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New Map Reveals Origin and Geology of North American Mid-continent Rift

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New aeromagnetic data from the north central United States are helping geophysicists and geologists better understand the 1.1-billion-year-old mid-continent rift, one of the fundamental components of the Precambrian basement of North America.

A detailed geologic map of part of the rift is being made and a myriad of new details concerning the history of rift subsidence, volcanism, sedimentation, and inversion are being deciphered. The data are also helping to establish a link between well-known parts of the rift in the Lake Superior region, where exposures of rift-related rocks are abundant and where a comprehensive geophysical data base has existed for more than a decade, and the buried extension of the rift to the southwest. Scientists from the U.S. Geological Survey (USGS), the Minnesota Geological Survey, the Wisconsin Geological and Natural History Survey, and Macalester College are using the new data in conjunction with field and laboratory investigations in a joint study that promises to produce new insights into the history and formation of the rift.

From 1996 to 1999, the USGS sponsored aeromagnetic surveys in Wisconsin to complete high-resolution, half-mile line spaced coverage for the state in areas where previous data were at 3-mile and 6-mile line spacing. These new data, combined with previous detailed surveys by the USGS, the Minnesota Geological Survey, and the University of Wisconsin Oshkosh, produced the high-resolution aeromagnetic map shown in Figure 1. The digital aeromagnetic grid was assembled from nine separate surveys in Wisconsin and Minnesota that were flown between 1961 and 1998, mostly along north-south flight lines. In Minnesota, flight lines were mostly spaced 400 m apart and flown at 152 m or 200 m above mean terrain. In Wisconsin, flight lines were mostly spaced 800 m apart and flown at 152 m or 305 m above mean terrain.

Importance of the Aeromagnetic Surveys

The general character of the mid-continent rift has been known for many years, but details of its geology and origin have been obscure because most of it is buried beneath a veneer of younger, Paleozoic sedimentary rocks. Because the Paleozoic strata have little magnetic character, they are essentially transparent to magnetic surveys. Consequently, the observed magnetic pattern can be attributed to variations in magnetic properties of rocks in the Precambrian basement. Aeromagnetic surveying is thus a powerful tool for mapping the geometry of rock units even where they are deeply buried.

Until now, detailed studies of the rift have been limited to the Lake Superior region, where direct observations can be made. The

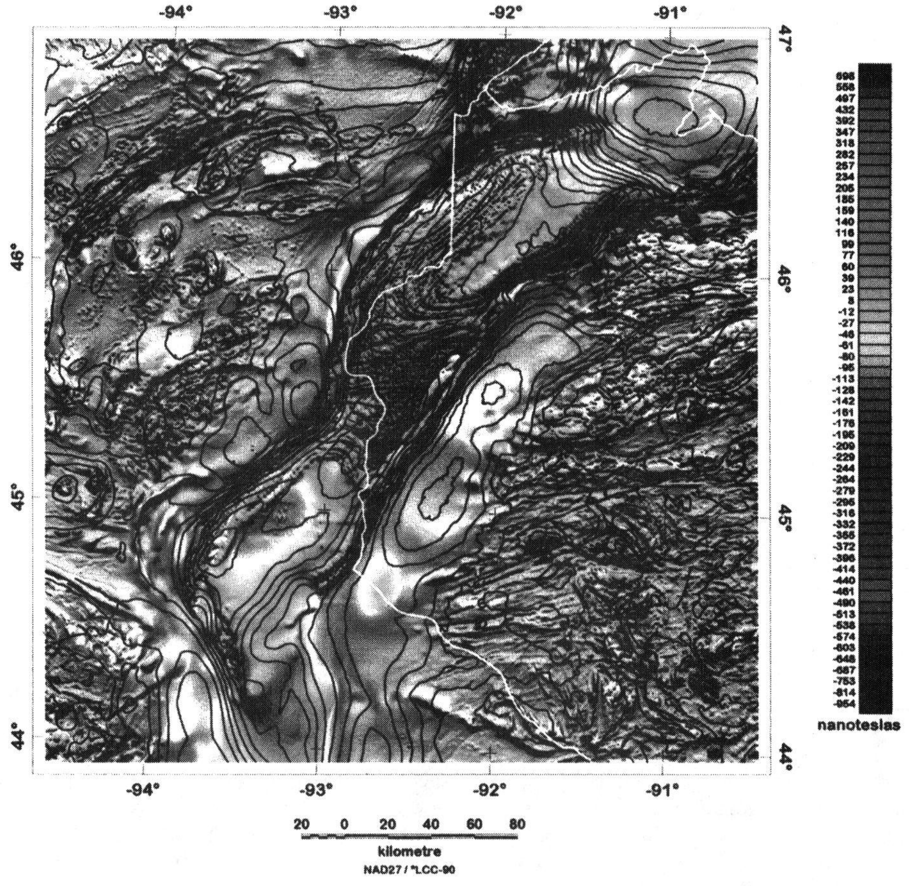

Fig. 1. Aeromagnetic anomaly map (color-shaded relief) of parts of Wisconsin and Minnesota, including the St. Croix horst (see Figure 2 for index); illumination is from the north. Individual digital grids for each survey were interpolated using a minimum-curvature algorithm [Webring, 1981], then adjusted based on overlap comparisons and stitched together with a weighted, blending algorithm [Phillips, 1997]. The overlay of Bouguer gravity contours was obtained by interpolating 15,600 gravity stations in Minnesota, available through the National Geophysical Data Center, and 13,500 gravity stations in Wisconsin, available through the Wisconsin Geological and Natural History Survey. The interval between stations is variable, typically 1.6 km along the road network, but the mean station spacing is somewhat larger. A light smoothing filter was applied to the gravity grid to generalize the contours suitable for presentation at this scale. Original color image appears at the back of this volume.

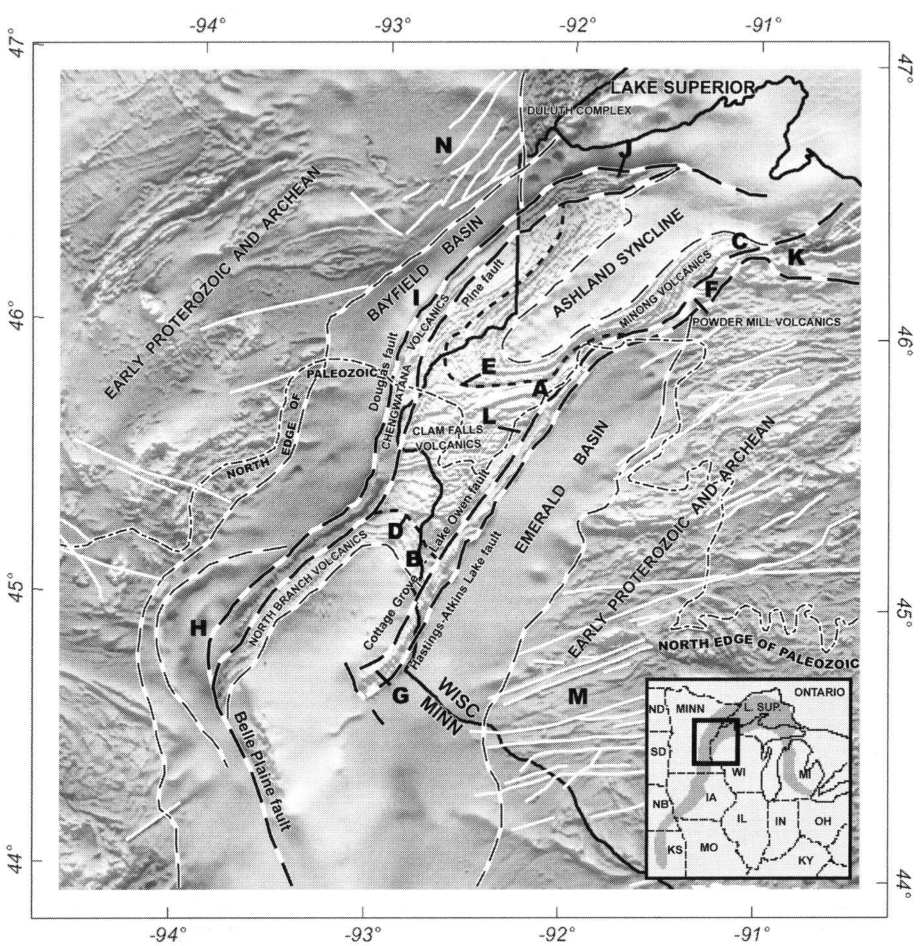

Fig. 2. Geologic interpretation of the aeromagnetic map of the St. Croix horst and vicinity. The magnetic field is shown in gray-shaded relief illuminated from the north. Major faults are shown in heaviest dashed black lines. Geological contacts are lighter dashed lines. Solid white lines are diabase dikes inferred from the magnetic pattern. Bold black letters are features referred to in the text. South of the dashed line labeled "north edge of Paleozoic," all features are buried by up to a few hundred meters of sandstone, shale, and carbonate rocks, and are inferred from magnetic and other geophysical data. North of that line about 5% of the rift rocks are exposed; the remainder are concealed by Pleistocene glacial deposits. The index map shows the location of Figures 1 and 2 and the extent of the mid-continent rift is shown by the gray shading.

new geophysical data are allowing a detailed study of the rift southwest of Lake Superior throughout a 250 km-long rift segment known as the St. Croix horst (Figures 1 and 2). Our new studies are showing that the St. Croix horst differs in many significant aspects from the better-known rift segments in the Lake Superior region. It appears to have formed at a greater structural depth and thus provides a view of the deep axial zone of the rift that is not exposed elsewhere. It also appears to record a history of volcanic eruption that is both longer and more complex than is known anywhere else in the region.

The dominant geophysical features shown in Figure 1 are the intense magnetic high and coincident gravity high produced by the St. Croix horst segment of the mid-continent rift. The striking magnetic pattern is caused by the rocks of the rift and surrounding older rocks, which are completely buried by Paleozoic strata in the south and more than 95% buried by Pleistocene glacial deposits in the north. The new aeromagnetic data have revealed an extraordinary degree of detail within the volcanic rocks of the horst. This new level of detail is crucial to ongoing studies of this segment of the rift, where direct observations of rift-related rocks are limited to very sparse exposures and widely-spaced drill holes.

Previous studies have suffered from an inability to place necessarily fragmented observations into a spatial and temporal framework that reflects the geometry and history of the rift. The aeromagnetic map provides a powerful new tool for correlating between these widely spaced data points that allows us to place both previous and new observations into an accurate geologic framework. Some preliminary findings and their significance to a revised understanding of evolution of the mid-continent rift are summarized below.

General Geology of the Rift and its Geophysical Expression

The mid-continent rift extends in a southward concave arc for 2,200 km, with its northern apex beneath Lake Superior (see index map in Figure 2). The rift developed during a period of extension within the Laurentian supercontinent about 1.1 billion years ago. Rocks that formed in the rift are exposed around Lake Superior. Elsewhere, they are buried by younger sedimentary deposits and are known mostly from geophysical studies supplemented by a few tens of deep drill holes. The western arm of the rift, from the western tip of Lake Superior to Kansas, produces the long-known mid-continent gravity anomaly and coincident mid-continent magnetic anomaly. The northern-most segment of the western arm, the St. Croix horst, was defined by Craddock et al. [1963] largely using gravity data and refined by many subsequent studies (particularly *Allen* [1994]).

The mid-continent rift is an alignment of deep, fault-bounded troughs filled with continental flood basalt and related intrusions. The rift was accentuated by post-extensional thermal subsidence of the lithosphere, which formed a somewhat broader basin that is now filled mostly with continental fluvial sediments. The grabens were partly inverted, beginning concurrently with sedimentation, so that the basalts were thrust upward through the overlying sedimentary rocks to form present-day horsts such as the St. Croix. Figure 3 shows a generalized geometry of the St. Croix horst segment of the rift.

The geophysical signature of the St. Croix horst reflects this structure. The inverted graben produces very intense positive gravity and magnetic anomalies because it is filled with a great thickness of relatively dense and magnetic basalt. Steep gradients in both the magnetic and gravity field along bounding faults are caused by steep fault contacts between the thick sequence of basalt and related mafic intrusive rocks of the horst and sedimentary rocks of the flanking basins, such as the Emerald basin on the east and Bayfield basin on the west. Although this general geophysical character was apparent on older maps, the new aeromagnetic data allow a much more detailed examination of structure and stratigraphy within the St. Croix horst. In particular, contrasting magnetic properties between the numerous basalt flows allows individual flows or packages of flows to be traced for long distances reaching nearly 100 km in some cases.

Structure of the St. Croix Horst Geophysical data coupled with sparse geologic data show the St. Croix horst to be a continuous, geologically coherent structure from about the southern shore of Lake Superior southward for about 250 km into southeastern Minnesota. Both gravity and seismic data indicate that the horst, even though partly eroded, contains volcanic and intrusive fill ranging from 10 to 20 km thick [*Chandler et al.*, 1989; *Allen*, 1994]. This thickness is less than determined by deep seismic surveys in Lake Superior, where more than 30 km of basalt and sediments are preserved [*Cannon et al.*, 1989]. The lesser thickness of preserved graben fill suggests that the St. Croix horst has undergone more uplift and erosion than previously studied horsts in the Lake Superior region. Many of the volcanic rocks in the St. Croix horst show burial metamorphic grades considerably higher than observed anywhere near Lake Superior [*Wirth et al.*, 1997], indicating that they were once buried deeper than the rocks that are now at the surface around Lake Superior.

The St. Croix horst is bounded on both flanks by an unusual arrangement of paired faults that are readily mapped with the new data, indicating that rift subsidence occurred on a series of faults rather than a single master fault. Each pair consists of parallel faults 5 to 10 km apart. The Douglas fault on the west and the Hastings-Atkins Lake fault on the east form the boundaries between the igneous rocks of the horst and the sedimentary rocks of the flanking basins. They are major reverse faults along which the graben was partly inverted. Their role as growth faults during graben formation and volcanism is not as directly demonstrable. Parallel faults—the Pine fault on the west and Cottage Grove-Lake Owen fault on the east—lie within the horst and appear to have been important growth faults that controlled the distribution and thickness of volcanic fill in the graben. The aeromagnetic data show that the basalt sequences form arcuate patterns in which flows commonly terminate against these faults at high angles (see points A, B, and C in Figure 2). These truncations are likely to be original terminations of flows where they abutted fault scarps of an actively subsiding graben. Such growth faults have been postulated in the Lake Superior region but have never before been observed with the clarity shown by the new aeromagnetic map.

Rocks within the horst are gently folded and tilted to form structures such as the northeast-plunging Ashland syncline in the north, a west-facing monocline in the central part of the horst, and a southwest-plunging syncline in the south as also shown in previous seismic studies [*Chandler et al.*, 1989]. The new aeromagnetic data show these structures with a new clarity that allows tracing of stratigraphic units through these regional fold structures.

Volcanic Stratigraphy

The new aeromagnetic data, combined with high-precision geochronologic studies, are revealing a volcanic history both more complex and longer than that documented in the Lake Superior region. Near Lake Superior, a sequence of basalt flows more than 20 km in places accumulated from about 1108 to 1094 m.y.a. With the advent of high precision U-Pb geochronology of zircon and baddeleyite, it has become possible to distinguish the volcanic history of the rift with a time resolution of only 1 or 2 million years [e.g., *Davis and Green*, 1997]. Prior to our current studies, all volcanic rocks in the St. Croix horst were referred to as Chengwatana volcanics. With the new data, five volcanic sequences are recognized; each is separated by a combination of unconformities and faults. The term Chengwatana now appears to be appropriate only for the thin panel of volcanic rocks, which includes the type locality, between the Douglas and Pine faults, and whose correlation with other volcanic sequences in the horst must be determined by future research.

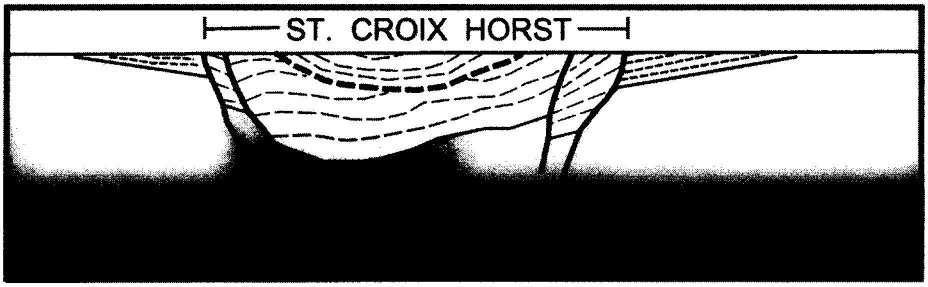

Fig. 3. Schematic cross-section of the St. Croix horst showing a typical geometric arrangement of the central graben filled with basalt flows (longer dashed lines) and flanking basins containing sandstone and shale (shorter dashed lines). Faults were originally extensional structures along which the graben subsided and against which basalt flows ponded. Complexities in the history of subsidence and volcanism are indicated by angular unconformities within the volcanic sequence. After extension ended, and a period of thermal subsidence produced a broad basin filled with sandstone, the faults were reactivated and became reverse faults along which the graben was partly inverted to form the present-day St. Croix horst. A thin cover of Paleozoic rocks is not shown.

In the western Lake Superior region, precise age dating suggests the possibility of a volcanic hiatus from about 1107 to 1096 Ma [*Davis and Green*, 1997], but physical evidence—such as an unconformity—for this or any other hiatus has been lacking. Within the St. Croix horst, the new magnetic data provide the first clear indication of unconformities in the volcanic section. Two discontinuities along which younger flows truncate older flows at a low angle are shown at points D and E in Figure 2.

In the north, a relatively young series of flows, the Minong volcanics (informal name), can be traced around the gently northeast-plunging Ashland syncline. On the east limb of the syncline, the Minong volcanics comprise the entire exposed volcanic section. The basal Minong flows can be traced by their magnetic anomaly around the keel of the syncline and onto the north limb, where they appear to be underlain unconformably by a thick series of older basalt flows that is informally called the Clam Falls volcanics. A rhyolite flow near the base of Minong volcanics was erupted about 1094 Ma [*Zartman et al.*, 1997], which indicates that the Minong volcanics are younger than all but the very youngest volcanic rocks in the Lake Superior region.

Farther south, the North Branch volcanics (informal name) also appear to lie with an angular unconformity on the Clam Falls volcanics, suggesting that they, too, might be younger than volcanics in the Lake Superior region. The Clam Falls volcanics are significantly older than the Minong volcanics. The stratigraphically lowest exposed volcanics were erupted at about 1102 Ma, and somewhat higher stratigraphic units are as young as 1098 Ma. The Powder Mill volcanics are exposed extensively northeast of the area of Figure 1, and their outcrop belt extends to near point F, where they lie between the Cottage Grove-Lake Owen fault and the Hastings-Atkins Lake fault.

The magnetic anomalies in the southern extension of this structural panel are interpreted to be caused by the continuation of Powder Mill volcanics to the south. The Powder Mill volcanics in the Lake Superior region were erupted in an interval ending at 1099 Ma [*Zartman et al.*, 1997], but the start of eruption is not constrained by radiometric ages. Near point G in Figure 2, in this same structural panel, a rhyolite has yielded somewhat equivocal age information, but it was most likely erupted at about 1130 Ma [*Zartman et al.*, 1997]. If this age is correct, this structural panel contains the oldest volcanic rocks so far identified in the rift.

Rift-related volcanic rocks are also inferred to be locally abundant external to the horst and were presumably deposited as relatively thin aprons of basalt flows that either spilled out of the periodically filled graben or were deposited before a well-defined central graben developed. These flows are now buried beneath sediment in the flanking basins, but their presence is shown by distinct magnetic and gravity anomalies (Figure 2, points H and I).

Intrusive Rocks

New aeromagnetic data have been especially useful in identifying previously unknown mafic intrusive rocks, both within the St. Croix horst and in the surrounding area. Two intrusions consisting of gabbroic rocks and lesser granitic rocks have been known from bedrock mapping for many years (near points J and K on Figure 2). Diabase dikes emplaced during rifting also have long been known to intrude the basement rocks surrounding the rift [*Green et al.*, 1987]. A major pluton may be present near point L. An area about 70 km long shows a magnetic pattern distinct from the prominently striped pattern of the adjacent basalt flows. We suspect that this pattern is caused by an intrusion within the Clam Falls volcanics. Such major intra-graben intrusions are unknown in the Lake Superior region, although they commonly have been inferred to occur at depth.

A swarm of east- to northeast-trending diabase dikes is also revealed by the new data in the southeast quarter of Figure 1. These dikes cut Archean and Early Proterozoic rocks well away from the rift. Their magnetic anomalies are attenuated as they pass beneath the sandstone of the Emerald basin. There are no known exposures of these dikes, but because they have a magnetic signature and orientation similar to known rift-related dikes, such as near points M and N in Figure 2, we tentatively consider them to be rift-related dikes. These dikes appear to be much more abundant east of the rift than to the west. This may indicate that most extension of the lithosphere occurred within the block east of the rift, interior to the overall concave shape of the rift.

The new data also show abundant dikes within the horst, especially in the Clam Falls volcanics. Numerous west- and northwest-trending linear magnetic anomalies cut the magnetic pattern produced by the flows. These linear anomalies all terminate against either the Pine fault on the west or against the inferred mafic intrusion along the Hastings-Lake Owen fault. No dikes have been found in outcrops in this area, but the geometric pattern of the anomalies strongly suggests that they are caused by mafic dikes similar to diabase dikes known outside of the horst. If future work confirms that these are indeed dikes, they will be the first documented swarm of dikes identified within the central graben of the rift.

Significance for Future Research

Preliminary interpretation of the new aeromagnetic data has identified an unexpectedly complex geologic history of the St. Croix horst. The history differs from that previously documented for the Lake Superior portion of the rift. We believe that the St. Croix horst provides a sample of the original deeply buried root zone of the midcontinent rift. It is probably analogous to the central part of the rift that is still deeply buried beneath Lake Superior, where observations are limited to seismic data and to magnetic and gravity data in which details are attenuated by many kilometers of overlying rocks. Thus, studies of the St. Croix horst promise to yield fundamental information on tectonic and volcanic processes along the rift axis that have only been inferred or poorly documented in the Lake Superior region. The aeromagnetic data shown here are a critical new piece of information because they reveal previously unknown details of the geometry of volcanic and sedimentary rocks of the rift and of geologic structures produced by the rifting process.

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Climate Implications of Changing Arctic Sea Ice

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Ertu kominn, landsins forni fjandi?
(Are you back, Iceland's ancient foe?)

Straddling the mid-Atlantic ridge, Iceland may be best known to the world for its fiery volcanic history, violent earthquakes, and massive jökulhlaups—episodic outbursts of sub-glacial lakes melted by underlying magma. But this poem, written by Matthias Jochumsson in 1888 and titled simply "The Sea Ice" [*Jochumsson*, 1915] illustrates why the most insidious disruption to the Icelandic people is the havoc wrought by the quiet approach of sea ice. No other natural disaster has brought such cruelty, famine, and death. From Jochumsson:

> *"Where is the ocean, where is the bright, free, silvery ocean? ..... When you [sea ice] appear, the nation and its history are extinguished; then is death, and deep, dark night..."*

Although sea ice may have occasionally reached the northern coasts of Iceland in modern times, medieval Icelandic sagas refer to its presence in the early centuries after settlement. Other historical records describe conditions in the 17th, 18th, and 19th centuries, when in some years sea ice nearly surrounded the island. Extensive sea ice limits fisheries and trade and depresses summer temperatures over Iceland, which leads to diminished grass growth. These impacts result in economic disruption, loss of livestock, and widespread famine.

The human consequences of sea ice variability documented in Iceland are paralleled by other impacts that reverberate through the global climate system. The extent and thickness of sea ice influence the planetary albedo and the exchanges of heat, moisture, and gases between ocean and atmosphere. Sea ice formation alters the salinity structure of surface waters through salt rejection, producing cold, dense brines that move into the deep ocean as gravity flows. Where winds or ocean currents maintain polynyas—persistent areas of open water in winter—the dense brines formed there play a significant role in the ventilation of the deep ocean. Because sea ice is mobile, substantial horizontal transports of fresh water are associated with sea ice drift.

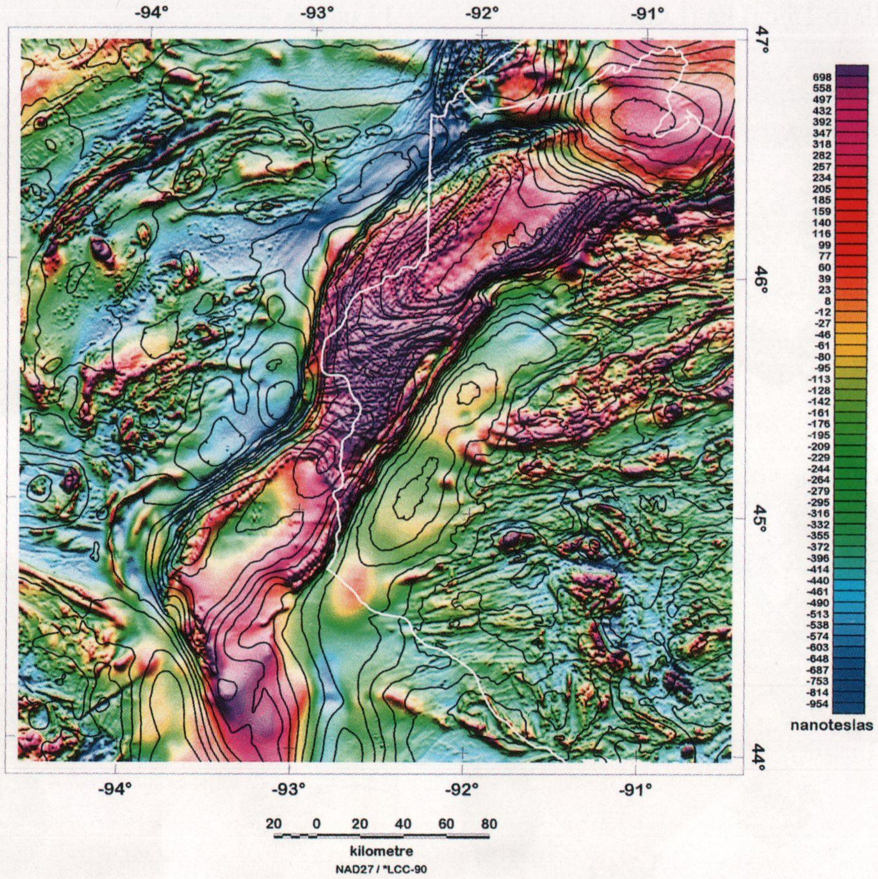
Currently, the export of sea ice through the Fram Strait accounts for 75% (2500 $km^3 a^{-1}$) of the freshwater outflow from the Arctic Ocean. When sea ice melts, generally far from its place of origin, it freshens and cools the surrounding surface water. In the 1960s, an unusually large flux of Arctic Ocean sea ice into the Nordic Seas diluted surface waters enough that vast regions remained buoyant, disrupting deepwater formation through the early 1980s. This phenomenon, known as the Great Salinity Anomaly [*Dickson et al.*, 1988], was the greatest disruption of the freshwater balance in the northern North Atlantic in historic times. Sea ice also affects society by acting as a contaminant transport agent, as well as through its direct impacts on polar ecosystems and maritime activities such as transportation and fishing.

Sea ice is a key variable in assessing future climate change because of its large feedback on the planetary energy balance and deep ocean convection. Reductions in the Arctic pack observed over the past decades are postulated to be a consequence of greenhouse warming [*Vinnikov et al.*, 1999]. Projections of these trends and some greenhouse scenario model results even suggest the eventual possibility of an ice-free Arctic Ocean in summer. The positive ice-albedo feedbacks associated with sea ice reduction amplify modeled anthropogenic impacts on climate, accounting for as much as one-third of the projected global warming. Negative feedbacks involving sea ice dynamics are also possible. Changes in atmospheric circulation associated with warmer climates can lead to greater ice export from the Arctic and a pattern of temperature change that partially mitigates the original warming. Lacking reliable models to simulate how sea ice may change in the future, we can instead capitalize on the dramatic changes that we know occurred in the past to gain a better understanding of the role of sea ice in the climate system.

Reconstructing Sea Ice of the Past

You, cold ghost, have drunk most of Iceland's blood.
Where do you come from? Nobody knows, nobody understands, nor visits you there.
You are outside, you are inside -
you have come from far away.

In Jochumsson's time, Icelanders recognized that sea ice was transported great distances,



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