Refining and Defending the Vail Sea Level Curve

The latest, most detailed version of Exxon's controversial record of changing sea level continues to gain supporters

In this issue of *Science* (p. 1156), Bilal Haq, Jan Hardenbol, and Peter Vail of Exxon Production Research Company in Houston present the most detailed version yet of their curves depicting the fluctuations of global sea level during the past 250 million years. The curves also double as a set of temporal bookmarks that allow geologists to identify and date sediments no matter where in the world they are reading the marine geologic record.

This potentially momentous contribution to geology by Exxon has been the "subject of a lively debate," as the authors put it, since Vail, who is now at Rice University, presented the first version 10 years ago. In part, the problem has been perceived errors of interpretation, which have been resolved. Exxon's 1977 curves turned out to be a measure not of the changing height of the sea per se but the interplay of sea level, crustal sinking, and other factors. The awkward instantaneous sea level falls of this early version have since been smoothed out. Some uncomfortably large sea level changes have also been moderated.

But the slow acceptance of the Vail curves, as they are known, derives largely from the failure of Exxon to release most of its data on continental shelf sediments from which the curves are derived. These oil exploration data are largely proprietary and beyond the means of academic researchers to reproduce. There being only spotty data outside the oil industry, public confirmation of specific events as global phenomena has been slow.

The Exxon researchers believe that they have now solved the data problem. They include in their new paper a list of about 40 rock outcrops around the world, each of which is universally recognized as the standard set of sediment layers for a particular few million years of the geologic record. They visited these heavily documented and quite public outcrops, as well as outcrops in other listed areas, to verify and refine their earlier curves that were based solely on continental shelf drill holes and seismic reflection profiling—the radarlike acoustic technique for imaging sediment layering.

The inclusion of outcrop studies has produced a "new-generation curve," says Hardenbol. It replaces the 1977 version, which had "suffered from incompleteness," he says. The correlation of the same sea level change as seen in the seismics and in wells had been "tentative, very approximate, and indirect," he says. Now, "we can see the same sequences [of sediment layers] if we go to an outcrop as we see in the seismics. You can go to any basin and use" these curves as a framework for identifying and dating sediment units. The new curves also include 58 minor sea level cycles—fully half of the cycles of the past 250 million years—that are rarely discernible in seismic profiles. And, say the Exxon researchers, the Vail curves are now clearly testable.

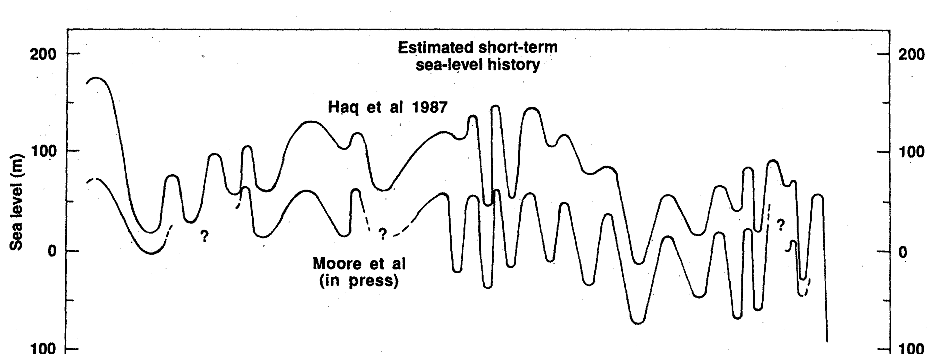
That may be a step in the right direction, say some researchers, but it still is not what they wanted to see. Wylie Poag of the U.S. Geological Survey (USGS) in Woods Hole, Massachusetts, has identified Vail sea level events on the U.S. Atlantic shelf, largely in a few wells and through seismics. "I was enthusiastic about the general framework of the Vail model," he says, "because it was simple enough that we could have some confidence in it. It seemed we could use it. But a second iteration such as this should be backed up by voluminous data and explanation. Without that, it's going to be hard to apply. It is a refinement and complication when we've hardly been able to apply the more simple system."

Although years will pass before geologists are able to compare the new Vail curve with enough outcrops to pass final judgment on it, new support continues to appear, often from elsewhere than the continental shelves. Erle Kauffman of the University of Colorado is under contract to Exxon to help fit the Cretaceous fossils and sediments of the central United States into the global Vail curve. These sediments were laid down 65 million to 145 million years ago when higher sea levels allowed the ocean to lap onto the central continent.

Cycles of changing sea level in the Cretaceous laid down sediments typical of sea levels that were rising, at highstand, falling, and at lowstand. In addition to forming these recognizable sequences, the cycles created the gaps in the sedimentary record bounding each cycle's sequence where exposed sediments eroded away, just as on the continental shelves. With the advantages of the continental interior's greater stability and with access to Exxon's own time scale, Kauffman and his colleagues set out to see how closely sea level curves constructed according to their own concepts of sequence interpretation matched the new Vail curve.

"What we're finding is a remarkably close correlation between our curves and theirs," says Kauffman. "They're holding up extremely well on very close scrutiny. I'm pleased and surprised. When they first came out, they weren't real sea level curves. Now they are." Those differences he does find can often be attributed to how the two groups judge where it was in the sediment pile that sea level began to fall faster than the continent was subsiding. The difference can amount to 0.5 million to 1 million years.

A major complaint has been that only Exxon researchers, with their worldwide



T. Moore, T. Loutit, and S. Greenlee

Two sea level curves—same wiggles, different magnitudes. *The two curves are similar, with the exception of two cycles, but the magnitude of the longer term fall on which the cycles are superimposed is much reduced in the curve of Moore* et al., *which is in line with another, independent estimate. Some peaks in the upper curve, which was derived from study of many sites, were not identified in the single-site study of the lower curve.*

data, were in a position to say whether global sea level change, called eustacy, or local subsidence of the rapidly cooling shelf crust created the sediment sequences. Kauffman thinks that that question has been resolved. "I believe we have global eustatic control overriding local control in 90% of the cases. I can take my epicontinental curves and match peak rises and falls around the world." The curves that work so well in North America, he says, work just as well in the Bohemian basin of Czechoslovakia.

Another piece of evidence comes from the deep sea, about as far from the complications of the unstable continental shelf as one can get. Sea level cycles do not affect deep-sea sedimentation directly, as they do on the shelves, but the forces that drive sea level change, such as the climate changes that control the size of polar ice caps and thus sea level, can also drive changes in the deep sea. Larry Mayer of Dalhousie University, Thomas Shipley of the University of Texas at Austin, and Edward Winterer of Scripps Institution of Oceanography have identified and dated eight points in the sedimentary record of the central equatorial Pacific at which changes in the chemistry of bottom water dissolved the carbonate component of the surface sediment or, in two cases, predisposed it to later alteration.

All eight of these deep-sea events of the past 25 million years coincide, within the 0.5-million-year or better precision of the group's dating, with highstands of sea level in the Vail curve. Mayer adds that Exxon researchers report that they have confirmed the coincidence of events by using their own time scale. All but one of the deep-sea events also coincide with the widespread or even global dissolution or erosion of sediments reported by Gerta Keller of Princeton University and John Barron of the USGS in Menlo Park, California.

"I didn't start out as a very strong believer in Vail curves," says Mayer. "I didn't know much about them. But after this work in the Pacific, these deep-sea events do look as though they tie into the Vail curves. There are major events that are globally synchronous."

Just how sea level and the deep sea might have been linked is unclear, but there are some ideas. One is that rising sea level flooded the continental shelves, trapping carbonates eroding from the continents. Starved of its usual supply of carbonate, the deep sea became depleted in dissolved carbonate. This more corrosive seawater could then dissolve carbonate sediments that had been preserved in shallower water depths, where seawater is normally less corrosive.

While the reality of the events depicted in the Vail curves gains increasing support, some characteristics of those events remain enigmatic. One question concerns the size of the sea level changes involved. "That is one of the most elusive parts of this story," says Hardenbol. "There has not been that much progress in the past few years. There are so many variables. I think we're in the right ball park, but I wouldn't be surprised if there were some downward adjustments."

Such adjustments may already be under way. Theodore Moore, Tom Loutit, and Stephen Greenlee, all members of groups within Exxon Production Research separate from those that include Haq, Hardenbol, and Vail, undertook an estimation of short-term sea level changes of the past 30 million years that after a point departed from the Vail approach.

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Moore, Loutit, and Greenlee used the downward tilt of sediment beds to estimate crustal sudsidence due to crustal cooling and the weight of sediments. That avoided the problem of any bias in the curve of long-term sea level change used by Haq and his colleagues to determine subsidence. Implicit in their use of this curve was the somewhat arbitrary assumption that sea level had not been much below its present level before major glaciation had set in.

Moore and his colleagues found that the amplitudes of their short-term events—the change from highstand to lowstand—as determined in the Baltimore Canyon area of the U.S. Atlantic shelf were in generally good agreement with those of the Vail curve. There were exceptions. The 100-meter event of 3.8 million years ago and the 160-meter event of 30 million years ago—one of the most dramatic falls in the entire record—do appear to be too large in the Vail curve, perhaps by more than 50 meters.

The timing and amplitudes of the rapid ups and downs of the Vail curve may be about right, but its estimate of sea level 30 million years ago appears to be twice as high as it should be, according to Moore. A smaller fall since 30 million years ago would put sequence analysis results in line with the 60-meter fall estimated by others from independent evidence, notes Moore.

Another independent assessment of broad sea level trends comes from work by Robert Halley of the USGS in Woods Hole on a 360-meter core recovered from Enewetak Atoll in the Pacific. He used the volcanic mountain forming the atoll as a dipstick on which sea level was marked by the growth of the coral reef as sea level rose and by the alteration of the coral as falling sea level exposed it to the weather. Halley found a sea level record of more than ten cycles during the past 20 million years that had amplitudes of 40 to 100 meters, not unlike the Vail curve. A major difference, he notes, is that the atoll record shows sea level being below the present level for most of the past 10 million years, while the Vail curve has it higher than the present level for about half that time. That would tend to support the existence of a bias in the Vail curve toward the high side, as indicated by the Moore, Loutit, and Greenlee curve.

Even if the record of the past few tens of millions of years can be adjusted to conform to the independent constraints being developed, there remains a major problem. Changes in the volume of glacial ice appear to be driving changes in sea level during the past 20 million or 30 million years, but short-term Vail cycles of similar amplitude appear as far back as 150 million years ago. The problem is that few researchers outside Exxon believe that more than a few alpine glaciers existed during the warm climate that prevailed earlier than 30 million to 50 million years ago. "We still think that ice would be the cause of those cycles," says Hardenbol, " but we don't have the proof of that."

An alternative mechanism has been proposed independently by Garry Karner of Lamont-Doherty Geological Observatory and Sierd Cloetingh of the University of Utrecht. They suggest that the Vail cycles may simply be the result of bending of the weakened crust of sedimentary basins by changes in stress on the tectonic plates in which the basins are embedded. The short-term cycles would reflect the jostling of plates, and major reorganizations of plate motion would produce the longer term cycles. The stress mechanism implies, however, that Vail cycles are regional, not global, events. Correlation of the Vail curves with outcrop records from around the world would thus seem to promise final vindication. ■ Richard A. Kerr

ADDITIONAL READING

L. A. Mayer, T. H. Shipley, E. L. Winterer, "Equatorial Pacific seismic reflectors as indicators of global oceanographic events," *Science* **233**, 761 (1986).
S. Cloetingh, "Intraplate stresses: A new tectonic mechanism for fluctuations of relative sea level," *Geology* **14**, 617 (1986).
G. Karner, "Effects of lithospheric in-plane stress on sedimentary basin stratigraphy," *Tectonics*, in press.