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Dry Climate Disconnected the Laurentian Great Lakes

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Recent studies have produced a new understanding of the hydrological history of North America's Great Lakes, showing that water levels fell several meters below lake basin outlets during an early postglacial dry climate in the Holocene (younger than 10,000 radiocarbon years, or about 11,500 calibrated or calendar years before present (B.P.)). Water levels in the Huron basin, for example, fell more than 20 meters below the basin overflow outlet between about 7900 and 7500 radiocarbon (about 8770–8290 calibrated) years B.P. Outlet rivers, including the Niagara River, presently falling 99 meters from Lake Erie to Lake Ontario (and hence Niagara Falls), ran dry. This newly recognized phase of low lake levels in a dry climate provides a case study for evaluating the sensitivity of the Great Lakes to current and future climate change.

The Laurentian Great Lakes

Collectively, these Great Lakes constitute one of the largest surface reservoirs of freshwater on Earth. The lakes contain 23,000 cubic kilometers of water, of which less than 1% is replenished annually by precipitation. Situated in the east central part of North America and shared by the United States and Canada (Figures 1a and 1b), the five lake basins and their ecosystems support a population of more than 33 million people (in 1990–1991) and host well-developed industries for shipping, fishing, recreation, and power production, as well as water supply and wastewater disposal for municipalities. The overall range of monthly water levels in all lakes during the past century has varied by less than 2.1 meters, and thus lake levels appear to be relatively stable; yet even this amount of variation causes economic stress.

The interplay of three air masses (Figure 1c) currently controls climate and water levels in the Great Lakes watershed; most of the moisture originates from humid air masses arising in the Gulf of Mexico and the subtropical North Atlantic Ocean. This interplay of air masses maintains positive surface water balance, sustaining major rivers and shipping canals between lakes, as well as discharge to the St. Lawrence River (Figure 1b). Although researchers have traditionally assumed the Great Lakes to have been hydrologically open since their formation after 16,000 radiocarbon (19,200 calibrated) years B.P. during retreat of the last ice sheet [*Larson and Schaetzl,* 2001], this paradigm of continuous, abundant water supply is now known to be false. Mounting evidence, described below, shows that hydrologically closed lakes (i.e., lakes having water levels below topographic outlets) existed in the Huron and Michigan basins, and likely in other basins, approximately 7900 radiocarbon or 8770 calibrated years B.P.

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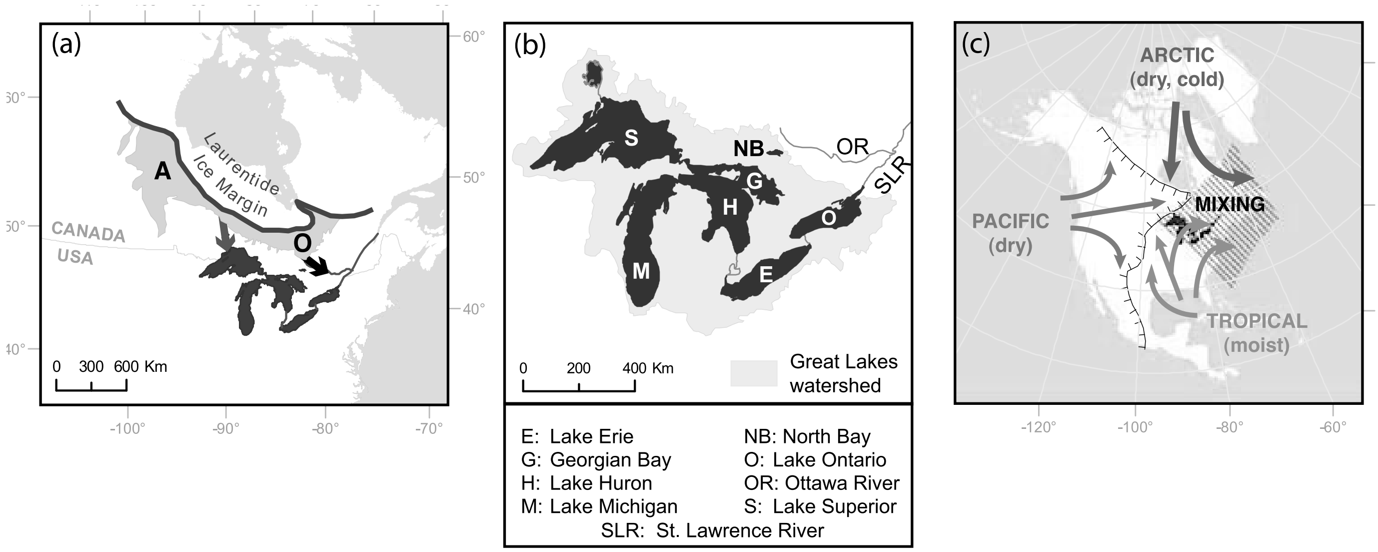

*Fig. 1. (a) Location of the Great Lakes (blue) in eastern North America. Glacial Lake Agassiz (labeled A) is shown ~8000 ^{14}C (~8890 calibrated) years before present (B.P.), when ice retreat caused its overflow drainage to switch from the Superior basin of the Great Lakes (red arrow) to Glacial Lake Ojibway (O) and the Ottawa River valley (black arrow). (b) The Laurentian Great Lakes and their watershed. (c) Major airstreams in North America with most water supplied to the Great Lakes by the moist air (tropical) from the Gulf of Mexico [*Bryson and Hare, *1974]. Original color image appears at the back of this volume.*

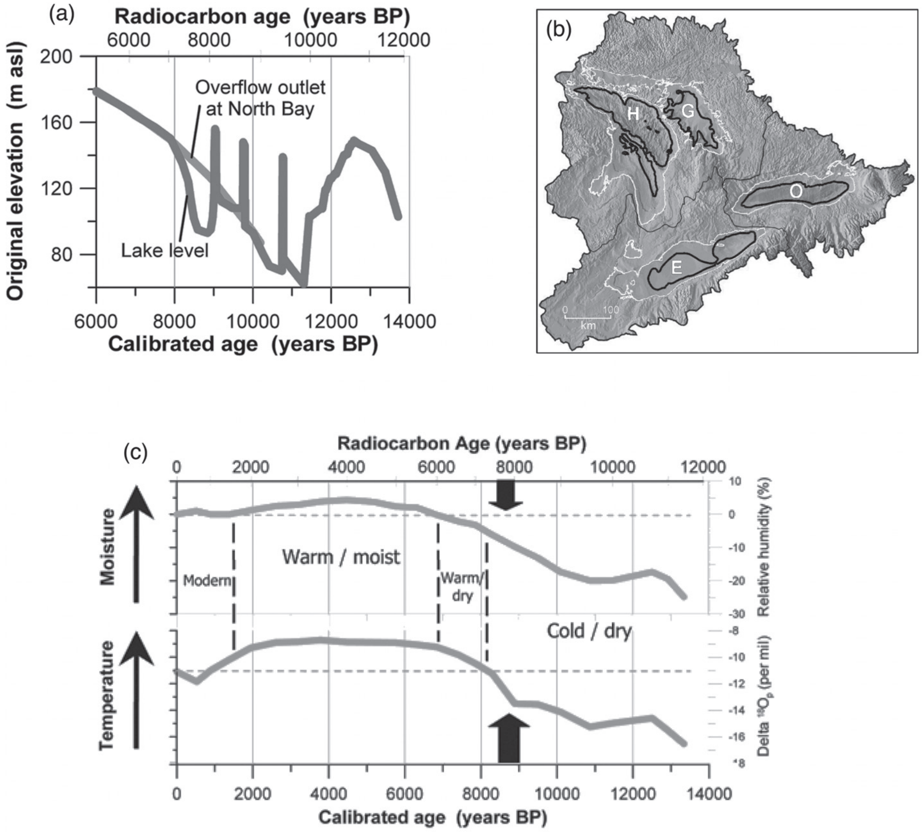

*Fig. 2. (a) Lake level (blue) in Huron basin compared with the outlet elevation at North Bay (gray) showing hydrologically closed lowstand when the lake fell by more than 20 meters below the basin outlet after 8000 ^{14}C (~8890 calibrated) years before present (B.P.). (b) Lowstand shorelines ~7900 ^{14}C (~8770 calibrated) years B.P. are shown in black, and present shorelines appear white in this colored watershed relief map. Lake basins: H, Huron; G, Georgian Bay; E, Erie; O, Ontario. (c) Temperature and moisture trends relative to present conditions (dashed lines) for the southeastern Great Lakes region [*Edwards et al., *1996]. Large black arrows indicate the time of the lowstands. Original color image appears at the back of this volume.*

New Understanding of Great Lakes History

Previous interpretations of past Great Lakes water levels lacked key information on the altitude of outlets during glacial rebound. Consequently, evidence for lowstands (lakes below present level) was taken to indicate that lakes overflowed more northerly outlets that were still depressed isostatically by the previous ice load [e.g., *Hough,* 1962]. However, a greater understanding has emerged from new empirical evidence and more precise analysis and modeling of isostatic rebound rates in the Great Lakes Basin (GLB). The evidence includes newly discovered lowstand indicators in Lake Huron and Georgian Bay, such as submerged tree stumps in situ and small lakes uplifted and isolated from the larger water bodies [*Lewis et al.,* 2005] and low-level erosion [*Moore et al.,* 1994].

This body of evidence now confirms that lowstands occurred approximately from 7900 to 7500 radiocarbon (8770–8300 calibrated) years B.P. in the Michigan, Huron, and Georgian Bay basins (Figure 2a) [*Lewis et al.,* 2005, 2007]. These hydrologically closed lakes formed when water supply to the GLB was greatly diminished by northward retreat of the Laurentide Ice Sheet. The retreat allowed discharge from Glacial Lake Agassiz to bypass the GLB into Glacial Lake Ojibway and drain via the Ottawa River valley directly to the St. Lawrence River (Figure 1a) [*Teller and Leverington,* 2004]. Following the retreat, the Great Lakes were then supplied only by precipitation falling within the GLB, as at present.

That the low-level lakes in the Huron and Georgian Bay basins were closed hydrologically is indicated by microfossil evidence of brackish conditions (signifying excess evaporation) and a pause in outlet basin sedimentation (suggesting cessation of river outflow). A lowstand also occurred in the Erie basin at the same time, as indicated by a submerged beach, while a shallow-water environment in Lake Ontario [*Duthie et al.,* 1996] suggests a correlative lowstand in that basin as well. Acoustic profiling data show that submerged beaches of low-level lakes also exist in the Superior basin [*Wattrus,* 2007]. A partial reconstruction of lowstands is shown in Figure 2b; lowstand reconstruction is part of ongoing research. This research also includes the assessment of residual meltwater and groundwater drainage in the lowstands.

Explanation of the Lowstands

Lakes without overflow, such as these lowstands in the GLB, can only be explained by a dry climate in which water lost through evaporation exceeded water gained from direct precipitation and catchment runoff. The dry regional climate that forced the lakes into hydrologic closure must have been substantially drier than the present climate. Hydrologic modeling of the present lakes shows that current mean annual precipitation would have to decrease by about 25% in the Superior basin and by about 42% in the Ontario basin, in conjunction with a 5°C mean temperature increase, to achieve lake closure [*Croley and Lewis*, 2006]. Paleoclimate simulations and reconstructions using pollen [*Bartlein et al.,* 1998] and stable isotopes [*Edwards et al.,* 1996] indicate that climate in the GLB (Figure 2c) was drier than present at 7900 radiocarbon (8770 calibrated) years B.P. Termination of the lowstand episode about 7500 radiocarbon (8300 calibrated) years B.P. coincides with the onset of a wetter climate as atmospheric circulation adjusted to the rapidly diminishing ice sheet [*Dean et al.,* 2002] and moist air mass incursions from the Gulf of Mexico became more frequent.

The discovery that the Great Lakes entered a low-level phase without having connecting rivers during the early Holocene dry period demonstrates the sensitivity of the lakes to climate change. The closed lakes of this phase occurred when the Great Lakes entered their present nonglacial state. Thus, the closed lakes afford a valuable example of past, high-amplitude, climate-driven hydrologic variation upon which an improved assessment of lake-level sensitivity in response to future climates can be based.

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Widespread Secondary Volcanism Near Northern Hawaiian Islands

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Hot spot theory provides a key framework for understanding the motion of the tectonic plates, mantle convection and composition, and magma genesis. The age-progressive volcanism that constructs many chains of islands throughout the world's ocean basins is essential to hot spot theory. In contrast, secondary volcanism, which follows the main edifice-building stage of volcanism in many chains including the Hawaii, Samoa, Canary, Mauritius, and Kerguelen islands, is not predicted by hot spot theory. Hawaiian secondary volcanism occurs hundreds of kilometers away from, and more than 1 million years after, the end of the main shield volcanism, which has generated more than 99% of the volume of the volcano's mass [*Macdonald et al.,* 1983; *Ozawa et al.,* 2005]. Diamond Head, in Honolulu, is the first and classic example of secondary volcanism.

Attempts to explain secondary volcanism in the context of the hot spot phenomenon—in particular, as attributed to mantle plumes—include hypotheses of conductive heating of the lithosphere by the plume, lateral spreading and uplift of the plume after its ascent, and flexure-induced decompressional melting related to the rapid growth of new volcanoes above the ascending plume [e.g., *Bianco et al.,* 2005]. Even more enigmatic than the shield volcanoes are recent discoveries of secondary volcanism not being confined to the islands but extending many tens of kilometers offshore [e.g., *Clague et al.,* 2000] and occurring in several pulses [*Ozawa et al.,* 2005].

To determine the where, when, and what of secondary volcanism on and near the northern Hawaiian Islands (Figure 1), the U.S. National Science Foundation (NSF) recently sponsored a multidisciplinary investigation (volcanology, marine geology, geochemistry, gravity, magnetics). A 4-week marine expedition in September 2007, aboard the University of Hawai`i's R/V *Kilo Moana* and using the JASON2 robotic submarine, revealed several fields of offshore volcanoes and lava flows, with each field spanning areas much larger than the nearby islands. Such expansive volcanism well away from the islands themselves raises many questions about hot spot evolution and magma genesis in general.

Seafloor Mapping

The seafloor around the islands of Kaua`i, Ni`ihau, and Ka`ula (Figure 1) was the focus of the marine expedition because Kaua`i has the most voluminous (~58 cubic kilometers) and enduring (~2.5 million year old (C. E. Gandy et al., Implications of the volume of Kauai's Koloa volcanics for the origin of Hawaiian rejuvenated volcanism, submitted to *Geology,* 2008)) secondary volcanism of Hawaii's main islands and because this seafloor had not previously been completely mapped. For comparison, the volumes and lifetimes of Hawaiian shield volcanoes younger than Kaua`i are 9–74 × 10^3 cubic kilometers [*Robinson and Eakins,* 2006] and approximately 1.5 million years old [*Garcia et al.,* 2006]. During the 2007 expedition, an area approximately 50% greater than the entire state of Hawaii was surveyed, yielding the first detailed bathymetry and acoustic backscatter maps of Ka`ula and the Middle Bank volcanoes, and confirming that secondary volcanism is widespread offshore rather than focused on the islands.

Extensive Secondary Volcanism

The new acoustic imagery map (Figure 2) highlights areas of extensive secondary volcanism around the islands of Ka`ula and Ni`ihau. More than 100 secondary submarine volcanoes surround these islands, most of which have a distinctive pancake shape (steep-sided and flat-topped) similar to some Venusian volcanoes [*Smith,* 1996]. To form flat-topped cones, sustained but slow effusion of low-viscosity magma from a point source is thought to be necessary [*Clague et al.,* 2000]. The question as to why these conditions should prevail throughout this area is being investigated using bathymetry and lava chemistry data. Some of the newly identified lava flows have areas of up to approximately 400 square kilometers, larger than some Hawaiian islands (e.g., Lana`i at 364 square kilometers and Ni`ihau at 180 square kilometers) and comparable to the flood basalt from Iceland's Laki volcanic fissure (565 square kilometers). Furthermore, the volcanism extends 100 kilometers off the axis of the Hawaiian Ridge and well into the surrounding flexural moat.

During 11 JASON2 dives (Figure 1), a wide variety of lava flow types and sedimentary rocks were observed on 71 seamounts (http://4dgeo.whoi.edu/jason/, km718 cruise link), and 363 rocks weighing more than 1200 kilograms were sampled. The compositions of these lavas range widely from shield stage tholeiitic basalts (especially south of Kaua`i) to secondary stage alkalic basalts (common around Ka`ula). Our geochemical study of approximately 5 million years of volcanism on Kaua`i has shown that secondary volcanism

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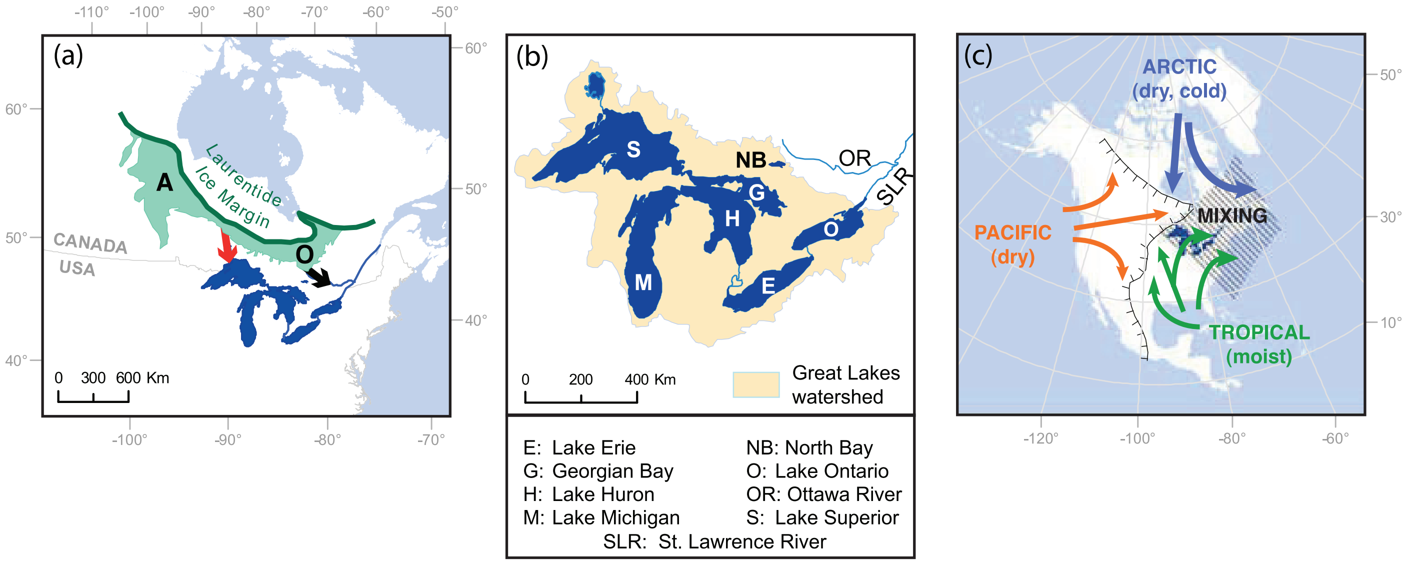

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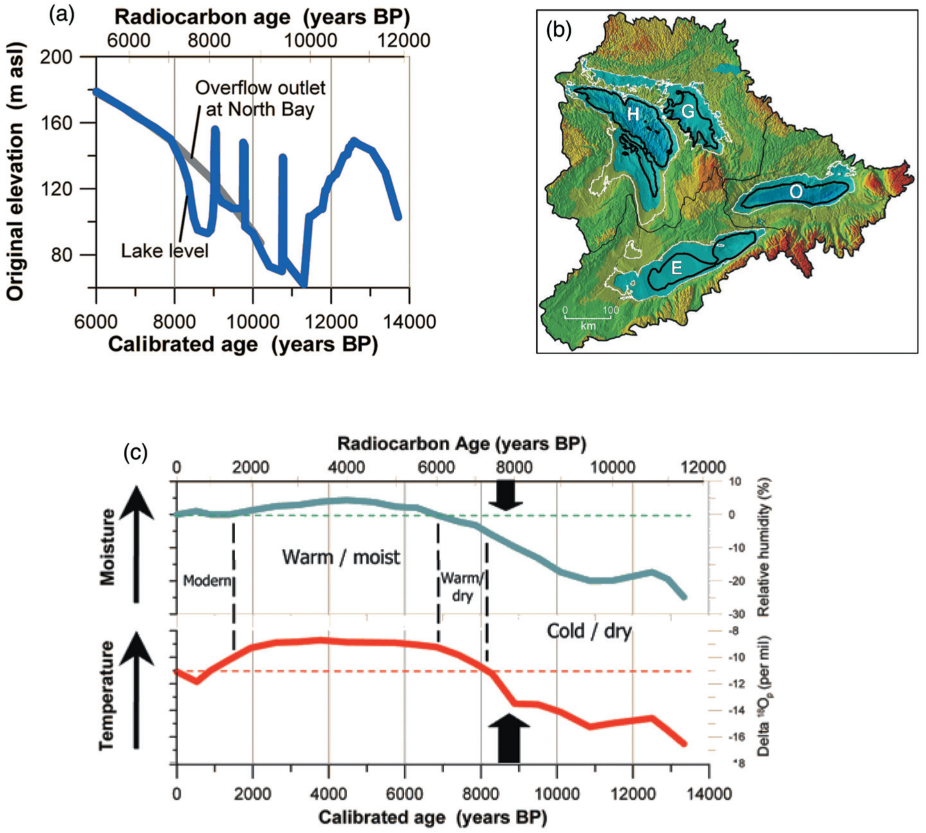

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