Old and New Geology Meet in Phoenix

The Geological Society of America held its annual meeting late last month in Phoenix, just a few hours' drive from the country's most famous geological feature, the Grand Canyon. The hot item in the press room was the analysis of dinosaur breath, as preserved in amber, but other areas of interest included more familiar considerations of what the deep crust is like and how incipient ore deposits are forming today.

Ancient Air Analyzed in Dinosaur-Age Amber

If the first reported analyses of air trapped in fossilized tree sap are accurate, the air breathed by the dinosaurs of 80 million years ago was 50% richer in oxygen than today's atmosphere. Although specialists in the evolution of the atmosphere had not given the matter much thought, elevated oxygen concentrations at that time do make geochemical sense. Aside from confirming these preliminary results, the work ahead includes figuring out whether amber is a secure repository of ancient air and what the ecological implications of high oxygen would have been.

Robert Berner of Yale University and Gary Landis of the U.S. Geological Survey in Denver reported at the meeting that they had crushed ancient amber in a vacuum system in order to release the gases trapped in bubbles as small as 10 micrometers. Analysis of the gases by quadrupole mass spectrometry revealed that 80-million-year-old amber had trapped air that contained roughly 30% oxygen (individual samples ranging from 25% to 35%) versus the 21% oxygen content of today's air. Bubbles in 25-million-year-old amber from the Dominican Republic contained somewhat less oxygen than the present atmosphere. Analyses of Baltic amber formed about 40 million years ago indicate values similar to modern air.

Perhaps the biggest surprise in these results is that the method works at all. As Heinrich Holland of Harvard University notes, "It seemed unlikely that oxygen would be present in significant quantities." He and others had avoided amber in their search for ancient air because they assumed that the oxygen trapped by pitch oozing from a tree would either react with the pitch or diffuse out of the bubbles during the millions of years that the pitch fossilizes to amber. But Berner and Landis have already been able to eliminate some major concerns.

Their principal argument for the fidelity of the bubble samples is simply the existence of high oxygen concentrations, up to 32%, even before correction for the presumed conversion of some oxygen to carbon dioxide by bacteria. Most concerns had centered on the loss of oxygen, not its creation, so elevated concentrations are a reassuring sign. In addition, the sum of oxygen plus excess carbon dioxide derived from oxygen maintains about the same proportion to less reactive nitrogen in various samples of the same age even when the oxygen–carbon dioxide ratio varies. The oxygen-nitrogen ratio in modern tree resin also agrees with that of modern air.

Berner and Landis are encouraged by signs that amber makes a good sealant for air samples. The bubbles contain little or no methane, a gas abundant in sediments, so gas does not appear to have leaked in while the amber was buried, they say. There is a small amount of hydrogen, the gas most likely to diffuse through amber, so leakage of oxygen out of the bubbles seems unlikely. In fact, bubbles apparently have preserved 10 atmospheres of gas pressure that overlying sediments imposed on them.

Although reassured, researchers still wonder about the chemistry of pitch bubbles. "We had assumed reactions with amber," says Berner, "but that does not seem to be the case. The oxygen should all be gone, but it isn't. That is curious."

If the last days of the dinosaurs were indeed enriched by high atmospheric oxygen, it would not surprise the geochemists who theorize about Earth's changing atmosphere. True, they have spent most of their time thinking about earlier times, such as when photosynthesis introduced the first significant oxygen a few billion years ago.

Since that time, the amount of oxygen in the atmosphere has depended on a balance between how rapidly reduced forms of carbon (such as photosynthesized organic matter), sulfur, and iron have taken up oxygen during weathering of the crust and the speed at which those same reduced species could be taken out of circulation by burial on land or in the sediments of the sea. By this reasoning, the Cretaceous Earth of 65 to 144 million years ago should have been a time of increasing oxygen. The deep sea was warm, presumably slow moving, and, within the opening Atlantic Ocean, constricted at times to the point of stagnation and anoxia. Those are perfect conditions for burying organic matter. The result was the Cretaceous black shales, a huge layer of organic-rich sedimentary rock that, all else being equal, represents a net addition of oxygen to the atmosphere.

Earlier this year Mark McMenamin and Dianna McMenamin of Mount Holyoke College made a ballpark estimate that the Cretaceous black shales alone could have raised atmospheric oxygen from 21 to 24%. But James Walker of the University of Michigan reported at the meeting that his model of evolving atmospheric oxygen, when set to Cretaceous conditions, indicates 27% oxygen. Considering the uncertainties, that amount could coincide with the 30% concentration measured in amber, he says.

Given a high-oxygen Cretaceous period, the potential for inference and speculation is considerable. Would the largest dinosaurs kick up their heels rather than plod about? Would the presumed decrease in oxygen since 80 million years ago have helped push the dinosaurs to extinction? Could the fire-enhancing effects of elevated oxygen have brought on a global conflagration that produced the soot found at the time of the terminal-Cretaceous impact? Tantalizing questions, but they might best wait until the analysis of amber bubbles is on a stronger footing.

Present at the Birth of an Ore Deposit

Given the alternatives of studying the fossilized remains of an animal and observing the living beast in its natural habitat, the choice is easy. Researchers wanting to know how ore deposits form have an equally clear choice. Study of a long-dead geological formation being mined for its metals can be informative, but getting inside a deposit as it forms has clear advantages.

That is what a group of researchers has done just south of southern California's Salton Sea. Under the Salton Sea Scientific Drilling Project headed by Wilfred Elders of the University of California at Riverside (UCR), drillers have penetrated more than 3 kilometers into sediment and rock where the crust is being pulled apart as blobs of magma rise toward the surface. The result is a hot, fractured crust whose salt-laden waters are tapped for their geothermal energy.

Michael McKibben, Alan Williams, and Jerry Andes of UCR reported at the meeting that fluids and core samples recovered from the borehole have helped reveal a clear picture of how metals present in rocks in trace amounts can be concentrated enough to make mining worthwhile. The first requirement is a large, if dilute, source of metals. In the case of the Salton Sea area, it is the sediments washed down the Colorado River into the trough formed by an extension and sinking of the crust.

The next requirement is a fluid that can dissolve the sediments' metals. Tap water is hardly strong enough, but in the lower reaches of the well there is a brine that contains up to eight times the salt of seawater and reaches a temperature of 365°C. Derived from the salt left by repeated flooding of the Salton Sea trough and subsequent evaporation, this brine has dissolved up to 1500 parts per million each of iron, manganese, and zinc and between 1 and 100 parts per million each of lead, silver, copper, and cadmium. That metal content is testament to the dissolving capacity of a hot, reducing brine whose chloride ions can complex metal ions and hold them in solution.

The final requirement for the formation of an ore deposit is a reason for the metal-rich fluid to deposit its load in one small area. The UCR group believes that it has found that reason—mixing of the deep brine with overlying, oxygenated, less saline brine along the thin boundary separating them. Wherever the two brines meet, dilution through mixing reduces the hypersaline brine's dissolving capacity by reducing salinities and increasing oxygenation. Unable to remain in solution, the metals precipitate.

Ore in the making. *These vertical veins cut through bedded sedimentary rock (12-centimeter core) and contain a variety of metallic minerals deposited from hot brines. The vein on the left is still open and contained brine actively depositing minerals before it was cored.*

Studies of many old ore bodies in sediments had implied that mixing at an interface was involved, but now it has been observed. Cores from the vicinity of the mixing zone in the Salton Sea borehole contain the expected precipitates, which seem to be forming even now. Partially filled fractures in the rock contain metallic sulfides such as pyrite, chalcopyrite, sphalerite, and galena, along with smaller amounts of specular hematite as well as some silicates. This assemblage of minerals is quite similar to that found in deposits formed in rifts that were opening more than 600 million years ago and are now mined for their copper, lead, and zinc, says McKibben. The Salton Sea site has not yet achieved ore grade, he notes. It is only on the order of 100,000 years old, and has low concentrations of the reduced sulfur needed to make the sulfides. But if this infant ore body can keep it up for another 500,000 years, it should be ready for mining.

Seeing Bright Spots in the Middle Crust

Geophysicists probing the crust with man-made seismic waves are seeing more and more unusually reflective features located 15 to 20 kilometers beneath the surface, about halfway through the crust. "By no means are they as rare as was thought 10 years ago," Larry Brown of Cornell University told the meeting. "They are becoming uncomfortably common." These seismic bright spots may be trying to tell researchers about the way continental crust grows.

The first bright spot was found in 1975 on a seismic reflection profile made across the Rio Grande Rift near Socorro, New Mexico, by the Consortium for Continental Reflection Profiling (COCORP) headquartered at Cornell. Because of the character of the bright spot, earlier suggestions based on other geophysical evidence, and its location in crust being stretched and thinned, COCORP researchers assumed that their seismic waves were reflecting off the top of a magma chamber. Instrusion by rising magma is common in areas of crustal extension. And the high contrast between the overlying rock and the hot fluid could account for the reflection of 30% and more of the incident seismic energy, the strongest reflection possible in the crust. That is five times the typical strength of reflection features and three times the reflection strength of the Moho layer at the base of the crust.

After a bit of a lull, bright spots began to be found elsewhere. In 1983 a COCORP survey found one 15 kilometers beneath Death Valley, then more were found 11 to 17 kilometers beneath the Snake Range in eastern Nevada and about 20 kilometers deep near the edge of the Colorado Plateau in southwestern Arizona. All of these are in areas of crustal extension, so magma intrusion seems a natural explanation, Brown noted. If true, intrusion and ponding in the middle crust would be a new way to add rock to continents away from their edges, where growth occurs through the collision of crustal fragments and subduction-generated volcanism.

Not so clear is why rising magma should tend to stop at all at midcrustal depths. The first kind of obstacle that comes to mind is a layer of ductile rock overlying a brittle layer, says Brown. The magma could more easily force its way through rock that can fracture than through a layer that tends to seal itself. In the latest theories of crustal structure, increasing temperature and changing rock composition with increasing depth interact to produce a ductile-brittle transition at midcrustal depths and another at the base of the crust. The first transition could produce bright spots and the second could perhaps produce the Moho itself, Brown suggested.

A complication developed in this picture of magma intrusion with the COCORP discovery of a bright spot 15 kilometers deep near the town of Surrency in southeastern Georgia. This part of the continent has been tectonically inactive for at least 65 million years. Magma intrusion thus being unlikely, COCORP researchers favor some other fluid, perhaps water trapped there the last time another continent collided with that part of North America. If that were the case, behavior of midcrustal rocks could be greatly altered by such trapped water.

The complexity only increased this year when COCORP profiling found strong midcrustal reflectors beneath Ohio and when the Great Lakes International Multidisciplinary Program on Crustal Evolution found them beneath the Great Lakes. This is crust more than 1 billion years old that forms the stable core of the continent. The absolute strength of these reflectors has not been determined, noted Brown, so they need not have the rock-fluid contrast required of true bright spots. Perhaps they are old, solidified intrusions that helped build the ancient crust, he said. Drilling in the Siljan Ring impact structure in Sweden this year has confirmed that strong horizontal reflectors can be caused by solidified magma intrusions. Drilling is not an option for identifying these bright spots, though; no hole deeper than 10 kilometers is even being contemplated outside the Soviet Union. ■

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