VOL. XVI, NO. 1, FEBRUARY 1971

OCEANUS

ON THE COVER—

Après midi d'un Rédacteur.

Apropos of nothing,

our cover represents an idle afternoon

spent on a lonely beach.

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COVER BY jl

Jan Hahn, *Editor*

OCEANUS™

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THE WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts

Columbus O'Donnell Iselin

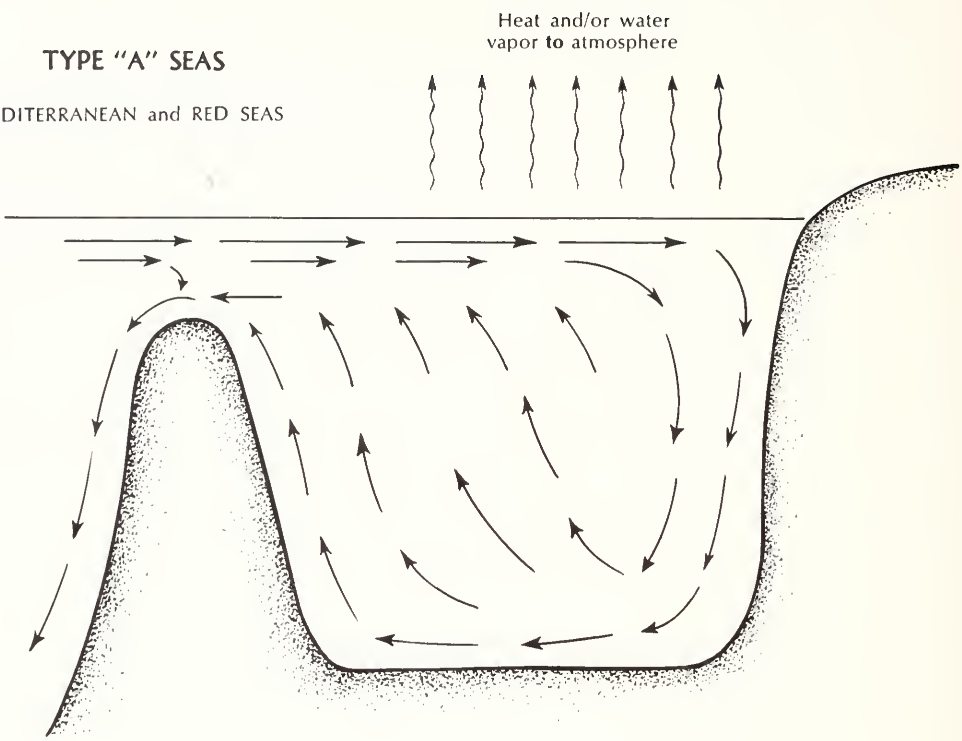
25 September 1904
5 January 1971

With a great sense of loss
we announce the death of one
of the last giants in oceanography

"An era has ended"

TYPE "A" SEAS

MEDITERRANEAN and RED SEAS



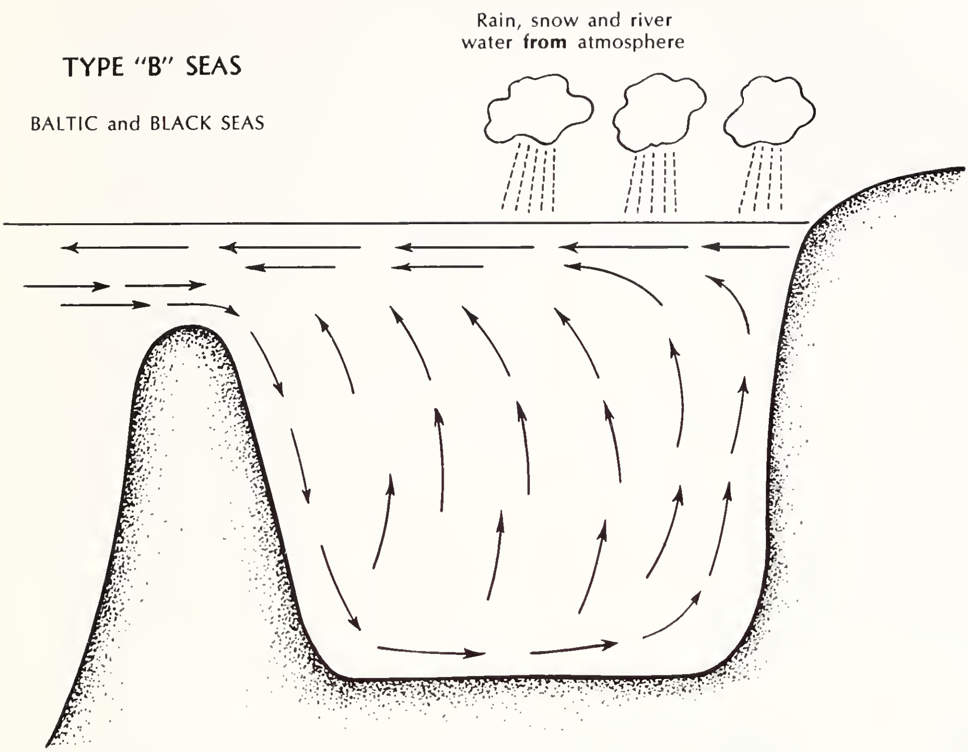
The Arctic Mediterranean Seas

"In the midst of lands"

The word "Mediterranean" generally brings forth romantic thoughts of the cradle of civilization — ancient Egypt, Greece, Carthage, Rome, Venice and the struggles with the Arabs, Turks, and Moors.

Oceanographers recognize other mediterraneans . . . the American Mediterranean (the Caribbean together with the Gulf of Mexico); the Red Sea; the Japan Sea; the Baltic and the Black Sea, although some consider the latter a part of the European Mediterranean.

In the following pages it is explained that the Norwegian Sea and the Arctic Sea also should be considered as mediterraneans.



by L. V. WORTHINGTON

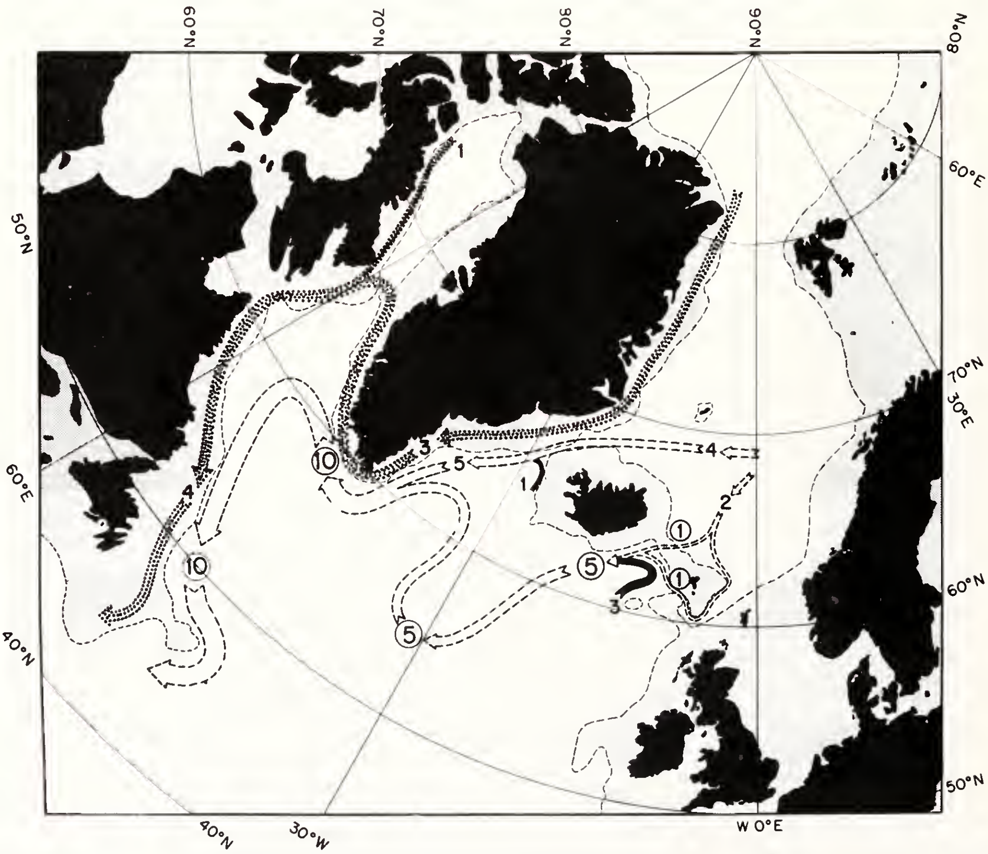
THE Mediterranean and Red Seas are well known examples of inland basins which have a narrow connection to the open ocean. In these seas the evaporation from the sea-surface is far greater than the addition of water from rainfall and the discharge of rivers. As a result the waters of these seas are much saltier and denser than those of the outside ocean. There is a second type of inland sea, best exemplified by the Baltic and Black Seas, in which the reverse is true; the discharge from rivers and precipitation greatly exceed the evaporation.

In both kinds of basins, dense water wants to flow downhill: in the first type of sea there is an outflow of dense water over the threshold or sill. This outflow must be replaced by a shallow inflow from the outside ocean. In the second type of seas there is a dense, salty inflow from the outside ocean and a fresh, shallow outflow. In type A seas the deep and bottom waters are formed within the sea by the action of the atmosphere, while in Type B seas they are obtained from the outside ocean. I believe that the Norwegian Sea can be considered properly as a mediterranean sea of Type A and the North Polar Sea (or Arctic Ocean) can be considered as a Type B.

The Norwegian Sea has all the characteristics of a Type A sea; it has deep, dense outflows and shallow, light inflows. It has unique bottom water formed locally. The reason why the Norwegian Sea has not generally been regarded as a mediterranean is that the deep overflows were generally ignored until 1955 when L. H. N. Cooper of the Marine Biological Association at Plymouth, England began to focus attention upon them. It was not until the 1960's that observers confirmed Cooper's hypotheses about the deep overflows with direct ocean current measurements. Also, oceanographers were accustomed to evaporative Type A seas which discharge saline water into their parent oceans. Mediterranean water can be traced from the Straits of Gibraltar clear across the Atlantic at some depths. The deep outflows from the Norwegian Sea are actually somewhat fresher than the Atlantic surface waters which flow in to replace them; they are denser by virtue of their excessive cold, which is caused by interaction with a frigid atmosphere in the winter.

Many oceanographers (twelve of us in fact)* have contributed to the overflow problem and some sort of consistency is beginning to appear from our efforts. I have drawn a schematic ocean current chart in which the amount of outflowing water transported is given in millions of cubic meters per second. To put this in perspective, the combined discharge, into the oceans, of all the world rivers amounts to slightly more than one of these units, or one million cubic meter per second.†

Three kinds of water are distinguished; the dotted lines represent the shallow discharge of cold, but fresh water and sea ice from the North Polar Sea. Of this, three units pass through the Norwegian Sea along the Greenland shelf and later, they are joined by an additional one unit which flows through the Canadian Archipelago. Together, these form the Labrador Current which transports four million cubic meters per second past Newfoundland. The dashed lines represent the new results, that is, the deep, dense overflows. There are two overflows between Iceland and Scotland which merge south of Iceland. In cascading over the sills they mix with and entrain three units of North Atlantic water. (The third type of flow, shown in solid black.) The resulting mixture, 5 units, flows southwest until it finds a gap in the Mid-Atlantic Ridge through which it passes into the Labrador Sea. Four units overflow between Greenland and Iceland picking up an additional unit of North Atlantic water.



*Including J. H. Steele, J. Crease, and J. C. Swallow of Great Britain; F. Hermann of Denmark; G. Dietrich of West Germany; J. R. Barrett and G. H. Volkmann of this Institution.

†The total water consumption of New York City, over a ten year average, amounts to only 50 meters per second!

The end result of all this is that 10 million cubic meters of cold, dense water are contributed every second to the deep North Atlantic; six million of these are pure Norwegian Sea water and four are entrained Atlantic water. The transport numbers which are circled indicate places where our estimates have been strengthened by direct current measurements.

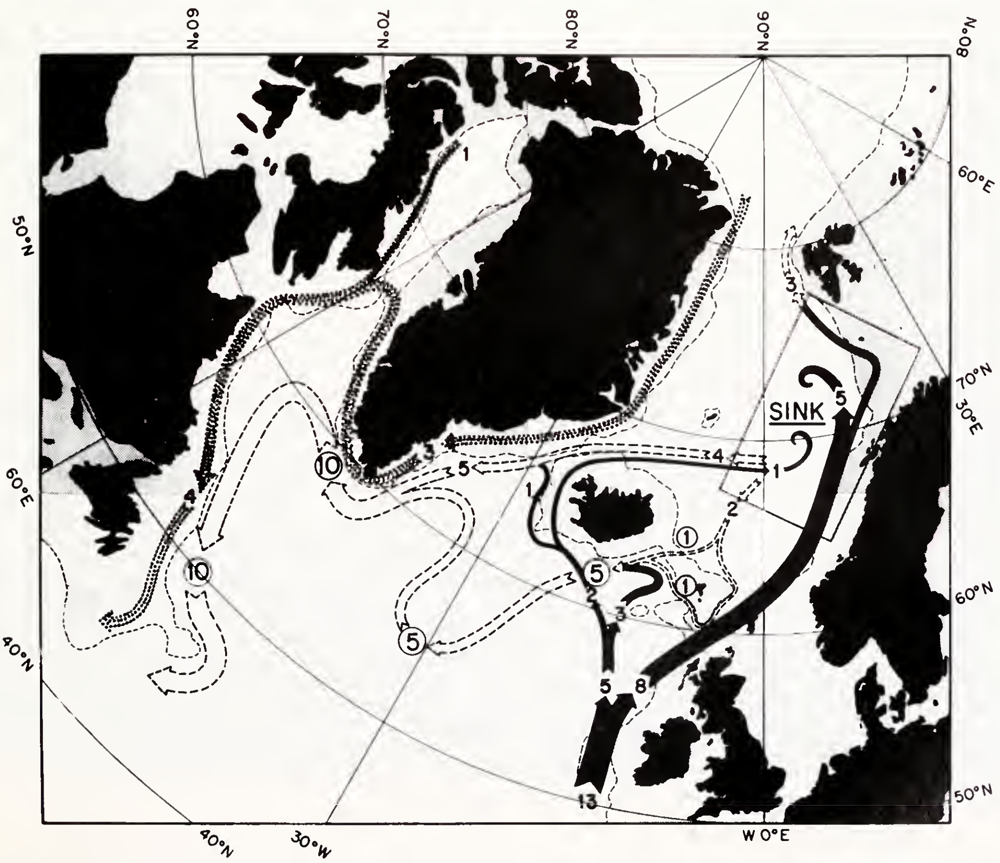
The important difference which these results bring out is that six million cubic meters per second, previously unaccounted for, flow out of the Norwegian Sea into the Atlantic, forming the greater part of its deep and bottom water. It follows that six million more must enter the Norwegian Sea in order to balance the books.

A new budget

A new Norwegian Sea water budget is shown on this page. It may look a little complicated at first but it is no more difficult than reading a financial statement in which only fourteen dollars are involved and no small change is used.

The outflowing water is the same as shown in the previous chart. The inflowing Atlantic water consists of eight units of warm, saline water entering to the North of Scotland and one unit north of Iceland. A careful auditor will remark that nine units are seen entering the Norwegian/North Polar Seas while ten units emerge from them. This discrepancy is balanced by an additional inflow of one unit from the Pacific Ocean through the Bering Strait.

Of the nine million cubic meters per second of inflowing Atlantic water six are converted into Norwegian Sea deep water, giving up their heat to the atmosphere in the heat sink illustrated. The remaining three enter the North Polar Sea west of Spitsbergen and submerge below the Polar Ice Cap. They return as the relatively fresh surface outflows which, with the addition of the Bering Strait inflow, form the Labrador Current. The North Polar Sea can thus be identified as a Type B Sea, like the Baltic. It gets its deep and bottom



Outflows from the Norwegian Sea are explained in the text of these pages. The numbers indicate the estimated volume transport in millions of cubic meters per second. The solid lines show the inflows and entrained Atlantic water, estimated at 13 million cubic meters per second which warms northern Europe.

MR. WORTHINGTON is a senior scientist in our department of Physical Oceanography. His interest in the northern circulation led him to land on Arctic Ice floes during Operation Ski-jump in the late 1940's.

water from an outside source (the Norwegian Sea), and precipitation, combined with the discharge from the great Siberian rivers greatly exceeds evaporation, resulting in a shallow, fresh discharge.

What the overflows have forced me to do is to raise the rate of inflow of warm Atlantic water into the Norwegian Sea from three to nine million cubic meters per second. Previously, only three million were supposed to enter, a number sufficient, when combined with the Bering Strait water to balance the outflowing Labrador Current. This three million was said to be a branch of the Gulf Stream System although its high salinity clearly brands it as eastern Atlantic water.

See also: "The Gulf Stream Problem" by L. V. Worthington. Oceanus, Vol. XI, No. 4. July 1965.

Northern Europe is warmed by a Mediterranean process.

Please do not think I am joking when I contend that it is this typical Type A mediterranean process which is responsible for the mild climate of northern Europe. There is no other mechanism which can draw so much warm surface water past the British Isles. While we have no direct evidence on this yet, it is probable that this northward flow is most active in winter when it is most needed. Paradoxically it is the frigid polar air which makes the system go. By extracting vast amounts of heat from the surface waters of the Norwegian Sea it makes them heavy enough to fill the deep basin and overflow the sills into the deep Atlantic. The surface water which is drawn in from the south to replace the overflow water provides 63 trillion calories per second with which to warm northern Europe.

WRIGHT

The chartered 'Erika Dan' in the harbor of Godthaab, Greenland.

Observations made in the northern North Atlantic do not reach the computer without a certain amount of misery. The white spots on this picture are snowflakes.

Oceanographers do have Fun

by JAN HAHN

BIRD banding undoubtedly has shown some record long distance flights, none of which can approach the record of an albatross which, straying from its native haunts, has flown several times across the North Atlantic and North Pacific at unprecedented heights.

Its latest flight, in September 1970, was from Tokyo, Japan to Boston, Mass., where, undoubtedly fatigued, the albatross accepted an automobile ride to Woods Hole. Accompanying the bird was our Dr. W. S. von Arx, who was appointed its Keeper for an unspecified period.

Although not being a zoologist, von Arx was appointed, or selected, or possibly forced, to be the keeper of the albatross at a ceremony of the American Miscellaneous Society (AMSOC) held at the Joint Oceanographic Assembly in Tokyo, September 1970. The bird (stuffed) is the Society's award for the most unusual contribution to oceanography, or more recently, the most obscure contribution to oceanography. Dr von Arx was honored for his invention of the GEK.* The citation stated: "All oceanographers will agree that the GEK has such unusual and obscure qualities that its inventor fully deserves recognition." The editor fully agrees and assumes that all oceanographers—especially those old enough to have been thrown out of their bunks during the 90° and 180° course changes attendant to GEK operations—will give a hearty cheer.

*Geomagnetic Electrokinetography, See: page 6, Oceanus, Vol. 1, 1952

The Albatross Award consists of a mature, black footed albatross *(Diomedea Immutabilis)* mounted on a bronze plaque and housed in a lightweight wood and wire cage. Originally having been found on a shelf in a backroom of the S.I.O. (Scripps Institution of Oceanography) the bird became a perpetual trophy in 1959 and is assigned occasionally by AMSOC to a worthwhile recipient who has to display the Award prominently and supposedly must take it everywhere with him: "North, south, east, west, to bed, and to the bathroom." In addition, the last recipient must deliver the trophy to the next assignee—not necessarily an easy task since the award ceremonies have been held from Tokyo to Helsinki and places in between.

Previous winners

For unusual contribution in oceanography:

"For conceiving the Award":

1959 Dr. John Knauss, Dean of Oceanography at the University of Rhode Island. Dr. A. E. Maxwell, Assistant Director at the Woods Hole Oceanographic Institution, and Dr. Gordon Lill, Office of Naval Research. Dr. Lill stated: "We wanted to enhance our reputation by inventing an award."

1959 "For something or another having to do with tidal friction": Dr. Walter Munk, Scripps Institution of Oceanography.

1960 "For current measurements, both AC and DC": Dr. John Swallow, National Institute of Oceanography.

1961 "For the development of political oceanography": Dr. Harrison Brown, California Institute of Technology.

1963 "For displacing the Pacific Ocean Floor 700 miles": Dr. Victor Vacquier, Scripps Institution of Oceanography.

1966 "For abandoning oceanography's most cherished Chairs": Professor Henry Stommel, Woods Hole Oceanographic Institution and M.I.T.

1968 "For the study of the oceans and other liquids": Mr. Sumner Pike, Director, Lubec Institute for the Marine Sciences.

Dr. von Arx with the Albatross Award and a sign having something to do with "Great Waters seen from Space".

Circa 1948 on the 'Atlantis', Dr. von Arx adjusts a tow fin for the GEK cable and electrodes.

The American Miscellaneous Society, founded in 1955, has, of course, no officers, no stated meetings, no roster, no dues, and as far as one can determine, no membership committee. Its motto is: Illigitimis non Carborundum. Some years ago AMSOC became widely known as the sponsor of "Project Mohole."

Frivolous as the Award may appear to be, it has been presented to recipients widely known for their accomplishments in oceanography. All of them seemed to have had identical problems in transporting the Albatross to and from the award ceremonies. Just about "seat size" in its cage, the bird is so lifelike that airline officials and stewardesses usually demur: "No animals except seeing eye dogs in passenger compartments." People keep asking if the bird is real and feel sorry for it being cooped up in its small cage. (It is not a large albatross, about the size of a happy seagull living on a good clamflat.) Customs officials sometimes are sticky, but more often wave the bird through, particularly since it is accompanied by a "TO WHOM IT MAY CONCERN" stating that the bird's guardian, *a priori*, can be assumed to be of the highest caliber and integrity.

Who will be the next recipient? The oceanographic world waits with bated breath.

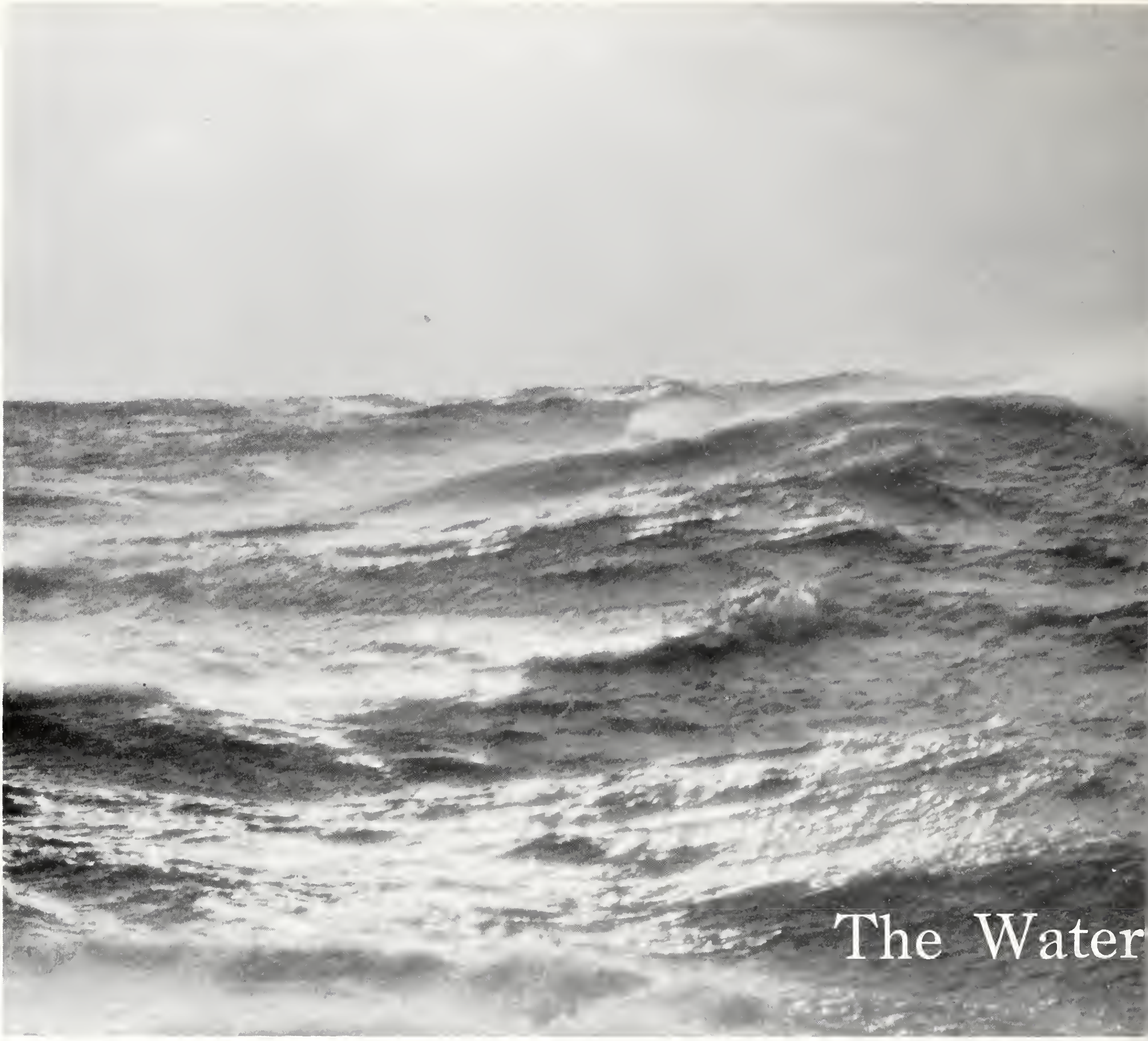
Two previous albatross award winners, Prof. H. Stommel (left) and Dr. A. E. Maxwell posed proudly on our dock in 1966. To try to have all three Woods Hole winners pose together turned out to be an impossible task—one of them always was off somewhere.

Associates' Day

The opening day of the 1970 America's Cup Races was attended by many of the Associates of this Institution and their guests. As the lower photo illustrates they are a hardy lot and their seamanlike apparel was well suited to the blistery, wet day.

The trip was made on our newest research vessel the 'Knorr' which provided adequate "below deck" shelter during the long run to and from Newport, R.I., a far cry from some of the earlier trips made on the 'Atlantis' when most of the guests had to stay on deck for the entire day.

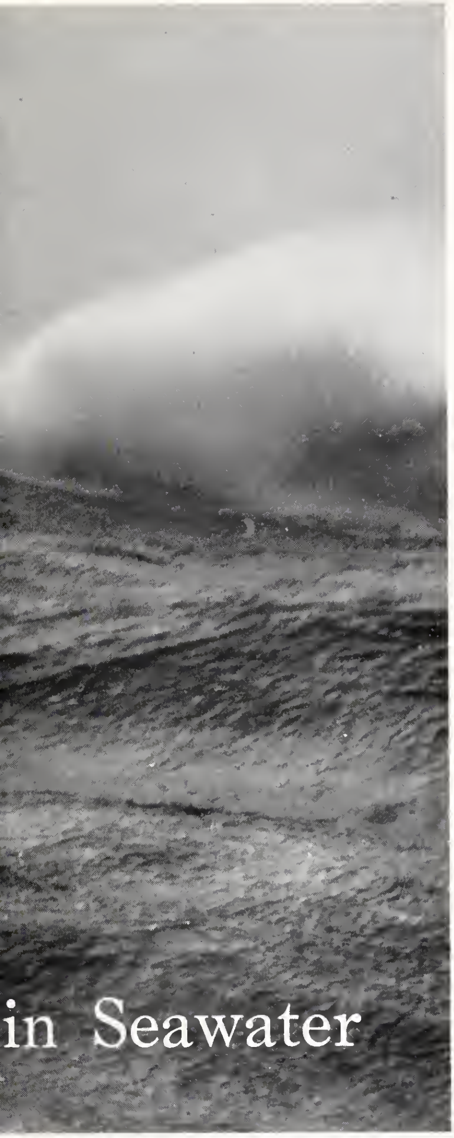
Start of the third race. 'Intrepid' (foreground) and 'Gretel II'. The Committee boat can be seen to the right in the distance behind the America's Cup buoy. Right under the blimp, between the contenders, is the replica schooner 'America'.


MUNNS

The Water

Hast thou perceived the breadth of the earth?
declare if thou knowest all—

—Job 38:18



by W. S. von ARX

THE concept of sea floor spreading appears to have explained away so many geological and geophysical questions that it seems interesting to ask whether or not it also explains the origin of the water in the world ocean? A calculation based on premises other than those used by H. Hess (1962) suggests that it does.

The JOIDES drilling program indicates that the oldest sediments on the ocean floor are of early Mesozoic age; roughly 200 million years old. Granting that the earth's core, mantle, and crust have existed for something like 4,000 million years and that sea floor spreading has continued at its present rate since that time, it follows that the sea floor has been renewed some 20 times in the earth's history. [In order for the sea floor to have been renewed some 20 times in the past 4,000 million years it would be necessary for each branch of the spreading to move at a rate which would span half the earth's circumference (20,000 km) in 200 million year; or at the rate of some 10 centimeters/year, which seems about right.]

Next, take account of the fact that the present world ocean has a volume which is almost equal to the volume of the marine crust; viz. the ocean has an average depth of a bit less than 4 km, the marine crust has an average thickness of about 5 km, and both their areas, even in the time of the primordial continent, can be assumed to have remained the same.

Were each volume of fresh rock to consist of 4 or 5 percent new water, and this to be released with each of the 20 replacements of the marine crust, the volume of water in the modern ocean would have been provided, little by little, from the earth's interior.

A yield of juvenile water amounting to some 4 or 5 percent seems possible judging from the laboratory work of Goranson (1931) who measured the water released from crystallizing basic rocks to be as high as 8 percent and the more recent work of Burnham and Jahns (1958) which suggests about half that yield. But either result provides a water volume interestingly close to that required to fill the ocean basins to their present level.

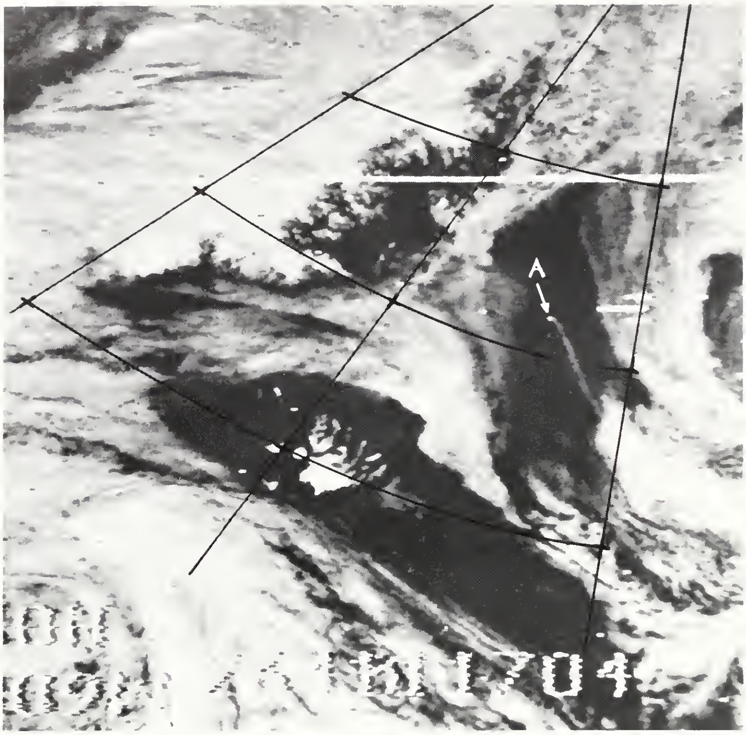
References:

Goranson, R. W., 1931, Am. J. Sci., 5, 22:481-502

Burnham, C. W. and R. H. Jahns, 1958, Bull. Geol. Soc. Am., 69:1544-1545.

Hess, H. H., 1962, Geol. Soc. Am., Petrological studies: A volume in honor of A. F. Buddington, Engel et al. Eds., p. 599.

ESSA (NOAA)



This satellite image, from ESSA 8, records temperature differences, clearly showing the cold ice cap of Beerenberg and the 400 km long vapor trail from the volcanic eruption, running in a SE direction.

What looks like a "handprint" at bottom center represents the highly reflective ice caps of Iceland.

The 2277 m. high volcano Beerenberg on the Norwegian island of Jan Mayen. Airphotograph from abt. 3000 m. by B. Luncke.
Copyright Norsk Polarinstitutt.

Of Volcanoes — Satellites — Whales — Jealousy and Cold Feet

The eruption of a long dormant volcano on the Arctic Island Jan Mayen provides some historical reflections.

by JAN HAHN

SCANNING through a German periodical "Umschau in Wissenschaft und Technik" recently, we noticed their "Photo of the Week," reproduced here, with the notation: "Since early Sunday morning, 20 September 1970, airplanes have observed activity of the volcano Beerenberg on Jan Mayen. The airplane observations showed that stones were thrown 5,000 to 6,000 meters high and that the volcanic cloud reached up to 11,000 meters. The next day, the weather satellite ESSA-8 showed a smoke plume 400 kilometers long running NW-SE in the prevailing tropospheric air currents."

Since "Oceanus" scooped most, if not all, of the U.S. press by its publication of the birth of "Surtsey"* and I had not seen any other notice of this volcanic outbreak, this seemed a good item for our readers, particularly so since I had long been intrigued by the shape of Beerenberg as illustrated in works of the early 17th century Arctic whale fishery.

*See: "A New Volcanic Island." by D. Blanchard, Oceanus, Vol. X, No. 4, June 1964.

Today, it is simple to find out additional information about a sudden outbreak of natural interest. One looks at the postcards sent out almost daily by the Smithsonian Institution's Center for Short-Lived Phenomena. Located in Cambridge, Mass., the Center was set up after the Surtsey eruptions to inform scientists of a sudden occurrence anywhere in the world (including oil spills) which someone may wish to investigate as quickly as possible. Indeed, the Center had sent out seven cards, labelled: "Event 89-70, Beerenberg Volcanic Eruption." The first card was dated 30 September 1970. No. 1022, and the last one, 23 October 1970, No. 1035.

Eruption site

The eruption of Beerenberg appeared to have been noticed first by commercial airplanes flying the polar route between the Far East and Europe. Within a day or so, Norwegian and Icelandic geologists started to make air, sea, and land observations. They found that the eruption took place on the northeastern slope of the 2,277 meter high Beerenberg (Bear Mountain) along a fissure about 6 km long and reaching from 40 to 1,000 meters above sea level. Five craters along the fissure (three of which became inactive within one week), spewed out large amounts of basaltic lava which flowed eastward into the sea. The lava formed a new coastal platform, some 500 meters wide and 3.5 km long, sloping down to the seabottom which is about 50-100 meters deep in the area. Naturally, this heated the sea surface temperature which is normally about 1°C. Reports stated that 13°C was measured some seven miles offshore while, near the lava front, surface temperatures of 30°C (102.2°F) were obtained. Large numbers of seabirds were seen swimming in the hot water and one can almost hear their satisfied "Ahhhh's" as they lowered their feet into the unusual bathwater! No dead fish were observed.

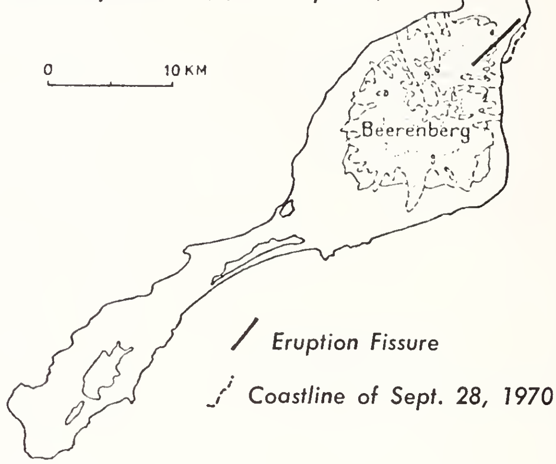
Difficult place

According to the Norsk Polarinstitut, the area of eruption is inaccessible without a ship. Landings are difficult and often dangerous with the swell breaking at the foot of the nearly vertical cliffs which have to be climbed to set foot ashore. Pack ice surrounds Jan Mayen during the wintertime. During the summer, fog is common and throughout the year gales and storms occur frequently. By late December 1970 the weather was so bad that it was not known if eruptions continued.

It is interesting to speculate if the eruption would have been noted from satellite observations if it had not been noticed from passing commercial airlines. On the day, after the eruption, September 21, an eagle-eyed operator of an amateur receiving station in Scotland noticed the long smoke plume by examining NIMBUS coverage taken from 1100 km above the earth.* Also, the U.S. Coast and Geodetic Survey reported an earthquake in the vicinity of Jan Mayen two days before the eruption. The quake had a magnitude of 5.1 on the Richter scale. (By comparison the destructive 1970 Peru earthquake had a magnitude of 7.7.)

**Jules D. Friedman, written communication, 1970.

Jan Mayen Island, (after Gjelsvik)



Smoke and steam arising from the fracture zone reached the stratosphere. Lava entering the ocean heated the water to 30°C.

Based on a careful study of ESSA 8 satellite images, showing the extent and height of the volcanic dust and vapors, the British Meteorological Office concluded that the eruption on Beerenberg had begun by 9h GMT on the morning of 18 September and that the main event may have been at the time of the strongest earthquake, reported about five hours earlier that day. "It seems possible, owing to the spread of the dust cloud by the 21st, that there were further explosions which put out material into the stratosphere between that time (the 18th) and the morning of the 20th". Volcanic dust sunset colors and prolonged twilight were noticed in southern England on some of these days. (From: Smithsonian cards 1078-79, 4 January 1971).

Jan Mayen is a part of the Mid-Atlantic Ridge and started to form in the post-Pleistocene by extensive submarine basaltic lava flows. It is a small island, 54 km long and up to 16 km wide. Located at 71° 05′ North and 8° 15′ West it has an area of 350 km², so that the new lava addition of 3 km² is not an insignificant growth. In recent years the Island's geology has been studied extensively, particularly by British geologists. The new eruption undoubtedly will lead to further studies.*

Former eruptions

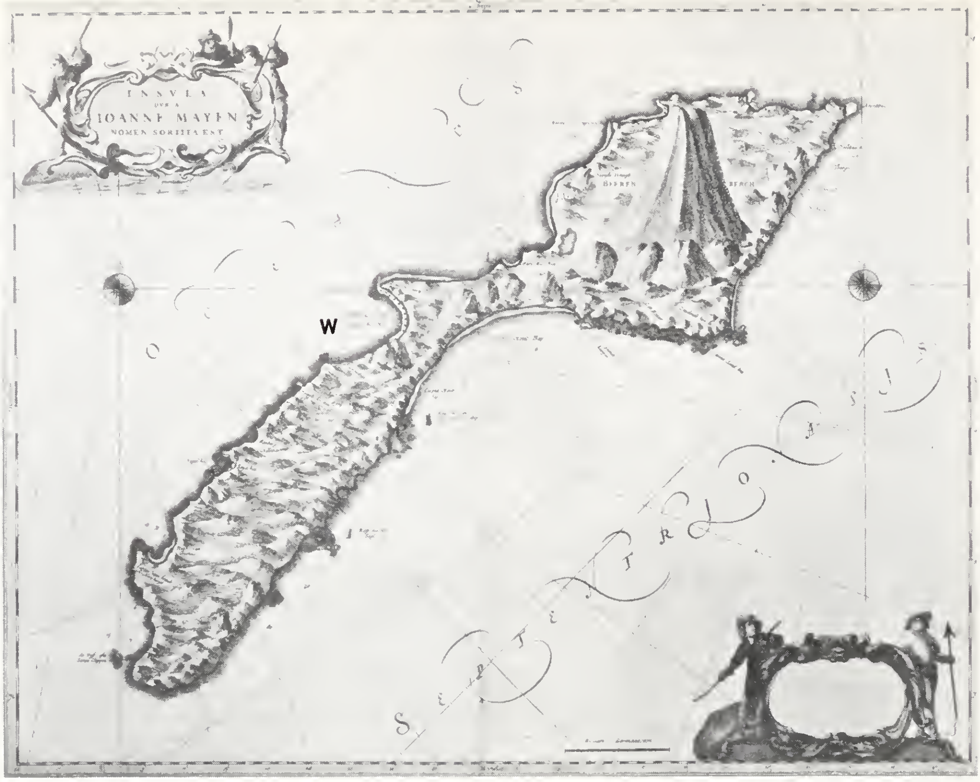
Remote and difficult of access, there is some uncertainty if former eruptions in historic times were noticed. In 1732, a whaling ship (Captain Jacob Jacobson Laad) reported an eruption with lava activity and ash falls. The famed William Scoresby in his "Accounts of the Arctic Regions" (1820), reported an ash eruption and smoke column 4,000 feet high, observed in 1818 on the north side of Esk Crater. For some reasons many geologists seem to doubt these observations, although there is increasing evidence of historical eruptions, always from fissures at the base of Beerenberg.**

*Tore Gjelsvik, Norsk Polarinstitut, Nature, Vol. 228, page 352, October 24, 1970.

**J. D. Friedman. Op. Cit.

Continued on page 20

Jan Mayen is situated on the most northern part of the Mid-Atlantic Ridge. The numbers indicate the age of the islands in millions of years.



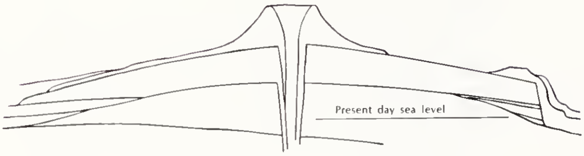
On the old charts and prints Beerenberg always appeared as an extremely steep cone. Above is a reduced version of a chart of Jan Mayen from Blaue's Great Atlas, Pars I, page 19. The Dutch whaling station was located at W.

"I beheld through the gap—thousands of feet overhead, as if suspended in the crystal sky—a cone of illuminated snow—There at last was the long-sought-for mountain actually tumbling down upon our heads." So wrote the Earl of Dufferin in 1856.

DUNKLE

Beerenberg, seen looking toward the north in 1956, shows a truncated cone, not in the least as pointed as the views in drawings from the 17th to the 19th century.

The diagrammatic cross section of Beerenberg is taken from F. J. Fitch in Proc. Geol. Assoc., Colchester, **75**, 133 (1964).



The whaling station of the Dutch Noordsche Compagnie in 1639. Occupied for about 15 years during the summer months, the houses (called tents) were occasionally plundered by foreign rivals. At left, below Beerenberg, a whale is being cut in, to be tried out in the cookeries shown at right. From a painting in the Rijksmuseum.

Something happened all right on 8 September 1633, when one of seven hapless Dutch seamen—who had volunteered to winter on Jan Mayen to protect the whaling station of the Noordsche Compagnie—wrote in his journal: "In the first quarter we heard a noise as if something had fallen down, yes it was so loud that our house shook, which frightened us terribly, not knowing what this could be, but we did not notice anything more ——." Undoubtedly this was an earthquake, but whether it was accompanied by an eruption is impossible to tell since the fissures at the base of Beerenberg would not have been in view of their camp. Poor Outger Jacobsz and his six companions. They held out until April 1634 when they died one by one of scurvy. The last notation was: "The 30 dito (April) the wind as before, clear sunshine that———." Here the pen must have fallen from the hand of the last survivor.

An imposing view

Lord Dufferin, an amusing chap, made a pleasure cruise to the Arctic in 1856 on his schooner 'Foam.'*

On the 14th of July 1856, he was stopped by ice in an attempt to land on Jan Mayen Island on the eastern side, south of the volcano, where Dr. Scoresby had landed. He stated: "It was easier to hear land than to see it."

Lord Dufferin's description of Beerenberg is interesting: "—and in a few minutes more the solid grey suddenly split asunder, and I beheld through the gap, thousands of feet overhead, as if suspended in the crystal sky, a cone of illuminated snow— in size, colour, and effect, it far surpassed anything I had anticipated. Imagine a spike of rock shooting straight up to the height of 6,870 feet, not broad-based like a pyramid, nor round-topped like a sugar loaf, but needle shaped, pointed like the spire of a church."

The shape of Beerenberg always has intrigued me. In the 17th century drawings, the mountain invariably is steep and ends in a point. Now, it is true that artists in those days were in the habit of stealing from one another and may not even have been on the scene but drew from descriptions given by seamen who are not adverse to "fish stories."

*Lord Dufferin. "Letters from High Latitudes," London 1857.

Shape of cone

Yet, a drawing made by Lord Dufferin in 1856 shows a cone identical to that of the 17th century drawings. A modern aerial photograph and two photographs made in 1956 by W. H. Dunkle, Jr. of our staff show a truncated cone, which also appears in a drawing of the British geologist F. J. Fitch. As stated, there is increasing evidence that historical outbreaks have been eruptions from fissures at the base of Beerenberg.* It seems unlikely that a summit eruption took place unobserved and changed the shape of the cone during the nearly 100 years between 1856 and the erection of a Norwegian meteorological station in the 1930's.

Is the mere fact that due to fogs and bad weather Beerenberg usually is seen only close up and for brief periods, responsible for the artist's perceptions? Looking up from a small ship to a height of 2,277 meters must be impressive. Lord Dufferin thought so: "You can imagine my delight. It was really that of an anchorite catching a glimpse of the seventh heaven. There at last was the long-sought-for mountain actually tumbling down upon our heads".

Discovery and jealousy

In the early 17th century Jan Mayen was always getting discovered and rediscovered, named and renamed. If you were educated in England, the island was sighted by Henry Hudson (then sailing under the British flag) in 1607 and was named Hudson Tutches (Touches?), while Thomas Marmaduke, a whaler from Hull claimed to have discovered the island about 1611 and named it Trinity Island. Other "discoverers" were Sir Hugh Willoughby and Basque whaler Jean Vrolicq, who named it Isle de Richelieu in 1612. Finally, there was a Robert Fotherby** who "stumbled upon the island in 1615" on the ship 'Matthew'.

*J. D. Friedman. Op. Cit.

Now, if you were brought up in Holland, you would know quite well that Jan Mayen† was discovered in 1614 by Jan Jz. May, Captain of 'de Goude Cath' who, in company with 'den Orangienboom' (Captain Jacob de Gouwenaer) was on a voyage to discover the northeast passage to India. As a matter of fact, all the early Dutch and English voyages in the Arctic were for the purpose of finding a way to the rich East that was not blocked or interdicted by the Portuguese. Unsuccessful in their search for a passage, the discovery of enormous numbers of whales around Jan Mayen and Spitsbergen led both countries—or rather their trading companies—to a tremendously rich fishery—to the first encounter for mastery of the sea between England and Holland, which was to last for over 150 years—and finally to the slaughter of so many whales that the fishery was abandoned.

Many whales

The high period of the fishery, started in 1612, was over by 1650, although whale ships continued to go out and make great catches until about 1790. During the initial period when the Right Whales (Balaena mysticetus and Eubalaena glacialis) were taken in large numbers, (as many as 1200 to 2000 during the short summer months), the Dutch had a shore station on Jan Mayen (as well as a much larger one on Spitsbergen) where wooden huts, a train cookery and a small fort were set up. Boats, harpoons and other equipment were left during the winter and sometimes demolished by competing English or Basque ships or Dunkerque pirates. This led to the plan to have people winter to protect the company's interests.

For over 100 years uninhabited Jan Mayen, visited only once in a great while by curious yachtsmen or seen by passing whalers, remained a spot on the map until it was annexed by Norway in 1929. It is rather amusing to realize that now, whenever there is no cloud cover, the island is seen several times a day by our satellites or by German and Japanese commercial airplanes.

†Although called Mauritius in honor of Prince Maurice of Nassau.

**An interesting manuscript with beautiful watercolors, attributed to Robert Fotherby, describes a whaling voyage made by seven ships including the 'Matthew' to Spitsbergen in the year 1613. Preserved in the collection of the American Antiquarian Society, Worcester, Mass., it is pretty hard reading. There is no mention of Jan Mayen. I spent three days learning how to read the handwriting and Elizabethan English and understand the abbreviation used, only to find afterwards that the MSS had been transcribed and printed about 100 years ago.

The volcano Beerenberg and the Dutch whaling methods were shown in an account of Capt. John Monck's voyages, printed in 1650. Monck (Munk) sailed in 1619 and 1620 to Hudson's Strait to find a passage to the Indies.

The old prints illustrating this article are in the author's collection.

"In some seas the wind comes from the bottom of the sea, stirring up the water. God knows how

The Flow of Deep Water in the Southern Hemisphere

st this cometh."

For once, theory preceded observation

in an oceanographic problem

by B. A. WARREN

In his entertaining and often informative geography book, "Meadows of Gold and Mines of Gems," produced in the year 947, the Arab scholar El Masudi relates many observations and ideas concerning the marine world. Some are surprisingly close to modern views, while others are best dismissed as whimsical fancies not founded on scrupulous observation, or good physics. In a discussion of air-sea interaction, for example, he remarks that, "In some seas the wind comes from the bottom of the sea, stirring up the water," and, in a later elaboration, he asserts: "Those winds which, as we have stated, come from the bottom of the sea, arise from the winds which blow from the land and penetrate into the sea, from whence they rise to the surface of the water. God knows best how this comes." El Masudi does well to refer to God for an explanation of this phenomenon, since no mere human observer is likely to provide documentation for it, and even an academic theoretician might be hard pressed to devise a dynamical model of so remarkable an occurrence.

We might be less inclined to smile, however, had El Masudi been speaking of the movement of water in the ocean, rather than of air, for it is well known today that cold water does sink from the sea surface in certain high-latitude areas, flows equatorward somehow at great depth, and rises slowly toward the surface again in middle and low latitudes. In El Masudi's time, of course, it was not realized that all deep water in the ocean is cold, whether in tropical or polar regions. Indeed, deep temperature observations in the open ocean were not made until the middle of the eighteenth century, the first ones apparently by Captain Henry Ellis, using a device which trapped a water sample at depth; this "bucket sea-gage" contained an ordinary thermometer which gave a reading of the temperature of the sample after it was brought aboard ship.

In a letter printed in the *Philosophical Transactions* of 1751, Ellis describes his use of the "Bucket sea-gage" on a voyage in the southeastern North Atlantic: "I charged it, and let it down to different depths, from 360 feet to 5346 feet; when I discovered, by a small thermometer of Fahrenheit's, made by Mr. Bird, which went down in it, that the cold increased regularly, in proportion to the depths, till it descended to 3900 feet: from whence the mercury in the thermometer came up at 53 degrees; and tho' I afterwards sunk it to the depth of 5346 feet, that is a mile and 66 feet, it came up no lower . . . I doubt not but that the water was a degree or two colder, when it entered the bucket, at the greatest depth, but in coming up had acquired some warmth . . ." In comparison with modern observations, it would appear that the water must have been more than 10°F colder "when it entered the bucket," rather than "a degree or two," but these measurements did indicate qualitatively the large reduction of temperature with depth.

Lowest temperatures

Other observations of better accuracy followed soon after, and natural philosophers realized how they should be interpreted. Alexander von Humboldt, for one, published the original German version of his "Cosmos: A Sketch of a Physical Description of the Universe" in 1845, and inferred, on the basis of fragmentary information: "This icy temperature of sea water, which is likewise manifested at the depths of tropical seas, first led to a study of the lower polar currents, which move from both poles toward the equator. Without these submarine currents, the tropical seas at those depths could only have a temperature equal to the local maximum of cold possessed by the falling particles of water at the radiating and cooled surface of the tropical sea."

To my knowledge, however, the first solid documentation of "the lower polar currents," the equatorward movement of deep water away from polar sinking regions, was given by Alexander Buchan in an appendix to the 'Challenger' Reports, published in 1895. He assembled all available deep temperature measurements (most of them made on the 'Challenger' Expedition of 1872-1876) on charts of the world ocean, and observed that "the lowest deep-sea temperatures are found in those parts of the ocean which lie in the Southern hemisphere, and that, on the whole, higher temperatures are encountered as we recede from the Antarctic region. It may also be pointed out that the lower deep-sea temperatures extend farther to the north from the Southern Ocean, just over those depths of the sea which appear to have, and probably do have, a direct communication with the south; that is, are not cut off by any intervening submarine ridge separating them from the cold waters of Antarctica. There can be no doubt that these very low deep-sea temperatures have their origin in the Southern or Antarctic Ocean, the icy cold waters of which are propagated northwards, the rate of propagation being so slight as to be regarded rather as a slow creep than as a distinctly recognizable movement of the water." Except for the discovery of an additional source of deep water in the North Atlantic, Buchan's description of deep flow is essentially what scientists used for the next sixty years.

DR. WARREN is an Associate Scientist in our Department of Physical Oceanography.

Different conception

A rather different conception arose in the late 1950's, however, when physical oceanographers began to probe deeply into the dynamics of the main thermocline. Through simple arguments, this thinking led to a radically new idea of just what pattern of deep flow was physically possible in the ocean. Some striking features of this theory have now been verified by observation, and it is the main purpose of this article to review that work and its import. This development provides an instructive example of how theory, laboratory experiment, and field observation can merge to yield significant new information about the ocean.

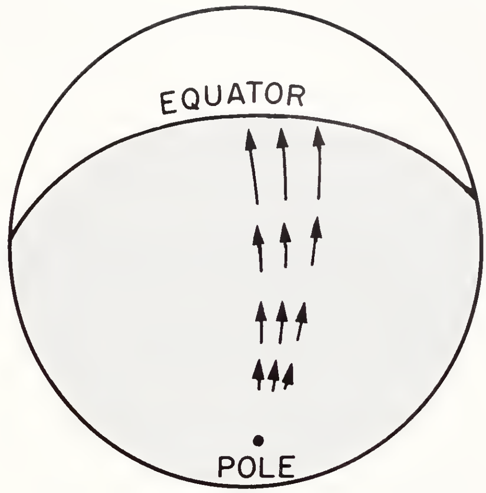
The main thermocline is a region of steep vertical temperature gradient in the upper kilometer of the tropical and subtropical ocean. Such a sharp decrease of temperature with depth implies a large downward diffusion of heat, which would tend to warm up the water below. Deep temperatures in the ocean are not increasing, however, but remain uniformly low, and it seemed likely that there existed an upward flux of cold deep water beneath the thermocline, to counteract the downward heat diffusion, and to keep the deep water cold. H. Stommel realized that an upward velocity of this sort had far-reaching implications with regard to the horizontal pattern of deep flow, and in 1960, in collaboration with A. B. Arons,* he published a schematic theory for the deep circulation of the world ocean.

The essential idea here was that the circulation in the deep sea was probably so slow, so steady, and of such broad scale that it should be truly geostrophic: the horizontal velocity should be directed parallel to the lines of constant pressure on a level surface, and its magnitude should be directly proportional to the gradient of pressure, while inversely proportional to the sine of the latitude. This is the condition of motion which is unaccelerated with reference to the rotating earth, and the latitude dependence results from the curvature of the earth's surface. If the condition holds, then a flow directed toward the equator would have to gain mass transport downstream because of the increase of velocity with decreasing latitude, while flow directed toward the poles would have to lose mass transport downstream. Conversely, if a deep layer of water does lose mass through a net upward flux of water into the thermocline, then the meridional component of velocity in it must be directed toward the pole.

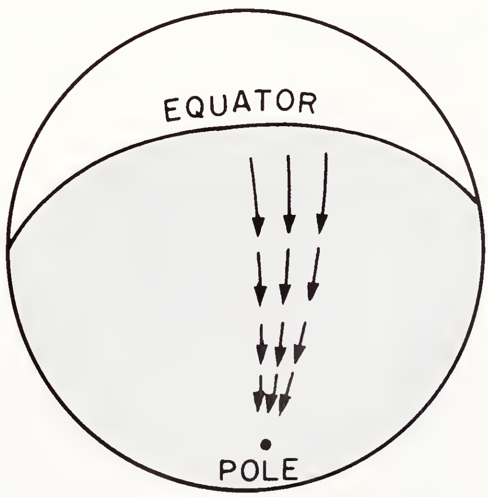
Narrow currents

The startling conclusion of this reasoning was that bottom water velocities in the southern hemisphere should be directed toward the Antarctic, even though the bottom water itself derived from the Antarctic. The only way to resolve this dilemma and to get deep Antarctic water

*Both are Associates in Physical Oceanography on our non-resident research staff and have long been connected with this Institution.



Flow directed toward the equator which is exactly geostrophic must gain mass transport downstream because the velocity increases with decreasing latitude.



Geostrophic flow which is directed toward the pole must lose mass transport, because the velocity decreases with increasing latitude.

into the tropical ocean, was to hypothesize deep northward-flowing currents sufficiently narrow and intense to escape the constraints of exact geostrophic balance; and these currents were required by the dynamics of rotating fluids to lie along the western boundaries of ocean basins, like the Gulf Stream at lesser depths. Such a picture contrasts markedly, of course, with Buchan's scheme of a slow, ocean-wide northward creep of deep water.

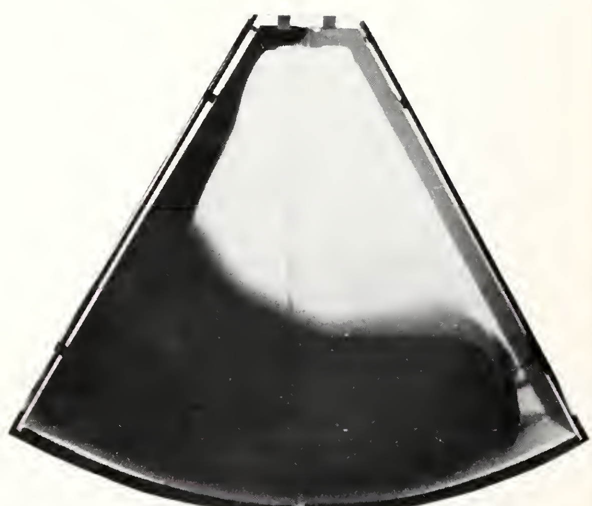
Model studies

We are accustomed by now to finding phenomena in rotating systems which are much at variance with our everyday experience, where effects of the earth's rotation are not noticeable, but sometimes the effects deduced are so astonishing that laboratory experiments are helpful to confirm the conclusions and assure the correctness of the reasoning. A. J. Faller* made a number of experiments of this sort bearing on large-scale steady flow patterns, and the figure illustrates three stages in an experiment designed to test the necessity of western boundary currents under the conditions just described. A wedge-shaped water container was mounted on a rotating table, and the effect of the earth's curvature (dependence of geostrophic velocity on latitude) was modeled dynamically by an increase in water depth from the apex to the outer rim of the container. The apex might be regarded here as analogous to the South Pole, and the outer rim, to the equator. Faller injected dyed water steadily at the apex and simulated an upward velocity at the "top" of the deep ocean simply by letting the free surface of the water rise steadily, in consequence of the inflow at the apex. The development of the dye pattern in time showed clearly that the "source" water flows directly from the apex to the outer rim in a narrow current along the left-hand edge of the container and that elsewhere the flow is indeed directed toward the apex, even though this is the source of the fluid. Because of the sense of rotation of the container, it is the left-hand edge which is analogous to western boundaries on the earth.

*See also: "Atmospheric Model Studies", by A. J. Faller. Oceanus. Vol. IX, No. 1. Sept. 1962.

10 minutes

20 minutes



40 minutes

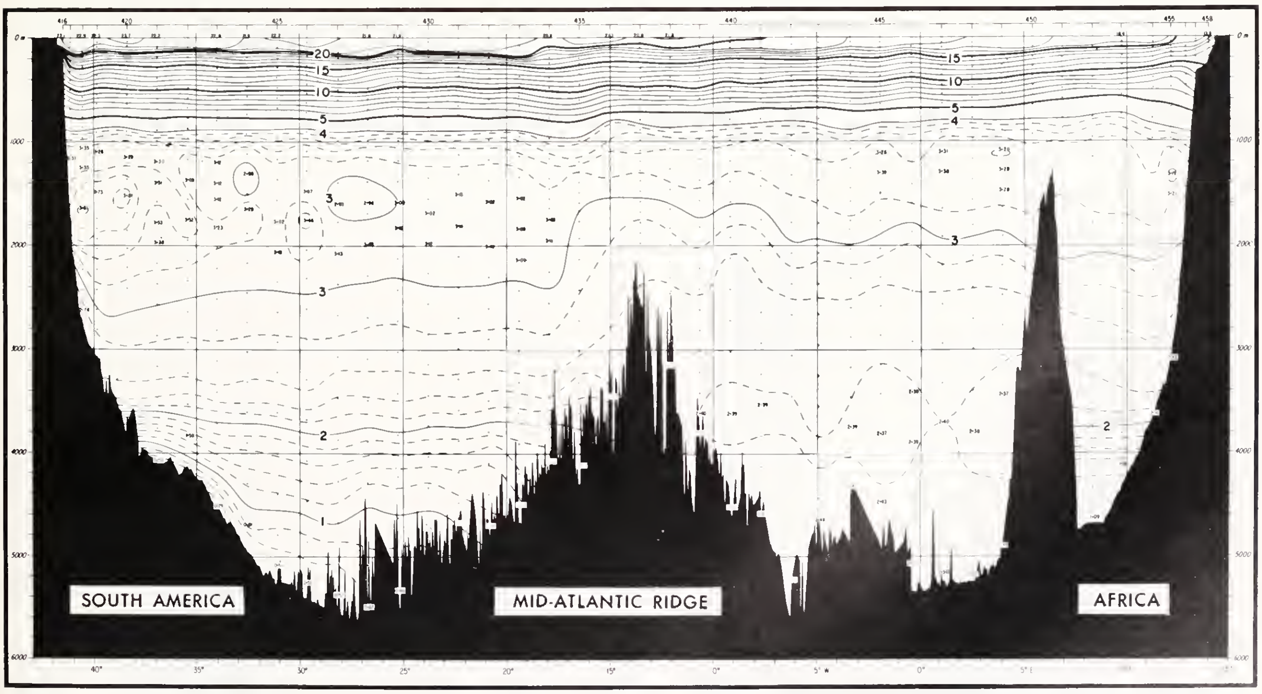
Flow in a rotating container where water enters at the apex So and then rises uniformly over the surface of the container. Dye was injected at the source (apex), and the pattern of flow is shown by the dye in the sequential photographs.

Although experiments like Faller's can verify so beautifully the internal consistency of a physical model, they cannot tell whether the assumptions (and therefore the conclusions) of the model are actually relevant to the ocean. The theory is so appealing in its scope and simplicity, however, that one feels that it really must have something to do with the real world, as well as the laboratory. We are thus prompted to find out whether the predicted deep boundary currents do indeed exist as the means by which deep Antarctic water is carried northward into the oceans of the southern hemisphere. As a matter of fact, at the time that Stommel and Arons were constructing their theory, indications of deep boundary currents in the South Atlantic had already been published, in the results of the 'Meteor' Expedition of 1925-27. Oceanographers do not seem to have appreciated their dynamical significance, perhaps because the western basin of the South Atlantic is not a great deal wider than the currents themselves. The figure for the South Atlantic shows a more recent temperature profile, taken across the ocean at Lat. 24°S; it was prepared by F. C. Fuglister from observations made on 'Crawford' Cruise 22, (W. G. Metcalf, Chief Scientist) during the I.G.Y. The coldest bottom water is pressed closely against the continental slope of South America, and at depths greater than 3500 m the isotherms near this western boundary — and only there — all slope downward to the east, consistent geostrophically with northward movement of the Antarctic Bottom Water below. Thus the flow from the south which supplies the very deep water in the South Atlantic actually does appear to be concentrated in a western boundary current.

Northern water

Here in the South Atlantic, there are peculiarities in the temperature field at

Profile of temperature (°C) across the South Atlantic along Latitude 24°S ('Crawford' Stations 416-458). Depths are in meters, station numbers are given at the top of the profile, and longitudes at the bottom. Dots indicate points of observation.



COURTESY OF F. C. FUGLISTER

shallower levels, which also are suggestive of a boundary-current structure. As remarked earlier, deep water is formed in the far North Atlantic as well as around Antarctica, and it is expected to flow southward in another western boundary current. The distortions of isotherms in the profile at depths of 1000-3000 m near South America reflect this current, lying above the deeper current from the Antarctic.

Pacific sections

Comparable observations were not made in the South Pacific until 1967, during Cruises 28 and 29 of the U.S.N.S. 'Eltanin.' The 'Eltanin' is owned by the Military Sea Transportation Service and is operated for the National Science Foundation as part of the U.S. Antarctic Research Program. Generally the 'Eltanin' undertakes regular 60-day cruises in the vicinity of Antarctica, but for the period March-August 1967 it was made available to a group of investigators from Scripps, M.I.T., University of Hawaii, and the Woods Hole Oceanographic Institution for the purpose of occupying two transpacific hydrographic sections. Our idea was to run sections at Lats. 28°S and 43°S, in the spirit of the transatlantic I.G.Y. sections,* with particular concentration of observations just east of New Zealand and the Kermadec Ridge to determine whether the hypothesized deep western boundary current existed in the South Pacific. (The effective western boundary for the deep South Pacific lies here, rather than along Australia, because the Tasman Sea is closed off to the north at depths greater than 3000 m.)

The work was successful, and we were delighted to find the predicted current. On the temperature profiles at both latitudes (Lat. 28°S is illustrated) the coldest deep water is concentrated toward the western boundary, as in the South Atlantic, and the deep isotherms near the boundary again slope downward to the east, indicating local northward flow. The Kermadec Trench seems to force a deformation of the isotherms just above it, but the mechanism is unclear.

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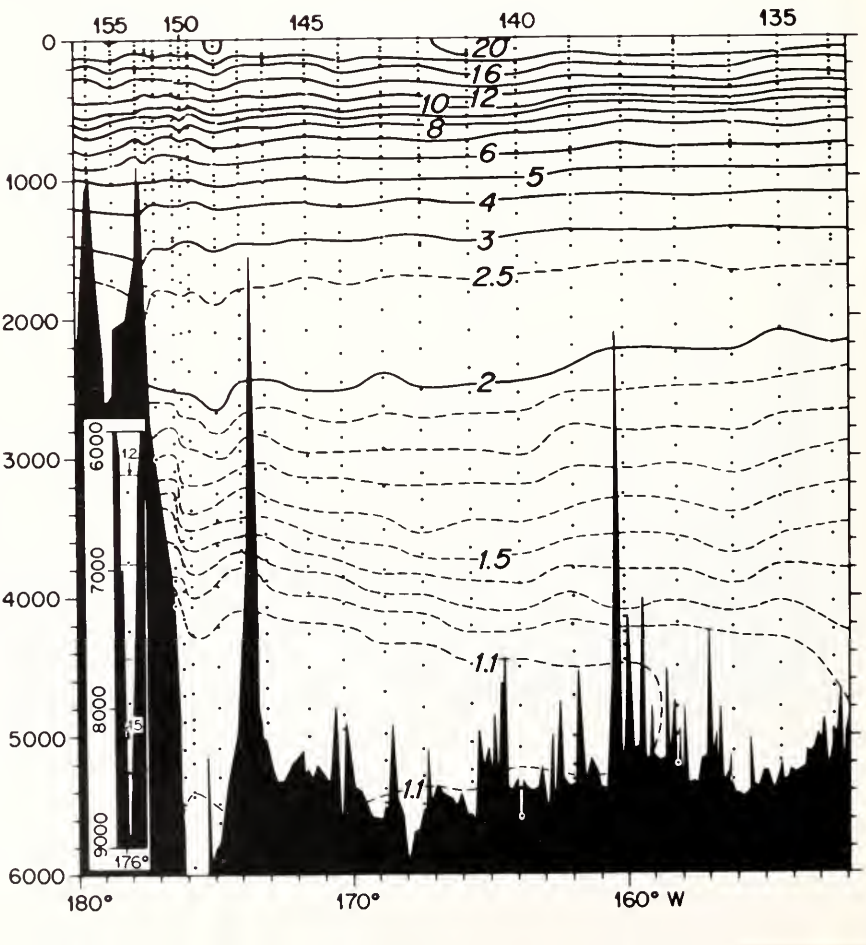
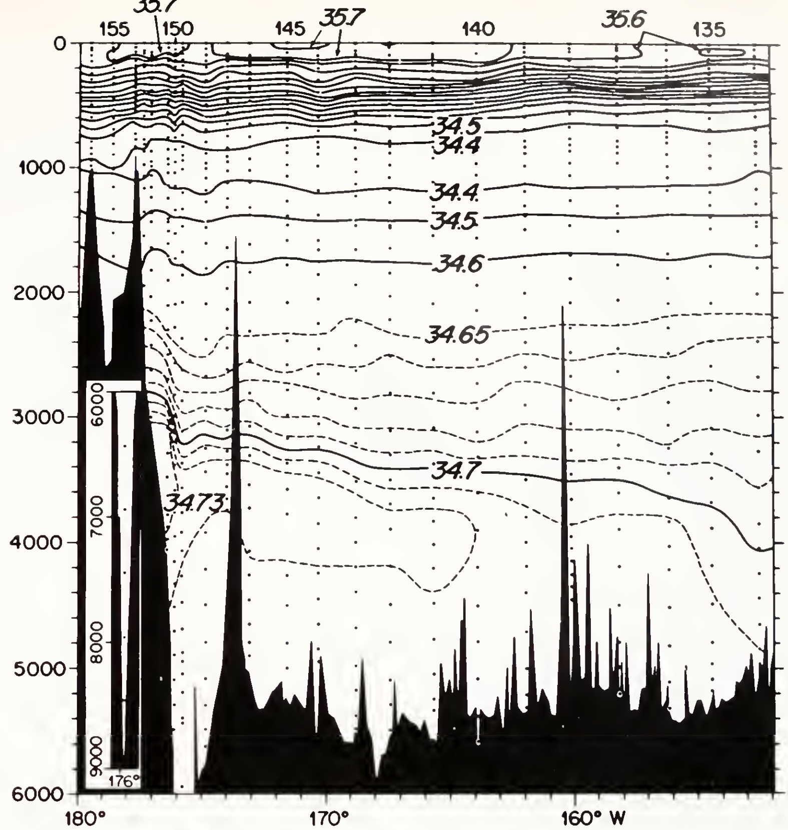
*See: I.G.Y. issue, Oceanus. Vol. V, Nos. 3 & 4, 1957.



Profile of temperature (°C) along Latitude 28°S in the vicinity of the western boundary of the deep South Pacific (Scorpio Stations 134-156, made from 'Eltanin'.) The Kermadec Ridge is on the left side of the profile, the foot of the East Pacific Rise on the right, and the Kermadec Trench is continued in the inset. (Reprinted from "Scientific Exploration of the South Pacific," National Academy of Sciences.)



Profile of salinity in parts per thousand along Latitude 28°S in the vicinity of the western boundary of the deep South Pacific. Compare this with the corresponding temperature profile at left. For details see description below.

Further evidence for the current is provided on the corresponding salinity profile, by a deep layer of relatively saline water (3000-4000 m) which is also concentrated toward the Kermadec Ridge. The deep water which is formed in the North Atlantic is high in salinity as compared with deep water in the rest of the world ocean; it flows southward through the Atlantic to the Antarctic, where it is caught up in the Circumpolar Current and transported eastward around Antarctica, and can thus enter the other oceans. The deep salinity maximum which we see in the South Pacific profile represents the very last traces of this water from the North Atlantic, here being carried northward into the Pacific by the deep western boundary current.

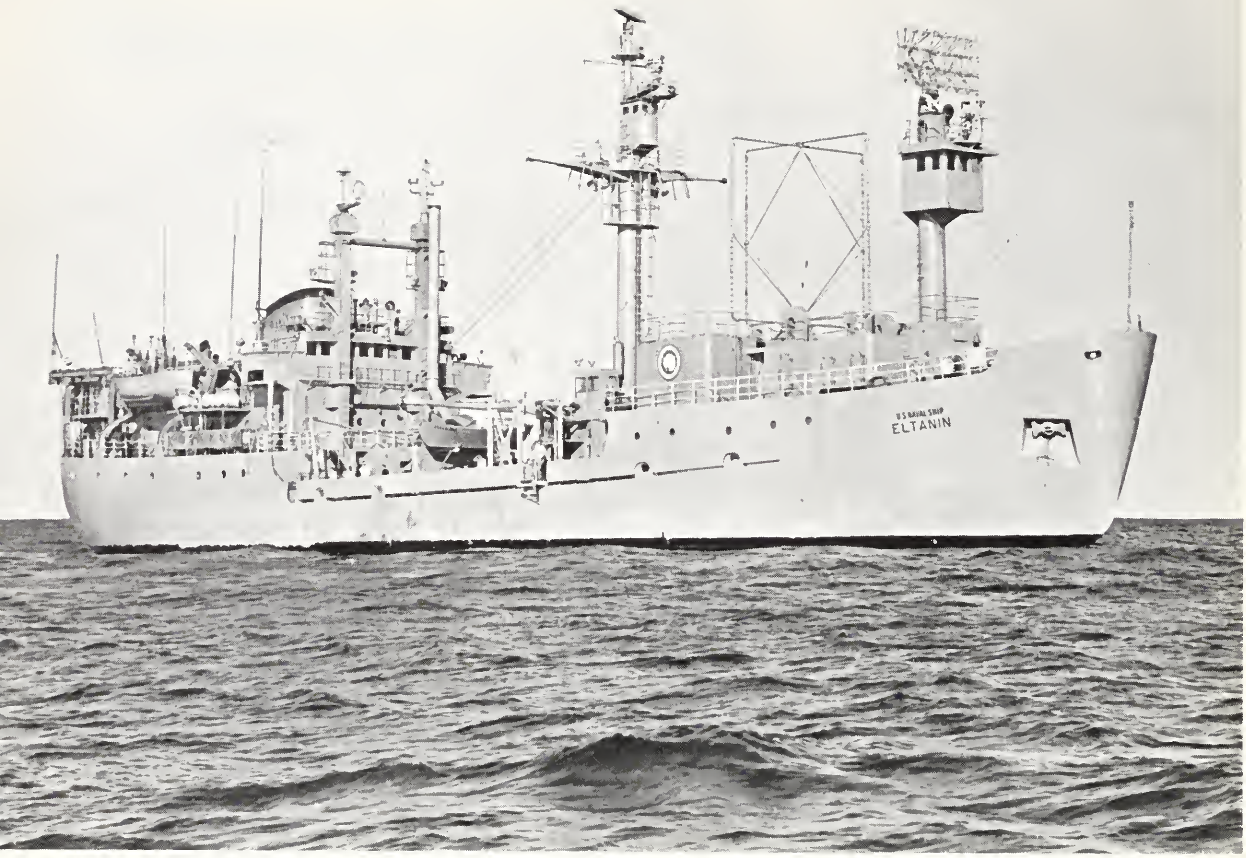
Direct measurements

The 'Eltanin' was again made available to a Woods Hole group during Cruise 40, September-November 1969, for additional investigations of the deep current. At this time we were able to improve our mapping of the current by making three more hydrographic sections across it, and, most important, we made velocity measurements by tracking neutrally buoyant floats set out in a line across the current along Lat. 22°S. These latter measurements provided direct confirmation of the northward flow inferred from the temperature and salinity distributions, and indicated that the "top" of the deep current lay at depths of 3000-3500 m.

Indian Ocean

With completion of the investigations in the South Pacific, the only part of the southern hemisphere which remained unexamined for a deep current was the South Indian Ocean. We had an opportunity to make critical hydrographic stations there during Leg 5 of 'Chain' Cruise 99, in July 1970. While the 'Chain' was enroute from Lourenco Marques to Mombasa we occupied hydrographic sections along Lats. 23°S and 12°S, between Madagascar and, approximately, Long. 67°E.

Reminiscent of the South Pacific, the effective western boundary for the deep South Indian Ocean does not lie along Africa in these latitudes but along the eastern side of Madagascar, because Mozambique Channel is shallower than about 3000 m. On the preliminary temperature profile for Lat. 12°S, we see the by now familiar feature that the coldest bottom water is pressed up against the lower western boundary (here, Madagascar).



P. HARPER

U.S.N.S. 'Eltanin', operated for the National Science Foundation as part of the U.S. Antarctic program. The ship usually makes 60 day cruises in Antarctic waters.

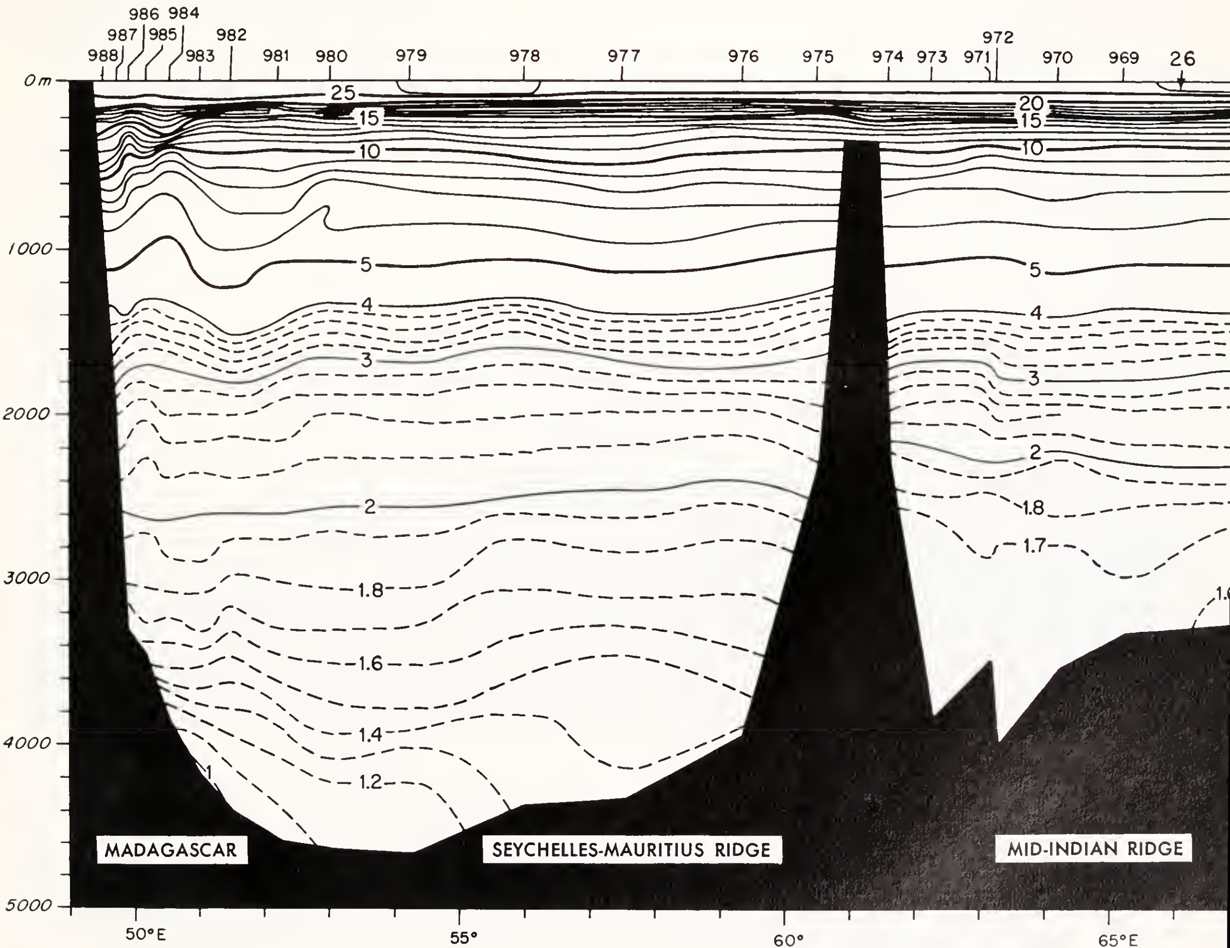
Above the cold core, up to a depth of about 3000 m, the deep isotherms also slope downward to the east, as in the South Atlantic and Pacific. Thus the northward flow of deep water from the Antarctic (deeper, say, than 3000 m) again seems to be concentrated against the western boundary of the ocean.

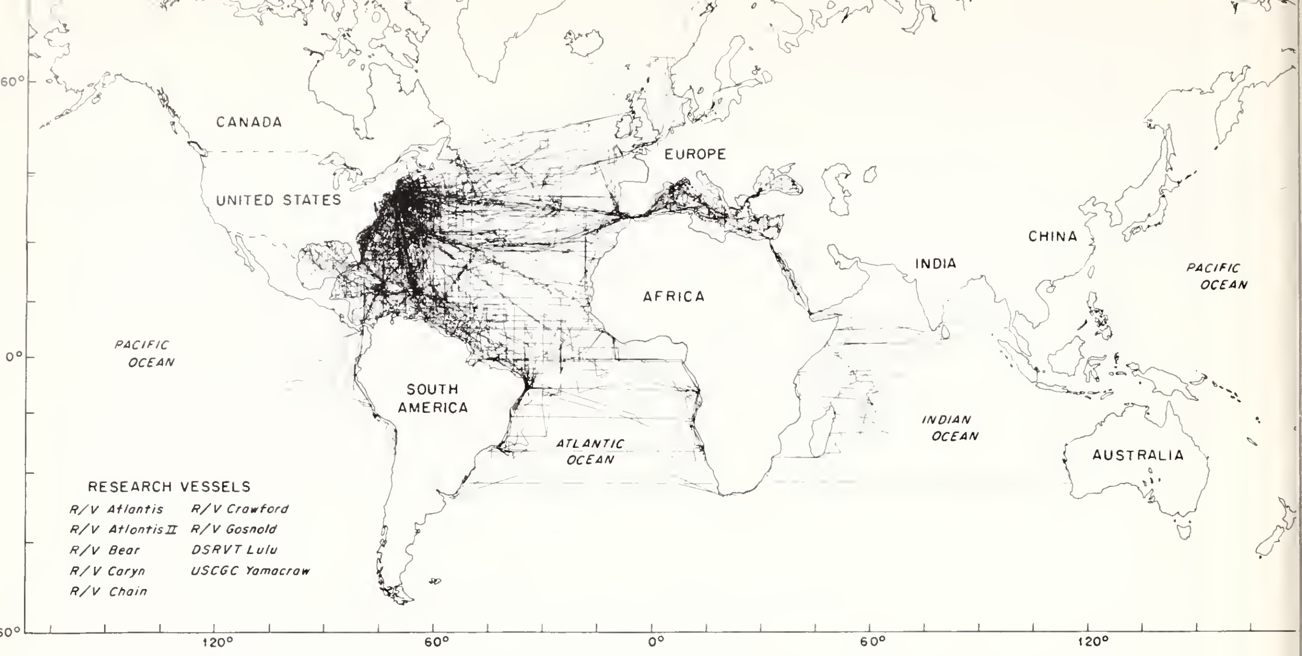
Theory and Observations

It is now clear that the bottom water in the southern hemisphere enters all three oceans from the south in the form of relatively narrow currents along their western boundaries. We must therefore reject the pattern of deep flow inferred by Buchan and later oceanographers, the essentially ocean-wide northward "creep," and suppose instead that these central ocean basins are actually filled from their western and even northern sides, as fed by the boundary currents. This, of course, is the dynamically consistent scheme of flow which Stommel and Arons developed, whereas the older interpretation is of doubtful validity. One might note that this revision in our conception of the pattern of deep flow is one of those rare instances in oceanography where theory largely preceded observation; usually it has been the observations made at sea which stimulated theoretical modeling, but here we have seen the reverse.

One must not, however, let elation obscure the imperfection of the prediction. Although the deep currents are indeed observed along the western sides of the ocean, they are much wider than anticipated: as one can see from the breadth of the zone of sloping isotherms in the figures, they are some five to ten times wider than western boundary currents in the near-surface water like the Gulf Stream and the Kuroshio, and also about an order of magnitude wider than the usual sorts of boundary-layer thicknesses given by theoretical analysis. The deep-circulation theory hypothesized boundary currents as regions of sufficiently high velocity and small horizontal scale that exact geostrophic balance would not obtain; these would therefore be regions where the condition of poleward flow did not apply and where the deep water originating in the Antarctic could flow north toward the equator. The real currents have turned out to be so broad and weak, however, that they may actually be subject to the strict geostrophic rules after all. What then would be the local dynamical basis for their existence? We do not doubt the fundamental soundness of the deep-circulation theory — its basic qualitative prediction was correct, of course — but we do not really understand how the boundary currents can be so wide. "God knows best how this comes."

Preliminary profile of temperature along Latitude 12°S in the vicinity of the western boundary of the deep South Indian Ocean ('Chain' Stations 968-988). The coldest bottom water is pressed up against the lower western boundary (Madagascar).





Forty Years of Cruising

This chartlet provides some idea of the coverage of the ocean by our research vessels from 1930 through 1969. The density of the tracks in the Western Atlantic Ocean and the Caribbean ought to indicate that there are few "holes" left in the observations, but strangely there is not much knowledge inside the 100 fathom curve. A new program is to be started to obtain this information, of value to pollution problems.

New Research Vessel

The R.V. 'Knorr' (Captain E. H. Hiller) joined our fleet in the spring of 1970. The ship was described by Mr. J. Leiby in the article "New Ship Design", Oceanus, Vol. XIII, Nos. 2 and 3, June 1967. Upon her first arrival at Woods Hole the Captain demonstrated the maneuverability of the cyclodial propellers by "turning the ship on a dime" near our pier. Incredulous laughter arose from the spectators.

Exit 'Crawford'

The brave little research vessel 'Crawford' left our pier for the last time in December 1970 having been sold to the University of Puerto Rico. Her name will be retained and she will continue oceanographic research. Acquired in 1956 by the Institution,* the 'Crawford' made 175 cruises until she was laid up in October 1968. Her long cruises during the International Geophysical Year added greatly to her laurels.

She was a happy ship, continuously skippered by Captain D. F. Casiles, with first mate J. Q. Bumer and chief engineer C. Backus. May she gather many more laurels.

*See: Oceanus, Vol. IV, No. 3, 1956

Columbus O'Donnell Iselin Issue

We intend to prepare an issue of Oceanus devoted to Columbus Iselin. Contributions are requested from anyone whose life was touched by him.

As literary executor of the "Iselin Papers", the Editor shall be grateful also for any information, notes, handwritten letters, memos (if any!), or any other memorabilia which ought to be included in a planned book.

Errata

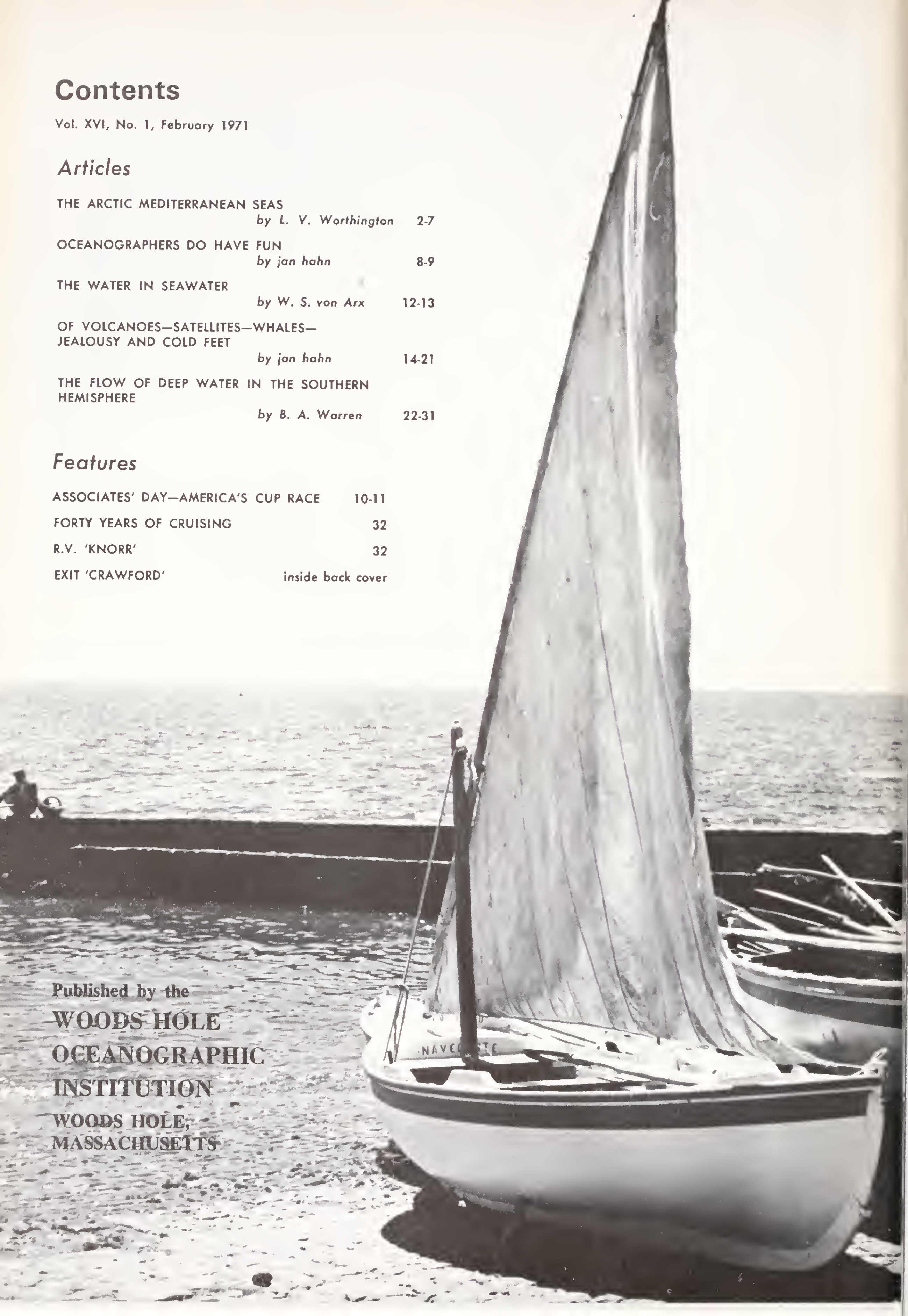
North Atlantic Atlas

ON the inside back page of the July 1970 issue we stated that Folio 19, Serial Atlas of the Marine Environment, was published by the "American Geophysical Society." This, of course, was an error. The series is published by the American Geographical Society, Broadway at 156th Street, New York, N.Y. 100032.

Associates of The Woods Hole Oceanographic Institution

President	TOWNSEND HORNOR
Executive Assistant	L. HOYT WATSON

MEMBERSHIP inquiries are invited. They should be addressed to Mr. L. Hoyt Watson, Woods Hole Oceanographic Institution, Woods Hole, Mass. 02543.



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