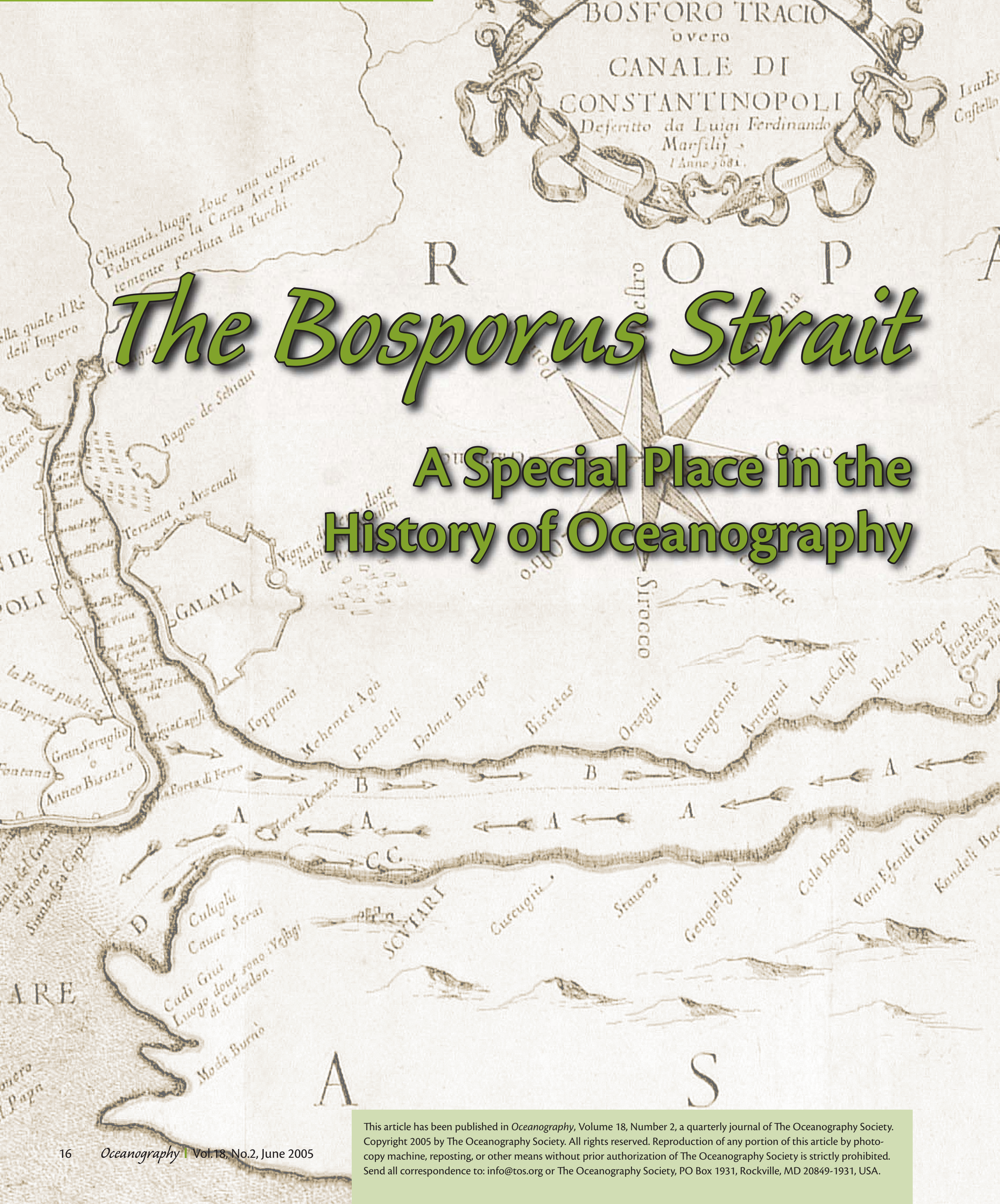
The Bosporus Strait

A Special Place in the History of Oceanography



BY BRUNO SOFFIENTINO AND MICHAEL E.Q. PILSON

The Black Sea and the Bosporus Strait hold an important place in the history of oceanography. In 1680, the impressive geographical features and remarkable current patterns of the Bosporus sparked the imagination of young Luigi Ferdinando Marsigli to solve the long-standing puzzle of two-layer flow. The observations and experiments were published in the 1681 book by Marsigli, originally published in Italian, *Observations around the Bosporus Strait or True Canal of Constantinople, Presented in a letter to Her Sacred Royal Majesty Queen Christina of Sweden by Luigi Ferdinando Marsigli*. (This book was recently translated into English by the authors of this article.) Marsigli understood that the Bosporus currents were a simple consequence of the different water densities in the Black and Mediterranean Seas. He demonstrated this density difference by building a physical model that captured the salient features of the phenomenon (Figure 1). Marsigli made a two-compartment box with the divider connected by two openings at top and bottom, and showed that waters of different densities in the two compartments would flow to the opposite side in a manner consistent with his observations. British scientists had long suspected that two-layer flow was occurring in places like the Strait of Gibraltar and the Skagerack, but at the time, no one had managed to convincingly demonstrate the existence of an undercurrent, nor had anyone put forth a convincing explanation for it.

The story of Marsigli in Istanbul, the breadth of his observations, and the premises of his famous experiment are very interesting but relatively unknown to oceanographers. This article therefore has two objectives: the first is to give an account of Marsigli's work that is more focused on his measurements and techniques than has ever been presented; the second is to understand how a 21-year-old man from a town uninvolved in matters of the sea managed to explain a phenomenon that had occupied the minds of many prominent British scientists and engineers for the previous 30 years. Most of Marsigli's measurements, when translated in modern units, turn out to be consistent with current knowledge and show that he was a remarkably keen and thorough experimentalist. We conclude that Marsigli was the right man in the right place: his unique educational background and experience in hydrostatics, ostensibly inappropriate for the study of sea currents, came to fruition thanks to a locality—the Bosporus—that was exceptionally well suited for observation and measurement.

TRAVELING TO ISTANBUL

Luigi Ferdinando Marsigli's eventful journey began on July 22, 1679 when he set sail from Venice for Istanbul. He was a "junior member" of the Venetian embassy to the Ottoman court, where he would be working as a messenger between the Turkish and Venetian diplomats. This was the first trip abroad for this 21-year-old. The connection with the Venetian embassy was a wonderful opportunity to spend time with scholarly people, Italian and foreign, and to learn about other cultures, including Muslims, that westerners found fascinating and disquieting in equal measure (Stoye, 1994). In the mid- to late 1600s, Ottoman relations with the rest of Europe significantly chilled, and the work of Western diplomats became proportionately more difficult (Abbot, 1920). Harassment of foreign envoys and restriction of their movements in and around Istanbul was a frequent occurrence. Within the overall dismal spectrum of European-Ottoman relationships, the Ottoman's relationship with Venice was among of the worst. Accused of espionage immediately upon arrival, Marsigli's diplomatic party faced an uphill battle from the start and prematurely left Istanbul less than a year later, carrying sanctions against Venice that were to be enforced for more than a century (Stoye, 1994). Despite all of this, Marsigli was surprisingly immune from this hostile situation, most likely as a consequence of his young age and lower rank, and his propensity to learn the local language and customs. This was fortunate, as he certainly could not have carried out the range of observation that we know about without the ability to freely move

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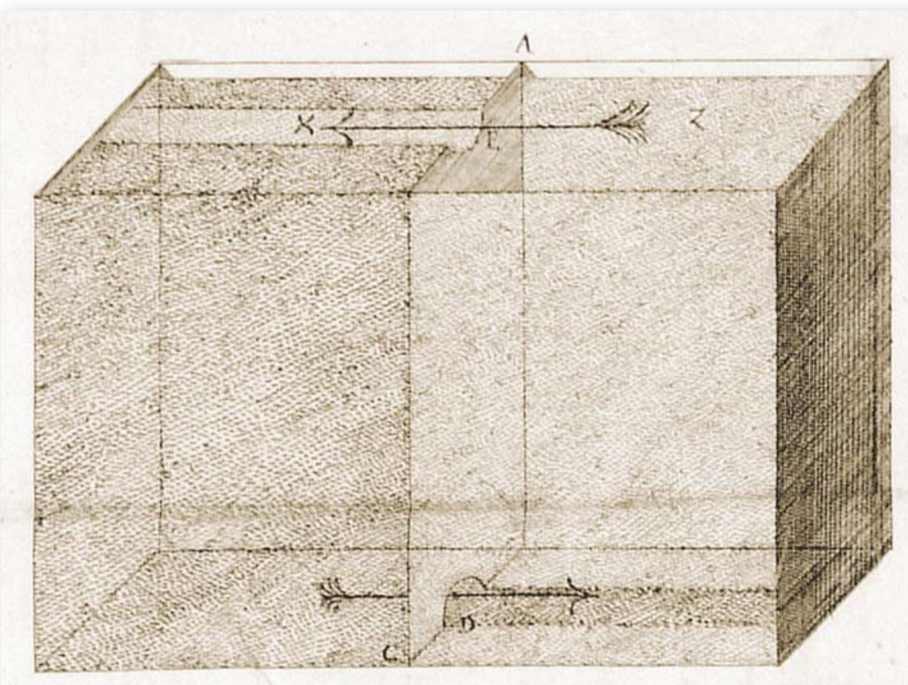

Figure 1. Luigi Ferdinando Marsigli's physical model of gravity-driven, two-layer flow, published in 1681. The model consists of a box divided by a partition (A) with openings at top and bottom, containing water of different density in the two compartments. Dense water (dark-colored side) flows to the opposite compartment through the bottom opening, causing lower-density water (light-colored side) to move in the opposite direction through the top opening. The conceptual synthesis of this model arose from the combination of Marsigli's atypical background in hydraulics and hydrostatics, his careful measurement of water densities in the Mediterranean and Black Seas, and the unique geographical and hydrological features of the Bosporus Strait.

about, and he could not have learned so much about the region without access to local people.

Marsigli made a remarkable range of observations during his voyage to Istanbul. He measured the density of waters at various locations in the Bosporus Strait and the Mediterranean and Black Seas. He measured the speed of the Bosporus surface current with a new type of current meter, and he determined the depth at which the flow reversed direction. He drew a map of the Bosporus region, reportedly using only a compass. He used a barometer to compare the height of various locations to sea level and surmised that the Black Sea and the Sea of Marmara were at the same altitude. He made repeated observations of the water level and meteorological conditions in Istanbul and correctly concluded that tides were imperceptible in the area, and that wind and weather were instead most important in determining water height. He illustrated an oil seep in the isle of Zakinthos. He gave an account of the seasonal migrations of fish to and from the Black Sea. He dissected and illustrated the anatomy of a mollusk, probably a mussel (Marsigli, 1681). For the purposes of this article, we will only concern ourselves with the measurements and observations that are pertinent to his model of two-layer flow.

MARSIGLI'S OBSERVATIONS OF TWO-LAYER FLOW

The most important measurement that led Marsigli to understand the causes of two-layer flow was water density, or "weight," as he describes it. Marsigli brought from home a "hydrostatic ampoule," or hydrometer, that he acquired from one of his teachers, Geminiano Montanari. With this instrument he measured the weight of water of the Adriatic and Aegean Seas, at several locations in the Sea of Marmara and the Black Sea, and of water retrieved from the undercurrent. We have found no evidence that Montanari encouraged Marsigli to make those measurements, and as far as we can tell, Marsigli was at the time of departure unaware of the two-layer flow problem. The hydrometer is not pictured in *Observations*, but from its sketchy description, it seems to have been similar to a later design found in Marsigli's 1725 book *Histoire Physique de la Mer*. It consisted of a small, long-necked bottle weighted with enough lead shot that it could float upright, on which metal rings of known weight could be placed until it sank to a reference mark. From Marsigli's reported weight of rainwater (42 grains), of water off the coast of Izmir (82.5 grains), the average value of salinity in that region (~38 ppt) (Miller et al., 1970), and a metric conversion of 0.055g/grain (Zupko, 1981) we calculated that the bottle had a volume of about 79.1 ml, a reasonable size for that type of instrument.

Marsigli found that Black Sea water at the northern mouth of the Bosporus weighted 56.25 Venetian mint grains. This corresponds to a salinity of about 12.5 ppt. Such a value is not inconsistent with what is found today at that location (16.5 ppt; Ozsoy et al., 1993). He also found that water from the undercurrent was 10 grains heavier than surface water, which corresponds to a salinity difference of about 8.7 ppt. This is less than the difference between the two end-member waters, so it is probable that his sample did not come from the bottom of the channel, where the salinity would be close to that of Mediterranean water.

Marsigli was intrigued by local reports on the current patterns of the Bosporus. Fishermen told him that fishing nets cast from the stern of boats anchored in the canal would resurface in front of the boat if allowed to sink to a certain depth. He also found out from an English merchant, Sir Dudley North, that an English ship captain had lowered a weight in the water and had seen it change direction of drift when it reached a certain depth.

Encouraged by John Finch, the English ambassador in Istanbul, Marsigli set out to investigate the currents. He surveyed the Bosporus and sketched a chart showing the essential features of the area (Figure 2). Compared to a modern map, the scale is only approximate, but considering the fact that it was drawn using only a compass and no surveying instruments, it is remarkably good for such a large geographical area. The compass orientation is fairly accurate, and the localities are in the right relative position. The surface currents also appear correct. The small nearshore currents running opposite to the main direction of flow are obviously eddies caused by local topography. Marsigli correctly interpreted currents C and D as such, but he incorrectly interpreted current B as a freshwater plume from the river that discharged in Istanbul harbor. Current D is a curious case: it is located in what is today the harbor of Haydarpasa, north of Cadi Koi; however, there is no report of this eddy in modern sources. Consulting a navigation chart, it is apparent why. Today the harbor is protected by two large breakwater jetties that prevent any significant circulation.

To measure the intensity of the surface flow, Marsigli had someone build for him a paddle-wheel current meter:

Figure 2. Marsigli enjoyed many opportunities to explore the Bosporus during his 11-month stay in Istanbul; this map summarizes many of the observations that he made. The map is remarkably accurate considering it was drawn without surveying instruments, using only a compass for orientation. The currents of the Bosporus were by no means young Marsigli's only interest in Istanbul: he observed and noted details of the fauna, flora, geography, and meteorology, as well as of the politics, military, and social customs of the place. The latter information would eventually become very useful to him in a few years' time, when fighting the Turks as a Habsburg army officer.

"*...a machine [made] out of wood, consisting of a wheel with six paddles, each two palms, four inches, and two quarts of Roman measure in length; in the wheel I placed an axle seven palms long, on which I mounted an index one palm and two quarts long at one end, for the purpose of showing the revolutions that the wheel made as it was held horizontally and was propelled by the water, that struck it at right angle in its submerged portion. In such position, the index made thirty-eight revolutions in the time of one-hundred swings of a pendulum eight inches and six eighths long*" (Marsigli, 1681, p. 27).

According to Frazier (1974), this is the first recorded use of this current meter design. Translation of the dimensions into modern units (Zupko, 1981) reveal that the paddles were between 33.1 and 42.9 cm long, and the axle about 87.5 to 156.4 cm long[1]. The current was measured by counting the revolutions of the index during 100 swings of the 16.8 cm-long pendulum. Marsigli does not report in *Observations* whether or not someone assisted him with the measurements, but we find it difficult to imagine that he could have done it alone. A pendulum of those dimensions has a relatively short

[1] The range of metric values has to do with the fact that "palms" and "quarts" units varied from city to city, and from trade to trade. Because Marsigli did not specify which ones he used, we translated all the ones that seemed likely candidates.

period, so counting swings and revolutions at the same time would seem quite a challenging exercise. In either case, at the southern end of the Bosporus, the current was 38 revolutions per 100 swings, which translates to approximately 2 to 2.5 knots accounting for the uncertainty in the dimensions and assuming a one-to-one correspondence between current velocity and tangential velocity of the wheel. This flow velocity is lower than the modern value of 3 to 4 knots known in that locality. The underestimation might have been due to the fact that one of the paddles broke shortly after deploying the instrument (!!), as Marsigli reported; otherwise it could have been that the instrument was deployed near shore, where the current is weaker. Comparing this measurement with others in different parts of the Strait, Marsigli correctly concluded that the surface current was higher in the narrowest part of the canal, at the Rumeli Castle, and that at that location it was one-third greater than at the southern mouth.

Marsigli did not have the means to measure the undercurrent, but he investigated it by lowering into the water a weighted piece of wood painted white, or a simple lead weight, and noticing the direction and strength with which the rope pulled his hand as it changed depth (Figure 3). At the southern end of the Bosporus, Marsigli found the current switching direction "...with great haste and strength at a depth of 8, 10, or 12 Turkish Paces, each Pace being approximately equivalent to the distance between the open arms of a man of average size" (Marsigli, 1681, p. 56). Given that an arm span is approximately equal to height (Schott, 1992), a reasonable metric guess for the Turkish Pace would be around 1.7 m, and the measured depths would correspond to 14, 17, and 20 meters. These figures are consistent with modern knowledge: the depth of the interface is known to vary between 10 and 20 meters (Ritchie, 1969) at the southern mouth where Marsigli was stationed. Marsigli also managed to get a sample of water from the undercurrent: "...with the use of a vessel, closed with a valve that I could open with a rope while submerged, I collected waters that I found weighed ten grains more than on the surface of the Canal" (Marsigli, 1681, p. 74). Unfortunately, no further description of the vessel is given. It would be interesting to know whether it was some ad hoc design, or whether it was similar to the design of Robert Hooke, who had, a couple of decades earlier, constructed a vessel for sampling subsurface water (Deacon, 1997).

Finally, Marsigli checked whether the Black Sea was at a higher elevation than the Sea of Marmara. He did this by taking a barometer to various locations and comparing the height of the mercury column, and found that, if anything, the Black Sea was lower than the Sea of Marmara. Of course, this seems like a useless exercise to us, as a barometer would never be able to detect such small differences in elevation above sea level amidst the meteorological variations of atmospheric pressure. In *Observations*, Marsigli made the remarkable statement that "...although I don't consider inclination important in this Canal, I report to Her Majesty the relative level [of Black Sea and Sea of Marmara] that can be read with the Mercury, or Torricellian Tube..." (Marsigli, 1681, p. 33). It is hard to tell whether this statement is made with the benefit of hindsight, or whether Marsigli truly thought all along that channel slope would not account for the flow.

Marsigli built his famous "box" (Figure 1) in Italy, upon his return from Istanbul, and tested it in the presence of Luc'Antonio Porzio, a physician from Padua who later made his name for writing the first treatise on water purification using sand filters. Upon encouragement from (ex) Queen Christina of Sweden, whom he visited in Rome, Marsigli wrote up his Istanbul experiences and results in the compact little book that was published in Rome in 1681 (i.e., *Observations*). The book reached the Royal Society of London in 1684, and although the two-layer flow problem had interested British scientists for some time, the significance of this work went largely unnoticed (Deacon, 1997).

MARSIGLI'S BACKGROUND

What special attributes of Marsigli's background put him in the position to understand the causes behind two-layer flow? The evidence points to an unusually diverse education. Marsigli was born in an affluent, noble family of Bologna, and had access to good education in the form of private tutoring by local university professors. His teachers were some of the best Italian scientists of the time: the astronomer, mathematician, and hydrologist Geminiano Montanari; the physician Marcello Malpighi; and the botanist Lelio Trionfetti. Though Marsigli showed considerable inclination toward mathematics and the natural sciences, he never enrolled in the university and never obtained a formal degree. There is no evidence that he ever considered an academic career. Instead, he was interested in politics and government, and ultimately he became an army officer at the service of the Habsburg Empire and

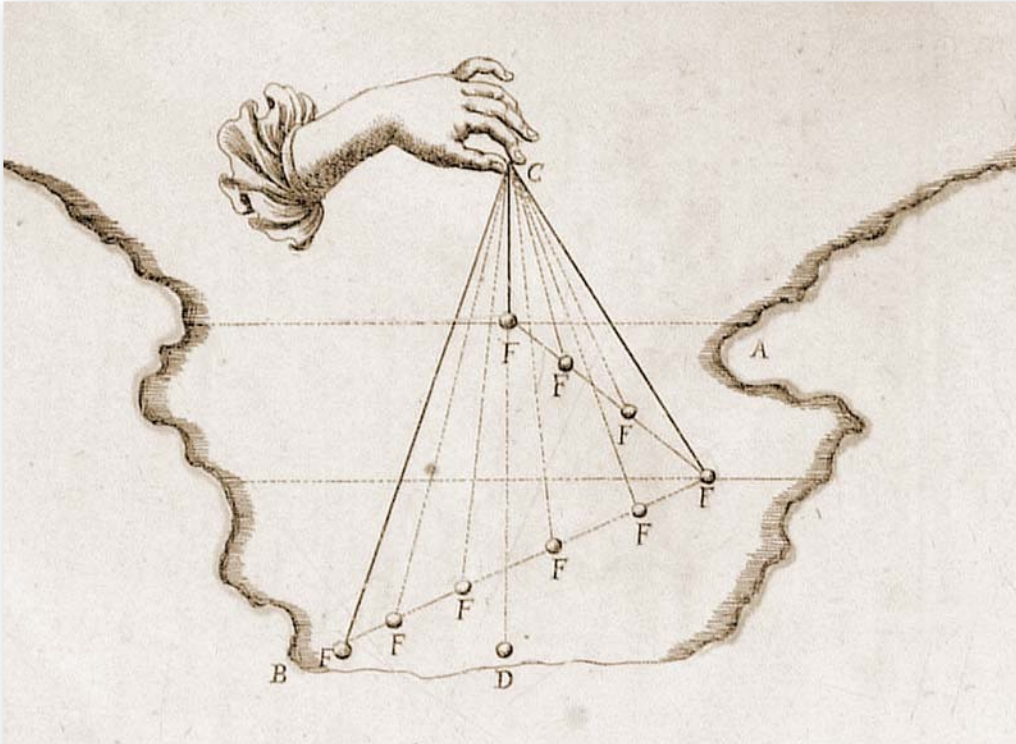

Figure 3. This drawing depicts the behavior of a tethered weight lowered through the water column from a boat anchored in the middle of the Bosporus channel. Marsigli carried out this experiment to demonstrate the presence of an undercurrent running opposite to the surface current. As the weight crossed the two oppositely running water layers, the currents dragged the weight in the opposite direction. He correctly estimated that the depth of this boundary varied between 10 and 20 m on different occasions.

remained a professional soldier, with varying degrees of fortune, for the rest of his life. The most peculiar feature of this eccentric character is that throughout his life he remained a scientist at heart, making observations, drawing, publishing, and patronizing science under the most extraordinary and often unfavorable circumstances (Stoye, 1994).

Geminiano Montanari appears to have had the most significant influence on Marsigli's thinking on water movement. An astronomer and mathematician by training, Montanari was hired by the University of Bologna in 1664, and soon after arriving he founded the Accademia della Traccia, a scientific society that he lead from 1665 until 1677. Montanari became interested in problems of hydrostatics and water movement, and with his student Guglielmini (a contemporary of Marsigli), he became a central figure in the late 1600 Italian school of hydraulics (Maffioli, 1994). Curiously, Montanari never formally taught this subject at the University, despite the fact that Bologna had long been confronted with water issues because of the recurrent floods of the river Reno. Montanari performed experiments on the equilibrium level and flow of fluids of different density (e.g., water and mercury) in various systems of connected vessels, and discussed the results at gatherings of his Accademia, which were held in an informal and convivial atmosphere mostly in his own home. These meetings could be attended by anybody with an interest in the discussions without distinction of social status, an unusual arrangement in those days. In the spirit of this casual organization, detailed records of the minutes and participants were never kept, but from Montanari's correspondence, it is known that Marsigli was a frequent attendee. The conceptual ancestry of Marsigli's physical model of the Bosporus is suggested by the descriptions and drawings of some of Montanari's experiments (Maffioli, 1994), and by the fact that, in *Observations*, Marsigli often refers to the teachings of his mentor Montanari.

The young man from Bologna was, therefore, well equipped to tackle the two-layer flow problem: he had learned principles of hydraulics and hydrostatics from a pioneer of the field, and he had participated in experiments and demonstrations of fluid processes akin to those he would find in nature.

SERENDIPITY

As we thought about the details of Marsigli's methods, experiments, and background, we realized that in and of themselves they were not sufficient to have led Marsigli to his conclusions about two-layer flow. The Bosporus was the other necessary ingredient. We could not think of another place but the Bosporus where Marsigli could have fruitfully applied his knowledge. In no other place where two-layer flow is known to occur are two basins with so strikingly different water properties as the Black Sea and the Mediterranean Sea connected by such a small channel over such a small geographical area. As keen an observer as he was, it is unlikely that Marsigli would have understood the causes of two-layer flow had he not been able to observe so closely the conspicuous current pattern, and to make measurements of density in water from the two communicating basins and from the oppositely flowing layers. The causal association of the currents to the different density of the water was possible because the Bosporus represented a natural analog to the experimental settings that Marsigli had seen. It was close enough in spatial scale and properties to allow the conceptual extrapolation.

Imagining Marsigli carrying out his observations in the Strait of Gibraltar makes this apparent. He could not have anchored a boat in the middle of the channel, and he could not have unmistakably detected a change in the flow direction with depth. Water samples clearly coming from the bottom layer would have been very difficult to retrieve. Furthermore, to realize that Mediterranean and Atlantic waters have different densities, samples of the Mediterranean would have had to be collected hundreds of miles from Gibraltar, and even then they would have been only slightly different (by hydrometer measurement) from the Atlantic.

This reasoning also suggests why the British did not came up with an explanation for two-layer flow despite their long-lasting concern with the currents in the Strait of Gibraltar. Although British scientists had anecdotal evidence for an undercurrent in Gibraltar similar to that available to Marsigli in the Bosporus, they could never take the next step and produce irrefutable, tangible evidence by systematic investigation. They were simply working in a setting that was inaccessible to human measurements. They could not go to the Strait of Gibraltar day in and day out and observe the undercurrent and convince themselves that it existed. When Edmond Halley satisfactorily explained the surface current in Gibraltar as the result of net evaporation in the Mediterranean (Deacon, 1997), he and other British scientists had no urgency to search for a new model, in the absence of pressing evidence for an undercurrent.

In conclusion, Marsigli owes his place in oceanography to two equally important elements: his conceptual preparation toward explaining what he would eventually see, and the unique and easily accessible features of the Bosporus region. Upon close inspection, there is a third ingredient in Marsigli's success story that cannot be disregarded: a lucky twist of fate. Who knows if he would have had a place in the history of science, had the departure of the Venetian ambassador not been delayed by personal reasons, allowing young Luigi Ferdinando Marsigli to get back from his travels and join the party leaving for Istanbul (Stoye, 1994)?

ACKNOWLEDGEMENTS

We owe special thanks to Ms. Roberta Doran, Head Librarian of Pell Library, Graduate School of Oceanography, URI, for her efforts in finding and obtaining copies of Marsigli's book and other references.

REFERENCES

Abbott, G.F. 1920. *Under the Turk in Constantinople.* MacMillan and Company, London, UK.

Deacon, M. 1997. *Scientists and the Sea, 1650-1900: A Study of Marine Science.* 2nd ed. Ashgate Publishing Company, Burlington, VT.

Frazier, A.H. 1974. *Water Current Meters in the Smithsonian Collections of the National Museum of History and Technology* [now the National Museum of American History]. Smithsonian Institution Press, Washington, D.C.

Maffioli, C. 1994. *Out of Galileo: The Science of Waters* 1628-1718. Erasmus, Amsterdam.

Marsigli, L.F. 1681. *Osservazioni Intorno al Bosforo Tracio overo Canale di Constantinopoli Rappresentate in Lettera alla Sacra Real Maestá Cristina Regina di Svezia da Luigi Ferdinando Marsigli.* Nicoló Angelo Tinassi, Roma. Translated into English by B. Soffientino and M.E.Q. Pilson.

Marsigli, L.F. 1725. *Histoire Physique de la Mer.* Amsterdam, NL.

Miller, A.R., P. Tchernia, and H. Charnock. 1970. *Mediterranean Sea Atlas of Temperature, Salinity and Oxygen From Cruises of R.V.* Atlantis *and R.V.* Chain. Woods Hole Oceanographic Institution, Woods Hole, MA USA.

Özsoy, E., Ü. Ünlüata, and Z. Top. 1993. The evolution of Mediterranean water in the Black Sea: interior mixing and material transport by double diffusive intrusions. *Progress in Oceanography* 31:275-320.

Ritchie, G.S. 1969. *The Black Sea Coast Pilot, Comprising the Dardanelles, Marmara Denizi, the Bosporus, Black Sea, and Sea of Azov.* 11th ed. Royal Hydrographer of the Navy, London, UK.

Schott, G.D. 1992. The extent of man from Vitruvius to Marfan. *Lancet* 340(8834-8835):1518-1520.

Stoye, J. 1994. Marsigli's Europe, 1680-1730. *The Life and Times of Luigi Ferdinando Marsigli, Soldier and Virtuoso.* Yale University Press, New Haven, CT.

Zupko, R.E. 1981. Italian Weights and Measures from the Middle Ages to the Nineteenth Century. *Memoirs of the American Philosophical Society* (Memoir 145). American Philosophical Society, Philadelphia, PA.