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**TIME-SERIES ANALYSIS FOR THE EPISODIC PRODUCTION AND TRANSPORT OF
METHANE FROM THE GLACIAL LAKE AGASSIZ PEATLANDS, NORTHERN MINNESOTA**

Final Report

The Department of Energy

Carbon Dioxide Research Grants

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SUMMARY OF COMPLETED PROJECT

The large peat basins of North America are an important reservoir in the global carbon cycle and a significant source of atmospheric methane. We investigated carbon cycling in the Glacial Lake Agassiz peatlands (GLAP) of Minnesota. Initially in 1990, we identified a dramatic change in the concentration of methane in the pore-waters of the raised bogs in the GLAP during an extreme drought. This methane dissipated when the drought broke in 1991 and the occurrence of deep methane is related to changes in the direction of groundwater flow in the peat column. The production of methane and its diffusive loss to the atmosphere was modeled and was about 10 times less than that measured directly in chambers at the land surface.

It is clear from the reversals in hydraulic head, changes in pore-water chemical composition over time, and paleostratigraphic markers, that regional ground water flow systems that are controlled by climate change are unexpectedly a major control over methanogenesis and carbon cycling in GLAP. Seismic profiles made showed that buried bedrock ridges particularly deflect regional groundwater flow upwards towards the land surface and towards raised bog landforms.

In addition, high-resolution GPS measurements from data stations funded by our DOE project have shown this year that the peatland land surface elevation changes daily on a scale of cms, and seasonally on a scale of 10s of cm. This most recent observation is exciting because it may reflect episodic degassing of free phase methane from the peat column to the atmosphere, a source for methane previously unaccounted for by methane researchers.

TECHNICAL INFORMATION

Publications Produced From the Project Support

Glaser, P.H., Siegel, D.I., Romanowicz, E.A., and Shen, Y.P., 1997, Regional linkages between raised bogs and the climate, groundwater, and landscape features of northwestern Minnesota. *Journal of Ecology*, vol. 85, p. 3-16

Glaser, P.H., Bennett, P.C., Siegel, D.I., and E.A. Romanowicz, 1997. Paleo-reversals in groundwater flow and peatland development in the Lost River peatland, northern Minnesota, USA. *Holocene*, vol.6, p. 413-421.

Ours, D.P., D.I. Siegel, and P. H. Glaser, 1997. Chemical dilation and the dual porosity of humified bog peat. *Journal of Hydrology*, vol. 197, p. 348-360.

Reeve, A. S., D. I. Siegel, and P. H. Glaser. 1996 Geochemical controls on peatland pore-water from the Hudson bay lowlands: a multivariate and statistical approach. *Journal of Hydrology* 181: 285-304.

Chanton, J.P., Bauer, J. Glaser, P.H., Siegel, D.I., Kelley, C., Tyler, S.C. Romanowicz, E.A., Lazrus, A. 1995. Radiocarbon evidence for the substrates supporting methane formation within northern Minnesota peatlands. *Geochimica et Cosmochimica Acta* 59: 3663-3688.

Siegel, D.I., A.S. Reeve, P.H. Glaser and E. Romanowicz. 1995 Climate-driven flushing of pore water in humified peat. *Nature* 374: 531-533

Romanowicz, E.A., D.I. Siegel, J.P. Chanton, and P.H. Glaser. 1995 Temporal variations in dissolved methane deep in the Lake Agassiz peatlands, Minnesota (USA). *Global Biogeochemical Cycles* 9: 197-212

Hansen, B.C.S. 1995 Conifer stomate analysis as a paleoecological tool: an example from the Hudson Bay lowlands. *Canadian Journal of Botany* 73: 244-252

Romanowicz, E.A., D.I. Siegel, D.I. Siegel, and P.H. Glaser. 1993 Hydraulic reversals and episodic methane emissions during drought cycles in mires. *Geology* 21: 231-234.

Whiting, G.J. and J.P. Chanton. 1993. Primary production control of methane emission from wetlands. *Nature* 364: 794-795.

Glaser, P.H. 1992. Raised bogs in eastern North America: regional controls on species richness and floristic assemblages. *Journal of Ecology* 80: 535-554.

McNamara, J.P., D.I. Siegel, Glaser, P.H. and R.M. Beck. 1992. Hydrologic controls on peatland development in the Malloryville wetland, New York (USA). *Journal of Hydrology* 140: 279-296.

Glaser, P.H. 1992. Peat landforms. In H.E. Wright, Jr. and B.A. Coffin (eds.), *Patterned Peatlands of Northern Minnesota*, University of Minnesota Press, Minneapolis, pp. 3-14.

Glaser, P.H. 1992. Vegetation and water chemistry. In H.E. Wright, Jr. and B.A. Coffin (eds.), *Patterned Peatlands of Northern Minnesota*, University of Minnesota Press, Minneapolis, pp. 15-26.

Glaser, P.H. 1992. Development of patterned peatlands. In H.E. Wright, Jr. and B.A. Coffin (eds.), *Patterned Peatlands of Northern Minnesota*, University of Minnesota Press, Minneapolis, pp. 27-42.

Glaser, P.H. 1992. Rare vascular plants in the patterned peatlands of northern Minnesota. In H.E. Wright, Jr. and B.A. Coffin (eds.), *Patterned Peatlands of Northern Minnesota*, University of Minnesota Press, Minneapolis, pp. 59-69.

Siegel, D.I. 1992. Groundwater hydrology. In H.E. Wright, Jr. and B.A. Coffin (eds.), *Patterned Peatlands of Northern Minnesota*, University of Minnesota Press, Minneapolis, pp. 59-69.

Janssens, J.A., B.C.S. Hansen, P.H. Glaser, and C.W. Barnosky. 1992. Development of a raised-bog complex in northern Minnesota. In H.E. Wright, Jr. and B.A. Coffin (eds.), *Patterned Peatlands of Northern Minnesota*, University of Minnesota Press, Minneapolis, pp. 189-221.

Glaser, P.H., J.A. Janssens, and D.I. Siegel. 1990 The response of vegetation to hydrological and chemical gradients in the Lost River Peatland, northern Minnesota. *Journal of Ecology* 78: 1021-1048.

Hill, B.M. and Siegel, D.I., 1991, Ground water flow and the metal content of peat, *Journal of Hydrology*, vol. 123, p. 211-224.

Bennet, P. C., D.I. Siegel, B. Hill, and P.H. Glaser. 1990 The fate of silica in a peat bog. *Geology* 19: 328-331.
Manuscripts in Review

Reeve, A.S., D.I. Siegel, and P.H. Glaser. Numerical simulation of groundwater flow in peatlands: Implications to Hudson Bay Lowland and Glacial Lake Agassiz Peatlands. *Water Resources Research*

Published Abstracts of Papers Presented from Project Support

Glaser, P.H., P.J. Morin, N. Tsekos, and D.I. Siegel, 1997, (abst.) Vertical Oscillations in the Land Surface of Northern Peatlands Determined by GPS: a Physical Expression of Climate Change and Methane Cycling, Fall Mtg. American Geophysical Union, EOS, in press.

Glaser, P.H., P J Morin, O Ruud, A Reeve, D. Rosenberry, JP Chanton, L. Stalder, D. J. Siegel, J. Rivers, P Bennett, 1996, (abst.) The Size and Distribution of Biogenic Gas Bubbles in Peat Cores Determined Directly by Magnetic Resonance Imaging (MRI), 1997, Fall Mtg. American Geophysical Union, EOS, in press.

Mishler, L. N., D.I. Siegel, Levinsohn, E.M., Morin, P, and Glaser, P.H., 1996, (abst.) Solute Transport and CATSCAN Visualization Experiments in Fen Peat, Fall Mtg. American Geophysical Union, EOS, in press.

Reeve, A. S., D. I. Siegel, P.H. Glaser, P. Moran, 1997, (abst.) Developing a regional 3-D groundwater flow model for the Glacial Lake Agassiz peatlands using global positioning system data, Fall Mtg. American Geophysical Union, EOS, in press.

Siegel, D.I., Glaser, P.H., Glasser, P.H., Chanton, J.P., Reeve, A.S. and Romanowicz, E.A., 1997, (abst.) Hydrogeochemical controls over the production of greenhouse gases in peatlands, Geological Society of America Annual Meeting, Salt Lake City, Proceedings, in press.

Reeve, A.S., Siegel, D.I., and Glaser, P.H., 1996, Simulation of ground-water flow within peatlands: evaluation of conceptual models and peatland settings, Abstracts with Programs Geological Society of America Annual Meeting, vol. 27, p.257.

Glaser, P.H., D.I. Siegel, and E.A. Romanowicz, 1993. Coupling of groundwater flow-systems and peat landforms in the Glacial Lake Agassiz region, northern Minnesota, ASLO (American Society of Limnology and Oceanography) Conference, Edmonton, Alberta, June 1993.

Glaser, P.H., Hansen, B.C.S., Janssens, J.A.J. and Siegel, D.I. 1993. Rates and stages of raised-bog development within the lower Albany River drainage of the Hudson Bay lowlands. ASLO (American Society of Limnology and Oceanography) Conference, Edmonton, Alberta, June 1993.

Chanton, J.P., Bauer, J., Glaser, P., Siegel, D., Tyler, S., Kelley, C.A. 1993. ^{14}C and ^{13}C isotopic composition of methane dissolved in porewaters and groundwaters and emitted from Red Lake Minnesota peatlands. American Geophysical Union, fall meeting, EOS 74: 151.

Romanowicz, E.A., D.I. Siegel, and P.H. Glaser. 1993. Temporal variations of profiles of dissolved methane in peat pore-water and evidence of confining layers formed of methane bubbles in the Lake Agassiz peatlands, northern Minnesota (USA). American Geophysical Union, fall meeting; EOS 74: 267.

Shen, Y.P., Siegel, D.I., Romanowicz, E.A., and Glaser, P.H. 1993. Differentiating sources of peat pore-water by statistical analysis of chemical composition, Glacial Lake Agassiz peatlands, Minnesota. American Geophysical Union, fall meeting; EOS 74: 267.

Miller, P., Shaw, G.H., Glaser, P.H., and Siegel, D.I. 1992. Bedrock topography beneath the Red Lake Peatlands. Geological Society of America, National Meeting, Cincinnati, Ohio; October 1992.

Glaser, P.H., D.I. Siegel, and E.A. Romanowicz. 1992. Methane storage in the peatlands of the Glacial Lake Agassiz region during a period of extreme drought. British Ecological Society Special Topic Symposium, University of Nottingham, U.K.

Stone, M.P., Siegel, D.I., Romanowicz, E.A. and Glaser, P.H. 1992. Relationship between subsurface sedimentology and occurrence of vegetation communities of northern Minnesota boreal peatlands. Geological Society of America, National Meeting, Cincinnati, Ohio; October 1992.

Siegel, D.I., Y.P. Shen, Glaser, P.H., and E.A. Romanowicz. 1992. A preliminary estimate of dissolved methane in bog and fen peat of the Glacial Lake Agassiz peatlands, northern Minnesota. American Geophysical Union, spring meeting 1992. EOS 73: 119.

Romanowicz, E.A., D.I. Siegel, and P.H. Glaser. 1992. Effect of drought on dissolved methane profiles in peat pore-water, Glacial Lake Agassiz peatlands, northern Minnesota (USA) American Geophysical Union, spring meeting 1992. EOS 73: 131.

Romanowicz, E.A., D.I. Siegel, and P.H. Glaser. 1992. Changes in hydrogeology and pore-water concentrations of methane during a severe drought in the Lake Agassiz peatlands, Minnesota. INTECOL'S International Wetlands Conference, Columbus, Ohio, 1992.

Glaser, P.H. and D.I. Siegel. 1991. The paleohydrology and development of the Lost River peatland, northern Minnesota. Peatlands; Society of Wetland Scientists Annual Meeting, University of Michigan, Ann Arbor, May 28-31, 1991.

Glaser, P.H., D.I. Siegel, and E.A. Romanowicz. 1991. Climate change, hydrology, and the subsurface methane pool in the Glacial Lake Agassiz peatlands, northern Minnesota. NATO-Advanced Research Workshop on the Atmospheric Methane Cycle: Sources, Sinks, Distributions, and Role in Global Change, Mount Hood, Oregon, October 6-11, 1991.

Siegel, D.I., P.H. Glaser, and Romanowicz, E.A. 1991 Methane concentrations in groundwater flow in peat, Glacial Agassiz peatlands, northern Minnesota. 10th International Symposium on Environmental Biogeochemistry, San Francisco, CA.

Romanowicz, E.A., D.I. Siegel, and P.H. Glaser. 1991 Deep methane in the Glacial Lake Agassiz peatland. American Geophysical Union, spring meeting 1991; EOS 72: 80.

Glaser, P.H. and D.I. Siegel 1990. Groundwater discharge and peatland patterns in the Glacial Lake Agassiz region northern Minnesota (USA). American Geophysical Union, fall meeting, San Francisco, EOS 71: 1299.

Romanowicz, E.A., J.P. McNamara, D.I. Siegel, P.H. Glaser, D. Nelson, S.G. Neuzil, B.C. Frederick, and C. N. Struck, Jr. 1990. Groundwater discharge beneath raised bogs, Lake Agassiz peatlands, Minnesota: Part I. Hydraulic evidence. American Geophysical Union, fall meeting, San Francisco, EOS 71: 1299.

Siegel, D.I. Romanowicz, E.A., J.P. McNamara, P.H. Glaser, D. Nelson, S.G. Neuzil, B.C. Frederick, and C. N. Struck, Jr. 1990. Groundwater discharge beneath raised bogs, Lake Agassiz peatlands, Minnesota: Part II. Geochemical evidence. American Geophysical Union, fall meeting, San Francisco, EOS 71: 1299.

SUMMARY DATA ON PROJECT PERSONNEL

Personnel

The following graduate and undergraduate students completed a thesis as part of this project..

Andrew Reeve, 1996 (Ph.D.). Dissertation title: The Hydrogeology and Geochemistry of Two Large Peatlands, anticipated completion July 1996. Reeve has been a major participant in the project. He has done seminal modeling work designed to determine the role of regional hydrogeology in solute transport in the HBL and GLAP. He has published a major paper on the geochemistry of the HBL pore waters, and has written a new computer code to modeling the accumulation of methane in peat columns caused by biochemical processes.

Edwin Romanowicz, (Ph.D. 1993), Dissertation title: Hydrogeology and methane transport in the Glacial Lake Agassiz Peatlands, northern Minnesota. Romanowicz was a major contributor to all aspects of the project, including the field and analytical efforts of the research. He developed analytical and numerical mathematical models to evaluate and simulation the rate of methane production and the mechanisms for methane transport in peat. He is author and co-author of numerous abstracts and has several publications in major journals (see list of publications).

Yiping Shen, (M.S. 1994), Dissertation title: Methane storage, vegetation communities, and water quality, Lake Agassiz Peatlands, Northern Minnesota. Shen did extensive multivariate statistical analysis to test the hypothesis that different vegetation landforms may be related to their methane pools. Her work also includes calculation of the amounts of methane in storage during sampling times 1990 and 1991. Volume modeling of methane storage was done using GIS based approaches. She is senior author of a paper presented at a meeting of the American Geophysical Union and co-author of a paper in press (see list of publications).

Nan Rutkowski, (M.S. 1993), Dissertation title: Trace element geochemistry of bog peat, Glacial Lake Agassiz Peatlands, Northern Minnesota. Rutkowski extended Hill's work in the Lost River Peatland to four other bog-fen complexes. Her data will be used in conjunction with Pat Korth's work to regionally determine the hydrogeologic controls over whether the hydrogeologic system of major bogs is sensitive to drought conditions. She is co-author of several abstracts of papers presented at AGU.

Rik Jansen (M.S. University of Utrecht, 1994). Dissertation title: The relationship of fire scars to peat landforms, regional vegetational boundaries, and cultural disturbances, in the Glacial Lake Agassiz peatlands, northwestern Minnesota, USA. Mr. Jansen mapped the distribution of wildfires within the Glacial Lake Agassiz peatlands utilizing aerial photographs, Landsat imagery, and the Optimus image-analysis software. Jansen determined the relationship of fires to drainage ditches, roads, climatic variables, and the distance to the prairie-forest border. This research project represented part of the requirements for Mr. Jansen's graduate degree from the University of Utrecht in the Netherlands.

Pat Korth, (M.S., June 1997), Dissertation title: Hydrogeologic controls over the trace element composition of bog peat, , Glacial Lake Agassiz Peatlands, Northern Minnesota. Korth has extended Hill's work in the Lost River Peatland to four additional bog-fen complexes. His data will be used in conjunction with Rutkowski's work to regionally evaluate the hydrogeologic controls governing which bogs are most sensitive to hydrologic reversals during drought.

Juho So, (M.S. June 1996) Dissertation title: Geochemical evidence for surface water and groundwater mixing in the Glacial Lake Agassiz peatlands, northern Minnesota. So is evaluating the chemical controls over pore-water chemistry in the peatlands, paying special attention to acid-base chemical reactions that occur when ground water mixes with organic-acid rich surface water. He used chemical equilibria modeling to evaluate mixing and water-peat-mineral reactions, especially involving the carbonate systems.

Mike Stone, (B.S. 1993), Senior Honors' thesis title: Relationship between sedimentological characteristics of mineral substrate under bogs and fens and their hydrogeologic function. Stone was a senior geology major who presented his research results at the 1992 National Geological Society of America. His research, coupled with seismic stratigraphic work by Dr. George Shaw (Union College), is critical to determine the hydrogeologic controls over bog formation in the peatlands, and will be incorporated in numerical models by Romanowicz to evaluate methane transport in the peat.

Dan Ours, (M.S. 1993), Dissertation title: The effects of ligands on the effective porosity, dispersivity and hydraulic conductivity of peat. Ours discovered that peat dilates as a function of the chloride concentration. His data on the effective porosity and dispersivity of peat are the first available. The dilation phenomenon is the first evidence that chemical processes can cause secondary porosity in peat, enhancing the transport of methane through the peat column.

Miller, P. (B.S. 1992), Senior Honors' thesis title: Bedrock topography beneath the Red Lake Peatlands. Miller completed a senior thesis based on a seismic survey with Dr. George Shaw and Paul Glaser in the Glacial Lake Agassiz peatlands. This survey confirmed the existence of bedrock ridges under discharge zones for groundwater as predicted by the Boldt model (1983).

Rivers, Jennifer, (Ph.D, in progress). Rivers has begun investigating aspects of the transient hydrogeologic and geochemical systems at the Glacial Lake Agassiz peatlands. She will continue work on carbon cycling in the peatlands, using Monte Carlo approaches among others.

Other Graduate Students

J. McNamara (Syracuse), C. Cirno (Syracuse), D. Verschuren (Minnesota)

Other Undergraduate Students

B. C. Frederick: (Colgate); D. Nelson: (U. of Minnesota); and C.N. Struck, Jr.-(Calvin College), Carter McFarlane, Vixayvong Sithiphonesack, Stacy Bulera, Ho Tran, Erica Haas, Sharon McGlip, Trinh Huynh, Paune Tran, (University of Minnesota), Dave Rebar (Syracuse University), and Robert Levehnson (Colgate).

Collaborative Studies

Dr. George Shaw, Union College. Dr. Shaw conducted the seismic geophysical surveys in parts of the Glacial Lake Agassiz peatlands to determine the topography of geological features under raised bogs. . His results set important bounding conditions on groundwater flow models that are being prepared.

Dr. Jeff Chanton (Florida State University) Dr. Chanton, a leading authority on gas fluxes and carbon isotopes in peatlands obtained data to determine a) substrates supporting methanogenesis, b) source strata for methane production, and c) methane emissions relative to net ecosystem exchange. These results were integrated with calculations of diffusive fluxes of methane within the deeper pore waters (see publications).

Dr. Stan Tyler and Dr. Alan Lazrus, National Center for Atmospheric Research.

Dr. Lazrus helped collect gas samples from chambers in 1991 for analysis of stable isotopes of carbon. Dr. Tyler performed these analyses at NCAR (see publications).

Barbara Hansen (University of Minnesota) completed pollen diagrams for 3 bog cores from the Hudson Bay Lowlands documenting a 6000 years record of primary succession along an isostatically rising chronosequence. These successional changes are linked to distinct changes in rates of carbon accumulation.

In addition the following senior personnel assisted with field studies and the laboratory analysis: S. Neuzil, water chemistry (U.S. Geological Survey), Dr. J.A.J. Janssens, bryophytes (University of Minnesota), Dr. P. Bennett, organic geochemistry (University of Texas), Dr. Brian Cummings, Chrysophytes (Queen's University), Cheryl Kelley (University of North Carolina).