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Experiment in Eastern Mediterranean Probes Origin of Deep Water Masses

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During the last decade the oceanography community has focused much attention on the Mediterranean Sea. One reason for the growing interest is that the Mediterranean's impact on the Northern Atlantic Ocean is more significant than previously realized. The warm, salty Mediterranean water tongue exits the Gibraltar Straits and spreads throughout the North Atlantic at all depths between 1000 and 2500 m. The second reason for the surge in interest is the well-recognized role of the Mediterranean Sea as a laboratory for studying ocean processes that are important in global climate dynamics [*Malanotte-Rizzoli and Robinson*, 1991; *Malanotte-Rizzoli and Robinson*, 1994].

The Mediterranean Sea is essentially divided into two basins, the Western and Eastern. The basins are separated by the shallow Sicily Straits, which prevent any direct communication between the deep and bottom layer water masses of the two basins. Although many theories about circulation in the Mediterranean and the origin of water layers have been proposed, many questions remain unanswered.

Reid [1994] suggests that there is a direct advective pathway of the Mediterranean water mass to the northern polar seas along the coast of Europe. This northbound route occurs on all of the isopycnals in the above depth range along with the classical westward route. *Lozier et al.* [1996], on the other hand, suggest that the Mediterranean outflow's link to the North Atlantic Deep Water (NADW) is indirect. They theorize that Mediterranean water mixes with the North Atlantic Central waters which, via the Gulf Stream and the North Atlantic Current, feed the Nordic Seas. Be it direct or indirect, it is clear that the Mediterranean water mass crucially affects the NADW thermohaline cell.

The Eastern Mediterranean is particularly important for studying global ocean processes. The Mediterranean salty/warm water mass exiting from Gibraltar is formed in the Eastern Mediterranean along the route of the open Mediterranean thermohaline cell that connects the Western and Eastern basins in the uppermost 300-m layer. Cold, light Atlantic Water (AW) flows in at Gibraltar. This water mass spreads eastward, undergoing progressive modifications, and reaches the Eastern Levantine as Modified Atlantic Water (MAW). Here intense evaporation in the wintertime and associated latent heat loss induce intermediate convection to 300–400 m depth with the production of a very salty, warm water formed in the Northern Levantine eastward of Rhodes (Figure 1), the Levantine Intermediate Water (LIW).

At the time it is being formed, the LIW core properties are $\theta = 15.2$–$15.5°C$ and $S \geq 39.1$ psu [*Ozsoy et al.*, 1993]. The LIW moves from the Northeastern Levantine, crosses the entire Mediterranean in the reverse westbound pathway, and exits from Gibraltar. The water masses formed in the Northwestern Mediterranean (the Lions Gulf) contribute very little to the water leaving Gibraltar. They remain confined in the western abyssal

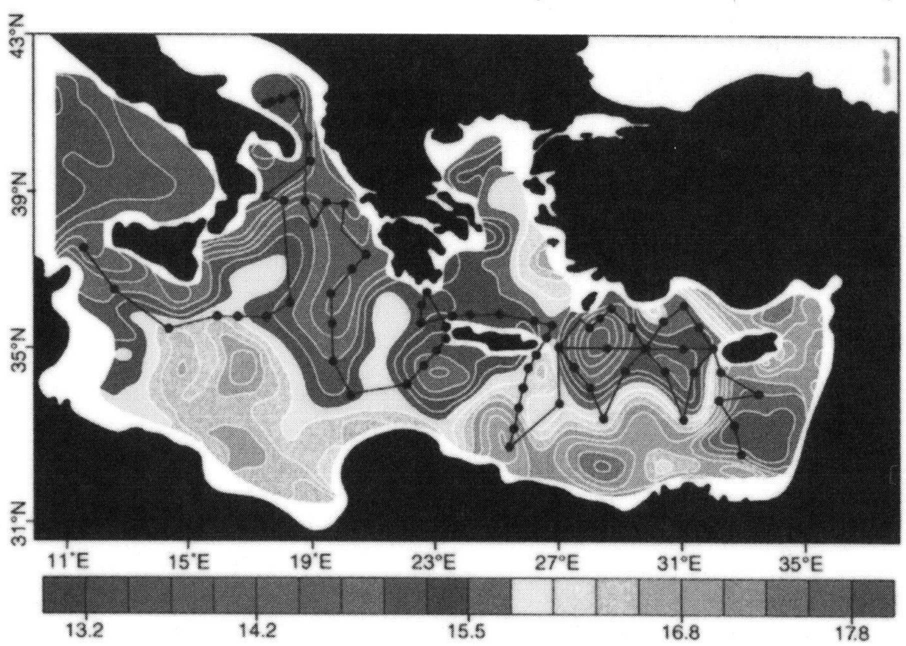

Fig. 1. The Eastern Mediterranean basin. Network of the January 1995 survey of the R/V Meteor *(Germany) superimposed on a map of the temperature at 125 m depth throughout the basin. Large dots indicate hydrographic and tracer stations, where the physical, chemical, and biological parameters were measured. The two diamond-shaped regions in the lower right section mark the area of intensive field work covered by successive surveys in February, March, and April 1995. Original color image appears at the back of this volume.*

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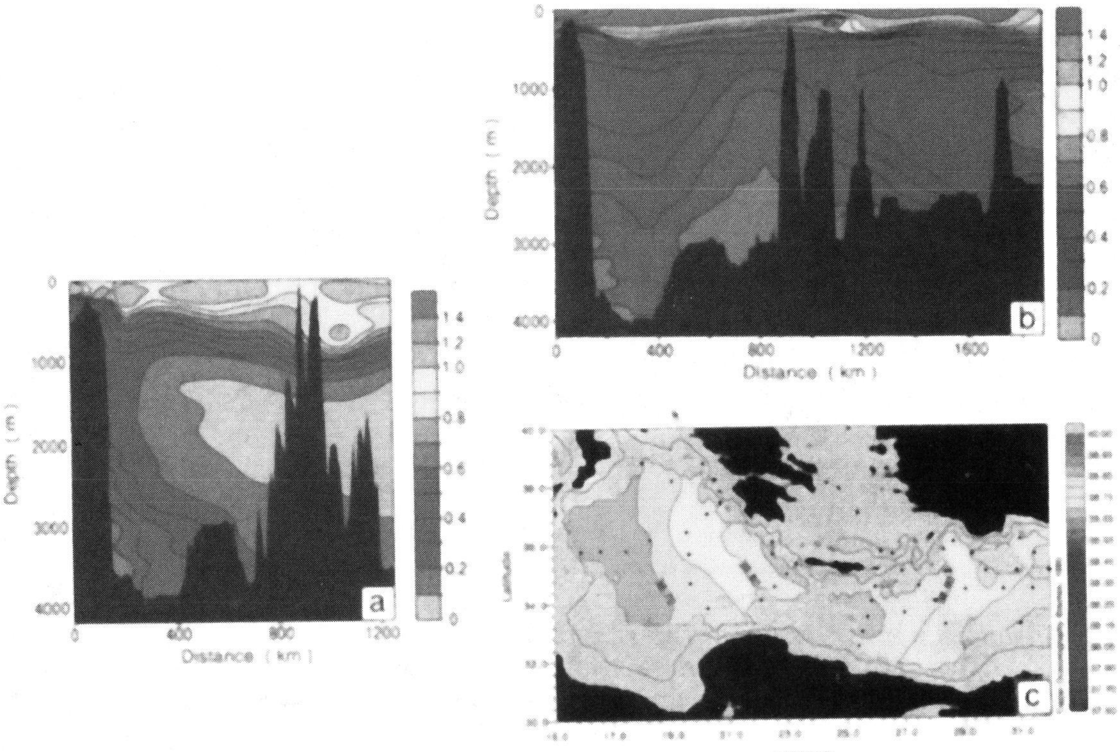

Fig. 2. a) East-west section of water layers and CFC-12 distribution obtained in August 1987. b) East-west section of water layer distribution and CFC-12 distribution in January 1995. The Aegean Sea played a crucial role in driving the deep thermohaline circulation in 1995. c) Salinity distribution at 2200 m depth. Original color image appears at the back of this volume.

layers. Thus the Eastern Levantine Sea is the "engine" that drives the upper open Mediterranean thermohaline cell.

POEM and POEM-BC

Physical Oceanography of the Eastern Mediterranean (POEM), an international collaborative program sponsored by the United Nations Educational Scientific and Cultural Organization and the Intergovernmental Oceanographic Commission, has studied the Eastern Mediterranean since 1985. After a preparation phase, POEM studied circulation and physical processes from 1985 to 1990, resulting in three unexpected findings.

Researchers discovered a closed thermohaline cell in the deep-bottom layers of water that originates in the Southern Adriatic and spreads into the Eastern Levantine, the Eastern Mediterranean "conveyor belt" [*Roether and Schlitzer*, 1991]. Also found were multiple scales of interacting motions that define the general circulation at the basin, sub-basin, and mesoscale [*Malonotte-Rizzoli and Robinson, 1988; POEM Group*, 1992]. And two convective regions with related water mass formation were found. The first is a deep convection cell in the Southern Adriatic, where the Eastern Mediterranean Deep Water (EMDW) was formed between 1985 and 1987. Second, a convective region exists, rather more extensive than previously recognized, surrounding the Levantine Rhodes gyre where intermediate convection leads to the LIW formation. Deep convection has also been observed in the Rhodes gyre leading to the formation of Levantine Deep Water (LDW) [*Ozsoy et al.*, 1993]. The results of POEM Phase 1 are summarized in a group paper [*POEM Group*, 1992] and in a special issue of *Deep Sea Research* devoted to POEM results [*Robinson and Malanotte-Rizzoli*, 1993].

In 1990, POEM evolved into POEM-BC, an interdisciplinary project with a biology and chemistry component. Field work began with a basin-wide interdisciplinary survey carried out in October 1991 by five research vessels from Greece, Israel, Turkey, and Italy, which contributed two research vessels. A second interdisciplinary survey was carried out in March 1992 in the Ionian and Cretan Seas by two of the research vessels. The data set collected is helping to quantify the distributions of major inorganic nutrients and biological properties in the context of the physical processes of the basin.

Levantine Intermediate Water Formation (LIW) Experiment

A major observational effort was carried out in winter 1995 with the execution of the LIW formation experiment. The three objectives of the experiment were to define the process of LIW formation through the successive phases of preconditioning, convection and formation, and spreading and dispersion; to study the internal (deep) and external thermohaline cells of the Eastern Mediterranean; and to conduct a mesoscale experiment in the Levantine Basin.

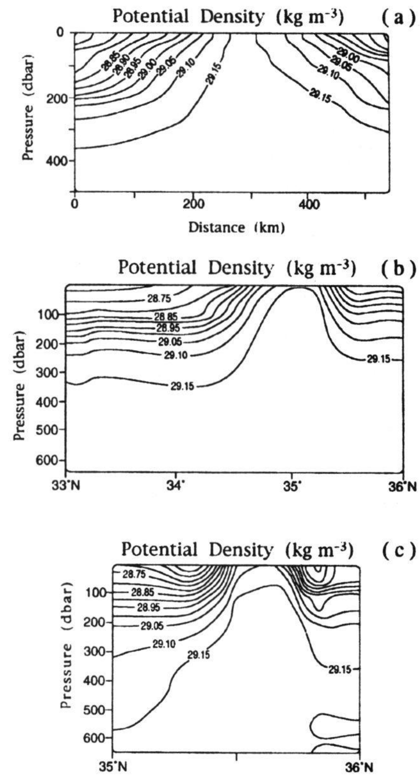

Fig. 3. a) Potential density distribution in the upper 500 m along a Meteor *CTD section crossing the Rhodes Gyre chimney, January 1995. b) Potential density distribution in the upper 500 m of the Rhodes Gyre chimney along a meridional section at 28.5°E in February 1995. c) As in Figure 3b, but in late March 1995.*

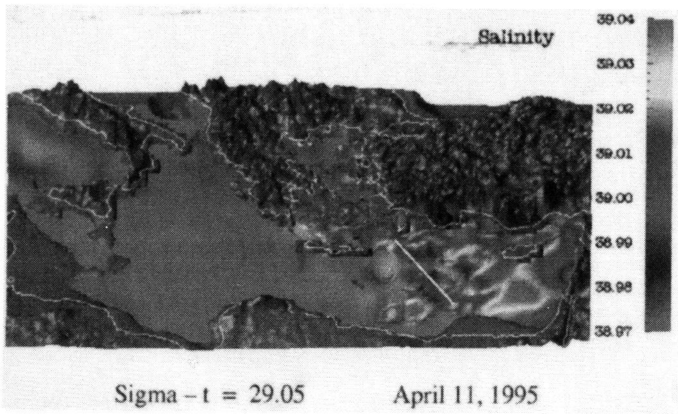

Fig. 4. The density surface σθ = 29.05 obtained from an objective analysis of the LIW data in April 1995, when three ships were in the region. Coloration indicates salinity. The LIW falls in the range of 38.97 to 39.04 psu. Pink indicates LIW salinity values of 38.97 psu, while red indicates values of 39.04 psu. The LIW is largely concentrated in the eastern Levantine, and it is absent from the center of the basin. Original color image appears at the back of this volume.

Figure 1 shows the area covered during the survey by Germany's R/V *Meteor* in January and February 1995. Large dots indicate hydrographic and tracer stations where the physical, chemical, and biological parameters were measured. Expendable bathythermograph (XBT) measurements were carried out all along the track with a resolution of ~10 km. The area of the LIW preconditioning is marked by the two diamond-shaped regions between the islands of Rhodes and Cyprus. This area was the site of intensive field work during four successive surveys carried out successfully by the research vessels of Turkey, Italy, Greece, and Israel from February to mid-April 1995. An aircraft-deployed expendable bathythermograph (AXBT) flight was carried out by the U.S. Navy on March 16, 1995. Figure 1 shows the *Meteor* survey track and the temperature field for water at 125 m depth on day 12 of a real-time nowcast/forecast made at sea of the complete Eastern Mediterranean. The initial fields for this simulation were derived from the Mediterranean Oceanic Data Base (MODB) winter climatology.

The first major result that emerged from the preliminary analysis was completely unexpected: the Eastern Mediterranean deep waters were in an entirely new configuration. Up until 1987, oceanographic observations showed that the major source of deep water in the basin was the Southern Adriatic Sea, where the Eastern Mediterranean closed thermohaline cell originated. The Winter 1995 observations show instead that the deep water mass of the entire basin is formed in the Aegean Sea exiting from it through the straits of the Cretan arc. Because this water is higher in salinity and density, it spreads at great depths, displacing the older water of Adriatic origin upward and to the west [*Roether et al.*, 1996]. Figure 2 shows the crucial role that the Aegean Sea played in driving the deep thermohaline circulation in 1995.

Figure 2a [*Roether et al.*, 1996] shows an east-west cross section of water layers and CFC-12 distribution during the summer of 1987 at 35°N, from 14°E to 28°E (Figure 1). The chlorofluorocarbon (CFC-12) distribution in 1987 shows obviously high concentrations in the surface layer in contact with the atmosphere. A further core of high CFC-12 is found at the base of the western side, the Sicilian Strait continental Slope, along the advective pathway of the water mass of Adriatic origin that exits at the bottom of the Otranto Strait (Figure 1). Figure 2b [*Roether et al.*, 1996] shows the analogous east-west section in winter 1995, again at 35°N, from 14°E to 33°E. As atmospheric CFC concentrations increase over time, the surface-layer concentration is also somewhat higher in 1995 than in 1987. The high CFC-12 core found at the base of the western Sicilian slope is still present, indicating that new water was added from the Adriatic source. However, on the eastern side of the basin, at the base of the Greek Continental slope, another core of high CFC-12 is visible that was absent in 1987. All along the eastern side, CFC-12 concentration is much higher in the layer below 2000 m. The high CFC-12 concentration indicates that the high-salinity intrusion contains a significant amount of "young" water. The denser deep water that spills out from the Straits of the Cretan arc (Figure 2b) in the layer below 2000 m pushes the core of minimum CFC-12, which in 1987 occupied the entire eastern half of the section, upward (Figure 2a).

Figure 2c, which illustrates the salinity pattern at 2200 m, further demonstrates that the Aegean Sea is the source of the high-salinity water mass that spreads out around the Cretan arc and occupies the entire Eastern Mediterranean deep layer. Rough estimates of the possible change in the fresh-water balance of the basin suggest instead that such a dramatic change in the deep waters might be linked to an instability of the deep thermohaline circulation [*Roether et al.*, 1996].

The second major result emerging from the preliminary analysis shows that a convective chimney was formed in the Rhodes gyre and that a complete time history of its evolution can be inferred through the preconditioning, mixing, and spreading phases. Figure 3a, from January 1995, shows the potential density distribution in the upper 500 m along a CTD section that crosses the center of the chimney, which is fully ventilating to the atmosphere, indicating that the formation process actually occurred in late January. The ventilated convective cell was well resolved by XBT measurements, which show a ~800-m deep, vertically mixed chimney with a temperature of 14°C. This deep convection, however, did not lead to the formation of actual LIW, but rather to the formation of the Levantine Deep Water, which is colder (14°C), less salty (S = 38.8 psu), and denser (σθ≅29.15) than LIW. Levantine Deep Water with slightly different properties was observed in the Rhodes Gyre in March 1992 [*Ozsoy et al.*, 1993], suggesting the existence of a continuum of water masses ranging from intermediate LIW to deep LDW.

Figure 3b, from February 1995, shows the potential density distribution in the upper 500 m along a meridional section at 28.5°E that crosses the center of the Rhodes gyre. In Figure 3b, Surface restratification has just begun, recapping the chimney core in the upper 50 m layer. By late March, Figure 3c, the same section through the chimney center shows it to be fully recapped to ~150 m depth, with the interior homogenized core at the same potential density of 29.15.

Finally, to illustrate the spatial and temporal variability of the LIW in the spreading phase, core values for density and salinity are selected. Figure 4 shows the density surface σθ≅ = 29.05 obtained from an objective analysis of the LIW data in April 1995 when three ships were in the region. The LIW is largely concentrated in the eastern Levantine, and it is absent from the center of the basin.

The sequential analysis of similar figures over the course of the experiment will be instrumental in tracking the spread of LIW. In fact, in examining the evolution of salinity in the slice marked in Figure 4, which cuts the Levantine Sea and Rhodes Gyre from northwest to southeast, the LIW is initially confined to the northwestern area surrounding the Rhodes gyre. By the end of the observational period, in April 1995, the LIW has spread southward and occupies the southern part of the basin. Complete analysis of the data sets obtained by the surveys will allow researchers to reconstruct the history of the convective process, from the formation of the convective cell to its recapping and horizontal collapse, which led to the dispersion of the newly formed water mass.

Acknowledgments

We acknowledge support from the European Union under the Mediterranean Targeted Project and by the governments, national agencies, and institutions of the participants in the experiment. We thank the Intergovernmental Oceanographic Commission for its sponsorship of the POEM Scientific forums. We also thank the U.S. National Science Foundation, which provides support to Harvard, contract number OCE-9403467 and MIT, contract number OCE-9403471.

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Clair C. Patterson (1922–1995)

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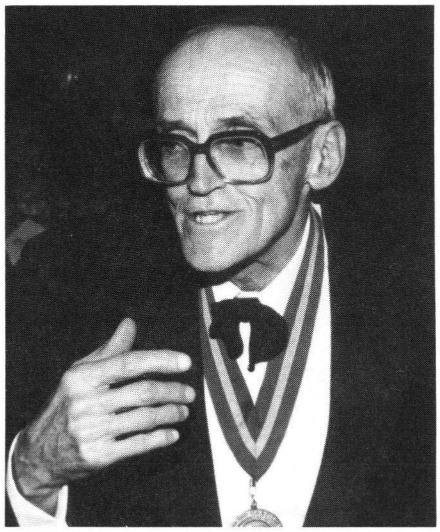
Clair C. (Pat) Patterson, 73, passed away unexpectedly at his home in Sea Ranch, Calif., on December, 5, 1995. Pat left behind one of the most prolific and influential legacies, not only in geochemistry, but in environmental biogeochemistry as well. In geochemistry, he is best known for first establishing the true age of the Earth and solar system at 4.6 billion years, a date the accuracy of which has survived four decades. This inherently accurate geochronology arose from Pat's development of stable lead isotope techniques clean enough to overcome contaminated and erroneous results of earlier workers. This allowed him to further develop lead isotope systematics for divulging the evolution of the crust and mantle.

As a native from Iowa, Pat was always proud of his midwestern heritage, to which he attributed his rugged spirit. He was born and raised in Mitchellville, went to undergraduate school at Grinnell College in 1943, and earned a Masters Degree at the University of Iowa in 1944. It was also here Pat met his wife Lorna, also a native Iowan and chemistry student at Grinnell, whose serenity was a perfect match to his scientific intensity.

During the war, Pat served in the Manhattan Project, where he was introduced to mass spectrometry, the analytical instrument central to all his later biogeochemical achievements. His horror in helping to develop nuclear weapons of mass destruction led Pat to develop peaceful ways to use nuclear geochemistry and imbued him with a deep devotion to the welfare of the human species. Armed with this spirit, Pat received his doctorate from the University of Chicago in 1951, and proceeded to follow his advisor and geochemical mentor, Harrison Brown, to the California Institute of Technology in 1952 as a research scientist. Pat remained there for the rest of his career.



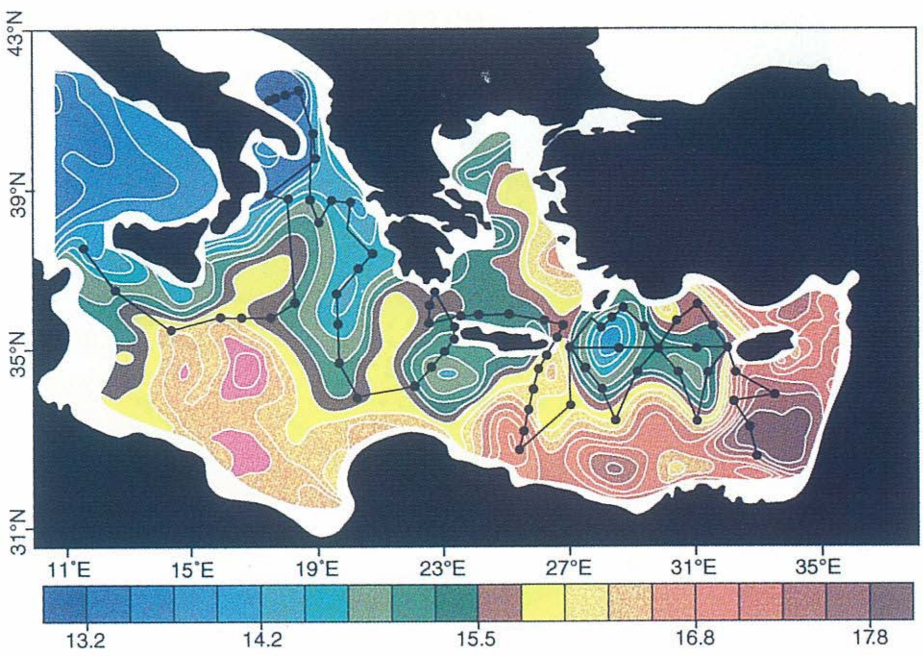
Clair (Pat) Patterson receiving the Tyler Prize for Environmental Achievement in 1995, the most prestigious international environmental award, for his work in exposing the dangers of lead pollution.

Pat's pioneering geochronological studies led him to the discovery of global lead contamination, and by 1963 and for the rest of his career, he was acknowledged as a pioneer in environmental biogeochemistry. He was able to show, for the first time, the extreme extent to which lead contamination has pervaded the Earth's surface reservoirs and biospheres. For example, Pat demonstrated that before man, the global flux of lead into the oceans and deep sediments was only 1/10 to 1/100 that of today.

Pioneering clean sampling of polar ices by Pat further revealed that lead in the atmosphere has increased globally 100-fold over the past thousands of years, starting with ancient silver refining, continuing with widespread industrial emissions of lead hundreds of years ago, and the even larger scale use of leaded gasoline fuels in past decades. In urban environments and modern man, Pat showed that the amount of lead enrichment over prehistoric natural levels is about 1000-fold. He further showed that the global extent and patterns of lead contamination could be "finger printed" using precisely measured ratios of stable lead isotopes that are imprinted by the radiogenic nature unique to each lead ore.

Pat's discovery of the pandemic lead contamination of the Earth raised some of the first environmental concerns about the effects of metal toxicity on ecosystems and man. Lead is known to be a powerful toxin to the central nervous system. It has the capacity to seriously affect brain development and function. In spite of the seriousness of these implications, the entrenched economics vested in industrial lead use and their sponsorship of erroneous toxicological studies resulted in malicious attacks on Patterson. Fortunately, his lifelong institution, Caltech, resisted powerful commercial pressures to have him dismissed. Equally impugned were the damaged reputation of other scientists whose environmental data had been compromised from their use of sloppy or unclean analytical practices. In the end, Patterson fought back and won using the power of pure science and its accurate practice. In the end and in every detail, his data and conclusions have been shown to be correct.

Until quite recently, Pat preferred to keep the title of Geochemist at Caltech, rather than accept a tenured faculty appointment because he believed it might interfere with his penchant for research. In fact, he believed uncompromised research could not be achieved under a system of faculty tenure; it was hypocritical to this spirit, he felt. In spite of such a curmudgeon reputation and iconoclastic personality, Pat won the steadfast loyalty of his closest colleagues, including the



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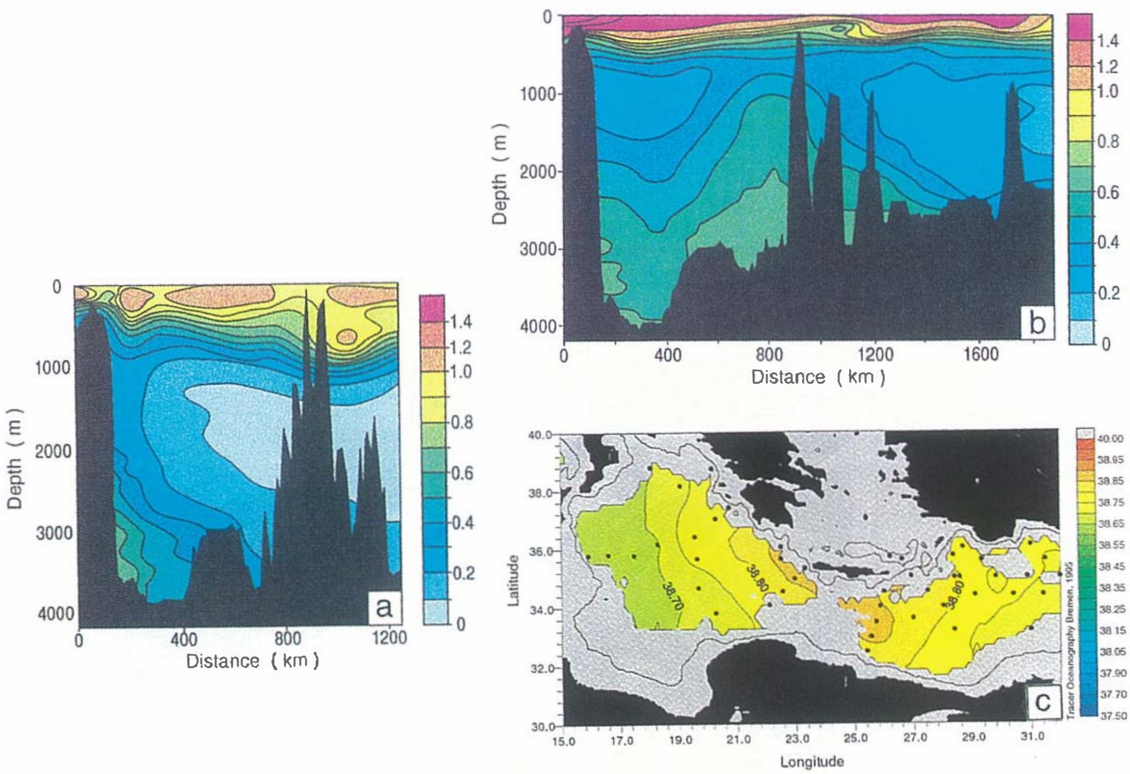

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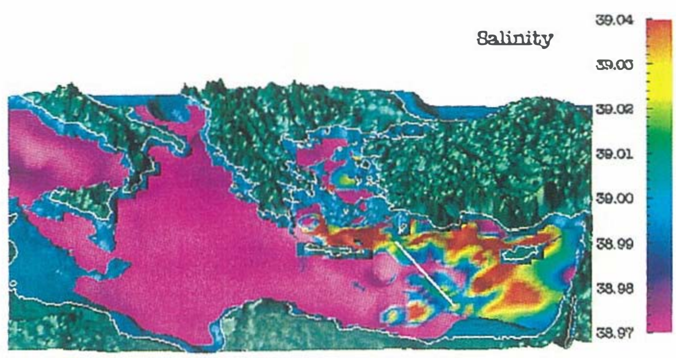

Sigma – t = 29.05 April 11, 1995

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