gradient of 2.5 m/km

In this case, a 20 cm/century lake level rise would translate to a lateral shift of 0.8 m/year, similar to actual shoreline erosion rates reported by Penner and Swedlo

From the centre of the south basin to Netley Creek, the surface under Lake Winnipeg sediments rises to the present land surface at a rate of about 0.3 m/km

A 20 cm/century lake level rise in this case translates to a lateral migration of about 6.7 m/year

Reconciliation of uplift and shoreline recession trends

This estimate is compatible with our data offshore from Gimli that shows that the south end of the lake has migrated 30 km to its present position in 4000 years, implying an average rate of shoreline retreat of about 7.5 m per year

This agreement is surprisingly good

Penner and Swedlo reported similar retreat rates over much of the southern shore.

Reconciliation of uplift and shoreline recession trends

- Large increments of basin expansion being driven by a few inches of lake level rise may seem counter-intuitive
- A one-metre rise in lake level happens frequently due to wind setup, and the water line only moves a few metres
- But according to the above reasoning, a one-metre permanent rise in lake level will drive the shoreline inland 400 metres to the west, and over 3 km to the south
- How can this apparent contradiction be reconciled?
- The key point is that shoreline processes have cut a notch at the water line that has a much higher gradient than the surrounding landscape

Reconciliation of uplift and shoreline recession trends

- Penner and Swedlo indicate that the gradient between the high water and low water line on Lake Winnipeg typically is about 10%, or 100 m/km.
- It is this slope that takes up the short term fluctuations
- The steeper nearshore gradient can also be seen on the hydrographic chart for the south basin
- Around Gimli, the offshore gradient is about 3.4 m/km between the shore and ten feet depth, while farther offshore, the gradient is less than 1 m/km
- Along the south shore, the gradient to ten feet depth averages 1.2 m/km, while farther offshore it is about 0.25 m/km

Reconciliation of uplift and shoreline recession trends

- Hence short term fluctuations are taken up by the high gradient slope at the water line, but a permanent rise exposes that slope to a sustained increase in wave power
- In the case of a one-step lake level rise, the shoreline would retreat and the shore profile would flatten until wave power delivered to the shore diminishes to a level that allows a stable coastal position. In the case of a steady, ongoing rise, a steady retreat of the shore results
- Even if a steady rise were to stop, retreat would continue until equilibrium is reached

Reconciliation of uplift and shoreline recession trends

- It is useful to compare shoreline erosion on Lake Winnipeg with global trends at sea level, which are probably best documented in the US
- In SEPM Special Publication No. 48, Pilkey and Thieler present a summary of erosion rates on the US coast.
- Values of 0.5 to 4 m/year are typical of the Atlantic and Gulf coasts
- There now is consensus that this erosion is driven by the present global (eustatic) sea level rise of about 20 cm/century, which happens to be similar to the rate of lake level rise that we estimate for the south end of Lake Winnipeg

More recent research

Lambert, A., T. S. James, and L. H. Thorleifson. 1998. Combining geomorphological and geodetic data to determine postglacial tilting in Manitoba; Journal of Paleolimnology, v. 19, p. 365-376

Lambert et al. (1998) combined geomorphological data with GPS, absolute gravity, and lake gauge data to better constrain estimates of postglacial rebound in central North America.

More recent research

Nielsen, E., 1998. Lake Winnipeg coastal submergence over the last three centuries. Journal of Paleolimnology, 19: 335-342.

Nielsen (1998) utilized radiocarbon dating of peat and drowned trees along the barrier beaches at the south end of Lake Winnipeg to indicate that water levels in that area have been rising at a rate of about 20 cm/century over the last three hundred years.

More recent research

Tackman, G.E., D.R. Currey, B.G. Bills, T.S. James, 1998, Paleoshoreline evidence for postglacial tilting in Southern Manitoba, Journal of Paleolimnology, 19, 343-363.

Tackman et al. (1998) utilized air photo interpretation and field surveys in southern Manitoba to infer that the once level paleoshorelines of Lake Winnipegosis and Dauphin Lake and Lake Agassiz have been tilted up by postglacial rebound.

More recent research

Lewis, C. F. M., Forbes, D. L., Todd, B. J., Nielsen, E., Thorleifson, L.H ., Henderson, P. J., McMartin, I., Anderson, T. W., Betcher, R. N., Buhay, W. M., Burbidge, S. M., Schröder-Adams, C. J., King, J. W., Moran, K., Gibson, C., Jarrett, C.A., Kling, H. J., Lockhart, W. L., Last, W. M., Matile, G. L. D., Risberg, J., Rodrigues, C. G. Telka, A.M., and Vance, R. 2001. Uplift-driven expansion delayed by middle Holocene desiccation in Lake Winnipeg, Manitoba, Canada. Geology, v. 29, no. 8, p. 743-746.

Lewis et al. (2001) outlined the uplift-driven expansion Lake Winnipeg, while drawing attention to the possibility that climate may have imposed fluctuations on the largely uplift-driven trend.

More recent research

Lambert, A., N. Courtier, G. Sasagawa, F. Klopping, D. Winester, T. S. James and J. O. Liard, 2001, New constraints on Laurentide postglacial rebound from absolute gravity measurements, , Geophysical Research Letters, v. 28, p. 2109–2112.

Lambert et al. (2001) summarized absolute gravity measurements at six sites along a 3000 km-long, mid-continental, North American profile from the coast of Hudson Bay southward to Iowa.

More recent research

Lambert, A., James, T. S., Courtier, N., Simon, K., Schmidt, M., Lewis, C. F. M., Mainville, A., 2005, An improved postglacial rebound model with applications to the Nelson River drainage basin; Geological Survey of Canada, Open File 4927, 24 p.

Lambert et al. (2005) produced a new map of vertical crustal movement rate for Manitoba by assimilating available geodetic and geomorphological data to a model of the Earth's response to the surface unloading associated with the melting of the Laurentide ice sheet.

More recent research

Brooks, G., C. F. M. Lewis, and L. H. Thorleifson. 2005. Influence of loss of gradient from postglacial uplift on Red River flood hazard; The Holocene, v. 15, no. 3, pp. 347-352

Brooks et al. (2005) outlined how the isostatic rebound that is causing expansion of Lake Winnipeg also occurs farther south, thus affecting the Red River, which has lost 60% of its gradient in post-Lake Agassiz time.

More recent research

van der Wal, W., A. Braun, P. Wu, and M. G. Sideris, 2009, Prediction of decadal slope changes in Canada by glacial isostatic adjustment modelling; Canadian Journal of Earth Sciences, v. 46, p. 587-595.

Van der Wal et al. (2009) described glacial isostatic adjustment as the dominant process causing vertical motion of the land surface in Canada, and went on to outline examples of impacts of isostatic rebound, such as on the Nelson River and Lake Winnipeg.

More recent research

Lambert, A., Henton, J., Mazzotti, S., Huang, J., James, T. S., Courtier, N., van der Kamp, G. 2013, Postglacial rebound and total water storage variations in the Nelson River drainage basin: a gravity-GPS study; Geological Survey of Canada, Open File 7317, 33 p.

Lambert et al. (2013) combined GPS, absolute gravity and GRACE satellite data to produce an updated map of postglacial rebound.

Summary

- During the Ice Age, Canada was covered by a continental ice sheet
- Removal of the ice sheet resulted in isostatic rebound of the land
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- Uplift rate diminishes in all directions from Hudson Bay
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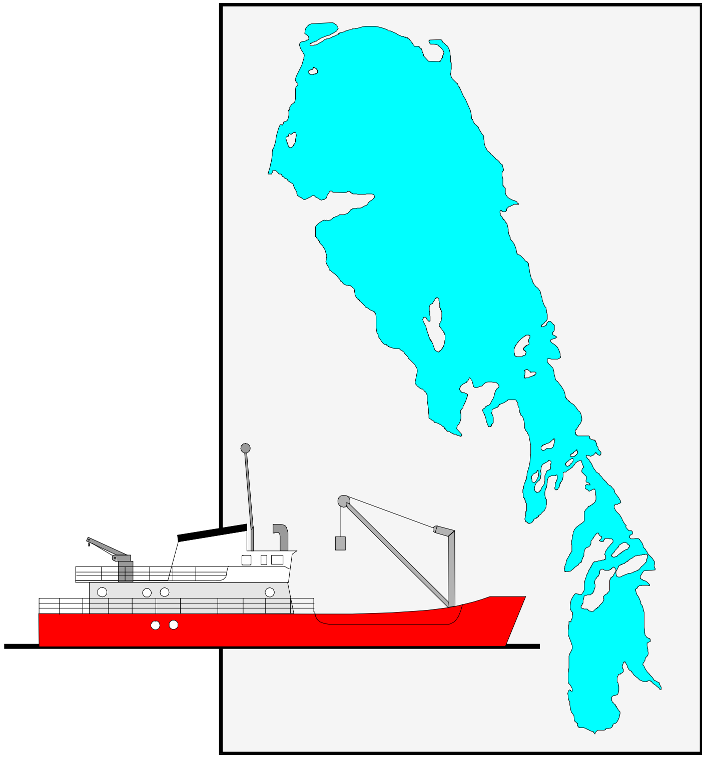
Influence of isostatic rebound on Lake Winnipeg



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