CHARCOAL BEDDING AS A TOOL FOR STRATIGRAPHIC INTERPRETATION

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ABSTRACT

Observations of modern charcoal and sediments at forest fire sites and of fossil charcoal in the Dakota Formation suggest that the bedding of the charcoal can be an indicator of the speed of the deposition processes. Buoyancy forces will normally place charcoal and other buoyant materials at bedding planes. Thorough mixing of buoyant plant fragments into sediments indicates catastrophic processes. Lack of redistribution of bedding plane charcoal can indicate rapid burial by subsequent deposits.

INTRODUCTION

Carbonized plant matter forms a significant part of the stratigraphic record. Coals of various forms have been studied for centuries because of their great economic importance. The coal classification by Stach *et al.* [7] includes fusain, or fusinite, which "closely resembles wood charcoal." It is generally a minor part of coals, occurring in lenses with thicknesses in millimeters and lengths in centimeters [6, p.134]. The variety named pyrofusinite is attributed to fires followed by bedding in subaquatic environments [6, p.218-219]. Other forms of fusinite arise from bacterial and geochemical action and by plant tissues that were originally black. This paper deals with the presence of charcoal and its fusain likenesses in modern and ancient sediments rather than the other forms of coal. It also refers to plant matter that has not been carbonized.

The vertical distribution, or style of bedding, of the plant matter in the stratigraphic record has become important to creationist studies. Austin [2] studied the deposition of formerly floating logs and root balls at Spirit Lake and found that they can produce a bedding style of upright stumps at multiple elevations after a catastrophic event like the eruption of Mount St. Helens. That has contributed to a reinterpretation of the fossil forest in Yellowstone Park. Orientation of petrified logs may be indicators of flow direction. Polystrata logs give testimony to generally rapid burial, before plant destruction by weathering and rotting. Preservation of morphological details in fine shales or volcanic ashes indicates a rapid process but possibly at reduced energy levels. Except for surface details, such studies generally involve plant fossils with dimensions in meters. The discussion in this paper refers to plant fragments resembling wood chips with dimensions in centimeters and millimeters.

Charcoal in the stratigraphic record can be locally abundant though macroscopic pieces are not a typical component of most sediments. Stach *et al.* [7] and Patterson *et al.* [6] provide extensive reviews of issues of charcoal generation (fires), transport, deposition, and the properties of resulting materials in the sediments. Their emphasis is on microscopic sizes as in soot and abraded charcoal powder. Williams *et al.* [8,9] focus on the properties and presence of large pieces of charcoalized wood in deposits at Big Bend National Park, Texas. Holroyd [3,4,5] found both macroscopic pieces and impressions of charcoal in the Dakota Formation at Dinosaur Ridge (between Golden and Morrison, Colorado, west of Denver) and elsewhere. He studied the interaction of charcoal and sediments at modern forest fire sites for further understanding. Two styles of bedding were identified. The common and expected type had the charcoal along bedding plane surfaces in thicknesses of millimeters or less, as described by Stach *et al.* [7], but laterally extending for many tens of meters. The unusual type had charcoal mixed within the sediments. Buoyancy considerations in those studies indicated that charcoal can be an important tool for interpreting depositional conditions for sedimentary rocks. The mixed style of bedding was attributed to catastrophic depositions of mud flows or slurries or similar geologic processes of very short time span.

CHARCOAL PROPERTIES

Some of the plant fossils examined by Holroyd at the various Dakota Formation sites varied from powdered carbon to carbon-stained cavities in the rocks to bulk carbon of up to centimeter sizes that was of light density and had a structural consistency of modern charcoal. Wood grain was visible only in the pieces exceeding millimeter sizes. Another style of fossilization had hematite hardening of the walls of cavities and no carbon stains or organic remnants. The hematite hardening preserved wood grain more frequently than did the carbon-based fossils. Of particular note were the abundance of wood chip-sized fragments in which the fractures were perpendicular to the wood grain. That is the natural fracture pattern of charcoal as can easily be verified at a forest fire or campfire site. Green wood that is broken by natural forces, such as by a flood, will exhibit frayed ends. Semi-rotten wood can have a range of edge styles depending on the degree of decomposition. Green and rotten wood are more readily attacked by bacteria and invertebrates than charcoal and may not survive long enough in sediments for preservation of their impressions. The hematite-hardened fossils were therefore attributed by Holroyd to have been pre-existing charcoal on the basis of the fracture pattern perpendicular to the wood grain. Carbonization of plant matter after burial would not produce the observed isolated fragments with the perpendicular wood grain/fracture geometries.

Charcoal can be buoyant though carbon is not. Air is trapped within charcoal by former cell walls. When dry some forest fire charcoal in my possession will rise to the top of a jar of water within about one second after shaking, floating with as little as one-third of its mass below the water line, thereby indicating a density of about 0.3. When waterlogged it will rise to the top of sediments in a slurry of sand (density about 2.6) and water (density 1.0) within about five seconds after agitation. Some charcoal can remain floating at a water-air surface for over a year while other pieces sink overnight. Thoroughly wetted or powdered charcoal may have a density of about 1.4. The strength of the buoyant forces upon charcoal indicates that it should most frequently be found at bedding planes in the stratigraphic record: a sediment-water or a sediment-air interface. However, a subsequent flow of water is likely to lift the charcoal from a bedding plane and deposit it downstream unless there are forces, like the drying of mud or entrapment by plant root fibers, bonding the charcoal to the surface of the sediments.

Water-soaked charcoal is slightly more dense than water and sinks. Because of its lighter density than other sedimentary particles, water-soaked charcoal is readily sorted and can be concentrated in sedimentary beds. Charcoal concentration (and abrasion to powder) can be observed as a result of wave action at shorelines and in similar agitated environments. A striking example of subaqueous accumulation of charcoal is a "fusain clast conglomerate" within the Kentucky No. 12 coal bed. The conglomerate has an area of about 130 km^2 according to Austin [1, p.148] and variable thicknesses from 0 to 7 cm.

Charcoal is sometimes found well-mixed with sediments. Such may be possible in a dry environment in which the carrying fluid, air, is three orders of magnitude less dense than the charcoal or sediments. However, if water is moving the sediments and charcoal, then the water must be such a minor component of the fluid that there is little opportunity for density separation of the materials. This mixing is indicative of catastrophic deposition conditions such as a mud flow or density current that move a thick slurry of sediments and charcoal into place.

Charcoal is fragile. It is easily crushed by animal traffic and abraded by wind-blown or wave-driven sand. Though generally immune from biological consumption, it is slowly consumed by oxidation at an exposed surface. It readily absorbs water and so it is somewhat vulnerable to fragmentation by repeated freeze-thaw cycles in cold environments. Normally macroscopic pieces of charcoal cannot remain at a dormant surface for centuries awaiting burial by today's slow rates of general deposition.

Observing what happens to charcoal at and from a forest fire site can give modern analogs from which we might be able to understand the fossil deposits. The following fire sites were conveniently close enough to the author's home near Denver that they could be repeatedly observed. Sediments generated by torrential runoff from the fire sites were examined for the presence and bedding style of charcoal fragments. All are in mountainous terrain, unlike the supposed coastal plain environment typically envisioned for the Dakota Formation deposition.

SUGARLOAF MOUNTAIN FIRE SITE

Sugarloaf Mountain, west of Boulder, Colorado, was burned in 1989, destroying dozens of homes. Black Tiger Gulch serves as a steep and narrow V-shaped drainage channel for much of that area. Although some initial runoff was sufficient to deposit several meters of sand and plug a culvert where the stream goes under the road, it does not appear that there have been major movements of sediment in the watershed in recent years. Spring and Summer flash floods have caused the stream to overflow its narrow banks in some places, depositing sand (mostly quartz from weathering granite) and debris up to a few meters away from the main channel. Scattered vegetation is only slowly returning to the slopes.

The new sand deposits were trenched at numerous locations, digging many to tens of centimeters down to rock or firm surfaces using various hand tools in an effort to look for intermixed charcoal. None was found. In December, 1994, a coring was taken of the top 14 cm of sand (of perhaps 20 cm of sediments) in one overflow area adjacent to (tens of centimeters above and a few meters away from) the stream. The samples were sieved through a series of standard meshes down to silt sizes. Charcoal and fire debris, apparently arriving by both air and by water, was found on the surface within a meter of the coring site but none was found within the core sample. Buoyancy appears to have prevented any of the charcoal from mixing within the recent sediments.

BUFFALO CREEK FIRE SITE

A swath was cut by an intensely hot fire in the Buffalo Creek area southwest of Denver, Colorado, in May, 1996. It was up to 2 km wide and 13 km long. Almost no vegetation survived the fire. Even the soil was burned and baked, leaving a surface of coarse sand from weathered granite. About three weeks later a hailstorm drenched the area and caused some flash flooding. The next day there were deposits of charcoal along stream channels marking high water levels. A generally flat-bottomed (tens of meters wide) stream bed parallel to the road south of Buffalo Creek was examined. The stream bed has the same moderate slope as the road. At one small culvert the charcoal debris was up to a half meter thick. Much sand was also moved by the flooding. Several of the new sand deposits made within the flood plain during that storm were hand-trenched that next day by up to several tens of centimeters to look for charcoal mixed within. All such examinations revealed no macroscopic charcoal mixed into the sand and no dark staining of the subsurface sand by powdered charcoal. This charcoal was initially very dry and soaked only by the overnight rain and hail. It was therefore highly buoyant and all of it stayed above the sand and most presumably floated on the water as well.

About a month later a much more severe thunderstorm occurred over the area watersheds, causing flooding that washed out roads and bridges, destroyed some buildings, and killed two people. Upstream of where the highway crosses Buffalo Creek a delta of sand several meters thick was made. The flood sent much sand and charcoal downstream to the South Platte River and into the Strontia Springs Reservoir. The Denver Water Board had to try to flush much of the debris out of the reservoir because it was contaminating the water used for human consumption. The upstream channels were examined again in the early Autumn of 1996 and the Spring of 1997. However, charcoal was hard to find in those and other sediments of Buffalo Creek and its tributaries. There were some trace layers of charcoal powder but no charcoal pieces of mm to cm size were found within the sediments examined. Such charcoal pieces were, however found on the gravely slopes denuded by the fire and there was an abundance of charcoal still on the remnants of the trees. Charcoal was also on branches and large debris piled up in log jams in some areas downstream.

Though the mid-summer flooding was catastrophic in terms of the damage that it did and in the thick delta that was created, the macroscopic charcoal was so buoyant that pieces never mixed into the sediments. Only powdered charcoal (denser than water) was present at bedding planes in the new sedimentary record. In the Spring of 1997, a year after the fire, there were some settling pools near the streams that were black with powdered charcoal. New sand was swiftly moving downstream in the main channels. There were a few locations where the new sand had buried a black layer of wet carbon paste and then subsequent erosion had exposed the black at a bedding plane. The powdered charcoal was not buoyant with respect to water and was somewhat immobile so that it did not move downstream when an overflow of the stream dumped fresh water and sand onto it and buried the deposit.

It appears that dense powdered charcoal can be deposited at a bedding plane during conditions calm enough for the settling of fine sediments. Such layers of black can survive subsequent deposition. However, at this particular fire site the macroscopic charcoal was typically of a density less than that of water. It accumulated only near high water marks and never within the sediments.

STORM KING MOUNTAIN FIRE SITE

In September 1994 the Storm King Mountain fire site near Glenwood Springs, Colorado, experienced an intense thunderstorm. It caused a debris flow to come down steep channels draining the southern face of the mountain. Sedimentary materials in the flow were from Upper Paleozoic red shales and sandstones. The largest channel, which was several meters wide with some near-vertical side slopes, showed scour marks about 2 meters up the banks, with higher rises on the outsides of bends in the channel and lower scour marks on the insides of those bends. Where the main channel widened and changed to a more gentle slope the debris flow dropped its boulders but the mud and charcoal fanned out and continued to Interstate-70. There some mud diverted into the gutters beside the lanes but most continued over the road and on to the Colorado River. The mud blocked the Interstate highway for three days.

Corings were taken of the mud on the third day and reported by Holroyd [4] along with other details. Two of the samples near the highway showed charcoal thoroughly mixed within the mud. Therefore there was insufficient water and time for buoyancy to separate the charcoal from the sedimentary materials. A third sample was taken upstream from the boulder dump at a depression coated with black charcoal. It had been a settling pool after the flood had passed. A coring there revealed stones on the bottom, mud in the middle, and charcoal on top. Buoyancy had been able to operate after the passage of most of the flood material when the stream returned to more normal flow conditions.

This site shows that it is possible for charcoal to mix into sediments, but the mud flow must be so dense (a relatively small proportion of water) and turbulent that buoyancy does not have an opportunity to cause separation. Such mixtures are indicative of catastrophic deposition mechanisms. The Sugarloaf fire site appears to have never had a catastrophic flow after the fire. Some of the flash floods at the Buffalo Creek fire site were comparable in severity to that at Storm King, yet the Buffalo Creek site's macroscopic charcoal floated on the water above the coarse sand. Perhaps the silts and clays at Storm King contributed to the thickening of the slurry and the ingestion of the large charcoal and vegetation fragments into that slurry. Flows with less than catastrophic energy appear to leave buoyant materials at bedding planes.

DINOSAUR RIDGE PLANT FOSSIL DEPOSITS

At Dinosaur Ridge between Golden and Morrison, Colorado, the Dakota Formation contains fossil plant fragments in fine cross-bedded sandstone. An 11 to 16 meter thick layer with such characteristics is exposed at the road cut along West Alameda Parkway. Most of the plant fragments are at about 5 mm sizes. Some show limited rounded edges indicative of abrasion during transport. There are also some occasional bark and branch impressions are up to a meter in length and up to 10 cm wide for the bark. They were presumably green or dead and not made of fragile charcoal in order to have survived deposition conditions. Many fossils are colored black by presumably carbon stains. Others are colored orange by hematite and other iron oxide hardenings that have preserved the wood grain after the deposition of the plant fragments. Though some surfaces hardened by this concretion process show the effects of modern weathering, freshly exposed surfaces have sharp, unabraded grain and edge features. As mentioned earlier, the hematite-hardened surfaces typically possess a sharp fracture pattern perpendicular to the wood grain strongly suggests a charcoal origin for the plant fragments. Green wood broken up to wood chip sizes will have frayed ends but charcoal has a natural shrinkage and fracture pattern perpendicular to the grain direction. Semi-rotten wood fractures have intermediate patterns. The isolated charcoal pieces on the ground at the forest fire sites had sizes similar to those observed at Dinosaur Ridge. No green wood chips of centimeter or smaller sizes were found at the forest fire sites nor in the flood debris downstream from them. The larger fossils at Dinosaur Ridge were comparable in size to the debris at log jams downstream from the fire sites.

The cross-bedded sandstones and siltstones with plant fragment fossils at Dinosaur Ridge have some beds with no fossils, some with fossils only at their upper bedding planes, and many beds with fossils fragments thoroughly mixed within the rock bed. The latter indicate a mud flow (though composed of sand and silt and almost no clay) with catastrophic bedding in minutes and with no opportunity for buoyant forces to separate the plant material from the sand and silt. Those with the plant material, usually black, at the upper bedding plane indicate either slower deposition or a flow with a greater fraction of water to create a buoyancy separation of the materials. The beds with no plant fragment fossils may have been pure sand and silt to begin with or perhaps the top surface had been washed free of plant debris before further deposition.

There is at least one bed that has a top surface with undulations of several millimeters amplitude. The distribution of black fragments is remarkably random and uniform. Floating plant material that is deposited on such an irregular surface should be concentrated in the depressions. Therefore it is assumed that the charcoal instead came from a thoroughly-mixed layer below, being lifted out of the lower sands and silts by buoyant forces, independent from the surface topography. Once on the surface the charcoal was then vulnerable to redistribution by strong winds, rains, and subsequent aqueous flows. Such will concentrate the charcoal in the depressions, thin it on the ridges, or wash it away entirely. Therefore there must have been sufficient adhesive forces (like surface tension on wet sand and adhering mud to counteract buoyancy or harden the surface upon drying) to hinder lateral movement and removal before the next deposit of sediments. That strongly suggests subsequent burial before the next rain or wind storm could overcome the adhesive forces and move the charcoal to other positions, i.e., a brief period of time that is insignificant against the normal geologic time scale. It was already known that the beds of sandstone were accumulated relatively rapidly because there are no indications of tree roots, animal burrows, soil formation, or biological displacement of the charcoal fragments anywhere in the cliff face. That means accumulation probably in less than a year, possibly extendible to a decade, but not to a century. The former rate is compatible with the Biblical Flood period and its aftermath. Accumulation of the ten meters of sediments must have been much faster than at today's typical slow deposition rates.

INTERPRETATIONS AND DISCUSSION

Fossilization

In general, any fossil must be buried rapidly or it could not have been fossilized. Plants and animals left on today's surfaces rot or are scavenged, leaving little or nothing for fossil production. The Dinosaur Ridge deposit yielded a set of fecal pellets (Holroyd [5]) that indicate invertebrate consumption of some of the biological material. Charcoal may be more immune from consumption than green or rotting material, but it is still vulnerable to weathering. It can be blown by the wind, washed away by water, abraded by blowing sand, oxidized by the atmosphere, and possibly fractured by the freeze-thaw mechanism. (Although the latter mechanism of converting charcoal fragments to powder seems reasonable, my experiment subjecting wet forest-fire charcoal to twenty cycles, two per day, of freezing and thawing in a home freezer did not produce noticeable fragmentation or powdering.) It is unlikely that the wood grain and sharp fracture edges seen at Dinosaur Ridge would survive a century of weathering in today's slow deposition conditions.

The source of the charcoal has not been addressed. It may have been from forest fires or from wood baked by volcanic ash. It may have been directly transported to its deposition location or it may have been reworked from previous deposits. Early indications are that the transport may have been from at least as far away as central Utah, giving ample opportunity for floatation, waterlogging, and fracturing.

The wood grain and fracture patterns, along with some carbon residues of similar wood chip size, indicate that the Dakota Formation fragments discussed here were charcoal before burial. Some fragments may have been subsequently crushed because they now have a flattened appearance. However, the original fragments may have been flat, like the small pieces of carbonized tree bark at the forest fire sites. The best surface details have been preserved by the concretion process, whereby iron-rich ground water deposited various iron oxides within the sediments, particularly at the surfaces of the already-buried plant matter.

Another aspect yet to be studied is how fragile charcoal can be preserved intact with sharp surface details in energetic transport and deposition conditions. Turbulent conditions within a sediment slurry or within a mass of floating debris on top of the water would tend to destroy quickly the charcoal, converting it to powder.

Bedding

The style of bedding of buoyant plant fragments in the fossil record may give us an opportunity for interpreting the speed of the deposition processes. Two styles have been identified. Concentration of buoyant matter at bedding planes is to be expected even under normal depositional conditions. However, buoyancy and density considerations, along with direct observation, indicate that buoyant matter should not be expected to be thoroughly mixed within sediments. Yet such mixtures were found within a mud flow at one fire site and at numerous outcrops of the Dakota Formation, including Dinosaur Ridge. Such observations and some simple experiments suggest that it takes catastrophic, turbulent, and brief deposition processes to achieve the observed mixtures. The appropriate time scale is in minutes and seconds, not centuries and longer.

The charcoal deposits of wood chip sizes at the Storm King fire site and in some of the Dakota Formation sites are in sediments of silt and fine sandstone. They are absent in the modern deposits involving coarse sand at the Sugarloaf and Buffalo Creek sites. Fruitful research may come from an examination of how mineral grain sizes in a slurry affect the turbulent ingestion of buoyant materials.

Some charcoal deposits are relatively pure. Powdered charcoal, which is denser than water and less dense than sand, was observed in gentle deposition conditions at bedding planes a year after the Buffalo Creek fire. Much thicker fusain clast conglomerates in the Kentucky No.12 coal bed were shown by Austin [1] to be from density currents, which are also catastrophic in nature. Such conglomerates have not yet been observed in this study.

Redistribution by various mechanisms of plant debris at a top sediment surface is to be expected in an environment of slow deposition. Uniform and random distribution of small plant fragments on an irregular bedding surface is a strong indication of rapid burial by the next layer. For a layer at Dinosaur Ridge, that suggested burial before the next rain or wind storm.

Distribution

Holroyd [5] describes charcoal presence in various styles about two-thirds of the way up through the Dakota Formation in central and western Colorado and eastern Wyoming. Each site has a different character for charcoal particle size from powder to centimeter sized pieces, with and without larger impressions like bark and branches, at bedding planes only and thoroughly mixed within the sediments, with and without hematite hardenings that reveal wood grain direction. One of the western-most sites examined, near Grand Junction, Colorado, had adjacent layers of light gray quartzite conglomerate with pebble sizes up to about a centimeter. The conglomerate was also found at Dinosaur National Monument in Colorado but without carbon deposits in adjacent layers. That may indicate a source of materials in western Utah because the Morrison Formation of shales and sandstones covered the nearby regional landscape, leaving no exposed source for the quartzite. The general slope of the land is thought to have had an eastward dip towards the Interior Cretaceous Sea, the shoreline of which is considered to be the Dakota depositional environment.

The widespread distribution of the charcoal-bearing outcrops already examined indicates that additional sites could also be found and studied. An efficient means of further study would be to examine the hundreds of drill cores (and their descriptions) into the Dakota Formation and comparable sediments that are stored at the Denver Federal Center in the USGS Core Research Center. Charcoal presence is to be expected somewhere in most of the cores and its bedding characteristics should be carefully noted and its depositional environments estimated. More surface outcrops could also be examined, though that may require considerable travel. They would provide a larger view of the bedding than is available in cores of only several centimeters diameter.

The charcoal bearing layers are only a minor component of the entire Dakota Formation thickness, but they may indicate a widespread and catastrophic deposition. The source of the material may also be identifiable from the distribution of particle sizes and indications of flow directions in the sediments. The variations in deposition style from one site to another (already seen on scales of a few kilometers) may suggest distribution of materials by numerous river channels. That will make mapping more challenging.

Further studies

The advancement of the Inland Cretaceous Sea westward over the study area may be interpreted as the last inundation of that area by sea water during the late stages of Noah's Flood. The Dakota Formation deposits are interpreted as from the leading edge of that advance. Sediments, including the charcoal, were apparently coming eastward by fluvial processes as the shoreline was moving westward. A puzzle, presented in the earlier papers, still remains of how there can be widespread catastrophic deposits of terrestrial materials in generally flat near-shore deposition conditions before the sea covered that area. It needs a major eastward flow of material over land that is temporarily above sea level. In general the Biblical Flood is a sufficient mechanism, but a one-time simple and simultaneous inundation of the entire world is not. There are complex details of the Flood sequences in each area that could be studied.

This discussion has been limited to the charcoal deposits in a thin portion of the Lower Cretaceous Dakota Formation. The bedding of charcoal needs to be examined in other formations and in modern environments like the California, Texas, and Carolina coasts to confirm the usefulness of charcoal and other buoyant materials as indicators of deposition rates. The author suggests that others continue such research by conducting sedimentation experiments with buoyant materials, by extending the observations of charcoal in modern settings, and by describing other fossil deposits in terms of their bedding styles. Reviewers have suggested additional related studies that should enhance our understanding of the deposition of buoyant materials within or on sediments, but these should suffice for now.

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