Sea Cycle Clock

By STEFI WEISBURD

Millions of years ago, along some ancient shoreline, the sea level fell. Winds and rain gradually ate away at the exposed rocks, weathering their surfaces. The eroded debris was carried to the ocean shelf, where it mixed with the remains of shallow-water organisms and formed a sandstone sedimentary layer that is preserved to this day.

Every process that shapes the earth's landscape—from sea level fluctuations to volcanoes and earthquakes — has left its calling card in the rock record. The geologist's job is to work backwards from this record, to interpret each stratigraphic layer as a chapter in the earth's history. And to do this, geologists need a way of marking geologic time.

The standard chronological yardstick is the stratigraphic time scale. Developed in the 19th century, this time scale divides the rock record into units that are classified according to the fossils they contain and, to a lesser degree, their rock type.

On March 6, SCIENCE published the most recent in a series of papers describing a relatively new approach for dating, correlating and explaining the origin of sedimentary layers. This approach, called seismic stratigraphy, has been applauded by many stratigraphers who say it is revolutionizing their science. But for some other scientists, especially those concerned with understanding the forces that change the face of the earth, seismic stratigraphy has been the focus of a decade of controversy.

Seismic stratigraphy was developed in the 1970s by Peter R. Vail and his colleagues at Exxon Production Research Co. in Houston. Vail's group studied Exxon's seismic reflection profiles — images of the crust produced by bouncing sound waves off of sediment and rock layers — of sedimentary basins. The profiles delineated "packages" of sediment that the researchers believe were deposited during different stages of sea level fall and rise.

Had the scientists profiled the basin in which that hypothetical sea level fall described above took place, they might have seen the outline of the sandstone deposit in one part of the basin. And in another part of the basin closer to the land, the seismic signals would have reflected off the "unconformity," or gap, in the rock layers, where there had been erosion and no deposits of sediment.

After examining reflection profiles of basins around the world, Vail's group saw some common patterns. The researchers found that the rock record everywhere is punctuated by unconformities and related sediment packages, which were presumably created at the same time all over the world by "eustatic" or global changes in sea level.

What's more, when the researchers dated these unconformities by looking at the fossils in oil-well holes, they concluded that the sea level had fluctuated in periodic cycles throughout the earth's history. Beginning in 1977, they published cycle charts showing changes in relative sea level as a function of time—important information for scientists studying such things as the earth's past climate and ocean circulation.

The realization that sea level changes have produced unconformities and sediment packages in the same-aged rocks around the world was a powerful one. Geologists using the traditional stratigraphic time scale can only roughly correlate the ages of rocks from different parts of the globe, because the fossils from these different places are rarely identical, given the great variations among the climates in which animals and plants live. But with Vail's global charts, a geologist might be able to directly link an outcrop containing a global unconformity in Australia with one in North America.

Vail's seismic stratigraphy has also been a godsend for oil companies. It enables them to hunt for oil in an unexplored area without going to the expense of drilling a lot of wells. Just by looking at a seismic profile, an oil company scientist can often tell where to drill for the porous, reservoir rocks that are made, for example, when coarse grained sands are deposited during low sea level stands.

"Seismic stratigraphy has saved the industry millions of dollars because it has given companies an inexpensive tool that doesn't require drilling before decisions have to be made," says Bilal U. Haq, who with Exxon colleagues Vail and Jan Hardenbol wrote the recent SCIENCE paper.

Even most critics of Vail's papers acknowledge the value of his work to regional oil exploration and stratigraphy. But the flares go up when Vail and his colleagues begin to interpret some sedimentary sequences in terms of *global sea level* change.

Most scientists do agree that the *slowly* changing cycles in the stratigraphic record were indeed made by global sea level changes. In particular, they think changes in the rates of seafloor spreading are responsible for both the "first-order" cycle, with its lowest sea level at 260 million years ago and its highest at about 90 million years ago, and the "second-order" cycles, which have periods of about 10 million to 110 million years.

Walter Pitman, James Hays and Michelle Kominz at Lamont Doherty Geological Observatory in Palisades, N.Y., have worked out the link between sea level changes and spreading rate: When ocean floor is churned out quickly at midoceanic ridges, the ridges tend to be broader. This displaces water in the ocean basin and pushes the sea up onto the land. Scientists believe that the first-order cycle in particular was caused by the changes in spreading rates associated with the formation and breakup of the supercontinent Pangaea.

But at third-order, higher-frequency cycles, with periods of about 1 million to 10 million years, the arguments begin. Vail thinks that these too were created by sea level fluctuations, brought on by the formation and melting of land glaciers. Other researchers agree that during some times (such as the Quaternary period starting 2 million years ago) the waxing and waning of ice sheets has triggered third-order sea level falls and rises.

"The problem is that we have absolutely no evidence whatsoever that there were regional ice caps anywhere in the world before the late Oligocene epoch [about 25 million years ago]," says Andrew D. Miall at the University of Toronto in Ontario. "In fact, most people assume the contrary, that the Cretaceous [65 million to 145 million years ago] was a period of unusually warm climate all around the world."

Vail says he's open to other ideas, but for now he believes that during these generally warm times there were short periods when there was an ice cap on Antarctica. He argues that the third-order fluctuations occurred too quickly to have been triggered by anything other than changes in the amount of land-ice drawing water out of the oceans.

Other researchers disagree. Lamont's Pitman thinks that tectonics, and in particular the subsidence or sinking of the ocean crust as it cools, has played the primary part in third-order cycles. After all, given a rise in the waterline on a beach, one cannot tell whether the land beneath the sea has fallen or the sea level has in fact risen.

Using tectonics, Pitman says, there are several ways to produce the same global strata patterns that Vail's group thinks resulted from a cycle of sea level rise to fall. One way, he says, would be for the sea level to continually fall, but for its fall rate to change with time. When, at the waterline, the fall rate was greater than the subsidence rate (which generally increases toward the sea), the net effect would be that the waterline would drop; when the fall rate was less than the subsidence rate, the waterline would move up the shelf until it reached a point where there two rates were equal. The resulting series of sedimentary deposits and unconformities, says Pitman, would look as if they had been deposited, with no land movement, by a complete cycle of sea level rise and fall.

Anthony Watts and his colleagues at Lamont have modeled basin subsidence to see if there is a time during the formation of a sedimentary basin when one effect – tectonics or sea level – might dominate over the other. They believe that tectonic movements are so vigorous early in basin formation that they can overwhelm any effects of sea level changes. But as a basin ages, Watts says, even small eustatic changes can control where the beach lies and the pattern of sediment deposits.

"We're saying that some of it is tectonics, while [Vail is] saying that nearly all of it is due to sea level," says Watts. "Maybe eventually we'll be able to agree on the various components."

If tectonics is important to the third-order cycles, says Watts, then the strata patterns cannot be global – as Vail's group claims – because not all basins formed at the same time or have the same tectonic history. This means that accurate dating of the unconformities and strata patterns is crucial.

"Unless you can correlate sea level changes very precisely with biostratigraphy and be convinced that they're the same age in all sorts of different basins, you have no basis to think that sea level change in those basins is controlled by one process," says Miall. "I am very doubtful that Vail's group can do this with the precision that they claim."

Counters Haq, "We are quite convinced that all the major events that we see are global."

Watts says he also suspects that the global sea level charts were constructed by "modal" averaging, in which some data are thrown out if they don't fit well with the rest of the information. "But this is just guesswork on our part," he says. "We don't know what they did. With two exceptions we couldn't see the parts that went into the whole."

Vail says his team has "never consciously thrown out information." He notes that he and his colleagues sometimes come across a datum that doesn't seem to fit the rest, but he says many of these anomalies have been resolved with more detailed study. "I may not know what causes [the higher-order cycles], but if you really look at the stratigraphic data you'll see these things going on," says Vail. Pitman, Watts and other critics "don't look at the stratigraphic data in the kind of detail [that we do], and so we've built up these differences," he adds.

And here lies the crux of much of the controversy. Some academic researchers say they have confirmed Vail's sea level charts in isolated spots; for example, in the Feb. GEOLOGY, C. Wylie Poag at the U.S. Geological Survey (USGS) in Woods Hole, Mass., and Lauck W. Wark at USGS in Reston, Va., report that their studies of outcrops, boreholes and seismic profiles of the U.S. and Irish margins in the Atlantic are consistent with Vail's lower-order sea level charts. But most of Vail's supporting seismic and drill-hole data, as well as some of Vail's methodology, have been kept proprietary and unavailable for scrutiny by researchers outside of Exxon.

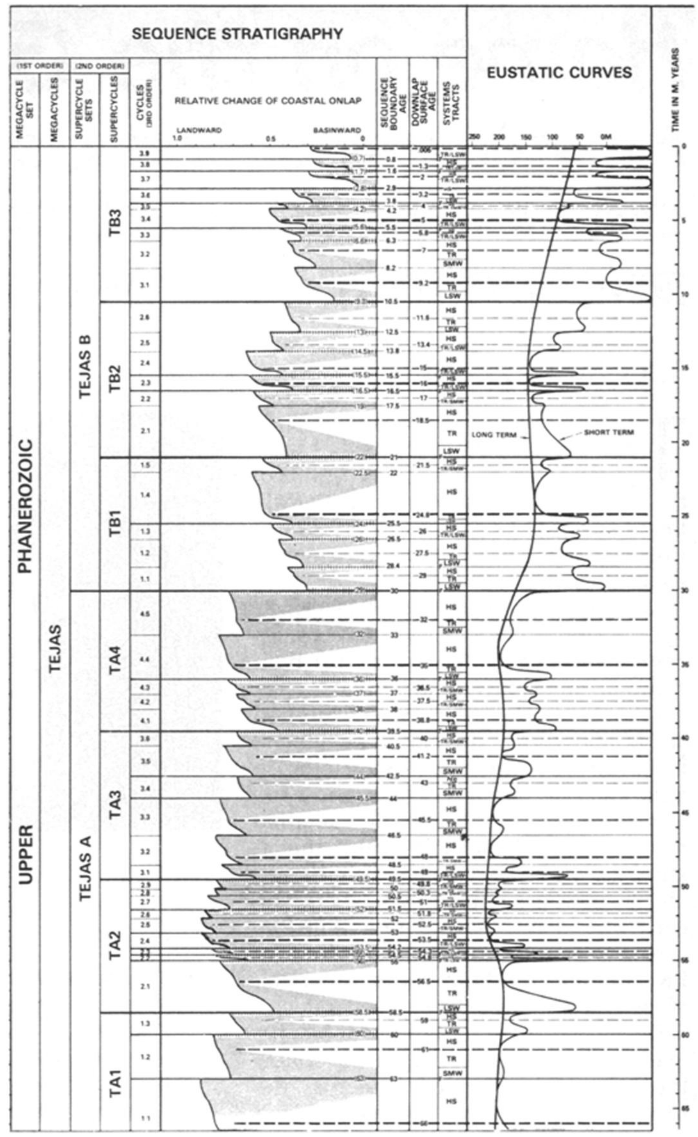
"It's easy to understand why an oil company would not want to publish all of its data," comments Miall. "But what surprises me is that some people are willing to accept Vail's group's conclusions without reexamining the original data upon which those conclusions are based. This is just not scientific."

Vail says one reason for publishing the March SCIENCE paper, and for his recent move from Exxon to Rice University in Houston, is to develop a data base that is in the public domain: The new sea level charts of the last 250 million years are based on marine outcrops around the world, which anyone can examine.

The incorporation of outcrops is also important because it is the first time the researchers have applied their models of sediment deposition, developed from their seismic work, to rock layers on land. The result, says Haq, is that "we're now able to interpret the outcrops with much more sophistication than we could before." For example, previously, a stratigrapher looking at an outcrop layer containing shallow-water fossils might have simply concluded that sea level had fallen. But the seismic models of Vail's group have shown that shallow-water deposits are also formed after the sea has been at a high level for a while.

Haq says the new charts are better constrained chronologically than previous charts because his group has come up with a more "rigorous and robust" dating scheme. In addition, the outcrops contain traces of sea level fluctuations that are too small to show up on seismic profiles. The researchers say their new sea level charts show fluctuations in greater detail than ever before.

Now that the outcrops have given Vail's group their "land legs," the researchers hope their new cycle charts will calm the waters of controversy. But because it takes time and resources to check Vail's outcrops, and because critics still disagree about the causes of some strata patterns, it's likely that Vail's sea level curves will continue to rock the boat. □



Part of the new sea cycle charts. The jagged lines on the left show how far up onto the land sediments were deposited. Vail's group interprets these sediment patterns in terms of global sea level changes, on the right.

Adapted from Haq, Hardenbol & Vail/SCIENCE