# Was the Younger Dryas Triggered by a Flood?

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vertebrate networks, only a small minority of signaling molecules (fibroblast growth factor, Nodal) and transcription factors (ZicL, FoxD, FoxA-a, Otx) affect the expression of a large fraction of the regulatory genes assayed. It will be interesting to test whether the majority of genes studied, which have few or no targets in the network, directly control differentiation genes. This would suggest that the simple and rapidly developing *Ciona* embryo may not need the cross-regulatory interactions used to stabilize gene expression patterns found in more slowly developing and also more complex embryos. Because extensive cross-regulatory interactions are a feature of kernels, the low level of connectivity of the *Ciona* network suggests their absence at the stages analyzed. Another surprise is the prevalent—though probably indirect—use of negative autoregulatory loops in the network. In contrast, very few positive autoregulatory loops were identified. This conflicts with the proposal that cell fate determination, which occurs very early in *Ciona*, is associated with the establishment of positive regulatory loops that lock in a given fate (*4*).

The structure of the current early *Ciona* network differs substantially from those of other deuterostomes. The maintenance of a chordate body plan in ascidians, in the absence of detectable kernels, may cast doubt upon the proposal that this type of subnetwork is important to stabilize a body plan across large evolutionary distances. It should, however, be considered that within a phylum, developmental strategies can be diverse in early embryos, converge at the phylotypic stage, and diverge again when terminally differentiated structures form. The network analyzed in the present work mainly covers pregastrula stages, and forms a necessary first step toward reconstructing networks for later stages in which chordate-specific kernels may be present. As it stands, the *Ciona* network has already allowed researchers to identify novel key regulators of specific fates and illustrates that whole-embryo reconstruction of gene regulatory networks is feasible provided that a suitable model organism is chosen. As was noted a few years ago, "Ascidians are back in the limelight, with a good chance of staying there" (*14*).


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GEOLOGY

# Was the Younger Dryas Triggered by a Flood?

**Wallace S. Broecker**

Draining of a huge lake into the Northern Atlantic may have triggered a cold period ~12,900 years ago. The route taken by the flood waters remains unknown.

As Earth's surface warmed at the end of the last glacial period, the Laurentide ice sheet that covered much of North America retreated and a vast melt water lake—Lake Agassiz—formed in the area of today's Great Lakes. But the transition from glacial to interglacial conditions was not smooth: Between ~12,900 and ~11,500 years ago, cold conditions returned during the Younger Dryas.

It is widely believed that this cold event was triggered by a flood of fresh water that poured into the northern Atlantic (*1*) and disrupted the thermohaline ocean circulation (*2*). The accepted scenario (*3*) is that at some point during the retreat of the Laurentide ice sheet, the northern and eastern shorelines of Lake Agassiz were breached, diverting the outflow from the lake eastward through Lake Superior and into the northern Atlantic via the St. Lawrence lowlands (see the first figure). Teller *et al.* have argued that the initial flood caused by the sudden drop in outlet elevation, rather than the subsequent steady-state discharge from the lake, was instrumental in causing the Younger Dryas (*4*).

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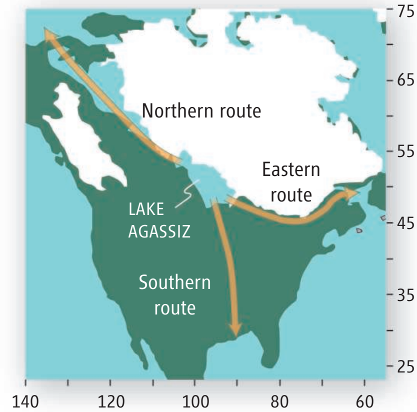
However, an aerial search to the west of Lake Superior (*5*, *6*) yielded no visual evidence for flood channels or boulder fields that might support the flood scenario. This absence is particularly disconcerting, because lesser floods thought to have occurred after the Younger Dryas created spectacular canyons (see the second figure) and boulder fields. If not a flood, then what else might have triggered the Younger Dryas?

Before considering alternate scenarios, a brief summary of the evidence in support of an Agassiz flood is in order. I will use radiocarbon rather than calendar years, because the exact conversion factor to calendar years remains uncertain. The Younger Dryas occurred 11,100 to 10,000 radiocarbon years ago.

During the Bölling-Allerod warm interval that preceded the Younger Dryas, Lake Agassiz overflowed to the south over the Big Stone Moraine (see the first figure). Around 10,800 ± 200 radiocarbon years ago, this overflow ceased (*7*). At this time, the level of the lake must have dropped to that of a newly created alternate outlet. The new level may have been that of the "Moorhead lowstand," when Lake Agassiz stood more than 40 m below the level of the southern outlet; radiocarbon ages for wood from the Moorhead lowstand fall within the span of the Younger Dryas (*5*).




**Drainage pathways from Lake Agassiz**

Oxygen isotope records from sediment cores from the Gulf of Mexico support the contention that the new outlet did not empty into the Mississippi River drainage. Planktonic shells have yielded a radiocarbon age of 11,100 years, marking the onset of a time of decreased inflow of $^{18}O$-depleted glacial melt water into the Gulf of Mexico (*8*). This interval lasted until about 10,000 radiocarbon years before the present and hence corresponds to the Younger Dryas time interval. But although the observed rise in $^{18}O$ is



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consistent with a diversion of Agassiz outflow to an alternate pathway to the sea, it can also be explained by a decrease in the rate of ice-sheet melting during the cold Younger Dryas.

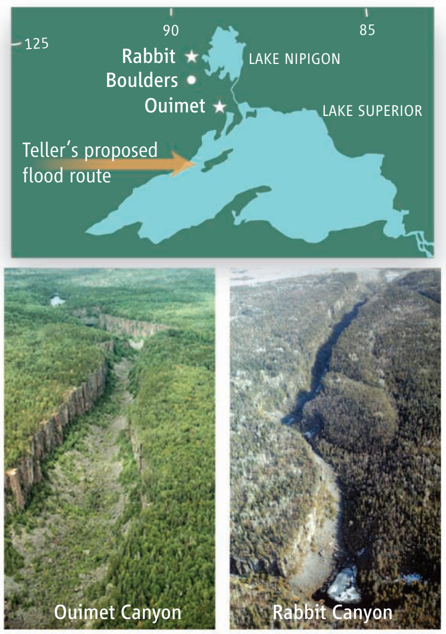
A complementary drop in the $^{18}$O in shells from the St. Lawrence Valley at the onset of the Younger Dryas would provide support for the Lake Agassiz flood scenario. In a recent paper (*9*), Brand and McCarthy present evidence for such a drop in mollusks from two sites south of Ottawa, Canada. However, the time of this drop is poorly constrained, and the event may postdate the onset of the Younger Dryas. Furthermore, de Vernal *et al*. (*10*) find no evidence in sediments from the St. Lawrence Estuary for an eastward flow of melt water during the Younger Dryas.

New radiocarbon ages for organic material from the bottom of borings in small lakes in the area west of Thunder Bay (*5*) suggest that the area through which the proposed pre–Younger Dryas flood had to pass was not deglaciated until 10,200 radiocarbon years ago, late in the Younger Dryas. These new radiocarbon ages are younger than those for wood from the Moorhead lowstand of Lake Agassiz (up to 10,900 radiocarbon years before the present). The wood cannot be older than the time of diversion of melt water to the presumed eastern outlet. Thus, it has been suggested that the oldest Moorhead wood is reworked (that is, it was transported after growth) (*5*). But there is another explanation: The area may have been deglaciated during the Bölling-Allerod warm period and reglaciated during the Younger Dryas. If so, then the sediment cores likely terminated in impenetrable silt deposited during the ice retreat subsequent to the Younger Dryas.

In the absence of geomorphic evidence for an eastern outlet, an alternate trigger for the Younger Dryas cold episode must be found. There are several possibilities.

First, flood waters from Lake Agassiz may have escaped to the north rather than to the east. Indeed, there is clear evidence that a catastrophic flood passed through the Fort McMurray area (*11*). A 1-km-wide, 30-km-long channel marks the path taken by these waters. At the channel's mouth, there is a large gravel field and beyond that, a huge apron of sand. However, these deposits are around 9800 radiocarbon years old and thus postdate the Younger Dryas. Of course, an earlier flood predating the Younger Dryas may have passed through the same area, but, to date, no convincing physical evidence for such an event has been found.

Second, the water from Lake Agassiz may have escaped beneath the ice. Were this the case, then no radiocarbon-datable material recording the event would exist, because nothing could grow under the ice roof. Further, boulders put in place by the subice flood would have $^{10}$Be ages reflecting the time of deglaciation rather than the time of the flood (radioactive $^{10}$Be atoms are produced within exposed




**Evidence for lesser floods thought to have occurred after the Younger Dryas. (Bottom left)** Ouimet Canyon appears to have been cut by flood waters escaping from Lake Agassiz. No material suitable for dating has been found. **(Bottom right)** Rabbit Canyon is one of the numerous channels to the west of present day Lake Nipigon. A granitic boulder from the mouth of a nearby channel has a $^{10}$Be age of 8400 years, fixing the time of deglaciation of this site.

boulders by cosmic ray neutrons that shatter the nuclei of oxygen atoms; no such cosmic rays could penetrate the ice roof). Indeed, there are spectacular canyons (see the first figure) and boulder fields to the north of Thunder Bay (*3*). The 2-km-long, 100-m-deep Ouimet Canyon is situated just north of Lake Superior. But no quartz-bearing rock suitable for dating has yet been found (quartz crystals can be acid-leached to remove contaminating $^{10}$Be atoms produced in the atmosphere and carried to the surface by rain. Hence quartz is the mineral of preference for $^{10}$Be studies). $^{10}$Be measurements on meter-size granitic boulders from west of Lake Nipigon yield an age of about 8400 years (*12*). This result provides a minimum age for the deglaciation of this area. Although a subice escape of water stored in Lake Agassiz may seem unlikely, it must be kept in mind that such an escape has been called on to explain the triggering of the 50-year cold snap that occurred 8200 years ago (*13*).

Third, the fresh water that triggered the Younger Dryas may have originated from the melting of an armada of icebergs rather than from the escape of stored melt water. In three marine sediment cores from southeast of Hudson Straits, a detrital $CaCO_3$-bearing horizon has been found (*14–16*). Such horizons are believed to be caused by armadas of icebergs shedding their debris upon melting. Although not precisely dated, this horizon appears to correlate with the Younger Dryas. However, no evidence for this iceberg armada is found in other sediment cores from the northern Atlantic, and the impact was therefore probably too small to have produced a shutdown of the ocean's circulation. In a variant on this scenario, the subice escape of Agassiz water may have passed through the Hudson Bay carrying debris-laden basal ice. In this case, the flood water rather than the melting of the entrained ice would have diluted the salt content of northern Atlantic waters.

Of course, the Younger Dryas may not have been triggered by a catastrophic freshening of northern Atlantic surface waters at all. Seager and Battisti have argued that a temperature anomaly in the tropics may have triggered a shift in the wind pattern over the northern Atlantic, in turn allowing sea ice to form (*17*). As a consequence, the thermohaline conveyor was shut down. Although these detractors disagree regarding the nature of the trigger, they agree that a reorganization of ocean circulation was necessary to stabilize climate during the 1400-year-long Younger Dryas.

The Younger Dryas is unique to the termination of the last glacial cycle. Ice cores from Greenland and Antarctica show that during the Younger Dryas, the atmosphere's methane content dropped from 680 to 460 parts per billion (*18*). The core from Greenland does not extend to previous terminations, but that from Antarctica records three earlier ones. None of these shows a Younger Dryas–like methane drop (*19*). Hence, the Younger Dryas was likely triggered by a freak event rather than by something common to each glacial termination. The sudden release of a large amount of stored fresh water qualifies as a freak event, because its occurrence depends on the detailed geometry of the retreating ice front.

Despite the flies in the flood ointment described above, my money remains on a flood of water stored in Lake Aggasiz. Otherwise, the confluence of dates for the cessation of the Big Stone Moraine overflow, the Moorhead lowstand, and the rise in $\delta^{18}$O in the Gulf of Mexico would have to be attributed to coincidence. But our inability to identify the path taken by the flood is disconcerting. Given that the Younger Dryas holds the key to understanding abrupt climate change, further detailed studies of key areas must be conducted. Of critical importance is precise radiocarbon dating.

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ASTRONOMY

# The Vacuum Energy Crisis

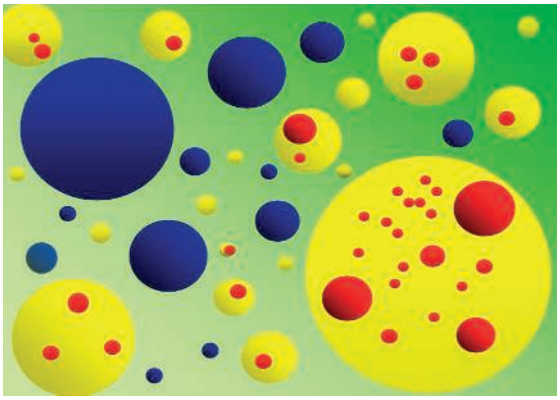
Even empty space has energy, but understanding its magnitude is a major puzzle. A cyclic series of big bangs has been proposed as a solution; anthropic selection offers another explanation

**Alexander Vilenkin**

One of the stranger consequences of quantum mechanics is that even empty space has energy. The problem of how to calculate this vacuum energy is arguably the most intriguing mystery in theoretical physics. For decades, physicists have tried to understand why this energy is so small, but no definitive solution has yet been found. On page 1180 of this issue, Steinhardt and Turok propose a new approach (*1*).

Vacuum is empty space, but it is far from being "nothing." It is a complicated physical object in which particles such as electrons, positrons, and photons are being incessantly produced and destroyed by quantum fluctuations. Such virtual particles exist only for a fleeting moment, but their energies combine to endow each cubic centimeter of space with a nonzero energy. This vacuum energy density does not change in time; it is called the cosmological constant and is usually denoted by Λ. The trouble is that theoretical calculations of Λ give ridiculously large numbers, 120 orders of magnitude greater than what is observed. According to Einstein's theory of general relativity, vacuum energy produces a repulsive gravitational force, and if the energy were so large, its gravity would have instantly blown the universe apart.

It is conceivable that positive vacuum energy contributions from some particle species are compensated by negative contributions from other species, so that the net result is close to zero. But then the compensation must be amazingly precise, up to 120 decimal places. There seems to be no good reason for such a miraculous cancellation. Until recently, the majority of physicists believed that something so small could only be zero: some hidden symmetry should force the exact cancellation of all contributions to the cosmological constant. However, observations in the late 1990s of distant supernova explosions yielded the surprising discovery that the expansion of the universe accelerates with time (*2*, *3*)—a telltale sign of cosmic repulsion caused by a nonzero (positive) cosmological constant.



**The inflationary multiverse.** Bubbles with different properties nucleate and expand in the inflating high-energy background. We live in one of the bubbles and can observe only a tiny part of it.

The observed magnitude of Λ has brought about another mystery: its value is roughly twice the average energy density (or, equivalently, the mass density) of matter in the universe. This is surprising because the matter and vacuum densities behave very differently with cosmic expansion. The vacuum density remains constant, whereas the matter density decreases; it was much greater in the past and will be much smaller in the future. Why, then, do we happen to live during the very special epoch when the two densities are so close to one another? This has become known as the cosmic coincidence problem.

Both puzzles can be resolved if one is prepared to assume that the cosmological constant is not a fixed number, but takes a wide variety of values in remote parts of the universe. In regions where it is much larger than the observed value, its repulsive gravity will be stronger and will prevent matter from clumping into galaxies and stars (*4*, *5*). Life is not likely to evolve in such regions.

The idea of "anthropic selection"—that certain features of the universe are selected by the requirement that observers should be there to detect them (*6*)—runs contrary to the physicist's aspiration to derive all constants of nature from first principles. It has been passionately resisted by the physics community, but has recently gained support from both string theory and cosmology. String theory, the most promising candidate for the fundamental theory of nature, predicts a multitude of vacuum states characterized by different values of Λ and other "constants." Inflationary cosmology, which now has substantial observational support, suggests that the universe on the largest scales is in a state of high-energy exponential expansion and is constantly spawning low-energy "bubbles" like the one we live in, with all possible values of the "constants" (see the figure). Galaxies and observers exist only in rare bubbles where Λ is small and other constants are also appropriately selected. Analysis shows that most of the galaxies are formed in regions where vacuum and matter densities are about the same at the epoch of galaxy formation (*7*–*9*). Our present time is close to that epoch, and this explains the coincidence (*10*, *11*).

Steinhardt and Turok propose an alternate explanation for the smallness of Λ. Building on an idea of Abbott (*12*), they postulate the existence of a long sequence of vacuum states, with Λ changing in small increments from one state to the next. If the universe starts with a large cosmological constant, its value will be gradually reduced through a sequence of quantum transitions to lower and lower values. Abbott showed that as Λ approaches zero, the transitions become increasingly slow, so the universe spends most of the time in the state with the smallest positive Λ. He found, however, that the descent to small values of Λ takes so long that

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