The Green River Formation: a large post-Flood lake system

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Evidence from lithology, sedimentology, paleontology, ecology, taphonomy, geochemistry and structural geology suggests the Green River Formation (GRF) was a large lake system. Certain features—such as multiple horizons of exploded fish, disarticulated fish and stromatolites—suggest the passage of more than the one year of time allowed for by the Genesis Flood. Since these deposits have multiple lacustrine characteristics, are relatively undeformed compared to the underlying basins on which they rest and since the GRF is near the top of the geologic rock record, it is argued that the GRF represents a post-Flood lacustrine deposit.

Introduction

It is apparent that the floodwaters did not retreat from the earth as fast as they had covered it (Genesis 8). Noah watched the water gradually retreat over a period of months. As the floodwaters returned to the ocean basins (Psalm 104:7–9), it is likely that large lakes formed in enclosed continental basins, worldwide. Some of these lakes may have been relatively short lived due to tectonic readjustments and drainage basin development, but some have likely remained until today (the Great Salt Lake in Utah, for example). The idea of immediate and large post-Flood lakes is not a new one. Whitcomb and Morris[1] and Morris[2] suggested this possibility, although they did not cite the Eocene GRF as an example. Rather, they believed it was formed during the Flood.[1]

The question as to where the Flood/post-Flood boundary occurs has been a difficult question for creationists to answer. Because of the geologically catastrophic beginning of the Flood (Genesis 7:11), its location in the geologic record is easier to recognize than its end (Genesis 8:19). Consequently, geologic criteria for recognition of its beginning are easier to make.[3] Since the publication of the *Genesis Flood*, many creationists have taken Whitcomb and Morris's approach to include all of the Cenozoic rock record in the Flood, except for Pleistocene and later deposits. In this paper, I argue that the Eocene GRF is a post-Flood lake deposit—one that formed and persisted as the floodwaters retreated. The Eocene is the second epoch of the Cenozoic in the standard geologic time column. *It is important to recognize that I don't believe all Eocene and later deposits are post-Flood! Likewise, I am not arguing that all pre-Eocene deposits are Flood deposits.* I am arguing something much different. Flood geologists need to use sedimentological criteria to recognize when the Flood ended in a particular part of the world. These criteria should probably be independent (at least initially) of the paleontological criteria (index fossils) that are often used to place a particular formation within the geologic time column.

In this paper, I argue that the lithology, sedimentology, paleontology, ecology, taphonomy, geochemistry and structural geology of the GRF, when considered as a whole, forces the inescapable conclusion that these rocks represent lacustrine deposits. As stated in the introduction to this forum, I don't believe that millions of years are represented by the sediments of the GRF, but that they have accumulated since the time of the Flood, only a few thousands of years ago.

Lithology and sedimentology

The stratigraphy of Fossil Basin is well known. Buchheim has developed a lithofacies map[4] showing concentric relationships between various laminated micrites and siliciclastics (figure 12*, table 1). This map could be developed because of vertical relationships within numerous measured sections and lateral relationships within ash-bounded beds, like the 'Lower Sandwich Bed' near the base of the Fossil Butte Member (figure 13). In general, siliciclastics occur around the margin of Fossil Basin. These are followed by bioturbated micrites (figure 14), partly bioturbated micrites, kerogen-poor laminated micrites and kerogen rich laminated micrites (sometimes called 'oil shales') in the very centre of the basin (figure 6). At some stratigraphic levels, kerogen-rich to kerogen-poor dolomicrite replaces the calcimicrites. Stratigraphic cross-sections and lithofacies analyses of other Green River basins have shown similar concentric patterns.[5–11]

Cross-bedded sandstones (figure 15) occur around the margins of the Green River basins. Current directions are roughly perpendicular to basin margins and dip toward basin centres. I have observed deposits like this along the south-eastern side of Fossil Basin,[12] along the north central end of the Greater Green River Basin,[7] within the Washakie Basin, near the Kinney Rim[13] and near Soldier Summit, Utah[14] Many other examples of these types of deposits can

* Figures are numbered continuously through all the articles in this forum.

Table 1. Summary of lithofacies patterns in Fossil Basin.[4,54] The lithofacies in this table match those in figure 12.

	Kerogen-rich laminated micrite (KRLM)	Kerogen-poor laminated micrite (KPLM)	Partly burrowed laminated micrite (PBLM)	Bioturbated micrite (BM)	Dolomicrite (DM)	Sandstone and siltstone (SS)
Total organic carbon	2–14%	< 2%	< 2%	< 2%	2–14%	no data
Sedimentary structures	laminated (alternating calcite and kerogen)	laminated (alternating calcite and kerogen), kerogen laminae much less distinct	same as KPLM, horizontal and vertical burrows up to 2 cm in diameter	structureless micrite, abundant macro burrows, bioturbation increases toward margin	laminae often disrupted by salt casts, soft sediment deformation features, mud cracks	trough and ripple cross beds, up to 4 m thick cross beds, loading structures
Grain size	clay	clay	clay	clay matrix, some sand to pebble sized angular clasts	clay	fine to coarse grained sand, carbonate interclasts
Mineralogy	calcite with minor amounts of dolomite, quartz, feldspar, and clay	same as KRLM, except calcite content is higher	same as KPLM	same as KPLM	dolomite, some units may contain some quartz, feldspar, clay and calcite	primarily quartz and feldspar, some clay
Paleontology	abundant fish, leaves, insects	abundant fish	abundant fish	gastropods, pelecypods, ostracods, and fish	some units contain abundant ostracods, **no fish**	gastropods, pelecypods, burrows

be found in the literature.[5,6,15,16] These sandy facies often contain fossil leaves and occasional loading structures.

Where sandy or conglomerate facies do not occur along the basin margins, carbonate mudstone facies often abound. These facies contain features interpreted as mud cracks,[10,17,18] nesting sites of birds and other animals,[19,20] ripples (figure 16),[21] flat pebble conglomerates,[10] animal tracks,[22,23] stromatolites,[24] caddisfly mounds,[25] fish fossils (often disarticulated),[8,26] crocodiles and lizards,[23] birds[27] and many other features.[28]

Carbonate spring mounds (tufa and travertine) with silica-rich cores are known to occur at several locations within the Green River Basin.[29,30] All of these mounds occur stratigraphically within the Green River Basin sediments (i.e. they interfinger with them) and are similar in morphology to modern mounds that currently exist elsewhere (in Searles and Mono Lakes, California, for example). I have observed other mounds at the extreme southern part of the Green River Basin, near Manila, Utah. Four mounds are present, about 10–15 m in height, parallel to the Henry's Fork Fault.[31] These particular mounds surfaced after the GRF was already in place, because they lie stratigraphically and unconformably on top of it.

Paleontology

The GRF is well-known for its exquisite fossils. Included are fish, birds, snakes, bats, crocodiles, lizards, turtles, sting rays, mammals, insects, sponges, snails, clams, various arachnids, various crustaceans including ostracods and many kinds of plants and microfossils. Numerous commercial fossil quarries are located in the GRF, especially

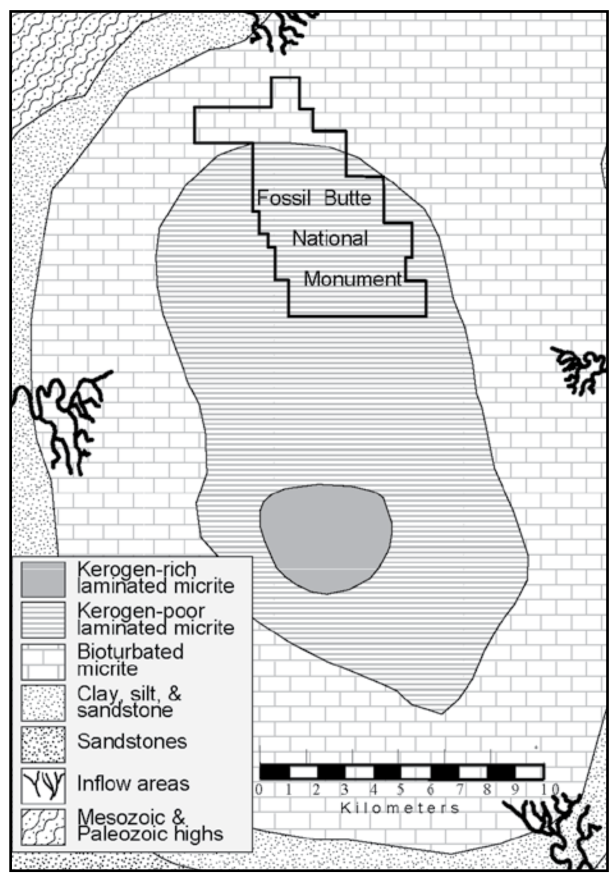

Figure 12. Fossil Basin lithofacies map developed by Buchheim and Eugster.[4] The map represents lithofacies during the time of the 'Lower Sandwich Bed', an isochronous (ash bounded) layer near the base of the Fossil Butte Member, Green River Formation, Wyoming.

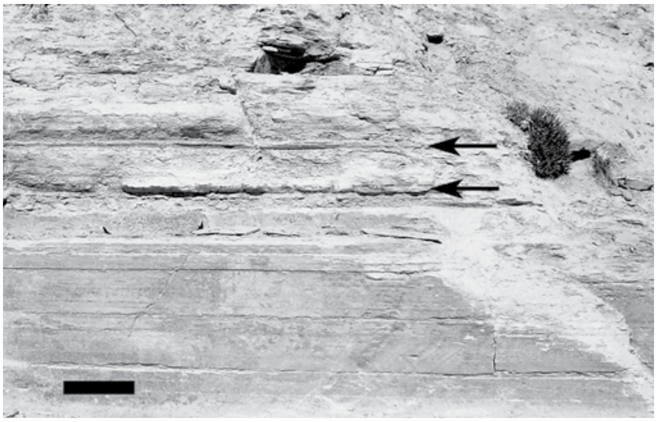

Figure 13. The Lower Sandwich Bed of Fossil Basin, Fossil Butte Member, Green River Formation, Wyoming. The bed is 'sandwiched' between two volcanic ash beds (indicated by arrows) and can be traced throughout Fossil Basin, giving excellent stratigraphic control. Several other prominent ash beds also occur throughout the vertical section. This location is Whitmore's[26] FBQ site (marked on figure 2) at Fossil Butte National Monument, Wyoming. Scale bar is 10 cm.

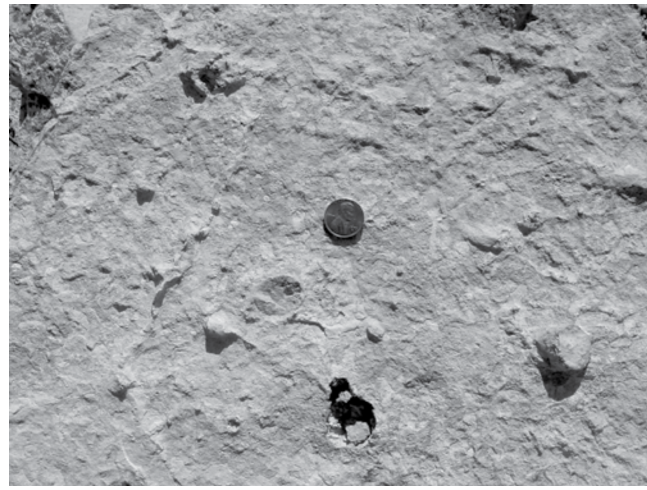

Figure 14. Bioturbated micrites of Fossil Basin, Fossil Butte Member, Green River Formation, Wyoming, at a location about 1.5 km west of Whitmore's[26] FBQ site (see figure 2), Fossil Butte National Monument, Wyoming. The coin in the picture is a U.S. penny, 1.9 cm in diameter.

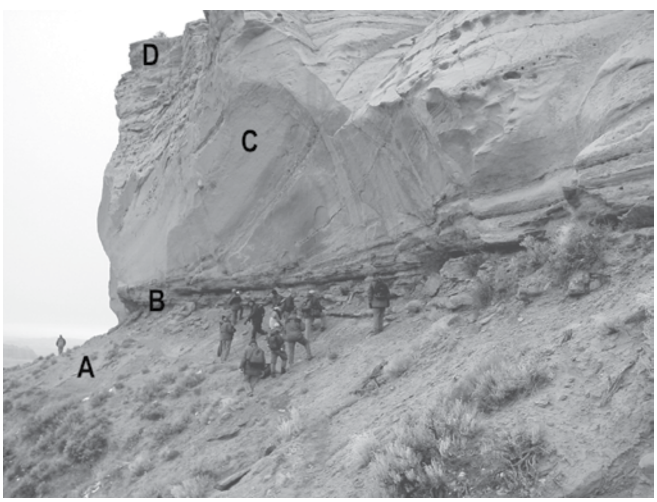

Figure 15. Supposed delta facies of the Farson Sandstone Member of the Green River Formation, Whitehorse Creek, near Oregon Buttes, Wyoming.[7] This location is near the north central edge of the Greater Green River Basin. A– Tipton Shale Member, Green River Formation. The Niland Tongue of the Wasatch Formation is on the slope directly below the photograph. B– A marker bed of thin, parallel bedded sandstone containing the gastropod Viviparus, base of Farson Sandstone. C– Planar cross bedded sandstone containing large, south dipping, foresets, Farson Sandstone. D– Trough cross bedded sandstone, Farson Sandstone. The Cathedral Bluffs Member of the Wasatch Formation lies stratigraphically above the Farson Sandstone.

Figure 16. Current ripples within a marginal facies on the Delany Rim, Washakie Basin. Bird tracks can also be found in this facies.

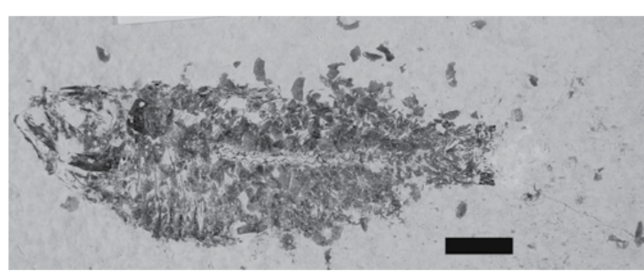

Figure 17. A fish (Knightia) collected near the margin of Fossil Basin at the Warfield Springs Quarry (Whitmore's[26] WSQ site on figure 2). Note that it is well-preserved, but some of the scales came loose and were scattered before the fish was completely buried and preserved. The specimen was exposed on the bottom long enough for the scales to come loose, but then was buried, preventing further disarticulation. The scale bar is 1.0 cm long. Specimen WSQ 21–7. Warfield Springs is a private quarry.

in Fossil Basin. They occur in both marginal and mid-basin areas. Ten years ago, it was estimated that well over 500,000 complete fossil fishes have been excavated from Fossil Basin.[32] Patterns of fish preservation have been noted.[9,18,26,32–34] In general, these studies have found that better preserved fish tend to occur away from the immediate edges of the basins, although occasional well-preserved fish can occur in these areas as well (figures 17 and 18). I

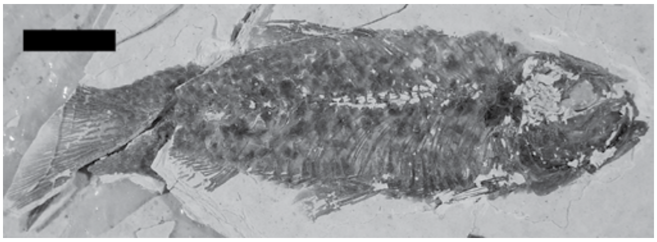

Figure 18. A fish (*Knightia*) collected from near the centre of Fossil Basin from the Clear Creek Quarry (Whitmore's[26] CCQ site on figure 2). Note that it is fairly well-preserved. The scale bar is 1.0 cm long. Specimen CCQ 1.5–1. This quarry is on BLM property and a permit was obtained to collect it.

Figure 19. Stromatolites on the Delany Rim, Washakie Basin. Multiple layers of stromatolites can be found at this location and many others within the Green River Formation. The pen is 14 cm long.

have argued that fish taphonomy can be a good indicator of water depth and depositional rates.[26,33] Multiple horizons of exploded and disarticulated fish were found in my study.

Fish fossils only occur in the calcimicrite facies and are absent from the dolomicrite facies.[35] Dolomicrites become more common near the top of the section (Angelo Member) in Fossil Basin. Grande and Buchheim[32] noted that, compared with mid-basin localities, marginal localities have a proportionally larger number of land dwelling animals (amphibians, lizards, birds and non-flying mammals), benthic organisms (shrimp, snails, crayfish), stingrays, juvenile fish, paddlefishes and mooneyes. Because of the widespread nature of freshwater species throughout Fossil Basin and the Green River Basin, Grande[35] argues that the water in which the organisms lived must have been fresh. However, he recognizes that dolomicrites and salt casts probably point to occasional saline phases of the basin, explaining why fish are absent in these facies.[36–38] Paleoecological studies have been completed in several marginal areas of the Green River Basins.[9,18,23,32,35,39] These have concluded that the fauna, flora and sedimentary structures are characteristic of shallow, near shore environments.

Not only are there distinct paleontological differences from the margin to the centre in Fossil Basin, there are distinct differences between the Green River Basins. Grande has published several excellent tables comparing the differences in fish species and abundance between the Green River basins.[23,32] Many species of fish are unique to each basin, not occurring in the others. Even though Fossil Basin has the smallest surface area (by far), it has the greatest richness and abundance of fossil fish species, indicating major ecological differences between the Green River basins.

Stromatolites (figure 19), which are sometimes referred to as algal bioherms (along with oncolites, pisolites, ooids, tufa and other related laminated carbonates) are common in multiple horizons along the margins of the basins.[6,24,40–42] In the Greater Green River Basin, single stromatolite horizons can be traced laterally over great distances, up to 70 km.[25,42,43] Tufa encrusted logs[39,44] (figure20) and caddisfly mounds surrounded by stromatolites and tufa (figure 21) have also been found near the margins of the basins.[25,45,46]

Structural geology

Bradley[47] describes the sediments at the centre of the Green River Basin as essentially flat lying with very little structural dip, unlike the steep dips and deformation present in the underlying pre-Tertiary rocks of the region.[42] Essentially the pre-Tertiary rocks were uplifted to make the structural depression in which the Eocene Green River rocks were deposited. Some uplift continued during and after the deposition of the Green River Basin because the sediments along the margins are often folded (figure 22), faulted, show steeper dips or are thicker.[48] Structural highs like the Rock Springs uplift were present before the Green River sediments were deposited, but continued to be 'accentuated' after the Eocene.[47]

Fossil Basin is a structural basin that is contained within a series of north-south trending, steeply dipping, thrust faulted ridges.[4,44] The underlying structure is complex, but well-known, because of extensive petroleum exploration in the Paleozoic and Mesozoic rocks below.[49] It is bounded on the west by Oyster Ridge, consisting of Cretaceous strata with rich coal reserves.[50] In the west, it is bounded by the

Figure 20. Tufa encrusted logs in the Wasatch Formation, Washakie Basin at base of Delany Rim. Rock hammer is 28 cm long.

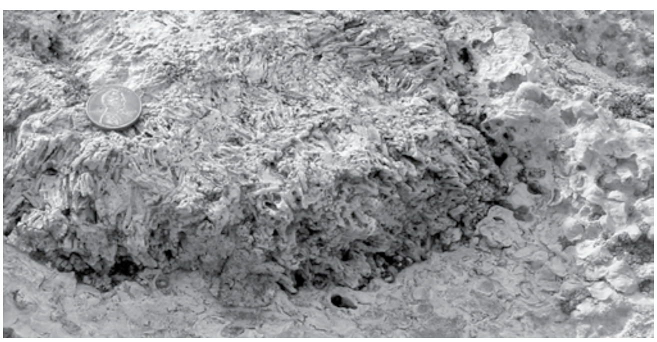

Figure 21. Structures interpreted to be caddisfly cases[25] (centre) surrounded by digitate stromatolites (perimeter). The hollow cases are tube-like structures several mm in diameter and about 10 mm long. Northern Green River Basin, near LaBarge, Wyoming. The penny is 1.9 cm in diameter.

Tunp Range. The strata in the centre of the basin form a north-south trending syncline with very gentle dips.[4]

Geochemistry

The Green River Basin is economically important because of its thick deposits of trona ($Na_3(CO_3)(HCO_3)\cdot 2H_2O$) and other associated minerals found in the central part of the basin, near Green River, Wyoming. Trona is known to be currently precipitating in several lakes worldwide, including Lake Magadi, Kenya.[29,51] These so-called 'saline facies' are isolated to the Wilkins Peak Member of the GRF.[29] Eugster and Hardie report there are at least 42 individual trona beds, 25 of which are greater than one metre thick, with the most massive being 11 m thick.[10] They also report a close association with halite (some beds up to 6 m thick) and oil shales (one under every trona bed).

In Fossil Basin, vertical and lateral changes in carbonate mineralogy (calcimicrite vs dolomicrite) have been well-documented.[4,36,52,53] The dolomicrite lithologies include salt casts, mud cracks, flat pebble conglomerates and other evidences of desiccation.[17] The 'K-spar Tuff' mineralogy grades from feldspar to analcime to clay, from basin centre to basin edge.[54]

Discussion

Studies of modern lake sediments have revealed that they generally have a concentric or 'bull's-eye' pattern of sedimentary facies.[11,55,56] The pattern may vary according to topography, river input, wind direction, transgressive and regressive events, etc.; but, in general, coarse sediments surround a lake basin, and they progressively become finer toward the centre. Walther's Law predicts these lateral changes will also occur vertically. Various ecological zones are coincident with the sedimentary facies. For example, animal tracks, bird nests, ripples and mud cracks would be expected around the perimeter of a lake, not in the middle.

Careful field investigations have revealed a concentric pattern of sedimentary facies for Fossil Basin (figure 12). Each concentric sedimentary facies contains a specific suite of features which gives clues as to water depth, chemistry, ecology and sedimentary environment of deposition (table 1).[54] A clear distinction exists between sedimentary features and fossils found near the margin of Fossil Basin (ripples, mud cracks, flat pebble conglomerates, burrows, animal tracks, fish taphonomy, cross beds, sandstones and various shallow water organisms) and those features found near the middle of the basin (laminated kerogen rich micrites, well-preserved fish and higher amounts of organic carbon). This dichotomy can be documented by the study of the sediments between isochronous ash beds, like the Lower Sandwich Bed.[57,58] I know of no other depositional model that can explain the coincidence of these concentric sedimentological and paleontological features, other than a lacustrine one.

The GRF consists of a series of enclosed *basins*. Cross bedded marginal sediments are often interpreted as deltas because of their three dimensional shape, clastic sediments, paleontology (mix of terrestrial and lacustrine), sedimentary structures (top set, foreset and bottom set beds, loading structures, dewatering structures, climbing ripples, wave ripples) and their association with the *edge* of a basin. I know of no other depositional model that can explain the coincidence of these features with the edge of these basins, other than a lacustrine delta.

Clear depth patterns can be established in Fossil Basin. Surrounding the basin are shallow water indicators (wave ripples, mud cracks, footprints, nests, etc.); towards the centre of the basin these features disappear. This same general pattern exists in the other Green River basins too. In Fossil Basin, I have shown that one can use fish taphonomy to estimate water depth.[26,33] From my

Figure 22. Red's Cabin Monocline, Green River Formation at Whitehorse Creek near Oregon Buttes, Wyoming. The picture was taken looking south-east, down the axis of the monocline, which is near the centre of the photo. The near-horizontal beds on the right, dip steeply towards the left, and plunge into the valley below. The structure was formed as result of movement of faults along the base of the Wind River Mountains.

taphonomy experiments, I was able to demonstrate fish carcasses disarticulate faster in shallow water than in deep water, probably due to explosive eruption of decay gases in shallow water. In deeper water, decay gases are compressed, not allowing carcasses to explode. Fish are better preserved in the centre of the basin, because the water was deeper. There are very few 'exploded' carcasses in the basin centre, where there are many at the basin margins. A lake appears to be the best explanation for the dichotomy of taphonomic features.

Fish taphonomy can not only be an indicator of water depth, but of time. To better interpret the depositional environment and taphonomy of the Fossil Basin fishes, I performed nearly 400 experiments using various fish species under conditions of temperature, salinity, oxygen and water depth.[26] Scales and flesh can begin falling off a carcass within days of death. Based on my taphonomy experiments, the fish in figure 17, must have been on the basin bottom for several days (in order for the scales to be scattered) before it was buried. Note that this is the longest time it could have been there before burial! If it was on the bottom any longer, it would have likely decomposed further and completely disarticulated (based on my experiments). It usually takes several days for a dead fish to build-up decay gases and explode (depending on water temperature, depth and fish species).

In my study, I found many examples of exploded fish in Fossil Basin (figure 23), most occurring around the margin of the basin.[26] A fish cannot explode and scatter its scales if it is already buried in sediment. Burial must occur *after* the explosion. Fish taphonomy is additional evidence that suggests the laminations of Fossil Basin cannot be annual varves.[59] Sedimentation at these rates is much too slow to explain exceptional fish preservation. Based on fish taphonomy, the laminations must represent shorter periods of time. Some have suggested the sediments of Fossil Basin were deposited catastrophically,[60] but fish taphonomy suggests depositional rates somewhere in between annual varves and catastrophic accumulation of the entire section.

Fossil assemblages, especially of fish, vary greatly between the Green River basins.[23] Fish occurring by the millions in one basin, are altogether lacking in the others. If all of the basins were formed catastrophically, at about the same time during the Flood, it might be reasonable to expect more similarities instead of differences between the basins. Instead, differences in fish species among the basins might be better explained by unique physical and chemical characteristics of each lake, and changes in these factors over hundreds of years or more.

Stromatolites (including algal mats and microbial mats) are known from many diverse modern environments including under frozen lakes in Antarctica[61] to harsh desert conditions in Southern California.[62] Leggitt and Cushman have found rich concentrations of organized caddisfly cases at the core of complex stromatolitic bioherms (figure 21) in the Green River Basin (up to 9 m tall and 40 m in diameter).[25] It is unknown how fast these large biogenic mounds could grow, but it seems likely that more than a few months would be required. Growth rates of modern stromatolites have

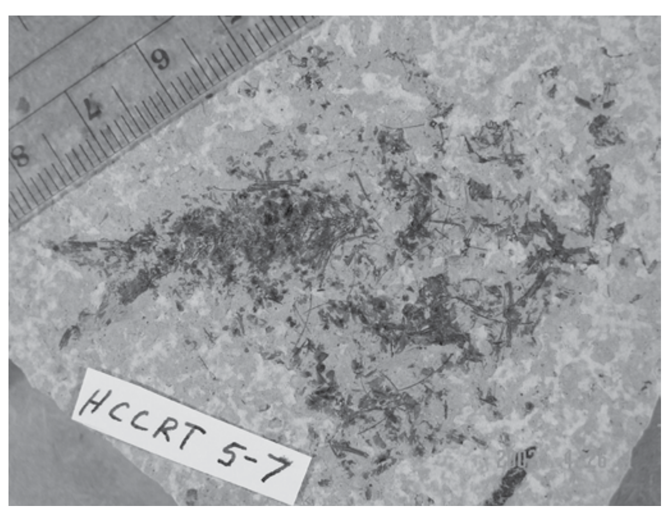

Figure 23. An exploded fish (Knightia) collected from near the margin of Fossil Basin (Whitmore's[26] HCCRT site on figure 2). This quarry is on BLM property and a permit was obtained to collect it. Specimen HCCRT 5–7. Scale in cm.

been reported of up to 1.1 mm per day (a daily couplet of a sediment-rich layer and an algal rich layer).[63] Stromatolites from the elevated shoreline of Lake Turkana in Kenya have nearly identical embedment cavities as those from the Washakie Basin in Wyoming.[40] Embedment cavities are holes in the surface of a living stromatolite that form when an infesting organism uses and maintains the hole as a domicile. These structures appear to be evidence that ancient stromatolites were living communities of algae and other micro-organisms that did require some time to grow, perhaps adding laminae as quickly as once a day. Multiple horizons of stromatolites in the GRF appear to be problematic for a Flood model.

Calcimicrite is the predominant carbonate in Fossil Basin, but at times it is replaced with dolomicrite and other saline derivatives, especially in the Angelo Member. Coincident with the change to dolomicrite are sedimentary structures (flat pebble conglomerates, salt casts, mud cracks, etc.) and paleontological changes (i.e. no fish). It has been proposed that a desiccating lake basin, with saline water in the centre, is the best explanation for the various changes.[4,17,37,38] I concur. The changes in the 'K-spar Tuff Bed' mineralogy appear to prove some kind of lateral changes in lake chemistry,[4,37] although the patterns are not as clear as in Pleistocene Lake Tecopa or other modern saline lakes.[64]

Trona and other saline minerals are present in the Wilkins Peak Member in Green River Basin, while Gypsum is conspicuously absent. Trona must form from calcium and magnesium poor solutions,[65] and thus cannot be precipitated from standard seawater, which instead precipitates gypsum and halite. Trona and other saline minerals are currently precipitating out of a Na-CO_3-SO_4-Cl rich brine in Lake Magadi, Kenya, where the waters are chemically enriched, partly because of thermal alkaline springs.[29] Bradley and Eugster cite springs as a possible source for the trona and halite in the Green River Basin, which concurs with the evidence for several spring mounds in the Green River Basin. Thus the presence of the trona and absence of gypsum, argues for a non-marine origin for the trona-halite beds of the Green River Basin.

The Flood was certainly marked by tremendous tectonic activity, beginning with its first day (Genesis 7:11). Tectonic activity must have occurred at the end of the Flood as the mountains and continents were raised out of the ocean (Psalm 104:8). I propose that the tectonic upheaval mentioned in Psalm 104:8, was responsible for the uplift of mountain ranges surrounding the Green River basins and the cause of numerous large thrust faults that enclose Fossil Basin. These upheavals likely would have caused the tremendous folding of the Paleozoic and Mesozoic basement strata that we find below the Green River basins. The Green River basins consist of primarily flat lying strata, which suggest the greatest mountain upheavals must have occurred *before* the strata accumulated in the basins. As discussed earlier, some of the edges of the basins do contain some minor folding and faulting, but it is local in extent and can be explained by minor readjustments along already existing mountain fronts during and after the Green River deposition. The fact that the strata of the GRF are primarily flat lying, and the strata below are severely deformed, suggests the GRF was deposited *after* major tectonic events in the area.

Conclusion

The GRF consists of a series of large post-Flood lake deposits that began to form as continents and mountains were uplifted, forming basins, at the end of the Flood. These basins began to fill with sediments from local rivers. Coarse sediments on the basin margins interfingered with fine grained lacustrine deposits at the basin centres. Over time, the lakes established normal lacustrine ecologies with plants, animals and other organisms that repopulated the earth following the Flood. Some volcanic and tectonic activity continued in the area as evidenced by ash beds and occasional folding and faulting of basin margins. Features such as multiple horizons of stromatolites, exploded fish and disarticulated fish suggest the passage of time, making it unlikely these features could have formed during the one year global Flood. For the most part, the GRF sediments are flat lying, indicating they were deposited *following* major tectonic upheavals near the end of the Flood. Although the deposits contain some unusual features (exquisite fossils, trona, stromatolites, tufa coated logs, etc.), evidence from lithology, sedimentology, ecology, paleontology, taphonomy and geochemistry all clearly indicate lacustrine patterns. The lakes ceased to exist, probably because they became filled with sediments. When this happened, rivers could flow across former basin divides and exhume the basins.

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