Science AAAS

When Still Waters Ran Deep

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Science **329**, 290 (2010);
DOI: 10.1126/science.1192295

OCEAN SCIENCE

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Near the end of the last ice age, the Pacific appears to have played a bigger role in forming deep ocean waters than it does today.

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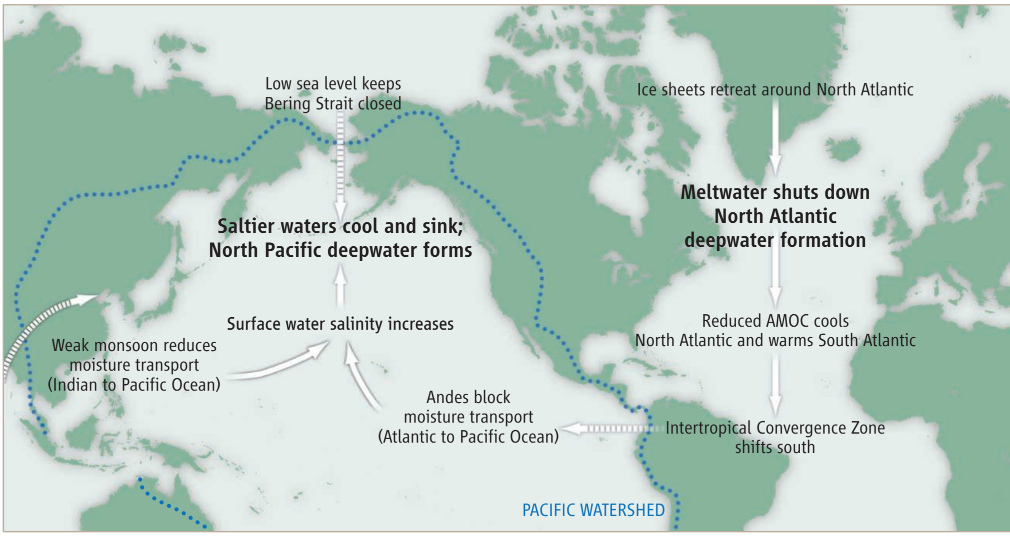

Deep history. During Heinrich event 1, a major glacial melting period terminating the last ice age, a set of atmospheric and oceanic changes appear to have enabled the formation of deep water in the North Pacific.

"Deep water" and "bottom water"—the waters that fill the deep parts of ocean basins—form when surface waters become dense and sink. Today, this occurs in the northern North Atlantic and around Antarctica, but not in the North Pacific. There, surface waters do not become dense enough to sink more than a few hundred meters. In the past, however, it seems things were different. Recently, Okazaki *et al.* offered new insight into the ancient history of the ocean from radiocarbon data and modeling analyses (*1*). They suggest that deep water formed in the North Pacific at the beginning of the transition out of the last ice age.

In the North Atlantic, winter cooling causes salt-rich surface waters to gain density and sink. Around Antarctica, the formation of sea ice causes surface waters to become saltier and denser. Neither of these processes, however, works effectively in today's North Pacific. There, Warren concluded that surface waters, relative to the underlying layers, contain too little salt to sink, even if cooled (*2*). Generally, the Pacific is much less salty than the Atlantic. A number of processes help to maintain this salinity difference. For instance, a large quantity of atmospheric moisture (about equivalent to the discharge of the Amazon) crosses the Central American Isthmus to the Pacific. A similar quantity of fresh water may come from monsoon precipitation originating in the Indian Ocean (*3*). On a regional scale, the exceptionally low surface salinity in the subpolar North Pacific is the result of greater precipitation than evaporation due to rain associated with the Pacific storm track and prevailing cool surface temperatures. The low salinity is further maintained by a zonal circulation pattern that minimizes the transfer of warm, salty subtropical waters. Emile-Geay *et al.* further concluded that the northern moisture flux of the Asian monsoon might transport substantial amounts of fresh water into the subpolar North Pacific (*4*). Together, these processes maintain robust stratification by salinity in the North Pacific and paralyze any potential vertical overturning. Very different conditions would be required to make the Pacific a place where water can sink to substantial depths. Yet the data presented by Okazaki *et al.* convincingly suggest that the conditions existed for such deepwater formation at the beginning of the last deglaciation.

Recovering the history of Pacific Meridional Overturning Circulation (MOC) is a tricky task because the preservation of calcium carbonate shells—the main source of the geochemical data used to reconstruct past environments—is particularly poor in the deep Pacific. Nonetheless, over the past two decades, paleoceanographers have produced a fair number of mostly geochemical records related to the northern Pacific MOC of the last deglaciation (*5*–*7*). The uncertainties were often too large, however, to safely infer a circulation history from single data sets.

Okazaki *et al.* bypass some of these difficulties by making three pragmatic strategic choices. First, as the crown witness for overturning circulation, the authors compare the radiocarbon (^{14}C) ages of the shells of seafloor (benthic) and sea surface (planktonic) organisms found in the same samples of seafloor sediments (*8*). If the ages converge, the researchers assume the benthic organisms grew in deep water formed nearby; if the benthic shells are much older, they assume the deep water formed far from the sampling location. Relative to other geochemical proxies for MOC, this benthic-planktonic ^{14}C difference is conservative (i.e., less sensitive to local conditions and postdepositional alteration in the sediment). Second, their database is a compilation of all previously published radiocarbon records from the North Pacific, which increases the robustness of the deepwater history and reveals the spatial structure of the reconstructed ocean circulation. Third, they recalculate the radiocarbon chronologies of sediment cores, but with no attempt to obtain submillennial precision. Such chronologies of Pacific sediments are usually based on shaky ground because the old Pacific waters provide large potential for spatial and temporal variability of the water masses' radiocarbon age relative to the atmosphere (*9*). The authors account for the age uncertainty simply by reflecting it quantitatively in their data set and accepting limitations on its interpretation.

Notably, the compiled and reprocessed data show that, from approximately 17,500 to 15,000 years ago, water masses near the sea floor in the northwestern Pacific (as deep as 2800 m) were, relatively, only a little older than the surface water and the atmosphere. This suggests a rejuvenation of the water masses at depth, most plausibly by deep sinking of surface waters.

This period coincides with a period of major meltwater input into the North Atlantic known as Heinrich event 1 (H1), which was fed by the early deglacial retreat of Northern Hemisphere ice sheets. During that time, data and simulations suggest that the formation of deep water, and hence ocean overturning in the North Atlantic, was greatly reduced. So it seems the North Pacific was the more active engine for MOC in the Northern Hemisphere

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Published by AAAS

during several millennia at the beginning of the transition out of the last ice age.

A simulation does provide support for a scenario in which a freshwater input into the North Atlantic results in deepwater formation in the North Pacific (see the figure). The fresh water reduces the Atlantic MOC, which results in sea surface cooling in the North Atlantic. The modified temperature gradient displaces the Intertropical Convergence Zone southward, in both the Atlantic and the Pacific. This retains more moisture in the Atlantic watershed east of the South American Cordillera, rather than exporting it into the tropical Pacific. The less diluted tropical Pacific surface waters become saltier and are advected by ocean currents into the subpolar North Pacific. There, winter cooling makes them dense enough to sink to depths of up to 3 km and to spread southward in a deep western boundary current. Once the sinking of surface water is established on a large scale, it initiates a positive feedback by being replenished by more subtropical waters. The continued advection of salt further increases the density of North Pacific subpolar waters. In addition, the associated sea surface warming in the northeastern Pacific increases local evaporation, further stabilizing the Pacific MOC.

Paleoclimatic data confirm that during H1, several favorable conditions coincided to allow North Pacific deep water to form. Seawater oxygen isotope reconstructions on both sides of the Central American Isthmus support the idea that the tropical Atlantic-Pacific freshwater export was reduced (*10*). In addition, the summer monsoon in southeastern Asia was weak during H1 (*11*, *12*), which may have reduced the moisture transport from the Indian Ocean into the Pacific catchment and the atmospheric transport of fresh water into the subpolar Pacific (see the figure). Finally, sea level was still low, so that the Bering Strait was closed (*13*), allowing the gradual buildup of salinity in the subpolar North Pacific.

The data, however, are not unambiguous. In particular, the timing of changes in Pacific circulation needs to be more tightly constrained before firmly inferring synchronicity with H1 and associated changes worldwide. Other challenges include confirming the increased Pacific MOC during H1 with other proxy records, finding out whether North Pacific deep water also formed during other meltwater events, and confirming the model result with alternate modeling approaches.

Regardless of the open questions, the study is an excellent example of the knowledge that can be extracted from data compilations and data-model comparisons. A fundamental insight is that the global ocean MOC has not always been bipolar, but varied among three "poles," including the Pacific. Modelers who compare their results with paleoceanographic MOC data (*14*) should divert some of their attention from the Atlantic to check whether they can get the Pacific right as well. More generally, climate scientists need to abandon their Atlantic-centric view and adopt the Pacific Ocean as an active player.

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10.1126/science.1192295

MEDICINE

Sickle Cell Disease at 100 Years

Effective strategies to treat sickle cell disease could involve manipulating the type of hemoglobin produced in patients.

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A 100th anniversary is often a cause for celebration. However, next week's First Global Congress on Sickle Cell Disease in Accra, Ghana, marking the centenary of the description of the disease (*1*), is a sober reminder that we have far to go to meet the global challenges posed by this disorder. Just over 60 years ago, sickle cell disease (SCD) was heralded as the first "molecular" disease (*2*), resulting from a single amino acid substitution in the β-globin chain of hemoglobin (HbA). Adult hemoglobin is a tetramer of two α-globin and two β-globin polypeptides ($\alpha_2\beta_2$). Despite extensive characterization of the properties of sickle hemoglobin (HbS, $\alpha_2\beta^S{}_2$) and red blood cells containing HbS, and 30 years of analysis of globin genes, consistently effective therapy for individuals with SCD remains elusive. The World Health Organization estimates that many of the more than 200,000 babies with SCD born annually in Africa will die before the age of 5 years from anemia and infection (*3*, *4*). In the United States, approximately 50,000 individuals are afflicted with SCD. The global need to develop uniformly effective and inexpensive therapy is enormous, and growing.

The tendency of HbS to polymerize at low oxygen tension leads to deformation of red blood cells into the characteristic sickle shape (*5*). These inflexible cells clog small blood vessels and cause intermittent occlusion, with ensuing tissue damage, pain, and anemia. Strokes, pulmonary infarction, and cardiovascular damage cause considerable morbidity. Therapy is mainly hydration, antibiotics, and blood transfusions, but in resource-poor countries, most patients receive little or no such care. Fifteen years ago, hydroxyurea was made available for treating SCD (*6*), reducing the incidence of pain in some cases, through largely unknown mechanisms. The sole "cure" for SCD is bone marrow transplantation, but it works best with matched donors. Proof-of-principle experiments in gene therapy and gene repair with induced pluripotent stem (iPS) cells (*7*) provide rationales for ongoing research into alternative curative strategies. Although prospects for gene therapy have improved with recent trials in patients with β-thalassemia (in which β-globin is inefficiently produced) (*8*), such a resource-intensive treatment is unlikely to succeed globally. Similarly, formidable hurdles in generating and expanding blood stem cells from human iPS cells prevent consideration of this regenerative medicine approach in the near future.

Although all individuals with SCD have the same mutation in the β-globin gene, disease severity varies widely. The concentra-

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