Changing Global Sea Levels as a Geologic Index

Other oil companies are adopting Exxon's new aid to finding oil and now academic researchers are also seeing its worth

Big American oil companies have had their share of bad press lately, but geologists who study the rocks beneath the sea floor are applauding one oil giant—Exxon—for its contribution to the advancement of science. Exxon's contribution, first made public in 1975, is a new approach to making sense of the jumbled, incomplete geologic record buried beneath the sea. The method has excited academic and government scientists because it provides a global framework on which they can tack many of their previously unrelated, local observations. Based on a staggering amount of data normally denied to outsiders, Exxon's new method, which uses the great ups and downs of sea level as geologic benchmarks, was an unexpected find for researchers. Even other major oil companies are grateful. "Exxon has made a tremendous contribution to both exploration and science," says one competitor.

Although appreciative, those outside the oil industry have also been frustrated. Exxon gave them the final product of its massive study, a record of the changing levels of the world ocean over hundreds of millions of years, but academic researchers will never see the supporting evidence—it will remain proprietary. Although the basic concept of linking local rock structures to worldwide sea-level changes appears to be sound, the academics say, they have some reservations about certain details. One is the insistence by Exxon workers that sea level could have fallen precipitously at times when most scientists find no evidence for the glaciation required for rapid sea-level changes.

But now, using evidence gathered outside the oil industry, researchers are finding that the sea-level changes presented by Exxon as faits accomplis were indeed recorded in sediments around the world. In addition, some researchers believe more acceptable explanations than ice caps during warm climates may exist for apparent rapid changes in sea level.

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The new method, developed by a group at Exxon Production and Research Company, Houston, under the direction of Peter Vail, involves no new technology. Rather, it is a more systematic way of looking at the kind of information every company gathers when looking for oil. In an unexplored area, such as the Atlantic outer continental shelf of a few years ago, company geophysicists first probe beneath the bottom by reflecting acoustic signals off the layers of soft sediment and rock, producing a seismic reflection profile. Once an oil company has a seismic picture of the way the rock strata are piled on one another, it can begin drilling for oil and also for samples of the rock strata seen in the seismic profiles. From these samples, geologists can tell much about how and when the rock strata were formed.

The how and when of geologic events are crucial to oil exploration. The beauty of the Exxon sea-level curves is that they can help geologists determine ages and compositions of rock strata even before the first well is drilled. Each rise and fall of the sea removes some sediment from continental margins and leaves piles of new sediment, producing a recognizable pattern. What Exxon did, that no one else had done, was to look at sedimentary rocks on continental edges all around the world, sort out all the patterns that showed up at the same time worldwide, and attribute them to global changes of sea level. The solely local patterns, which had tended to confuse previous interpretations, could be attributed to local ups and downs of the continental margin rather than of the sea. After dating the major global sea-level changes on the basis of well data, Exxon could survey an unexplored part of the ocean and have a clearer idea of when and how the crucial steps in the formation of oil deposits could have occurred.

The methods developed by Vail and his group helped Gulf Oil to identify one of those steps and to find oil in the Middle East, according to Stanley Frost of Gulf Science and Technology Company in Houston. Several events must occur in the proper order to create an oil deposit—accumulating organic matter in sediments, cooking it into oil, forming the right kind of rock strata to trap it, and, finally, having the oil migrate from its source to the reservoir rock that it becomes trapped in. The source of oil in Abu Dhabi, a layer of 150-million-year-old limestone rich in organic matter, is well known, Frost says; the trick is to identify the overlying pockets of younger, more porous rock that have caught the oil seeping up from below. The thousands of meters of limestone laid down in shallow seas and lagoons in the Middle East since 150 million years ago are not good reservoir candidates unless some process increases the normally small amount of pore space in limestone.

A fall in sea level, recognized by using Exxon's approach, made room in the limestone for the oil found in the Bu Hasa field of Abu Dhabi, according to Frost. Gulf found that a drop in sea level 120 million years ago exposed a particular dome-shaped set of strata to the weather, eroding and leaching the limestone until as much as 40 percent of it was empty space. When the sea returned, it deposited a layer of mud that became an impervious cap of shale,

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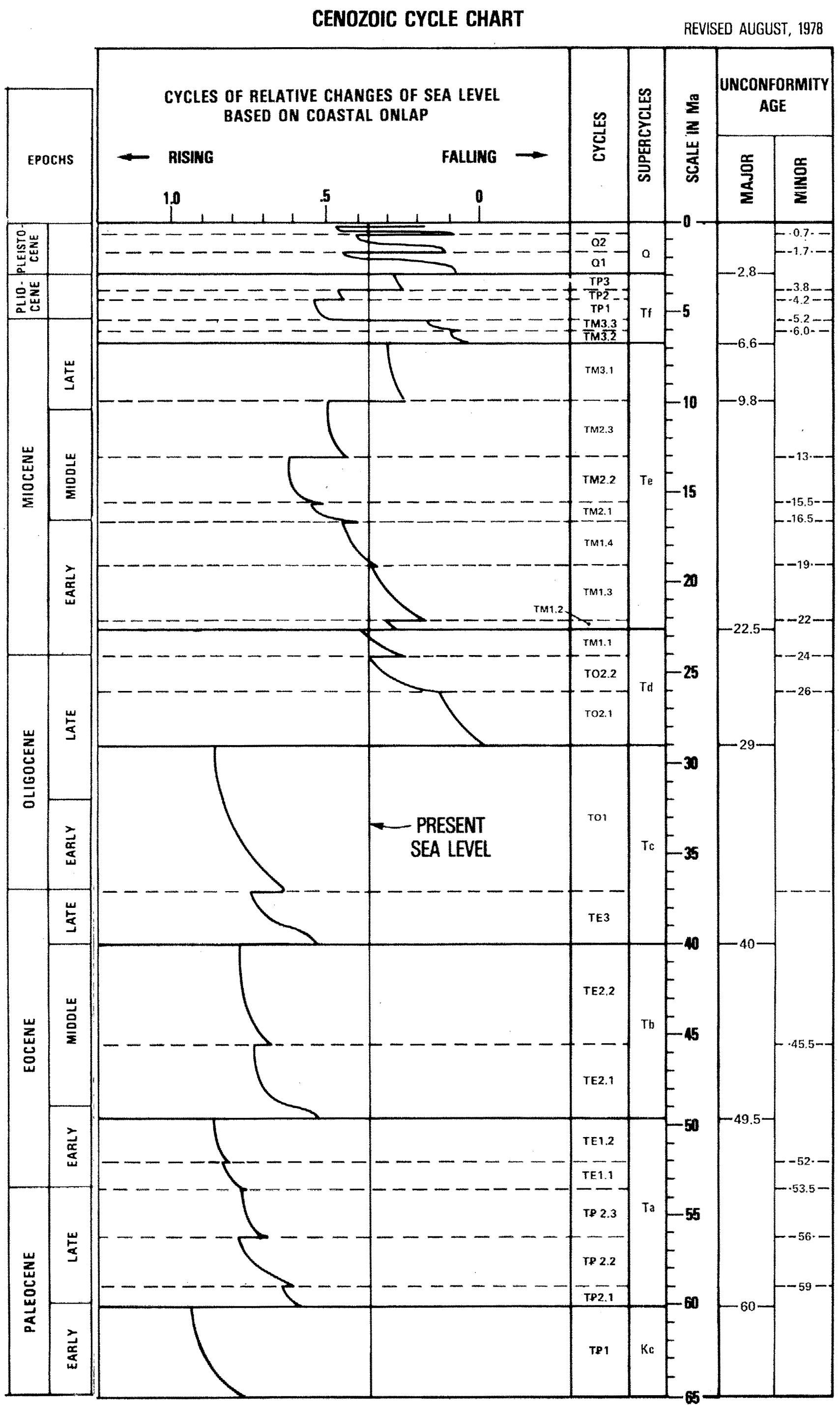
which eventually trapped the oil in the weathered limestone. The gap in the steady accumulation of sediment between the eroded limestone and the shale, which is called an unconformity, served as a geologic index to the proper rocks to investigate. "The exciting aspect," Frost says, "is that we can use global sea-level highs and lows as a predictive tool."

Reports of other examples of the usefulness of the sea-level curve have begun to appear. On the Exmouth Plateau off Australia's west coast, Esso Australia surveyed a prospective area by using seismic reflection. They then identified unconformities from the pattern of strata and predicted the type and age of rock by matching the unconformities with those produced by known global changes of sea level. When they compared the predictions with subsequent drilling results, "The results were very good," according to an Exxon researcher.



Changes in sea level relative to present sea level as developed by researchers at Exxon Research and Production Company. The time scale from 65 million years ago to the present is on the right. Each cycle consists of a slow rise and a rapid fall. Supercycles include several cycles of increasingly higher high stands of the sea and end in particularly large falls. [*Source: P. Vail and R. M. Mitchum, in* Oceanus]

In the North Sea, 15 of 17 unconformities identified on the basis of well results and seismic data matched Exxon's global sea-level curve, Vail reported in April at a meeting in Woods Hole, Massachusetts.* The method is even helpful on the coast of Alaska where the earth's crust is more active, according to John Armentrout of Mobil Exploration and Producing Services, Inc., in Dallas. After a thorough analysis of both dated rock outcrops on land and U.S. Geological Survey (USGS) seismic data in the Kodiak Basin, he could see the same pattern of sediment layers separated by unconformities that changes in sea level had shaped in the North Sea and off Australia. In spite of reported successes, Frost warns, the method is not foolproof, as he learned in the Persian Gulf, where drilling failed to find 3700 meters of 100-million-year-old rock predicted by the Exxon approach.

Although some companies are beginning to use global sea-level curves in exploration, Exxon established and maintains a commanding lead in the field. Industry researchers say this is because Exxon has had a wide-ranging international drilling program, because it developed a large, integrated staff of researchers, and because Peter Vail was a student of Laurence Sloss of Northwestern University. As a graduate student in the 1950's, Vail became familiar with the recurring, worldwide inundations that Sloss saw recorded in the sedimentary rocks at the center of continents. When Vail began to look at the continental shelves for Exxon, linking supposedly local sedimentary cycles into a worldwide process seemed logical. This new view of sedimentary processes could have been used exclusively for Exxon's benefit longer than it was, according to several industry sources, if Exxon had not greatly overestimated the ability of its competitors to decipher sea-level records and allowed release of its approach in 1975. Now, every company can match its data against the benchmarks of Exxon's sea-level curve.

In contrast, for the last 5 years academic and government researchers have had little data with which to test Vail's curve. "Until 1 year ago," says Anthony Watts of Massachusetts Institute of Technology, "only one well in the United States was available. If Vail's curve has had any credibility, it is be-

*Conference on Interregional Unconformities, Woods Hole, Massachusetts, 28 to 30 April 1980; organized by John Schlee of the U.S. Geological Survey, Woods Hole.

cause Vail has said, but not demonstrated, that it is based on a large amount of unpublished data from around the world. There's a certain amount of frustration about not seeing the data." Vail cannot provide the original data because his curve was first based on proprietary information, although he will soon begin publishing applications of his methods, such as the North Sea example, using publicly available data.

In the meantime, investigators outside industry are beginning to develop support for the general concept of Vail's sea-level curves, but they are casting doubt on the large, sharp drops that Vail wants explained by the formation of ice caps. The most recent support comes from USGS studies of the five continental offshore stratigraphic test (COST) wells drilled offshore of Georgia, New Jersey, and Massachusetts for the government by an industrial consortium. As Wylie Poag of the USGS in Woods Hole reported at the April meeting, their first look at the COST wells tended to support Vail's curve in the period from about 150 million years ago to 65 million years ago. But the six unconformities found in all five of the wells did not seem to match Vail's curve since that time. Most dramatically, the sea-level high that precedes Vail's abrupt drop 29 million years ago did not appear in the geologic record. That did not bother Vail. Poag recalls that "Vail was saying we can't rely on wells alone. You have to tie them into a regional network" of seismic profiling lines.

After the meeting, Poag and John Schlee of the USGS at Woods Hole attempted to tie the well and seismic data together. "Indeed," Poag says, "you can see most of the things Vail says you can." As Vail had said, the missing sediments that had to have been deposited during his proposed high stand of sea level were completely eroded away when the sea level fall of 29 million years ago exposed them to the weather—a whole unit of sediment deposited between unconformities had been eroded away until the two unconformities had become one. Poag could also see that extra unconformities in the COST wells, which could not have been caused by exposure during Vail's low stands of sea level, marked times when no sediment was deposited rather than times of erosion. The sea had rushed up the shelf so far that it temporarily cut off the supply of sediment washing down from the continent. "These were some of the things we couldn't tell from the wells alone," Poag says.

Other data supporting the global applicability of the Exxon curves has been in hand longer—about 30 years longer. In the early 1940's, H. J. Finlay and J. Marwick of the New Zealand Geological Survey grouped the marine sedimentary rocks exposed on New Zealand into subdivisions or stages depending on the kinds of fossils they contained. In the mid-1960's, Paul Vella of Victoria University in New Zealand decided that some of the boundaries between stages matched geologic boundaries seen elsewhere in the world. Global changes in sea level seemed to Vella to be the most likely connection, but he conceded that he had too little evidence to prove it.

The necessary evidence is in the Exxon sea-level curve, according to Tom Loutit and James Kennett of the University of Rhode Island. They have recently compared the ages of the stage boundaries with the ages of Vail's unconformities caused by low stands of sea level. "We find that of the 18 New Zealand stage boundaries falling between 53 and 5 million years ago," Kennett says, "we can correlate ten of them perfectly with the Vail curve, five correlate pretty well, and the others still have a few problems. We are sure these are natural sediment cycles reflecting global events." The idea that global changes in sea level control the layering of sediments has been around for about a century, Kennett says, but now that geophysicists can survey large areas through the use of seismic profiling, geologists are becoming convinced that there is something to it.

The periodic floods that covered the continental shelf and coastal plain also spilled into such low areas as the central United States and Canada, according to Erle Kauffman of the Smithsonian's National Museum of Natural History in Washington, D.C. Between 140 and 65 million years ago, the sea deposited sediments higher and higher on Utah, Colorado, Kansas, Oklahoma, and elsewhere for 4 to 5 million years, retreated for 3 to 4 million years, and then repeated the cycle. The timing of the floodings closely match those proposed by Vail and his group, Kauffman says.

The timings of the flooding of continental margins and centers may be consistent, but Kauffman and most other academics cannot accept Vail's large, sharp sea-level drops. Kauffman's nearly symmetrical curves contrast sharply with Vail's lopsided ones, which rise for 8 to 10 million years and then fall 50 to

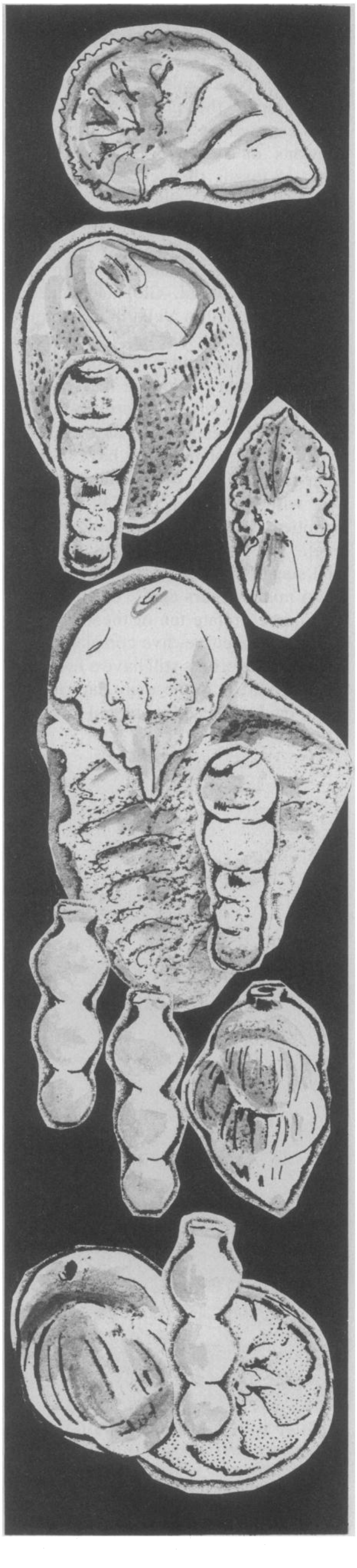
Exposure of major unconformity in a quarry near St. Stephens in southwest Alabama. The light, sandy limestone at the top of the cliff sits directly on top of the dark shale or clay below. The unconformity, which corresponds to Vail's unconformity of 29 million years ago (see accompanying chart), is the contact between the limestone and the shale. It represents sediment deposited over 4 million years that was eroded away during a low stand of sea level. [*Source: Joseph Hazel, U.S. Geological Survey*]

100 meters in less than 1 million years. Most researchers cannot imagine a way to make sea level fall that fast at the times Vail wants it to. Locking up the water as ice in Antarctica could do it in tens of thousands of years, but no one has found any generally accepted evidence of ice before 40 million years ago, which is long after Vail's curve shows sharp drops.

The only alternative to ice is shrinking the volume of the ocean basins so that the water is pushed onto the continents, but Walter Pitman of Lamont-Doherty Geological Observatory has found that most of the possible mechanisms cannot change sea level enough and none can do it quickly enough. Many researchers believe that the most effective of these mechanisms, changes in the volume of the midocean ridge system, cause broad rises and falls of sea level over hundreds of millions of years. The ridges do that by expanding when the rate at which they create new sea floor increases and contracting when the rate decreases. Pitman calculates that sea level could be changed by 300 to 500 meters, but only at the rate of 12 meters per million years at most.

A possible solution to this quandary, Pitman says, may be that the pattern of sediments laid down by the rising and falling sea has misled Vail and his group. As sea level rises and the water's edge pushes up the gently sloping continental shelf, layers of sediment accumulate on top of one another with each layer extending a little farther inland than the one below it. When sea level begins to drop, the edges of the sediment layers also begin to retreat, reversing the pattern of overlapping strata begun during the sea's rise, according to Vail's interpretation. As sea level approaches the sharp edge of the continental shelf, rivers cut canyons into the sediments on the shelf, fans of sediment form at the canyon mouths, and erosion of the exposed shelf creates an unconformity as some of new sediment is washed into the deep sea.

Pitman contends that, contrary to Vail's interpretation, sediments can continue to lap higher and higher onto the continent even though the sea is retreating down toward the shelf edge. Instead of being trapped beneath the retreating shelf waters, the sediment washing off a continent that is being gradually uncovered by the sea can stop on the freshly exposed shelf and on the old coastal plain, he says. It will do that until the new coastal plain it creates has a slope with the same grade as the old one. The observed retreat of marine sediments while coastal sediments continue to lap onto the continent support such a process, Pitman says. Frost and Christopher Kendall of Gulf have also concluded that falls of sea level start sooner and last longer than the sedimentary record might appear to suggest.



Shells of bottom-dwelling foraminifera (single-celled animals) used to determine ages and depths of sediment deposition. [Drawing by Jane Walsh]

These differences have not been reconciled. Vail points out that his group does not identify rapid falls solely by the pattern of coastal sedimentation, but also by the presence of sediment fans beyond the shelf edge, canyon cutting on the shelf, and evidence of submarine erosion along the edge of the deep sea. Low stands of the sea identified by these features do sometimes fit the model proposed by Pitman, he says, but usually they do not. Vail also notes that some independent studies of water depth on the continental shelves support rapid sea-level changes. In one such study of the fossil record in both California and Libya, William Berggren of Woods Hole Oceanographic Institution found that, over geologic time, bottom-dwelling animals that preferred water depths of 30 to 40 meters closely succeeded others that preferred depths of 400 to 500 meters. Both apparently rapid drops marked by the change in bottom-dwelling species occurred 49 million years ago, which coincides with a major fall in Vail's curve. Although they still see relatively rapid sea level drops, the Exxon group continues to make refinements (such as allowances for the sinking of the shelf due to the weight of its sediment) that could shrink the size and slow the speed of the drops.

Five years after it was first presented, the Exxon sea-level curve continues to be debated, but its basic integrity remains intact. Its rate of change has been questioned, its range of sea levels is still among the larger estimates, and its exact timing has not been settled, but support continues to increase for its usefulness as a general approach to deciphering the geologic record of the continental margins.—RICHARD A. KERR

Additional Reading

1. P. R. Vail and J. Hardenbol, "Sea-level changes during the Tertiary," *Oceanus* **22**, 71 (1979).
2. P. R. Vail *et al.*, "Seismic stratigraphy and global changes of sea level," in *Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (American Association of Petroleum Geologists, Memoir 26), pp. 49–212.
3. Abstracts from the Symposium on Ancient Sea Level Changes, 19 and 20 November 1979, Palisades, N.Y., available from W. Pitman, Lamont-Doherty Geological Observatory, Palisdes, N.Y. 10964.