Marine sediments tell it like it was

John P. Smol*
Paleoecological Environmental Assessment and Research Laboratory (PEARL), Department of Biology, Queen's University, Kingston, ON, Canada K7L 3N6

We live in a constantly changing environment. Although some changes are natural and therefore beyond our control, there is no question that many anthropogenic activities have dramatically altered our planet. The "human footprint" is now discernable around the globe, so much so that Crutzen (1) proposed a new geological epoch (the Anthropocene) to delineate the recent human-dominated era of Earth's history. The list of environmental problems that can be related to cultural activities continues to grow, including ecosystem changes linked to climatic warming from elevated greenhouse gas emissions, acidic precipitation, industrial pollutants, invasions of exotic species, as well as many other environmental insults. While new problems continue to be recognized, perhaps the oldest and most commonly reported water quality problem is anthropogenic eutrophication, or the overfertilization of waters by excessive nutrient inputs (especially nitrogen and phosphorus). Typically, anthropogenic nutrient sources can be divided into point and nonpoint sources. Point sources include those with easily defined origins, such as a sewage pipe or nutrient-rich industrial effluent from a factory. Nonpoint or diffuse sources, such as agricultural runoff from fertilized fields, are more difficult to control. Nutrients are of course essential for biological growth; however, excessive enrichment can result in numerous undesirable effects, such as increased algal blooms (including some toxic forms), excessive growths of certain aquatic macrophytes and periphytic algae (with the displacement of other biota), taste and odor complaints, decreased oxygen levels in deeper waters (which can eventually result in fish kills and the extirpation of some benthic species), and major shifts in food web structures and biogeochemical changes in both the water column and sediments. Loss of ecosystem services, as well as declines in fisheries and tourism, can also have many social, health, and economic ramifications. Daunting challenges become evident, however, when one attempts to track and study these environmental problems, because monitoring data are rare or nonexistent for most aquatic ecosystems. Most environmental assessments are done only after a problem has been identified. Therefore, without long-term observations, how can environmental scientists, water quality managers, and policy makers be certain that ecosystems have been detrimentally affected by human activities and that current observations are not simply reflecting "natural" conditions and/or falling within the boundaries of natural variability? In this issue of PNAS, Kidwell (2) proposes one method to answer these questions: by examining compositional differences between living and dead mollusk assemblages in a suite of estuaries and lagoons.

Paleoenvironmental Perspectives on Reconstructing Missing Data Sets

For most aquatic ecosystems, little or no long-term monitoring data exist (3). Fortunately, a variety of "natural archives" can be exploited to gather proxy data on past environmental conditions. For example, polar and alpine ice cores have been used widely to track past climatic and other environmental changes. Information contained in tree rings, pack-rat middens, and cave deposits, to name just a few terrestrial examples, has also played a key role in environmental reconstructions (4). For aquatic systems, such as lakes, rivers, estuaries, and ocean environments, most of the key proxy data have been gathered by paleolimnologists and paleoceanographers from the physical, chemical, and biological information preserved in sediment profiles (3, 5).

"Natural archives" can be exploited to gather proxy data on past environmental conditions.

A considerable number of sedimentary studies are now available that have reconstructed past pollution trends and/or the ecological ramifications of human interventions on aquatic ecosystems. Much of this work has been completed in lakes, where proxy data (e.g., diatoms, other microfossils, isotopes, and geochemistry) in high-resolution sediment cores have been used to track past changes in acidification (6), cultural eutrophication (7), and other environmental problems (3). Similar approaches have been applied to estuarine and offshore sediments (e.g., see refs. 8–11). Typically, the paleolimnologist or paleoceanographer must collect a sediment core of appropriate quality and length for the study in question, section the sediment into time slices relevant for the investigation, date the material so as to establish geochronological control, and identify and analyze the proxy indicators under study (3). These detailed paleoenvironmental investigations can provide important insights on ecosystem change and can be used, for example, to determine preimpact reference conditions (i.e., those that predate the periods of marked human interventions), to track the trajectories of change associated with human impacts, to help define the boundaries of natural variability, and to assist in the setting of realistic mitigation goals. However, such detailed assessments are time consuming and are not practical for regional assessments where many sites have to be considered. In these cases, a shortcut or snapshot approach must be used.

Paleolimnologists, working on lake acidification in the 1980s, were charged with developing methods to define preimpact (i.e., pre-1850) pH levels for large numbers of lakes in acid-sensitive regions. Because many biological indicators, such as diatom or chrysophyte species, had reasonably well-defined pH optima, their remains in dated sediment profiles could be used to quantitatively reconstruct past lakewater acidity levels (6). Clearly, fine-resolution sediment analyses would not be feasible given the large number of study sites involved in some of these regional assessments. Instead, researchers developed the so-called "top–bottom" or "before and after" paleolimnological approach (12). Instead of analyzing a large number of detailed sediment cores, only two sediment samples would be analyzed per lake (not including replicate analyses completed to define sampling variability, etc.). The first sample was the core's

---

Author contributions: J.P.S. wrote the paper.

The author declares no conflict of interest.

See companion article on page 17701.

*E-mail: smolj@queensu.ca.

surface sediments (i.e., the top 0.5 or 1.0 cm of sediment accumulation), representing recent lake conditions, or the so-called "top" or "present-day" sample. The second sample was taken from a section of the sediment core that predated the environmental problem under investigation (in the acid rain examples cited above, this would be pre-1850 sediment layers), representing the "bottom" or "preimpact" sample. Then, by comparing environmental inferences from these two samples from a large number of lakes, regional assessments of environmental changes could be reconstructed showing changes between preimpact and present-day conditions. These snapshot approaches were subsequently used to investigate a variety of other types of environmental problems, including eutrophication (13), metal pollution (14), and taste and odor problems (15).

Environmental problems, such as anthropogenic eutrophication, are certainly not restricted to lakes; many coastal ecosystems have been severely affected by nutrient enrichment as well. For example, loss of sea grass (e.g., *Ruppia*) is a common symptom of eutrophication. With higher nutrient levels, this plant's competitive abilities are hampered by enhanced algal growth that results in increased turbidity and hence decreased light penetration. The loss of such an important habitat and food source cascades throughout the ecosystem. As Kidwell (2) shows, using mismatches between the composition of living and death (i.e., dead remains sieved from the upper sediments) molluscan assemblages from lagoons and estuaries, before-and-after snapshot approaches can be used to reconstruct faunal changes associated with eutrophication. Such temporal data can then be used to show where and how much change has occurred because of human activities.

Of course much can (potentially) go wrong with these types of investigations. For example, researchers must first demonstrate that preservation artifacts or mixing processes have not blurred the record to a degree that would make inferences meaningless. However, as Kidwell (2) shows with her molluscan study, the reliability of these proxy records can often be assessed, and the signals of environmental changes deciphered with these approaches are often stronger than any confounding effects related to taphonomic or other processes. As with earlier paleolimnological work, researchers may often be overly pessimistic concerning the fidelity of their approaches because one can easily think of a wide spectrum of reasons why these and similar procedures may not work. Nonetheless, by comparing proxy inferences to the few places where instrumental and other monitoring data are available, one can "ground truth" many of these approaches and independently assess the reliability of the records (3). The success of these investigations should empower other researchers to develop similar methodologies for other indicators and environmental settings.

The Future Looks Bright for Reconstructing the Past

Examining assemblage changes is clearly the first (and most important) step in biologically based environmental assessments, such as those described by Kidwell (2). Hopefully, the success of this study will be a catalyst to examine new approaches and indicators from similar environments. As has been done with other indicator groups, the environmental optima and tolerances of individual mollusk taxa can be defined more clearly, thus fine-tuning environmental inferences. Furthermore, coastal sediments also preserve a wide array of other morphological, biogeochemical, and physical indicators of environmental change. Multiproxy studies, although not without their own challenges (16), can be used to provide more holistic overviews of ecosystem change because different sources of proxy data provide additional information on environmental change (3).

Importantly, there is still a considerable library of information waiting to be tapped from mollusks, in addition to shifts in taxonomic assemblages. For example, the shells can be analyzed for a variety of chemical and isotopic variables that can increase the volume of information extracted from these indicators. The developing field of sclerochronology, which uses calcified structures (such as mollusk shells) to reconstruct environmental conditions (17), has considerable potential to provide very-high-resolution records of water quality changes. For example, by measuring the chemical and/or isotopic content of mollusk shells, which retain at least a partial "memory" of past water quality conditions, additional information can potentially be gleaned, including past changes in metal contamination (18) and oxygen depletion (19). By examining changes in the annual growth rings of some mollusk shells, there is even the possibility of tracking environmental changes at a subannual level.

A Muddy Past Made Clearer

Some may argue that the snapshot approaches, such as those described here, still lack the accuracy and precision needed for environmental assessments. However, when no data exist on past changes, then even some data are better than no data at all. To paraphrase Håkanson and Peters (20), if one is going into battle, then a blunt battle-axe is better than no weapon at all. Given the magnitude of environmental problems affecting our planet today, we do not have the luxury of dismissing any procedures that will provide a better understanding of how our activities have affected ecosystem functions. The approach espoused by Kidwell (2) on using mollusks to reconstruct preimpact ecological baseline conditions in lagoons and estuaries is one key step in that direction.

1. Crutzen PJ (2002) *Nature* 415:23.
2. Kidwell SM (2007) *Proc Natl Acad Sci USA* 104:17701–17706.
3. Smol JP (2008) *Pollution of Lakes and Rivers: A Paleoenvironmental Perspective* (Blackwell, Oxford), 2nd Ed.
4. Bradley RS (1999) *Paleoclimatology: Reconstructing Climates of the Quaternary* (Academic, San Diego).
5. Cohen AS (2003) *Paleolimnology: The History and Evolution of Lake Systems* (Oxford Univ Press, Oxford).
6. Battarbee RW, Charles DF, Dixit SS, Renberg I (1999) in *The Diatoms: Applications for the Environmental and Earth Sciences*, eds Stoermer EF, Smol JP (Cambridge Univ Press, Cambridge, UK), pp 85–127.
7. Finsinger W, Bigler C, Krähenbühl U, Lotter AF, Ammann B (2006) *J Paleolimnol* 36:55–67.
8. Cooper SR, Brush G (1991) *Science* 254:992–996.
9. Bianchi TS, Engelhaupt E, Westman P, Andrén T, Roff C, Elmgren R (2000) *Limnol Oceanogr* 45:716–726.
10. Gupta BKS, Turner RE, Rabalais NN (1996) *Geology* 24:227–230.
11. Weckström K (2006) *J Paleolimnol* 35:571–592.
12. Cumming BF, Smol JP, Kingston JC, Charles DF, Birks HJB, Camburn KE, Dixit SS, Uutala AJ, Selle AR (1992) *Can J Fish Aquat Sci* 49:128–141.
13. Dixit SS, Smol JP, Charles DF, Hughes RM, Paulsen SG, Collins GB (1999) *Can J Fish Aquat Sci* 56:131–152.
14. Rognerud S, Fjeld E (2001) *Ambio* 30:11–19.
15. Paterson AM, Cumming BF, Smol JP, Hall RI (2004) *Freshw Biol* 49:199–207.
16. Birks HH, Birks HJB (2006) *Veg Hist Archaebot* 15:235–251.
17. Schöne R, Surge D (2005) *Palaeogeogr Palaeoclim Palaeoecol* 228:1–3.
18. Ravera O, Trincherini PR, Beone GM, Maiolini B (2005) *J Limnol* 64:113–118.
19. Nyström J, Dunca E, Mutvei H, Lindh U (1996) *Ambio* 25:350–355.
20. Håkanson L, Peters RH (1995) *Predictive Limnology* (SPB Academic Publishing, Amsterdam).