BY WALTER MUNK WITH DEBORAH DAY

GLIMPSES OF OCEANOGRAPHY IN THE POSTWAR PERIOD

>>> Dedicated to Captain Charles N.G. (Monk) Hendrix

Several recent histories give a critical review of American oceanography in the postwar period. Ronald Rainger (2000a,b, 2001), who has written extensively about the history of oceanography, reviews the Navy-oceanography partnership, and Jacob Darwin Hamblin's monograph, *Oceanographers and the Cold War*, examines the history of Soviet-US oceanographic relations at a time of increasing Navy sponsorship of US oceanography (Hamblin, 2005). Written by professional historians, these books give a long view of oceanography. Here, I share some personal glimpses of this era, which differ from the historians' accounts, especially in regard to relationships between oceanographers and the Navy. Oceanography is again in a state of great flux—the reviews by Rainger and Hamblin may offer guidance concerning future developments.

OCEANOGRAPHERS LOSE THEIR INNOCENCE

Navy sponsorship following World War II brought about a precipitous enhancement of oceanographic research. At the same time, oceanographers faced new responsibilities as they conducted open-sea experiments in a Cold War environment. These developments coincided with two revolutionary changes in understanding the oceans: *plate tectonics*—great horizontal mobility of the earth's crust implied by geophysical measurements at sea, and *mesoscale eddies*—energetic ocean "weather" (incredibly overlooked in the past hundred years) made visible by improved measurements in the water column. American oceanographers were on the revolutionary side of these developments, whereas their Soviet colleagues took the conservative, even skeptical view (with one important exception). In those years, our discipline changed from isolated research at a few marine field stations to participation in developments at the center of national and international affairs. Rainger and Hamblin somewhat bemoan our loss of innocence; indeed, there were losses and gains. Like most oceanographers of my generation, I participated in some of the events described in these histories and generally found the experience rewarding, exciting, and, yes, fun. I would like to share some of my personal glimpses with The Oceanography Society membership, and then comment on the issues.

OCEANOGRAPHERS ENCOUNTER THE COLD WAR

The start of the Cold War is usually identified with Churchill's speech on March 5, 1946, in Fulton, Missouri,

"…an iron curtain has descended across the continent." For oceanographers, it started two years earlier, when Maurice Ewing and J. Lamar Worzel discovered the deep ocean acoustic wave guide. The SOFAR sound channel (for Sound Fixing and Ranging) has been at the heart of submarine detection ever since.

When I arrived in Woods Hole in the fall of 1944 to work on wave prediction for Allied landings, oceanographers were agog with Ewing and Worzel's discovery. Sound speed increases with temperature and pressure (and salinity). With temperature dominating in the upper kilometer, and pressure dominating beneath, Ewing and Worzel reasoned simply that sound speed should increase upwards with temperature in the upper ocean, and increase downward with pressure in the deep ocean, with a minimum around 1-km depth. Sound waves would be channeled along this minimum.

In summer 1944, Ewing and Worzel departed Woods Hole aboard *Saluda* to test this hypothesis (Munk et al., 1995). A second ship dropped four-pound charges at distances up to 900 miles. Detonations and the hydrophone were both in the sound channel. In the words of Ewing and Worzel, "the end of the sound channel transmissions was so sharp that it was impossible for the most unskilled observer to miss it" (Munk et al., 1995, p. 356). This case is the only one I know of in which an oceanographic experiment unequivocally confirmed a previously held theory. Ewing spoke even then of transmissions over 10,000 miles; it was then and there that I caught the antipodal bug that led to the Heard Island Test some 50 years later.

Two years after the Woods Hole experiment, Russian acoustician L.M. Brekhovskikh[1] was scheduled for some work on wave scattering in the Sea of Japan, but the equipment was not ready (*pers. comm.,* 1989). Rather than lose ship time, it was decided to make some spontaneous measurements of sound transmission. Charges were dropped from a vessel, detonating at 100-m depth, with a suspended hydrophone drifting at 100 m, not unlike the *Saluda* experiment. Brekhovskikh wrote (Munk et al., 1995, p. 357):

> *Something very strange was observed in the course of the experiment. Peak amplitude decreased markedly only for the first 30 nm, whereas at greater distances the decrease was hardly noticeable. The acoustic signal form was also drastically different at different distances. At small ones it resembled shock waves, whereas at long distances the signal started very weakly, then increased with time resembling a thunder in the final stage before coming to an abrupt end. It was my duty to treat these results. It appeared that the only way to explain them was to take into account the existence of an acoustic wave guide with its axis at a depth of about 150 m… The picture fitted very well the summer hydrological conditions in the Sea of Japan. Since this work could have military applications, its publication was delayed till 1948… Due to the weakened international scientific relations we did not know of Ewing's paper until later.*

It is surprising that Ewing, the experimentalist, was testing a theory, whereas Brekhovskikh, the theorist, made his discovery looking at data.

The next few years saw a rapid sequence of discoveries: the anomalous absorption of sound in seawater, convergence-zone focusing, and the biological origin of certain ambient noises. I was present when we heard a report of "false bottoms," nighttime shoals on fathograms in regions of great depth. Martin Johnson of Scripps, who had been studying the diurnal migration of zooplankton for a decade, was also present and said, instantly, "copepods."

Most of the work was classified, and when it was eventually reported in the open literature some 15 years later, the authorship bore little or no relation to the people who had done the pioneering work.[2] In the meantime, the acoustic and oceanographic communities drifted apart, separated by a veil of secrecy, to the detriment of both.

WORKING WITH THE NAVY IN BIKINI LAGOON

In 1946, a large fraction of the US oceanographic community made its way to the Marshall Islands to participate in the first underwater nuclear explosion. Roger Revelle was in charge of the

[1] Leonid Maksimovich Brekhovskikh (1917–2005) is considered the founder of ocean acoustics in Russia. Brekhovskikh was trained in physics at Perm State University. During World War II, he worked closely with the navy and developed an acoustic minesweeper. After the war, he worked on wave scattering, again in close cooperation with the navy.

[2] An authoritative review can be found in the "green book" produced by the Committee on Undersea Warfare's Panel on Underwater Acoustics: National Academy of Sciences-National Research Council Committee on Undersea Warfare. 1950. *A Survey Report on Basic Problems of Underwater Acoustics Research*. Washington, DC.

science. William von Arx of Woods Hole and I were tasked to estimate the rate at which radioactive contamination would be flushed from Bikini Lagoon.

When viewed on Pacific maps, the lagoon appeared as an insignificant speck, but it was not so small when we got there. We were given 10 days to do our job.

We requisitioned a Navy reconnaissance plane and rigged up a simple bomb site. Von Arx was navigator and I was bombardier. We dropped dye markers filled with a highly concentrated mixture of green hexafluoride (used to locate downed fliers) into the lagoon openings, and the colored spots were photographed over the subsequent half tidal cycle. These spots gave a rough idea of the in- and outflow. There are about ten lagoon openings, and by the end of the week we had monitored nine, each showing a net inflow! The tenth (and last) channel came to our rescue, with a large net outflow. (The night before we had despaired as to how to report a violation to the principle of mass conservation.)

In spite of great care, some tiny volume of the green dye would rub into my trousers. Our bunks were on *USS Allen M. Sumner* (DD-692). After a few days, I noticed that the uniforms of the hundred or so officers and crew had taken on a greenish tinge. On the last day, Captain Ciano invited von Arx and me to his quarters for some "heart of palms." He received us in (not so perfect) dress-whites with the words, "I don't know what's wrong with the ship's laundry…"

A year later, in summer 1947, some 50 scientists, accompanied by an equal number of Navy personnel, descended upon Bikini Atoll in what was called the Bikini Scientific Survey (the subject of Rainger, 2000a). Roger Revelle was again in charge. The principal objective was to take stock of long-range effects of the atomic bomb tests in the previous year. But it gave the opportunity to test Darwin's 1842 theory that atolls are formed by coral growing on sinking volcanic islands. Core samples taken on the resurvey definitely confirmed Darwin's theory. This activity is a prime example of how far Navy-oceanography collaboration had come.

The Bikini tests and many subsequent experiences established a bond with the Navy that was to last throughout my career.

Three years after Bikini, the Russians surprised the world with their first nuclear explosion, and three years after that (in 1952) we tested our first H-Bomb at Enewetak Lagoon. The Scripps Institution played a crucial role in the Ivy-Mike test (Munk and Day, 2004).

FIRST MEETING WITH OUR SOVIET COLLEAGUES

Jacob Hamblin points out that the death of Stalin in 1953 led to a little thaw in Cold War relations between Soviet and American scientists (Hamblin, 2000). We met our Russian counterparts for the first time in September 1955 in Brussels. The meeting was sponsored by the International Union of Geodesy and Geophysics (IUGG) as part of the International Geophysical Year (1957–1958), in which oceanography was a late component.

> It was an exciting time, a fulfilling time, in part because of our fellowship with the Navy, in part because of our growing partnership with other countries.

Roger Revelle chaired the American delegation, and Vladimir Beloussov chaired the Soviet delegation. Beloussov was a renowned geophysicist and the leader of Russian opposition to plate tectonics. He did not have much contact with physical oceanography, and left the discussion in the hands of oceanographer Vladimir Kort. Revelle and Kort looked somewhat alike, both tall and handsome, but they had very different ideas of what to accomplish. Kort had ambitious plans for covering the southern ocean with traditional hydrographic sections. Revelle wanted to deploy multiple moorings with some new instruments. This was at the dawn of the mesoscale revolution, and there was a

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developing suspicion that an important component of ocean dynamics had slipped through the coarse grid of hydrographic sections.

After 10 years of Cold War, this was the first opportunity for personal contact with the other side. Revelle presented some ideas for a joint effort; these were translated into Russian by two members of the Soviet delegation (believed to belong to the KGB). Kort shook his head, *nyet*. Thereupon Kort spoke of his plans centered on hydrographic sections. And Revelle did not go along. And so it went all day, all very civil but no progress.

We met again next morning. Before the meeting got underway, the Finnish representative Ilmo Hela said he wanted to make a statement: he said that he spoke fluent Russian and English, and that yesterday's translations (in both directions) had not only been false, they had been actively misleading. He saw no object in repeating the procedure from the previous day. He also offered to do the translations. After some strong protests by the Soviet translators, Hela's offer was accepted. From then on we made progress. Kort and Revelle became friends.

We met our Soviet colleagues again at the First International Congress of Oceanography held in New York in 1959. The relation between the Soviets and the western world had been jarred by the launching of Sputnik in 1957. And so we looked forward to the New York meeting with apprehension. I have a picture of the French vessel *Calypso* alongside and dwarfed by the Soviet research vessel *Mikhail Lomonosov.* Captain Cousteau was serving wine amidst freshly laundered shirts flapping in the wind, while a forbidding armored guard was protecting the gangplank leading to the towering *Lomonosov*.[3]

At a reception hosted by the American delegation, Revelle and Kort were exchanging stories and testing Vladimir's newly acquired English language skills when they were interrupted by one of the Soviet translators. They looked at each other and then, as if on command, picked up the little man (they were both well over six feet), opened the door, and tossed him outside. Roger asked, "Will you be in trouble when you get back?" to which Vladimir replied, "Oh no, I will just tell them I was drunk."

WE VISIT OUR COLLEAGUES IN THE SOVIET UNION

On three subsequent visits to the Soviet Union, I benefited greatly by the growing friendships. On my first visit, after reading newspaper stories, I rather expected a beautiful lady spy to knock at my hotel room door at night, but she never came. At breakfast the next day, one of my colleagues recounted searching his room for hidden bugs until finally, at midnight, he found one under the carpet, which he promptly unscrewed. We asked another member of our party how he had slept: "Just fine, until midnight when the chandelier came down on my bed."

Kort[4] was my late wife Judith's and my thoughtful host on two occasions, and Andrei Monin (his successor as Director of the Shirshov Institute) on a subsequent visit. Both have been our guests in La Jolla, California. Later, I became a Foreign Fellow of the Akademie Nauk. On my first visit to the Oceanological Institute in Moscow, W.B. Stockmann met me with the words, "I have been waiting for 12 years to meet you and give you hell for not referring to my papers."[5]

Judith and I had our most interesting visit to Russia in October 1962. Judith's letters home recalling that trip report that Kort's office in Moscow was very simple, but had a stuffed penguin, as did the offices of many Russian oceanographers. I did not want to spend more time in Moscow and was looking for an excuse to drive across the country. The Shirshov Institute maintains a marine station at Gelendzik on the Black Sea. I pleaded that the work on sand transport by a member of the Gelendzik staff was of great interest, and was granted permission to visit there. We drove our Land Rover, entering from Finland and leaving a month later via Odessa. This was October 1962 during the Cuban missile crisis (we were unaware that our two countries were almost at war), but not once did we encounter any unfriendliness. We had been warned not to go off the central highway, but decided to ignore the warning (obviously the product of senseless regulations) and have a look at a neighboring village. We

[3] The preliminary program for the Congress announced that the following oceanographic research vessels would be in New York harbor during the Congress, with anchorages, piers, and visiting hours to be announced: *Atlantis*, *Chain*, *Crawford*, *Maury*, *Calypso*, *Mikhail Lomonosov*, and *Gibbs*. S.I.O. Subject Files, Box 79, folder 1, Scripps Institution of Oceanography Archives, UCSD Libraries.

[4] Vladimir Grigoriyvich Kort, (1913–1994) was a graduate of the Geographic Facility of Leningrad University and gained research experience in the Arctic and Antarctic. He served in the Russian Navy during World War II and became chief of the Naval Marine Observatory and Deputy Chief of the Navy Institute after the war. He served as director of the P.P. Shirshov Institute of Oceanology from 1953–1960 and was succeeded by Andrei Sergeevich Monin (1921–2007), who was director until 1987.

[5] Walter H. Munk to Robert B. Abel, April 3, 1963. Walter H. Munk Papers, Box 80, folder 5, "Russia, 1952," Scripps Institution of Oceanography Archives, UCSD Libraries.

promptly got stuck in the mud.

We arrived at Gelendzik on the anniversary of the October Revolution with a big party in progress. We were given a warm welcome as the first foreign visitors to the field station. We left next day in the early morning hours in time to meet our ship in Odessa. Two hours out of Gelendzik, I turned to Judith and said, "My God, I have totally forgotten to meet the man who worked on sand transport." Some years later we told the story to Director Monin when he visited La Jolla. "I know," he said, "but he got promoted anyhow."

POLYGON, MODE, AND POLYMODE

These three experiments were in response to a realization in the early 1970s that the ocean was filled with eddies of 100-km spatial scales and 100-day temporal scales. For a century, eddies had escaped the traditional sampling schemes of a few uncoordinated vessels chasing around the ocean at 12 knots. Yet, these mesoscale eddies (the ocean "weather") contained more than 90% of the kinetic energy of ocean circulation. Traditional sampling was not adequate to the job.

Scientists proposed different ways to study the role of mesoscale eddy motions in the dynamics of general circulation. Carl Wunsch and I proposed using acoustic transmissions between moorings, taking advantage of the temperature dependence of sound velocity (and that the mean sound velocity of 3000 knots exceeded the velocity of oceanographic vessels). We called it "ocean acoustic tomography" with the expectation that the obscure name would raise further interest.

It is interesting that Vladimir Kort opposed the "mesoscale revolution" (called "synoptic vortices" in Russian literature), just as Beloussov opposed plate tectonics. But the motivations of these two traditionalists were quite different. Beloussov objected on theoretical grounds; Kort objected because he wanted to make traditional hydrographic sections, and these sections were not up to resolving (in time and space) the mesoscale eddies.

In response to the mesoscale challenge, Woods Hole set out in the 1960s to develop reliable deep-sea moorings. The development of such now-reliable technologies as moored current meters took 20 years, with early years of failed or missing moorings, inoperable tape recorders, and nasty, late surprises that the measured velocity spectrum depended strongly on the strumming of the mooring lines.

At about the same time, Russia organized the POLYGON program under the leadership of Leonid Brekhovskikh, the co-discoverer of the SOFAR sound channel. POLYGON was by far the most pioneering and ambitious Soviet oceanographic effort, involving six research vessels and a network of current-meter moorings. It was astounding that this effort was personally led by acoustician Brekhovskikh, who had no previous record in physical oceanography, and not by Kort or Monin, directors of the Shirshov Oceanological Institute. We can only surmise that Brekhovskikh understood the fundamental role that the mesoscale revolution was to play, whereas Kort and Monin did not.

Brekhovskikh takes great care in thanking Kort and Monin for their "elaboration" in the planning of POLYGON. "Even with somewhat less sophisticated gear than was desirable," (read: half the current meters failed and the calibrations were unreliable), "the results… exceeded all expectations in terms of… the significance of the scientific results obtained. Undoubtedly the experience… will be very useful in the preparation for the forthcoming international campaign MODE… It looks as though some large-scale eddy or wave disturbances were travelling across the POLYGON site from east to west. Their scales were close to those of the planetary baroclinic Rossby waves" (Brekhovskikh et al., 1971).

The results were greatly extended by the Mid Ocean Dynamics Experiment (MODE) under the leadership of Henry Stommel, followed by POLYMODE in 1977 under Andrei Monin, who placed emphasis on mapping with closely spaced (but still traditional) hydrographic sections. So POLYGON ignited

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the mesoscale revolution (Swallow had previously set the fuse), and MODE defined the new order. Oceanography has never been the same.

The Soviet and US programs were not well coordinated, leading to some disagreements, but still resulted in a significant advance in the understanding of ocean dynamics. I recall nervousness on the US side that the Russian sections were designed to provide information on our classified SOSUS system. A major mystery was the disappearance of the central MODE mooring while a distant, unidentified ship left the area.

On October 11, 1986, Gorbachev and Reagan met in Reykjavik, Iceland, signaling the end of the Cold War.

THE 1988–1989 GREENLAND SEA EXPERIMENT: BREKHOVSKIKH TO THE RESCUE

I maintained contact with Leonid Brekhovskikh. Some years later, he telephoned me in La Jolla: "I am in Washington, can I come for dinner?" He did, and went home the next morning. His concept of US geography must have been a bit distorted.

In 1987, Peter Worcester was planning for a Greenland Sea ocean acoustic tomography experiment that would deploy six moorings with acoustic transceivers in summer 1988 and recall them in summer 1989. During this planning stage, the Chairman of the Board of the Nansen Environmental and Remote Sensing Center, Bergen, Norway, Jan A. Andersen, visited us and told the following story. The Norwegian Meteorological Institute had maintained a satellite reporting weather buoy moored at "Tromsøflaket" off the northern coast of Norway. The buoy radioed weather information on a daily schedule via the ARGOS satellite system. One day, the latitude/longitude channel showed an unexpected variability. This went on for many days and eventually the buoy was satellite-tracked all the way to the Russian port of Murmansk in Northern Russia. After strong protests by the Norwegian government, the buoy reappeared and was redeployed at the original mooring site (Andersen, 2006).

Andersen asked, "By what magic do you expect that six moorings in the Greenland Sea strategic area, transmitting a coded [m-code] signal, would survive for a full year?" I promptly sent a telegram to Brekhovskikh in Moscow asking whether we could visit him (Judith would not let me go alone). As we entered his office, and before I could utter a word, he said, "I will tell you why you are here. You want me to arrange that the Greenland Sea moorings are left alone." As it turned out, the US Navy had some maneuvers using coded acoustic transmissions in this very area until the very day we deployed. They were continuously shadowed by a Russian electronic intelligence vessel. The vessel left the area the day we arrived. A few days into the experiment, a ship passed with searchlights sweeping the horizon. But no further contact.

We were uneasy when we left the area, so we returned home on a circuitous route via Iceland. At the local SOSUS station, we waited anxiously for our signals to arrive. And there they were, all six sources reporting to the nearest second! During the mooring array's winter deployment, while covered by ice, it recorded a convective overturning event.

Judy and I maintained our contact with Leonid until his death in 2005, and I was pleased to be present in 1997 when he received the Munk Award (given jointly by the Navy and The Oceanography Society).

LOOKING BACKWARDS

Hamblin's discussion of the reception of plate tectonics in the Soviet Union is interesting and important (Hamblin, 2000); I agree with the view that institutional conservatism worked against Soviet reception of plate tectonics. During the Soviet era, work was done at different institutes, and the Russian tradition at the time was to keep them intellectually separate. So Beloussov left the oceanographic planning and discussion to Kort. The leading role played subsequently by Brekhovskikh in the search for mesoscale eddies (the POLYGON experiment) is a departure from the usual pattern. It affirms that revolutionary ideas originate in the minds of men and not in institutions, no matter where.

It is a curious circumstance that, in the United States, data underlying both the plate tectonics and the mesoscale revolutions were collected under Navy auspices. At the same time, the data were of tactical and strategic importance, providing a source of friction and controversy. Many of the data were initially classified, and bitter battles were fought on the declassification issue. But this was not a battle of the Navy against the oceanographic community. The point here is that decisions were made by an *interacting* group of Navy officers, some with deep scientific interests, and academic oceanographers who were unusually well informed on, and cared about, Navy matters.

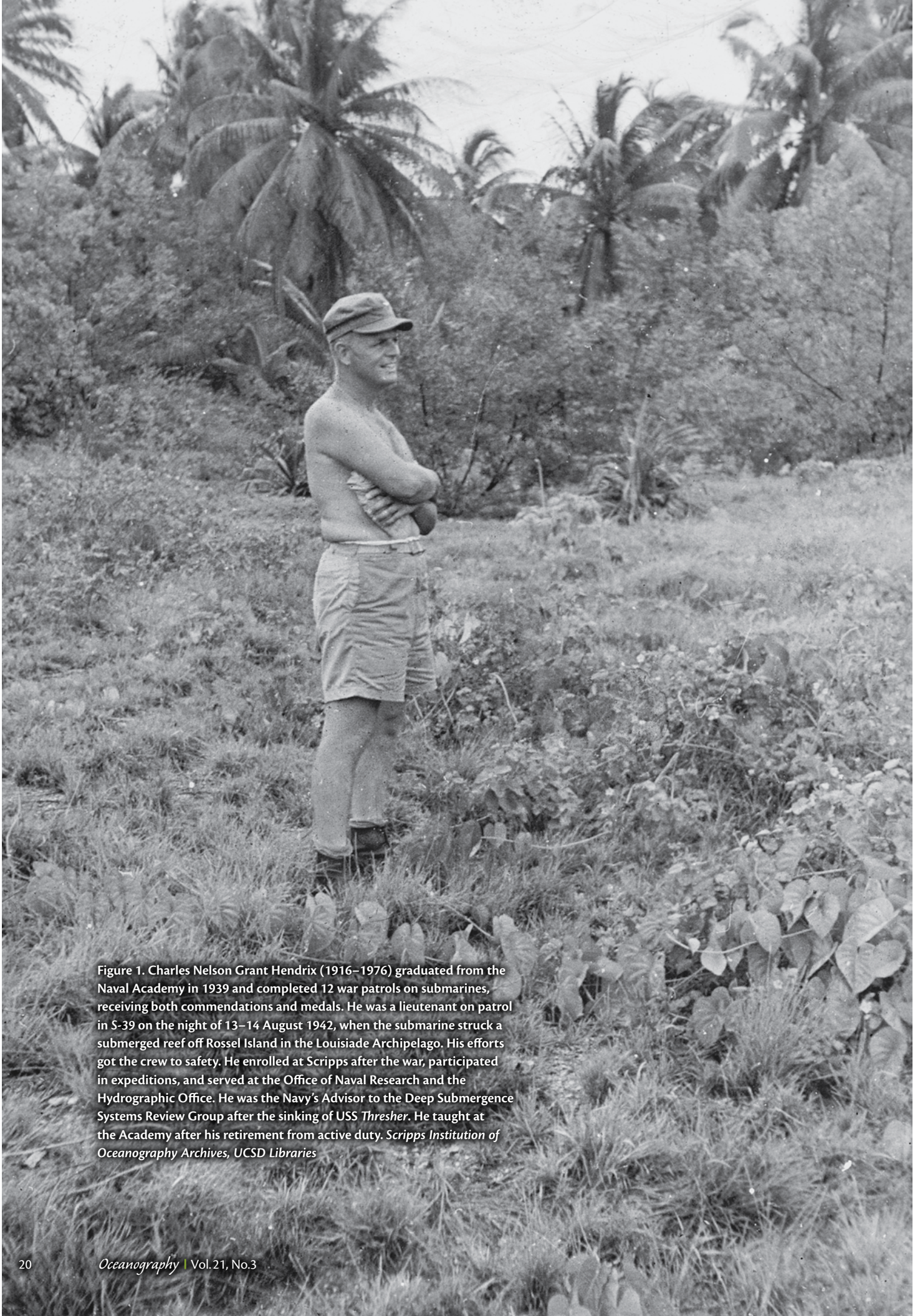

Figure 1. Charles Nelson Grant Hendrix (1916–1976) graduated from the Naval Academy in 1939 and completed 12 war patrols on submarines, receiving both commendations and medals. He was a lieutenant on patrol in *S*-39 on the night of 13–14 August 1942, when the submarine struck a submerged reef off Rossel Island in the Louisiade Archipelago. His efforts got the crew to safety. He enrolled at Scripps after the war, participated in expeditions, and served at the Office of Naval Research and the Hydrographic Office. He was the Navy's Advisor to the Deep Submergence Systems Review Group after the sinking of USS *Thresher*. He taught at the Academy after his retirement from active duty. *Scripps Institution of Oceanography Archives, UCSD Libraries*

We have dedicated this essay to "Monk" Hendrix as a fine example of that bond (Figure 1). Monk was commissioned Lieutenant when Munk was appointed Assistant Professor at Scripps Institution of Oceanography. Monk became Captain the same year Munk became a full professor. We first worked together at Bikini. Along the way, we developed a friendship and trust that played a central role in our careers. Monk Hendrix is now considered the father of the US Naval Academy's oceanography program. The Hendrix Oceanography Laboratory at the Academy is named in his honor.

On the academic side, we may cite Harry Hess, Professor of Geology at Princeton University, and an acknowledged leader of the plate tectonics revolution. His famous paper on sunken seamounts was written while he was on active duty and with data collected under his command. Upon retirement, Hess was promoted to Rear Admiral (USNR). Revelle was in uniform throughout the war; H. William Menard and Robert Dietz (two of the leading pioneers in plate dynamics) were civilian employees of Navy laboratories with wartime military experience. While Hamblin is right to note that politics and ideology divided the international community in oceanography, the American community was not divided into opposing camps.

We oceanographers were very young at the end of the war, many in our twenties. Roger Revelle was 41 when he became Director of the Scripps Institution of Oceanography in 1950, and he was considered one of the mature men in the field. Our instrumentation was often one-off, built on the spot, new and untested. There were many failures, but as we were all young and confident, we were not surprised by our successes. We had all experienced wartime research that required improvisation and resilience and demanded success. This experience created some powerful scientific personalities. Although the historians mention the names of the leading actors, both Navy and civilian, they do not always perceive that the strongly held views of powerful scientific personalities, more often than not, carried the day.

Oceanographers differ from our theoretical and laboratory-oriented colleagues. *Time* said it well when featuring the seagoing Woods Hole Director Columbus Iselin on the magazine's July 6, 1959, cover. The staff had written a parallel article featuring Roger Revelle, and the cover choice was made only at the last minute. But then an article on Revelle appeared in *Science* magazine under the heading "Oceanographers have more fun."

FINAL COMMENTS

I remember with fondness the inaugural meeting of TOS in Monterey, California. I had the opportunity to make some closing remarks:

> *The last three days have been quite an experience… It was somewhat like being together at sea for a short cruise. We are going home elated and a bit exhausted.*
>
> *Participation in the Inaugural Meeting…was like participating in a bit of history. I sense that we have felt comfortable in each other's company—is it because of our tradition of life at sea? As Henry Stommel put it, survivors (of sea trips) are congenial people or they wouldn't be here.*

We thank The Oceanography Society for this opportunity to recall glimpses of half a century of oceanography. It was an exciting time, a fulfilling time, in part because of our fellowship with the Navy, in part because of our growing partnership with other countries. Some of this spirit is now gone. When TOS meets again in 2028 to celebrate another 20 years, will we have recovered some of the excitement and joy of the postwar period?

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