Readings and Notes

An Introduction to Earth Science

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The Silurian Period

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THE SILURIAN PERIOD

Introduction: The Silurian Period is the shortest of all the periods of the Paleozoic Era, lasting only 30 million years from 438 million years ago until 408 million years ago. As the Silurian Period opens, the eastern margin of Laurentia was dominated by the Taconic Highlands that had been created during the Taconic Orogeny at the close of the Ordovician. The rest of the craton was essentially flat-lying and covered by a shallow sea.

Except for the northeastern margin which was involved in a major orogeny following the Taconic Orogeny, Laurentia was tectonically quiet throughout the Silurian. About 10 million years before the collision of Avalonia in the Devonian , Baltica collided with the northeastern portion of Laurentia during the Caledonian Orogeny and creating the Caledonian Mountains. The Caledonian Orogeny involved eastern Greenland, the northeastern margin of Laurentia down to about the latitude of Nova Scotia, western British Isles from Ireland and Scotland to the eastern margin of Scandinavia **(Figure 1)**. The Appalachian region was not affected by the Caledonian Orogeny.

The Appalachian Basin: During Early and Middle Silurian time, clastic sediments were shed from the Taconic Highland into the Appalachian foreland basin to the west. The basin quickly filled with sediment and alternated between being covered with a shallow ocean and being a low coastal plain that extended from the western base of the Taconic Highlands nearly to the Cincinnati Arch. In the stratigraphic record, the beginning of Silurian time is marked by the **Tuscarora Sandstone**, a sandstone created from the quartz-rich clastics that accumulated along a coastal plain that bordered the western margin of the Taconic Highlands **(Figure 2)**. The layer of sand from which the Tuscarora formed was one of the most extensive accumulations of pure quartz sand to form in the eastern portion of the continent. Because it is cemented with silica, the Tuscarora is referred to as a ***sedimentary quartzite***, one of the toughest lithologies found in the Appalachians.

Today, the Tuscarora Sandstone is the major ridge-former throughout the Valley and Ridge Province of the Appalachians with outcrops being found all the way from New York to Alabama. The formation reaches a maximum thickness of more than 1,000 feet in southeastern New York. The Tuscarora is known locally by other names including the Clinch, Medina, and the Albion. To the east, the sands give way to more coarse clastics that were accumulating nearest the base of the highland. This lateral change in particle size is recorded in a lateral change eastward from the Tuscarora Sandstone to a conglomerate called the Shawangunk in New York and New Jersey (refer to Figure 2).

Following the deposition of the Tuscarora sands, the return of finer-grained, alluvial sediments to the shallow, oxygen-rich basin is represented by the presence of the relatively thin redbeds of the **Rose Hill Formation** that, in time gave way to the buff-colored Rochester shales as the basin slowly subsided (refer to Figure 2). By the end of Early Silurian time, the Taconic Highlands had been worn down to the point where only fine muds were being transported westward into the foreland basin. These muds are now represented by the Middle Silurian shales. With the rocks of the continental margin thickened by the suturing of the Piedmont Micro-Continents to the edge of Laurentia during the culmination of the Taconic Orogeny, subsidence within the foreland basin decreased. It is estimated that the total depth of the basin during Silurian time was only about 600 feet. One of the results of the decreased depth of the basin was to limit the total thickness of the accumulated alluvial and deltaic sediments.

During lower Silurian time, the intense chemical weathering of the highland generated unusually high concentrations of iron which was introduced into the basin where it formed the **Clinton Iron Ore**. The iron ore consists of iron oxide (Fe_2O_3) that occur in relatively thin, lenticular beds within the Middle Silurian shales. Exposures of the Clinton Iron Ore, found all the way from New York to Alabama, provided much of the iron used by the early settlers of Appalachia. In the vicinity of Birmingham, Alabama, the combination of the iron ore, where the beds of ore reach their maximum thickness of 15 to 20 feet, locally available Cambro-Ordovician limestone to be used as flux, plus Pennsylvanian coal from the Warrior Coal Basin allowed the formation of the steel industry of Birmingham, Alabama, a city once known as the "Pittsburgh of the South".

By mid-Silurian time with the Taconic Highlands reduced to near sea level, the amount of clastic sediments shed into the foreland basin decreased to the point where carbonates began to accumulate along with the muds, giving rise to the calcareous shales of the **Wills Creek Formation**. Along the eastern margin of the basin, the muds that accumulated in the shallow, oxygenated waters became iron-stained as the iron oxidized and precipitated to form the **Bloomsburg redbeds** (refer to Figure 2) while to the west carbonates were accumulating in the basin that would become the **Tonoloway Formation**. The limestones of the Tonoloway Formation are of special interest in terms of what they recorded about the basin during the later part of the period. Fossil and sedimentological evidence indicates that the Tonoloway limestone formed from chemically precipitated carbonate muds that accumulated in very shallow, very warm water where the salinity of the water was higher than normal due to evaporation. These conditions resulted in an extremely low diversity of life and the preponderance of chemically precipitated carbonate materials. A comparable depositional environment can be seen today in Florida Bay where evaporation of the shallow waters results in abnormally high salinity that precludes the existence of all but the most hardy animals along with sea grass and algae that can tolerate the extreme conditions (**Figure 3**). In the case of the Tonoloway limestones, the presence of mud cracks on many of the upper bed surfaces clearly indicates that the sediments were periodically exposed to the atmosphere.

By the end of the Silurian, the sea encroached across the entire basin as the eastern margin of Laurentia once again become a carbonate platform. The result was the accumulation of carbonates across the entire region; limestones now represented in the Appalachian region as the **Keyser Formation**. Not only was the eastern portion of Laurentia covered by the sea by the end of the Silurian, but the entire continent was covered by a vast shallow sea depositing carbonate sediments across the continent (**Figure 4**).

Silurian Life

Silurian Reefs: The Silurian saw the first development of the tabulate-strome reefs that consisted of tabulate corals, colonial rugose corals, and stromatoporid sponges. Reef structures had existed since the Cambro-Ordovician, but these were surpassed in both complexity and dimensions by those that developed in the Silurian seas. Unlike the relatively simple archaeocyathid and sponge reefs that had existed since Cambrian time, the Silurian reefs consisted of a complex assemblage of animals and algae never before seen. Many of the individual reefs rose more than 40 feet above the ocean floor and extended for tens of miles.

Reefs can develop under a number of different environments. Charles Darwin was the first to comprehensively study reefs and it was Darwin who demonstrated that reefs will grow only where the water is warm, free of suspended sediment, and shallow enough to be in the photic zone where the sunlight is of sufficient intensity to allow the survival of the algae that are not only a major component in all modern reefs but actually exist symbiotically within the bodies of modern reef-building coral. It was also Darwin who described the three major types of reefs, *fringing reefs, barrier reefs,* and *atolls.* In many cases, the reefs develop in the order fringing-barrier-atoll as sea levels rise (**Figure 5**).

Darwin observed **fringing reefs** forming in the shallow water immediately adjacent to land. Excellent examples can be seen in the older Hawaiian Islands from Maui westward. Although fringing reefs can be found around the youngest island, Hawaii, the island is not yet old enough to have developed extensive fringing reefs.

As the water deepens over a fringing reef, the reef builds upward to maintain itself in the photic zone. In time, the reef is separated from the land by a lagoon that is protected from the energy of incoming storm waves as the reef serves as a "barrier", giving rise to Darwin's assigning the name, **barrier reef**.. Barrier reefs also commonly form at breaks in slope where the ocean bottom drops off into deep water. An example of such a barrier reef is the one now growing along the edge of the continental shelf just south of the Florida Keys (**Figure 6**). As the name implies, the largest modern barrier reef is the Great Barrier Reef off the east coast of Australia.

The **atoll** is a reef located around a submerged land mass such as a seamount. Most seamounts are shield volcanoes that built above an oceanic hot spot and rose from the ocean bottom to become volcanic islands. Soon after emerging as an island, a fringing reef began to grow in the shallow waters adjacent to the island. Eventually, lateral movement of the oceanic plate moved the volcanic island moved off the hot spot, severing it from a supply of magma. As a result, the volcanoes on the island became extinct while the island moved into ever-deepening water. Because of the need to maintain itself in shallow water, the fringing reef grew upward to become a barrier reef. In Darwin's succession, sealevel eventually rises to the point where the original central island submerges to form a seamount. The reef, still building upward to remain in the photic zone, now becomes a ring of coral surrounding the inner lagoon. (refer to Figure 5).

Individual reefs complexes generally develop three components (**Figure 7**). The **fore reef** is the portion of the reef on the seaward side of the structure. Impacting waves, especially during storms, break off portions of the reef which are then carried down the seaward face of the reef into deeper water. The **reef core** consists of the living portion of the reef and the underlying abandoned portion of the reef complex. The **back-reef**, located on the leeward side of the reef core, consists of a combination of carbonate sands derived from the reef, chemically and biochemically generated carbonate sediments. In some cases, evaporite minerals may accumulate behind the reef structure.

While the Appalachian Basin was being filled with clastic sedimentation, the Cincinnati Arch served to prevent sediments derived from the Taconic Highland from being transported beyond into the cratonic interior. As a result, with little or no influx of clastic sediments and with the craton straddling the equator, the entire craton west of the Cincinnati Arch became an extensive carbonate environment.

Silurian Evaporite Basins: Several basins began to form within the craton that became sites of extensive reef formation; two in particular were a small basin in northeastern Ohio and a much larger one in Michigan (**Figure 8**). Barrier reefs developed around both basins where the shallow ocean floor dropped down into the basin interior. As the barrier reefs developed, they served to restrict the flow of water from the open sea into the basins interior. There, the combination of a warm climate and high evaporation rates resulted in the precipitation of evaporite minerals. The Michigan Basin is of special interest (**Figure 9**).

The origin of the Michigan Basin is not fully understood but is believed to be a response to the crustal loading of the eastern margin of Laurentia during the Taconic Orogeny. As the basin formed, a barrier reef formed along the break in slope at its margin, grew vertically, and eventually began to restrict the flow of seawater into the basin to the point that it became an evaporative basin. In time, the rate of evaporation within the basin became so high that evaporite minerals began to precipitate, eventually filling the entire basin. The most abundant evaporite mineral deposited within the basin was dolomite $[Ca,Mg(CO_3)_2]$ followed by rock salt ($NaCl$) and anhydrite ($CaSO_4$). Where the total thickness of Silurian carbonates throughout most of the cratonic interior amount to only a few hundred feet, the Upper Silurian sediments within the Michigan Basin alone were in excess of 4500 feet, most of which were the result of evaporation of seawater within the reef-restricted basin. It is interesting to ponder just how much water had to evaporate to provide the mass of evaporite minerals that accumulated in the Michigan Basin. If we assume that the salinity of the seawater at the time was the same as that of modern seawater, it is estimated that a column of seawater 600 miles thick over the entire basin would have to evaporate in order to produce the thickness of evaporite minerals found within the basin! Because the water within the basin was always very shallow in order to allow the water to warm to the point where evaporation took place, it means that the evaporating seawater was constantly being renewed by "fresh" seawater coming into the basin from the surrounding sea. Today, a comparable situation exists in the Gulf of Kara-Bogaz, an embayment of the Caspian Sea that is separated from the sea by a shallow bar (**Figure 10**). As was the case of the Michigan Basin during Silurian time, the waters within in the Gulf are constantly being replenished across the shallow bar at the mouth of the embayment with the extremely arid conditions of the area resulting in such extreme evaporation that hyper-saline brines form at the surface and sink to the bottom where evaporite minerals are constantly precipitating. The importance of the Michigan and Ohio evaporite basins is that today, they are major sources of salt both for both industrial and domestic use.

The Silurian of the Cordilleran: Throughout Silurian time, the Cordilleran portion of Laurentia was covered with a shallow sea within which similar reef development was taking place (**Figure 11**). It is important to note that, unlike the eastern margin of Laurentia that had undergone a mountain building event, the Cordilleran region along the western margin of Laurentia had experienced no tectonic activity since the breakup of Rhodinia. However, that was to change in the next period.

Other Marine Invertebrates: Reef-builders were not the only new life forms in the Silurian seas. Because the mass extinction that occurred at the close of the Ordovician had mainly affected the warm-water invertebrates, those that survived into the Silurian were mostly cold-water forms that had either moved in from the higher latitudes or from deeper water. As a result, the diversity of marine invertebrates during the Early Silurian was quite low. By Late Silurian time, however, the invertebrate community had returned to a level of diversity and complexity comparable to that of the Ordovician. The brachiopods, bryozoans, corals, crinoids, and graptolites that returned to the Silurian seas were, however, represented by different families and orders than had dominated the Ordovician seas.

The thin-shelled Ordovician brachiopods had been replaced with brachiopods with thicker and more robust shells, the most characteristic brachiopod of the Silurian were the ***pentamerids*** **(Figure 12)**. Pentamerids lived in dense communal clusters that served as the core for some of the reefs that were plentiful in the warm Silurian seas. Later, in the Devonian, the pentamerids will be replaced by another new group of brachiopods, the ***spirifers*** **(Figure 13)**.

Bivalves and **gastropods** were present in the Silurian sea but were far outnumbered by the brachiopods. More important than their low abundance, however, was the fact that the bivalves had expanded into the freshwater environment for the first time. The invasion of the land had begun. The scarcity of trilobites in the Silurian fossil record definitely indicates that they were on the decline along with the nautiloids . The nautiloids, however, would remained a major predator in the seas until they were replaced in the Devonian by the **ammonites.** The only nautiloid remaining today is the **chambered nautilus** of the South Pacific. The major difference between the nautiloids and the ammonites was in their shells. While the shells of most nautiloids were straight, those of the ammonoids were tightly spiraled shells **(Figure 14)**.

The nautiloids were, however, not the major predator of the Silurian seas; that role belonged to the **eurypterids**, an arthropod related to modern scorpions **(Figure 15)**. The eurypterids were armed with claws on their front appendages with which to attack and hold their prey while their rear appendages were shaped like paddles that provided them with an efficient means of locomotion during the attack. Most eurypterids were relatively small, being less than 20 inches in length, although at least one representative reached a length of 9 feet. Although they would be present in the seas throughout the Paleozoic, the eurypterids reached their maximum population in the Silurian.

Planktonic forms thrived in the warm Silurian waters. Graptolites, that had nearly gone to extinction at the end of the Ordovician returned to the Silurian seas. However, by Late Silurian, they were in their final days. Shortly after the close of the Silurian, nearly all forms of graptolites went to extinction with the exception of one type that did survive until the Pennsylvanian.

Marine Vertebrates: Of all the evolutionary developments of the Silurian, the greatest advance was definitely in marine vertebrates. Although simple jawless fish had been around since Cambrian time, fish began a rapid evolution during the Late Silurian and by Devonian time had become so abundant that the Devonian is often referred to as the "Age of the Fish". Their lack of jaws indicated that they were largely filter-feeders while the fact that they developed both head and body armor during the Silurian would indicate that they were the prey for some predators. Because the skeletons of the jawless fish were made of cartilage, fossils are rare except for preservation of the bony armor.

Perhaps the most important evolutionary development of the Silurian was the appearance of the first **jawed fish**, the **acanthodians, (Figure 16)**. The acanthodians had large eyes which, combined with the presence of jaws, definitely contributed to their success as predators. The combination of their prowess as predators along with the presence of many fins supported by spines gave rise to their being commonly referred to as "spiny sharks". True sharks would not appear until the Devonian.

The Invasion of the Land:

Land Plants: Until the Ordovician, only the very edge of the land had been invaded by plant life where fungi, bacteria and algae could still take advantage of the protection of the marine environment. However, the finding of fossil spores clearly indicate that by Late Ordovician advanced plants were present on land, although we have no idea what they looked like. Several requirements had to be met before plants could truly invade the land. Most importantly, they had to develop a waterproof outer layer that would prevent desiccation when exposed to the atmosphere. They also had to develop tissues that would allow the development of a supporting structure that was strong enough to allow them to grow vertically against the force of gravity. They would also need some kind of structure that would both anchor them to the land while at the same time allow them to acquire the water and nutrients needed for survival. And finally, in the absence of seawater, they needed to develop a system whereby sperm could be passed to the eggs to allow successful reproduction. The first plants to develop all of the necessary requirements for the invasion of the land were the **vascular** plants that evolved in the Early Silurian. Although the remains are very fragmentary, stems bearing what appear to be bract-like leaves similar to modern ground pine were found in Australia. This primitive plant, ***Baragwanathia longfolia***, is one of the oldest example of true terrestrial vegetation. The plant grew to a height of about 0.5 meters and, like most of the early land plants, consisted of branches rising vertically from horizontal rhizomes (**Figure 17**). The branches were covered with what appeared to be leaves except they did not contain vascular tissue.

Another well-known early plant was ***Cooksonia caledonica***., the earliest remains being found in the Middle Silurian near Tipperary, Ireland. Since then, fossils of Cooksonia have been found throughout the British Isles, as well as in Czechoslovakia, Kazakhstan, Siberia, New York and Ontario, Canada. Cooksonia was a small plant growing only a few centimeters high and was perhaps the most primitive of the known vascular plants. The plant consisted of stems that bifurcated several times, terminating in small sporangia in which the spores developed (**Figure 18**). It would not be, however, until the Devonian that the vascular plants evolved to the point where they did, in fact, successfully invade the land.

Land Animals: Possibly, the first air-breathing land animals were **scorpions** and **millipedes**, the fossil remains of which have both been found in the Upper Silurian rocks. The scorpion of the Silurian was almost exactly like the modern scorpion and appear to have been descendants of their marine cousins, the eurypterids.

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