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Taphonomy of Oil

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The other day, I was buying some small items at a store. The young man at the cash register asked if I'd like a plastic bag. I replied no, and remarked to a woman nearby that we needed to conserve all petroleum-based products because we're running out of oil. That unleashed a torrent of vitriol and misinformation from the man about oil reserves, offshore oil, Alaska, production, and uses. I left thinking I'd never go back there again.

The incident made me wonder why Americans and probably people in the rest of the world are so poorly informed about oil, their primary source of energy and perhaps one of the most valuable resources they have (Fig. 1). As paleontologists, we understand these issues for the most part and we should be teaching about the problem in our classes and informing the general public and especially the politicians about it. Mostly, the oil problem is taphonomic, and that we do know about. Oil, like any other fossil material, is not in infinite supply. But we should not be the only ones discussing this problem from a factual base, so should everyone else. It is a very complex geologic, paleontologic, economic, political, and emotional issue that will continue to dominate world forces for the foreseeable future. Will war and chaos or a reasoned transition to rare and high-priced oil be in our future? The fate of our children and grandchildren are in jeopardy.

The level of ignorance about oil is compounded in the US by the recent rapid increase in the cost of gasoline. Everyone is up in arms and everyone has a solution. Few have the facts. Nothing provokes emotion in America like fooling with people's cars—we love them dearly and many love the biggest ones best of all. America

Figure 1. A California oil field. Like the rest of the world, early California oil fields were quite productive but began to lose their higher volumes in mid-century. Many of these wells were sold to small independent operators who could make them profitable. Most of these fields are still active. Here, the Round Mountain Oil Field, which has produced over 100 million barrels of oil since it was spudded in 1927, making it a "giant" field. J. H. Lipps image, 1960.

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has long had a love affair with the road--it is almost like a right, the Right to Drive. So Americans get very upset about the cost of gasoline. The average is well over $4.00 for a US gallon and in California, it's been over $5.00 even for the lowest grade. This of course does not compare with the $8.00 to $9.00 that Europeans pay, but Americans do not think of other people's plights when it comes to their own economics. We've never paid that much; it's unfair and someone is to blame for it—speculators, oil company profiteers or bad politicians are the usually named culprits. Probably none of these are currently much affecting the high prices for oil (see http://www.ucei.berkeley.edu/PDF/csemwp177r.pdf , see the *New York Times* (http://www.nytimes.com/2008/07/20/opinion/20irwinsanders.html?pagewanted=1&sq&st=nyt&scp=2).

The price of oil is now dictated chiefly by too much demand and too little supply. Demand is largely the result increasing world population and of booming economies in newly developing countries, especially China and India, as well as continued demand elsewhere but especially in the US. The world's population grew from 3.5+ billion to 6.7+ billion people in the last 40 years and it will grow to 9.4+ billion people in the next 40 years (http://www.census.gov/ipc/www/idb/worldpop.html). Some of us may even see 12 billion people on Earth before we die. Can the world support this number of people? They need oil now and the demand will continue to grow perhaps for quite a long time into the future, at least up to 8 billion people, that is in 20 years. Their countries must supply it, if they can, by purchasing it or finding it in their own territories. Of course alternatives like coal, solar, wind, perhaps methane, and nuclear will help, but oil is likely to remain the primary energy source for commerce and even personal uses. The other possibilities are not well enough developed yet to help the entire world, although France, Japan and some others are mostly nuclear. Of the 86 million barrels of oil supplied daily to the world, the US uses 21 million barrels (~25%). Over 60% of this goes to fuel vehicles (gasoline and diesel) and airplanes (jet fuel); the rest is used for heating, manufacturing, and others. As of 2003, the US operated 231,389,998 vehicles (excluding an unknown number of military vehicles), of which 134,336,851 were private or commercial automobiles (http://www.fhwa.dot.gov/policy/ohim/hs03/htm/mv1.htm). This too is about 25% of the world's estimated total of around one billion vehicles of all sorts world wide. Apparently, Americans are not the only ones who love to drive and fly. Most people do and most want what the other countries have. And that's half of the problem.

The other half of the problem is supply, and it is much more critical. Supply is a matter of the taphonomy of oil. Taphonomy, as we know, is the study of what happens to organisms from the time they die until they are discovered by a paleontologist. In reality, it is a gradation of processes that start before organisms die and extend in many cases to long after fossils are discovered. I sometimes add to that definition on either end to include certain biological conditions of the living organisms that determine what happens after organisms die and other conditions that impact fossils after they are discovered to the time they are utilized in a study or curated into a museum, or in the case of oil, burned. However we define it, taphonomy is critical in the study of fossils. For the fossils that make oil, I'll use the traditional definition with my own addenda at the beginning and end: "production of organisms" and "until the time it is used". This will give us a more complete perspective and perhaps clarity on the very complex problem of oil.

The origin of oil is clear in spite of a few outspoken voices who claim it is inorganically made deep in the earth. Biomarkers in the oil indicate that it is derived from algae, phytoplankton, and other organisms chiefly in the oceans. Terrestrial oil occurs but is uncommon compared to ocean-derived resources. This fundamental starting point is, of course, what limits the oil supply to begin with. From these chiefly microscopic organisms oil is derived and accumulated in a series of critical steps. If any one of them fails, then we get no oil.

These organisms must grow and reproduce in vast quantities to make significant amounts of oil. They do this only in regions of the oceans where nutrients are carried into the photic zone. The photosynthesizing algae grow well in nutrient-rich waters, just like your garden or grass when you apply fertilizer. Nutrients and sunlight are critical in making oil, as they fuel the first step. However, regions where nutrients are abundant are few in the world's oceans today, as they have been throughout geologic history. Most of the world's oceans have been biological deserts most of geological time. Eutrophic conditions today are most common near the continents, along the equator, near Antarctica, and in certain marginal basins, like the Black Sea. Only in these areas today are nutrients sufficient to produce a reliable high supply of dead or dying organisms to the sea floor over a

Figure 2. Probably 90% of oil formed in the sedimentary deposits of the world has migrated to the earth's surface where it formed oil seeps and pools, and eventually disappeared altogether. Here, at the famous La Brea deposits on Wilshire Boulevard (A) in Los Angeles, California, active oil seeps from underlying Tertiary rocks form pools in Pleistocene and Recent alluvium (B). These pools, like so many others in the world, have trapped animals, plants and protists in the gooey mess. J. H. Lipps image, 2008.

long period of time. Although the open ocean has a lot of production overall, in any particular place it is low, so low that most of the material is absorbed back into the water or degraded otherwise. Overall, the productive areas amount to about to less than 20% of the oceans today, and the most productive upwelling regions amount to a fraction of that. Even that amount of captured productivity would release us from the oil squeeze, but there's more to it naturally.

The bodies of these organisms must be deposited on the sea floor where oxygen is lacking or the organic material will not be preserved. In the presence of oxygen, the organic matter cannot fossilize or be preserved because their tissues and cells are destroyed by bacteria or oxidation itself. This alone eliminates most of the world's oceans as a place to preserve the organisms required to make oil. We have now reduced the area of preserved organic matter to just a small fraction of the ocean floor today. Although the total area of organic matter preservation has varied through geologic time, it has always been a small proportion of the earth's surface. Most sedimentary rocks have a tiny percentage of organic matter in them; not enough to make oil.

After preservation, the organic material must undergo diagenesis. Oil is not just buried organic matter, it is organic matter that has been buried deep enough for heat (about 80ºC) to break the complex organic compounds into the smaller molecules of oil but not so deep that those molecules are degraded to single carbon compounds such as methane. That temperature is found between about 2285 and 4570 m deep in the earth. All fossil material must pass into but not through this range, the so-called "oil window", to become oil. Diagenesis obviously is very important in oil formation. A good deal of the fossil organic matter never gets hot enough and doesn't convert to oil or becomes too hot and turns to gas.

Where oil differs taphonomically from other fossil material is that once it forms, it becomes mobile, because it is less dense than water, and so moves towards the surface. About 90% of the oil formed in the oil window makes it all the way to the surface, forming oil seeps, pools and traps, and where the volatiles evaporate into the atmosphere (Fig. 2). Although useful in its own right and an indicator of oil buried at depth, much of this oil has been and continues to be lost altogether. The other 10% gets trapped by impervious rocks, such as very fine-grained shales and muds or salt and anhydrite that has been folded or faulted in such a way as to block the upward migration of the oil in porous, permeable rocks that are well connected with each other. These traps are what the oil men search for—domes, anticlines, stratigraphic pinch-outs of permeable rocks into impermeable ones, or faults that move impermeable rocks across permeable ones. So the right geology and sedimentology become important in oil taphonomy too.

If the oceans or the Arctic slope were as full of oil as many ordinary people and politicians think, we'd have a real glut of oil. But that's not the case because if any of these particular taphonomic conditions are missing, no oil can be present. It either never formed for lack of organic material, or the material was oxidized, or it didn't reach the right temperature or it got too hot, or it migrated straight to the surface and never was trapped. In many respects, it's a wonder there's any available oil at all.

Digging for trilobites or dinosaurs has similarities to looking for oil—the right environments are required, the fossils cannot have been heated too

Figure 3. In the early 1900s, oil was regarded as infinite in supply, as more and more giant and super giant oil fields were discovered. Early methods of extraction included hand-dug wells, then impact tools, and finally rotary drilling bits in 1901. The wells shown here were drilled along the Kern River in central California. Like almost all wells, they require pumping to lift the oil to the surface—very few wells flow under their own pressure which is rapidly depleted. The pumping method shown here was to link the pump jacks (A) over a wide area by cables (B) to a single engine that pulled them up and down to pump the oil. All oil costs money to produce, and those costs have grown dramatically over the history of the industry and will continue to grow as more and more difficult oil is produced. J. H. Lipps image, 1960.

much or under too much pressure, and they have to be exposed at a particular place in the Earth (road cut, hillside, etc). They do not have to experience a particular diagenetic process that changes them into something we seek; indeed we try to avoid such places. Thus far the taphonomic principles are remarkably similar between the usual fossils we study professionally and the fossil fuels we need in our ordinary lives.

It's the collecting that's different. For body or trace fossils, we merely prospect along outcrops and dig them out with rock picks, shovels or sometimes bulldozers and air hammers. To find oil is quite different. It is the discovery aspect of my extended taphonomic scheme that makes the oil business.

When oil men find one of these traps, they might drill a well (Figs. 3, 4) to check for oil, or search or continue exploration by seismic means. Truck-mounted plates vibrate the surface of the earth to generate seismic waves that then reflect or refract from the rock layers below from which two and three dimensional images of the subsurface are assembled by massive computers. It's an expensive business. Offshore, seismic waves are generated from "air guns" towed by ships and blasting sudden bursts of air that send a sound signal through the water and into the rocks below. Recently, while I was sailing across the North Sea at night in a sailboat, the radio suddenly squawked and the radar showed an image of ship approaching at an angle to our path but not making any concession to us. I started a maneuver but the captain of the other ship told me to stop. He informed us he was a seismic ship towing several cables over two miles long with guns and hydrophones, and he didn't want us fouling his lines. He commanded us to follow his directions that he gave with new bearings every so often. After making many turns, lowering and hoisting the sails, we were finally clear of the seismic ship and her lines. I was impressed. That captain was so calm and collected as he ordered us around the North Sea that I figured he must have done this quite often. He was obviously very concerned too. Sea-going oil exploration is also a complex business, but a bit cheaper than using trucks on land. Oil exploration has gotten very complex.

Once all this data is collected and analyzed, the real test of the oil people's hypothesis is in the drilling. Then the expenses really begin to increase. Not all wells are successful; some are duds and others just dribble a little oil. It's the ones where the oil flows easily into the wells through the permeable rocks that make the business worthwhile. Even whole fields sometimes are not worth drilling. Once a field is drilled and production begins, it is only a matter of time before the oil can no longer be extracted, even using so-called secondary recovery techniques where hot water, steam or chemicals are pumped into the field to encourage the oil to flow (Fig 5). Of all this oil that is discovered, only about 50% of it can be produced from the rocks. That's like knowing an out-

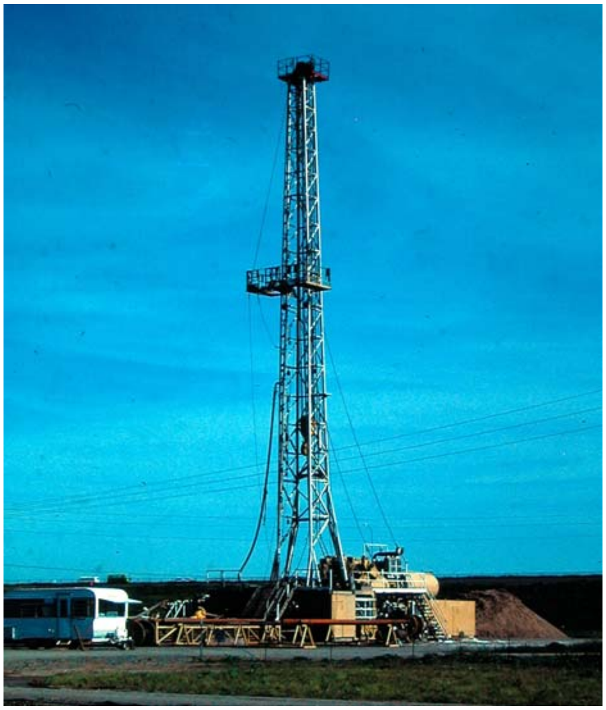

Figure 4. Modern oil well used for oil field exploration and maintenance. J. H. Lipps image, 2007.

crop has a lot of trilobites, but you can only find a fraction of them—very frustrating indeed.

We should have been teaching about this and more effectively preparing our countries and the world for leaner oil times. Like all fossils, oil is a finite resource. Sooner or later we will have produced it all. Fifty years ago we knew that the US, and later the world, would use more oil than it could produce. Petroleum geologist M. King Hubbert explained it all back then and showed his famous graph with a peak in production for the US in 1971. He was about right, and we have been on the downside of that curve ever since. For the US, this means having had to imported increasing amounts of oil ever since. Hubbert and others have run the curves for the entire world (Figure 6), and peak production probably occurred in late 2005 (Deffeyes, 2006, suggests Thanksgiving Day, 2005, as the day we passed over the peak). All the easy oil was found long ago and new oil fields have not changed the picture. Likely areas of high production are unknown, although oil is still being explored for and produced, just not as steadily or at such cheap prices as before. Production cannot grow because there is not enough oil known, and amazing new finds are highly unlikely. The more we use now, the less we will have in the future. Although controversial the world probably is now on the downside of Hubbert's curve at the same time that demand is growing more rapidly than ever before. The squeeze is getting tighter and tighter. Predictions are now that we will see $10-12/gallon in the US and probably nearly $20 in some other parts of the world in just a few years. Unlike the US, when world oil production falls below demand, there is no where else to go to for oil. That's the end. It won't come suddenly, of course, because we will slide down the world's Hubbert curve and we will be willing to pay for it for sometime. Oil is unlikely under any scenario to get cheaper than it is now on the average. Fluctuations are likely and dips in price may occur, but the prices will inevitably increase yet again. It's a finite resource! We really only argue about how fast that might happen.

No one predicts that oil will last forever—the taphonomy shows that it can't. Some experts believe it will last for a few more decades at a reasonable cost because of improved techniques and new finds. Others downplay the taphonomic factors and suggest that we will have plenty of oil into the foreseeable future. As Professor Deffeyes notes, none of these things have ever changed the Hubbert curves significantly in the past and he believes that there's no reason to think anything has changed now. He urges conservation and a switch to other energy sources right away. The famous lifetime oil man, T. Boone Pickens, now recognizes that the demand for oil is increasing while the supply remains flat. This is costing the US $600 billion/year, the largest transfer of wealth from one place to another in history. This is untenable he says. For these reasons, he is now promoting massive production of wind-power in the windy parts of Texas and the midwest (http://www.cnn.com/2008/US/05/19/pickens.qa/). That's quite a switch for an oil man.

Most of the evidence and the instincts of people who know indicate that the world is on a downhill slide with regard to oil. Additional drilling will not likely get us out of this problem in the short term, and in the long term, the oil may be too valuable for other uses to burn it in transportation. In 1962, I toured a Chevron refinery and the leader of the tour, an employee, told us "It's a shame to burn all this oil when it could be used for so many other good things". Even then he knew the folly of burning oil. I still vividly remember him standing there before us. If the US drills the offshore or the Arctic slope now (and those sources will not relieve our problem for long) and the rest of the world uses up its oil, we may be creating yet another oil crisis in

Figure 5. Secondary recovery is used in most oil fields to enhance production. Water is injected commonly and is used in Saudi Arabian fields, while steam shown here is used too. The steam plants, shown in the distance venting steam, pump steam into the oil-bearing strata and force the oil to other wells nearby where it is extracted. The technique works on heavy crude and fields that are somewhat depleted. See http://www.heavyoilinfo.com/thermal . J. H. Lipps image, 1960.

the more distant future. Taphonomy shows us there's not a lot left.

The final question in oil taphonomy is what becomes of the oil once it is used? As we use it today, most of it is converted into CO_2 and released into the atmosphere. And this we know, as paleontologists who have examined the fossil record, can lead to increasing greenhouse warming that will change the face of the Earth to something like we had at previous Pleistocene warm periods or, worse, the Eocene warm events. This anthropogenic warming comes on top of the natural Milankovich warming trend we have already documented. That will be a world so different that we will have trouble imagining it, even as informed as we are. Think of a much hotter world, perhaps an ice-free world, a world with higher sea levels that inundate major centers of civilization, a redistribution of cultivated and natural animal and plant populations, and perhaps a world without the biodiversity we have today on land or in the sea. Growing seasons will differ and societies will have to restructure and may wish to migrate. And, societies will have to do all of this without the availability of oil to drive those changes. We may be creating our own problems and the inability to deal with them effectively. Back to the Stone Age!

Something must change fast. If you are in the US, watch television and you will soon see ads by the oil industry about how much we still have, or the coal industry that promotes a switch to "clean coal", or the wind and solar power industries that have the solution already, or the politicians running for office or not who have their own ideas aimed chiefly to get votes. Everyone is trying to capitalize on this crisis, and it's not all helpful. We can help by speaking out. I've only touched on the problems; much more is important and also needs to be made apparent to the general public and politicians. A lot of people who know are already doing it. For example, Dr. Pete Palmer, most famous to us as a trilobite expert, has been speaking to senior and church groups for many years about this problem. He made a most useful one-page handout with four points that he gave me to use in my classes. I like one of his conclusions: "Honor