James E. Barrick is Professor of Geosciences at Texas Tech University. He received his B. S. degree in geology from Ohio State University and M. S. and Ph. D. degrees from the University of Iowa. His research interests focus on using conodonts and other microfossils in biostratigraphy and interpreting past oceanic events.

Microscopic Marvels of the Paleozoic: Conodonts

Microfossils are important fossils

When most people think of fossils and paleontology, they visualize large and impressive vertebrates, like the spectacular dinosaur skeletons seen on display at major museums, or strange and unusual invertebrates, trilobites, brachiopods, or crinoids, specimens of which can be purchased in rock shops or even from auctions on the Internet. Although the geological record of these larger fossils (macrofossils) gives us important information about the history of life on earth, for the practical matters of ordering geological and paleontological events in time and preserving evidence of past climatic changes, microfossils clearly out muscle their larger relatives. Microfossils are small fossils, usually less than one millimeter in size, and sometimes only a few microns in diameter. They are so small that the casual fossil collector is unlikely to see them on outcrops, but they may be abundant enough to comprise significant volumes of sedimentary rock.

Included in microfossils are representatives of a vast variety of prokaryotes, protists, plants, and animals. In some instances, the microfossil is the mineralized shell (test) of a protist. The amoeba-like foraminifers, which are common marine organisms today, secrete tiny chambered shells of calcium carbonate that have been found in rocks as old as the Cambrian Period (Fig. 1). In many other cases, the microfossils are just a portion of the organism. Coccoliths, the tiny calcium carbonate skeletal shields that cover a single cell of planktic algae, are a major constituent of calcareous oozes accumulating in the oceans today and have formed beds of chalk (Austin Chalk of central Texas) since the Cretaceous Period. Spores and pollen, the reproductive grains of plants that flood our landscape every summer and provoke allergic reactions in many people, are amazingly durable over geological time, and are common constituents in rocks dating back to the origin of land plants, over 400 million years ago. In fact, we have a better record of the evolution of land plants preserved in their spores and pollen than we see through their leaves, stems, and roots.

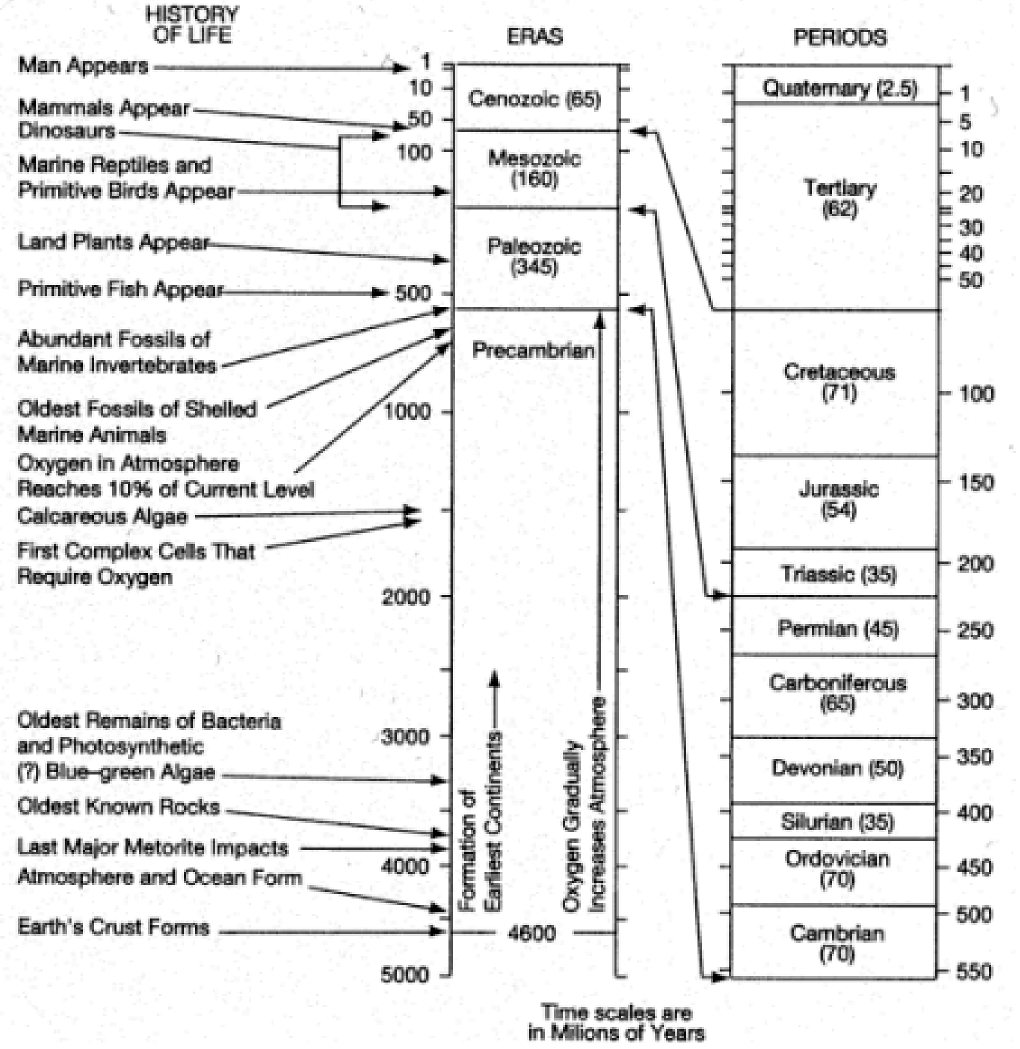

Figure 1. The geological time scale, showing major biological and geological events. Conodonts appeared in the middle Cambrian, survived the major mass extinction at the end of the Permian, only to disappear during a lesser extinction event at the end of the Triassic. After McKinney (1993).

It is the small size, vast numbers, and widespread distribution of microfossils that make them invaluable geological tools. Even a small sample of rock, from a surface outcrop or an oil well being drilled, may contain tens, hundreds, or even millions of microfossils that can be identified and analyzed in order to date the sample or reconstruct the environment in which the sediment accumulated. Recent work on microfossils shows that they may also contain invaluable information about the chemistry of the oceans and the atmosphere millions of years ago, essential information in interpreting the pattern of global climate change. Much of what we know about the last 100 million years of climate change is based on studies of oxygen isotopes as preserved in the tests of foraminifers.

The microfossil remains of foraminifers, coccoliths, and other groups that still live today have provided us information about the last 200 million years (Mesozoic and Cenozoic Eras; Fig. 1) of earth history. However, in order to obtain the same kind of information about the Paleozoic Era (560 to 225 million years), we must rely on another marine microfossil group, the conodonts, which became extinct early in the Mesozoic. Despite their importance in making geological correlations and an 100-year long controversy about their zoological affinities few people outside of paleontology have even heard of them. This paper describes conodonts and shows how they fit into geological research.

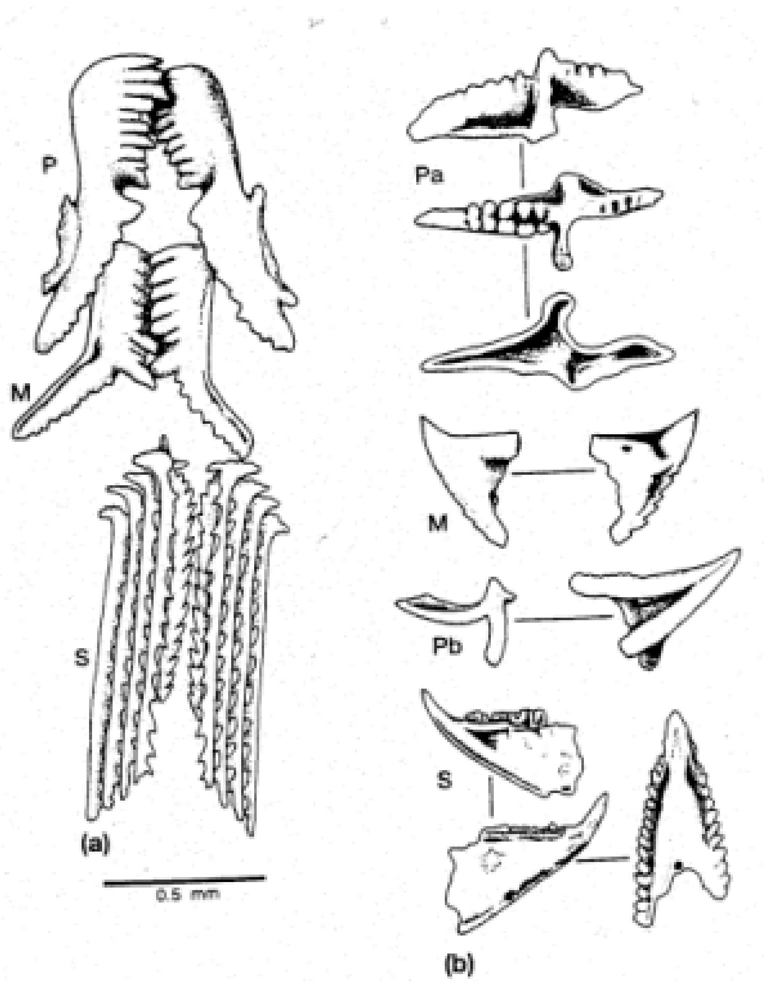

Figure 2. Conodonts. (a) A natural Assemblage of Pennsylvanian conodonts. (b) A reconstruction of an apparatus of Ordovician conodonts. P - pectiniforms (platforms); S - ramiforms. After McKinney (1991).

Conodonts

Conodonts are amber-colored, tooth-like microfossils composed of apatite (calcium phosphate), a composition similar to that of vertebrate teeth (Fig. 2). When he first described them over a century ago (1859) from clays near St. Petersburg, Russia, C. H. Pander thought that they were a variety of small fish teeth. For the next 80 years, conodonts were nothing more than a paleontological curiosity and only a few geologists attempted to obtain them by washing marine shales through fine sieves or splitting open layers of black shales. This early work demonstrated that conodonts had been an abundant group throughout most of the Paleozoic and into the early Mesozoic Era. The tremendous morphological diversity of shapes of conodonts (Fig. 2) is far greater than that typical of fish. Some conodonts are slender conical forms that closely resemble teeth (coniforms). Others possess numerous fine tooth-like denticles with complex three-dimensional shapes (ramiforms). A third major morphological group (platforms, or pectiniforms) includes low flat elements with complex morphological features on their upper surfaces.

Some attempts were made to use conodonts to date Paleozoic rocks, but like most other fossils they were limited by the distribution of shales from which they could be collected. In addition to collecting individual conodont specimens, a few paleontologists discovered natural assemblages of conodonts (Fig. 2), where several different morphological classes had been preserved together and clearly belonged to the same animal. However, the discovery of the natural assemblages did not resolve a basic question: to what type of animal do conodonts belong? Only the assemblage was preserved and no outline of the animal's body could be seen.

In the late 1930's, a revolution occurred in the study of conodonts. Paleontologists in the Iowa and Missouri discovered that when limestones are dissolved in weak organic acids, conodonts do not dissolve and are easily separated from the small insoluble residues. This discovery meant that paleontologists could collect every layer of marine limestone from an outcrop and expect to find conodonts in each sample after it was dissolved in weak organic acid. Some of the first work in acid dissolution occurred in Texas. Sam Ellison, who taught at the University of Texas in Austin, and a student (Roy Graves) published one of the first papers in 1941 using the acid dissolution technique, a description of Pennsylvanian conodonts from the Marathon region of west Texas, just north of Big Bend.

During the next twenty years, conodont workers in North America and Europe dissolved vast quantities of Paleozoic limestones in hope of obtaining conodont faunas. Although not every limestone contained conodonts, most did, and in many instances, thousands of conodonts were obtained from a kilogram of rock. Hundreds of new species were described and named. This evidence showed that conodonts had a complex evolutionary history that included many rapid bursts of evolution, where numerous species, especially platform species, appear successively over short intervals of time. Out of this work arose biostratigraphic zonations where the presence of a particular conodont species could be used to recognize a small interval of geologic time. This interval of time could be traced, or correlated, wherever the diagnostic species was found. Within 25 years, conodonts had risen from a paleontological curiosity to the primary means by which Paleozoic time was subdivided.

Conodonts as timekeepers

The essential contribution of conodonts to geology is the ease by which they are obtained in chronological order from the rock record. The construction of a biostratigraphic zonation that can used for dating and correlating strata depends on reconstructing the sequence of fossil species in time. The basic time-ordering principle in sedimentary rocks is that of superposition - in a series of layered sedimentary rocks, the oldest beds lie at the bottom of the section and the youngest at the top. From this we infer that a fossil species that occurs only near the bottom of the section lived (and died) earlier in time than one found only near the top. The time value of fossils is obtained through the collection of fossils in superpositional order - superposition is the sole assumption with regards to time. No model of earth history, organic evolution, or other belief system is necessary, only superposition. However, due to the uncertainties of preservation of fossils and incomplete collecting, it is not possible to determine the age of fossil species from only a few collections from a few localities. One needs to obtain as many samples bearing the fossils as possible from numerous localities. Because conodonts are readily collected and extracted from limestones, conodont workers have been able to amass large volumes of superpositional data on the distribution of conodonts and create highly refined and reliable zonations. In several cases, conodont zones represent an interval of time far shorter than one million years, a level of time resolution that has not been attained by other means, even radiometric dating.

The primacy of conodonts for time resolution and time correlation has been subsequently validated during the recent revisions of the Paleozoic time subdivisions. When the Paleozoic periods were first used in the nineteenth century, the boundaries between adjacent periods had been poorly defined. These indistinct boundaries were not a problem until refinement in radiometric dating and biostratigraphic correlation during the mid-twentieth century permitted geologists to resolve small intervals of geologic time. As greater level of precision was achieved, geologists saw that a more precise boundary between each adjacent subdivision of geologic time needed to be defined. Since 1970, the boundaries of each of the major and minor geologic time periods have been under restudy in order to provide a more precise and easily correlated level. For the vast majority of the Paleozoic boundaries, conodonts have been selected as the fossil group to be used to recognize and correlate the boundary level from the primary reference section to other geologic sections around the world. Even today this process of boundary definition and characterization continues, and the distribution of conodonts across the boundary interval is an important factor in the making the final decision. Our interpretations of cause and effect for past geologic, biologic, oceanic, and climatic events all require that these events be placed accurately and precisely in geological time.

Other applications of conodont research

In addition to their role in biostratigraphy, researchers found other applications for conodonts. Conodonts display a regular and predictable distribution in sedimentary rocks that formed in different sedimentary environments. Through analysis of the species present and their relative abundance, conodont specialists can interpret the approximate water depth or distance from shore in the which the sediments accumulated. This information has been valuable in the reconstruction of sea-level curves that depict the major global rises and falls in sea level during the Paleozoic. In a similar manner, as collections of conodonts from different geographic regions were assembled, it was discovered that the geographic distribution of conodonts contained valuable information that has assisted in the reconstruction of the positions of continents and oceans during the Paleozoic. Conodonts figured prominently, both in time correlation and paleogeographic analysis, in the recent discovery that during the Ordovician, the current western margin of South America was attached to what is now the eastern coast of North America.

Because conodonts are composed of apatite, geochemists have been eager to use them to sample the Paleozoic oceans. Most fossils, large and small, are composed of calcium carbonate (calcite or aragonite), which over time can change chemically and lose any original geochemical signal of the ocean water in which it precipitated. Apatite, though, is more resistant to natural geochemical alteration. In conodonts, the apatite is densely layered and impermeable, unlike the porous structure of vertebrate bone. Although the small size of conodonts initially hindered geochemical research, the development of new techniques to analyze very small samples have permitted research on conodont geochemistry to proceed. Conodonts have been analyzed for their trace metals, rare-earth elements, oxygen, carbon, and strontium isotopes, all in hope of being able to recover the geochemical characteristics of the Paleozoic oceans. Enough uranium occurs naturally in conodont apatite that it may be possible in the near future to obtain radiometric dates and biostratigraphic ages from conodonts.

The petroleum industry uses conodonts as indicators of the degree of maturation of hydrocarbons in sedimentary basins as well as for biostratigraphy. Unburied and unheated conodonts have a light amber color because they retain complex organic molecules in the skeletal framework. When conodonts undergo deep burial and heating, these organic molecules change or mature in the same manner as do organic substances in the strata that are transformed into oil and natural gas. As the organics in the conodonts mature, the conodonts change color from light amber to dark amber to brown until they turn black. Experimental work and field research shows that when conodonts are light brown, the sediments have been buried and heated to a degree such that hydrocarbons have fully matured into oil and gas. However, black conodonts indicate that the rocks have been heated too high or too long, that any organic material has been completely destroyed and no oil or gas will be present.

What are conodonts?

By 1970 conodonts had clearly been established as a major fossil group. The number of conodont researchers, especially in the midwestern United States, had increased and they informally organized themselves into a professional society, the Pander Society. The name of the society was taken from the name of the discoverer of conodonts, C. H. Pander, and the researchers capitalized on the general meaning of the word to call themselves Panderers who would go Pandering and, of course, the head of the Society was the Chief Panderer. However, despite the success of conodonts in solving a variety of geological and geochemical problems, conodont specialists were left with one embarrassing fact: they still did not know to what kind of animal the conodonts belonged!

There had been no lack of speculation and argument about what conodonts may have been. Conodonts had been aligned with bony fish, hagfishes, mollusks, worms of different types, chaetognaths (a group of modern zooplankton), even jellyfish, and algae, but no consensus existed about their zoological affinities. In textbooks and reference books, conodonts were listed under Other groups or Miscellany . In the Zoological Record, a publications that catalogues all the animal kingdom, conodonts were found hidden at the end of the volume on Vermes (worms). Paleontologists developed functional models of the conodont apparatus, based on the arrangement and number of conodonts found in the natural assemblages. Some conodont specialists thought that the conodonts functioned as teeth that were used to grab and stab prey, and then to slice and dice it for ingestion. But others argued that the small size and delicate nature of some conodonts was such that they could only be used to support a series of tentacles that would be used to filter small plankton out of the water and into the mouth.

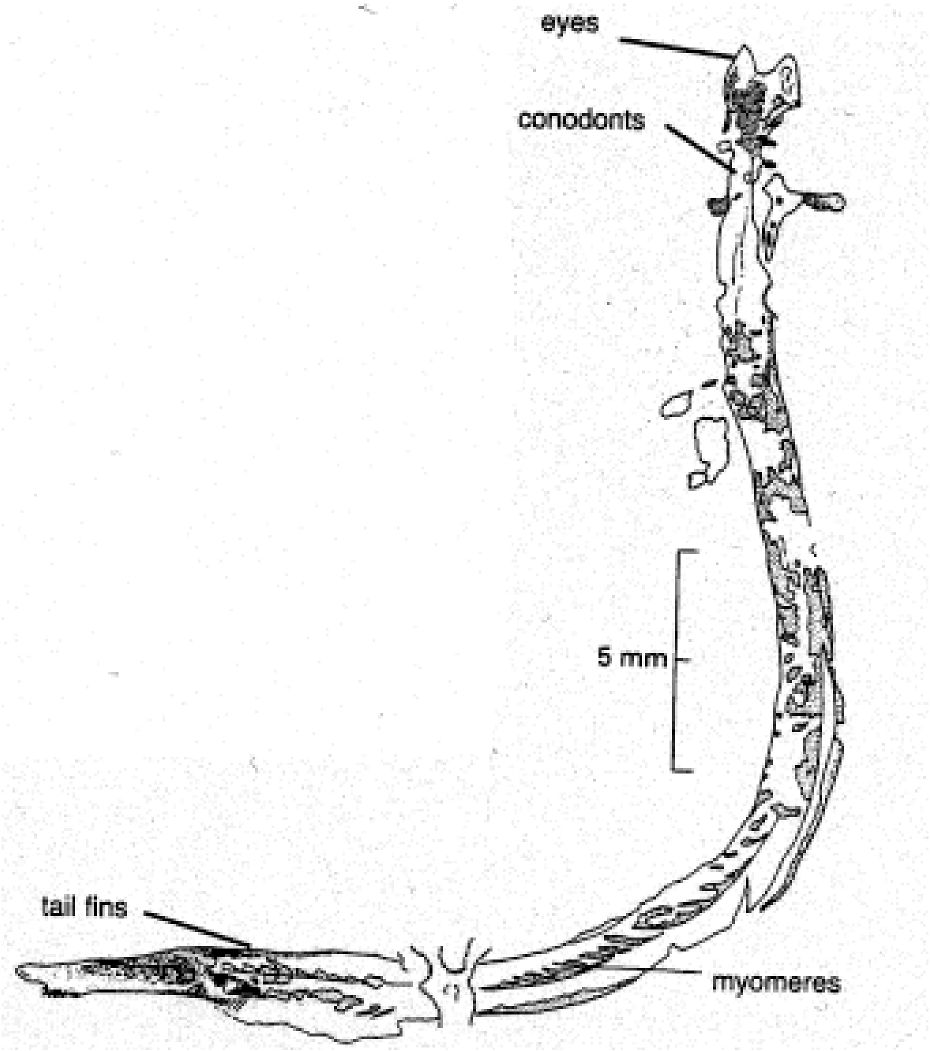

Figure 3. One of the conodont animals from the Granton Shrimp Bed. Drawing after Prothero (1998) from a photograph in Briggs and others (1983).

Not surprisingly, a soft body impression of an animal with the conodonts in place became one of the most sought after prizes of paleontology. Every few years, a discovery would be announced only to fail critical evaluation. A potential conodont animal from Montana was finally interpreted to have been a conodont predator, not the conodont animal. An unusual segmented impression from the Cambrian Burgess Shale was thought to be an early conodont animal, but detailed study of the conodonts in the animal revealed them to have the wrong chemical composition. Finally, a true conodont animal was discovered. Paleontologists studying samples of the Granton Shrimp Bed (Carboniferous) in a Scottish museum in the early 1980 s accidentally noticed a small slender body impression at one end of which was a slightly disturbed natural assemblage of conodonts. Subsequent study of this specimen and similar ones obtained from the Granton Shrimp Bed by Dick Aldridge and colleagues in England verified that this indeed was the conodont animal (Fig. 3). Since then, additional conodont animals have been found in South Africa and a fragmentary animal from southeastern Wisconsin. As of 2000, about twenty conodont animals have been discovered.

However, the discovery of the soft-body impressions of the conodont animal has not completely resolved the zoological affinities of conodonts or their function. The animals lack skeletal parts except for the conodonts, which occur in the mouth region. There is an indication of a notochord, the muscle fields (myomeres) on the trunk display a chevron like-pattern, and a caudal fin appears to be present (Fig. 3). These features indicate that the conodont animal was a chordate (zoological group to which vertebrates belong), but not a vertebrate. Exactly where they fit within the chordates remains a matter of active controversy. This new information about the conodont animal has been integrated into new analyses of the evolutionary history of chordates and the origin of the vertebrates. Studies of the histology of conodonts is providing some important information about how the early chordates first formed apatite skeletons and about the origin of the vertebrates. In one interpretation of chordate history, the conodont animals possess more derived characters than even the more primitive groups of early fish, the ostracoderms.

Large flap-like features on the head on the soft-body impressions have been interpreted by Aldridge and colleagues as large eyes, which are an essential feature for a the predatory lifestyle that they envision for the conodont animal. Their reconstruction shows a small actively swimming predator, bearing an impressive array of conodont teeth (Fig. 4). Still, not all paleontologists accept this interpretation of how conodonts lived and fed. We must remember, though, that the conodont animals that have been collected to date represent only three out of more than 1500 species that have been placed in about 250 genera! Given the morphological diversity of the conodonts, we can only predict that when we find additional soft-body impressions of other species, we should discover a far greater variety of animals than we have seen to date. Even today, the chance of finding another, perhaps different, kind of conodont animal keeps paleontologists searching.

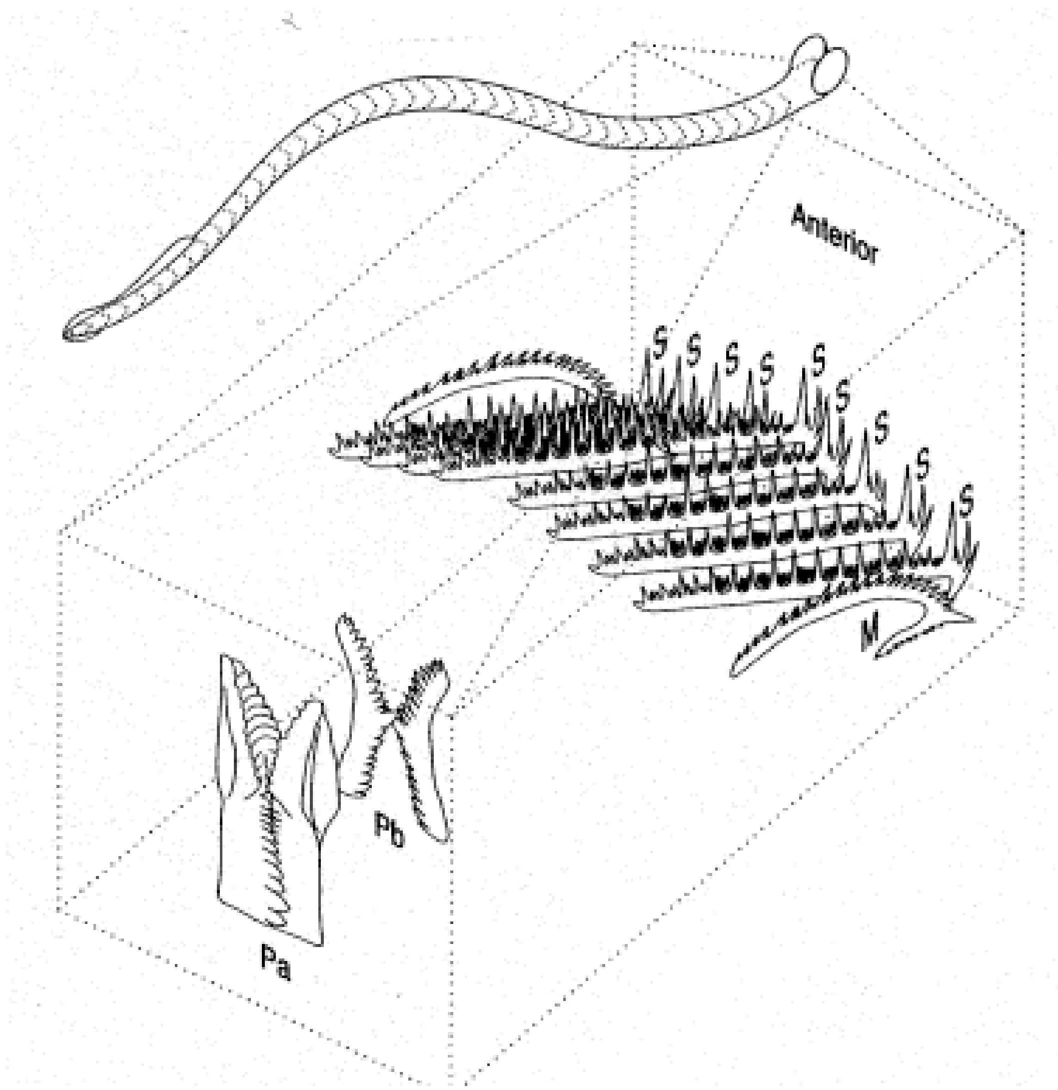

Figure 4. Reconstruction of a Pennsylvanian conodont animal showing arrangement of conodonts in head region. The drawing is from Purnell (1994), based on reconstructions by Aldridge and others (1987; 1993).

Conodont research at Texas Tech

Conodont research at Texas Tech focuses on the use of conodonts in correlating Paleozoic rocks. Some is applied research, where samples from wells and outcrops are processed for conodonts in order to determine the age of petroleum-bearing strata. This information provides the petroleum geologist with a better picture of the local geology and enhances hydrocarbon exploration and production. Basic research efforts include the evaluation of the global time scale for the Paleozoic and redefinition of boundaries (especially Carboniferous Period), as well as proposing refinements to existing biostratigraphic zonations. More recently, cooperative work with paleontologists from the Baltic region (Sweden and Estonia), is directed toward determining the magnitude and cause of major global oceanic/climatic events during the Silurian, based on conodont faunas.

Conodonts are on the Internet. Check the Pander Society web page (http://www.geology.utoronto.ca/pander/) for informational about the Society and for paleontology links. See the following site for color photographs of conodonts and more links (http://www.geocities.com/CapeCanaveral/Hall/1383/2TopCone.htm).