ABSTRACT

The recent discovery of radiocarbon in dinosaur bones at first seems incompatible with an age of millions of years, due to the short half-life of radiocarbon. However, evidence from isotopes other than radiocarbon shows that dinosaur fossils are indeed millions of years old. Fossil bone incorporates new radiocarbon by means of recrystallization and, in some cases, bacterial activity and uranium decay. Because of this, bone mineral – fossil or otherwise – is a material that cannot yield an accurate radiocarbon date except under extraordinary circumstances. Mesozoic bone consistently yields a falsely young radiocarbon “date” of a few thousand to a few tens of thousands of years, despite the fact that it is millions of years old. Science educators need to be aware of the details of these phenomena, to be able to advise students whose acceptance of biological evolution has been challenged by young-Earth creationist arguments that are based on radiocarbon in dinosaur fossils.

Key Words: dinosaurs; creationism; radiocarbon; collagen; recrystallization; carbonate; uranium; fossilization.

Introduction

The recent discovery of radiocarbon in dinosaur fossils has the potential to generate much puzzlement, because radiocarbon has a half-life too short for measurable amounts of original radiocarbon to remain in fossils that are millions of years old. Taking advantage of the popularity of dinosaurs, young-Earth creationist (YEC) authors now proclaim in an ever-increasing number of books and DVDs that radiocarbon in dinosaur fossils demonstrates that the dinosaur fossils must be only thousands, not millions, of years old (Helfinstine & Roth, 2007; Wilson et al., 2007; Lyons & Butt, 2008; Isaacs, 2010a, b; Woetzel, 2012; Thomas, 2013, 2014; Clarey, 2015; Institute for Creation Research, 2015). Many of the other dinosaur-based anti-evolution arguments from YEC authors are less worrisome, because they are plainly absurd (e.g., Senter, 2012, 2013a, 2013b, 2017a, 2018, 2019; Siebert, 2013; Senter & Wilkins, 2013; Senter & Klein, 2014), but the absurdity in the YEC arguments based on radiocarbon is less plain. That is because students and science educators often lack knowledge of the finer details of radiocarbon dating and the fossilization process that show how radiocarbon in dinosaur bones is consistent with an age of millions of years. Appropriate responses to such YEC arguments are therefore not always at hand. Here, I present an overview of the relevant details, to arm science educators and their students with the information they need to recognize such YEC misinterpretations as incorrect.

Radiocarbon

Radiocarbon Dating & Confounding Factors

Radiocarbon (14C) is a radioactive isotope of carbon that decays into 14N by emitting beta particles. Radiocarbon forms in the atmosphere after cosmic rays knock neutrons off molecules of atmospheric gases. When 14N in the air is exposed to such neutrons, a nucleus of 14N captures one of the neutrons and emits a proton, thereby becoming 14C. The 14C is incorporated into atmospheric CO2, some of which is absorbed by oceans and lakes and some of which plants absorb during photosynthesis and animals take in when they eat plant matter. The level of 14C in a plant or animal remains constant until it dies and therefore ceases to take in more 14C. At death, its 14C level therefore begins to drop. Because the remaining 14C decays at a known rate, it is possible to calculate the date at which a plant or animal died by measuring its remaining 14C. That is the basis of radiocarbon dating (Walker, 2005; Willoughby, 2016).
Radiocarbon has a short half-life of only about 5700 years, so it is only useful for dating materials no older than about 50,000 years (van der Plicht & Palstra, 2016). Of the radiocarbon that was present in an organism at the time of its death, no measurable amount remains after 100,000 years. The fossil of an animal that died during the Mesozoic Era, tens of millions of years ago, therefore does not have any measurable amount of its original radiocarbon left.

Most science textbooks explain radiocarbon dating in no further detail than that (e.g., Campbell et al., 2009; Bergstrom & Dugatkin, 2016; Urry et al., 2017), because their goal is to provide only a general overview of it. However, the reality of radiocarbon dating is more complicated. There are several factors that can add $^{14}$C to samples so that they yield falsely young ages (e.g., nuclear fallout, bacterial contamination, and contamination with coal), and there are other factors that add $^{14}$C-depleted carbon to samples so that they yield falsely old ages (e.g., volcanic gases, industrial emissions, and the reservoir effect) (Table 1). However, corrective calibration techniques and other procedures can correct for all these confounding factors (Pasquier-Cardin et al., 1999; Goslar et al., 2000; Nadeau et al., 2001; McGee et al., 2004; Mihara et al., 2004; Quarta et al., 2007; Nakanishi et al., 2015; Tankersley et al., 2017; Wang et al., 2017; Yang et al., 2017). Once corrective calibrations and other corrective procedures are implemented, radiocarbon measurements yield correct dates, as has been demonstrated with radiocarbon dating of samples of known ages (e.g., Jull et al., 2018). However, as explained below, bone mineral is an exception to the rule, and there are no corrective measures that can get fossil bone mineral to generate a correct radiocarbon date.

### Radiocarbon “Dates” from Mesozoic Fossils

In two 1990 articles, YEC authors reported $^{14}$C analyses of Mesozoic wood and dinosaur bone. The fossils yielded radiocarbon “ages” between 9000 and 40,000 years (Dahmer et al., 1990; Fields et al., 1990). Since then, YEC authors have submitted several more Mesozoic fossil samples for $^{14}$C testing. All have had enough $^{14}$C to yield radiocarbon “ages” between 9000 and 50,000 years. The samples include petrified wood, coal, ammonite shells, and bone from several species of dinosaurs, including the Jurassic genera Allosaurus and Camarasaurus and the Cretaceous genera Acrocanthosaurus, Edmontosaurus, and Triceratops (Dahmer et al., 1990; Fields et al., 1990; Helfinstine & Roth, 2007; Snelling, 2008; Thomas & Nelson, 2015). YEC authors consistently claim that the radiocarbon in the fossils demonstrates that the fossils are only a few thousand years old (Dahmer et al., 1990; Fields et al., 1990; Helfinstine & Roth, 2007; Lyons & Butt, 2008; Isaacs, 2010a; Woetzel, 2012; Thomas, 2013, 2014; Clarey, 2015; Institute for Creation Research, 2015; Thomas & Nelson, 2015). However, that is incorrect. Radiometric dating of Mesozoic strata using radiotopes other than radiocarbon (e.g., $^{238}$U/$^{206}$Pb, $^{235}$U/$^{207}$Pb, $^{87}$Rb/$^{86}$Sr, $^{40}$K/$^{40}$Ar, $^{40}$Ar/$^{39}$Ar) shows

| Table 1. Factors that affect radiocarbon dating. Factors that add $^{14}$C-depleted carbon cause the samples to yield falsely old radiocarbon “ages,” and factors that increase samples’ $^{14}$C cause the samples to yield falsely young radiocarbon “ages.” |
|-----------------------------------------------|
| The reservoir effect: the tendency of lakes and the ocean to act as reservoirs for old carbon derived from dissolved CO$_2$ and carbonate rocks that are radiocarbon-depleted | Due to the reservoir effect, the carbon content of lake and marine samples is $^{14}$C-depleted. The magnitude of the reservoir effect varies from one location to the next within the ocean, from one lake to the next, and from one shelled species to the next (Nadeau et al., 2001; Nakamura et al., 2007; Nakanishi et al., 2015; Wang et al., 2017). It is responsible for the famous case in which the shells of live freshwater mollusks yielded false radiocarbon “ages” of thousands of years, due to the mollusks’ incorporation of radiocarbon-depleted carbonate into their shells (Keith & Anderson, 1963). It also affects radiocarbon dating of the remains of terrestrial organisms that feed on marine organisms (e.g., humans that eat seafood; Arneborg et al., 1999; Mihara et al., 2004). |
| Volcanic gases | Samples’ exposure to this factor adds $^{14}$C-depleted carbon (Pasquier-Cardin et al., 1999). |
| Industrial emission of fossil fuels | Samples’ exposure to this factor adds $^{14}$C-depleted carbon (Quarta et al., 2007; Flores et al., 2017). |
| Nuclear explosions and fallout | Samples’ exposure to these factors increases their $^{14}$C content (Gentry et al., 1998; McGee et al., 2004; Lachner et al., 2014; Yang et al., 2017). |
| Contamination with coal | This factor increases samples’ $^{14}$C content (Tankersley et al., 1987, 2017). |
| Contamination with bacteria or fungi | These factors increase samples’ $^{14}$C content (Lowe, 1989; Bonvicini et al., 2003; Tankersley et al., 2017). |
| Burial | This factor can increase samples’ $^{14}$C content via bicarbonate in groundwater and via crystallization of calcite (Zazzo & Saliège, 2011; Oslen et al., 2013; van der Plicht & Palstra, 2016). |
| Cremation | Radiocarbon dating of cremated bones destroys the collagen in the bones and adds $^{14}$C from the wood used in the fire (Olsen et al., 2013). |
| Fluctuation in atmospheric $^{14}$C through millennia | This factor causes elevation of $^{14}$C in samples from some past time intervals and reduction of $^{14}$C in samples from other past time intervals (Goslar et al., 2000). |
that the sediments that entomb Mesozoic fossils are 65–251 million years old (Gradstein et al., 2004), which means that the fossils that they entomb are that old – far too old for any measurable amount of original radiocarbon to remain in the fossils. So how is it that measurable radiocarbon is indeed present in the fossils? The answer is that although the fossils have lost their original radiocarbon, they have since accumulated new radiocarbon, which yields a falsely young radiocarbon “age.” To elucidate how that happens, here I review the composition of bone, what happens to it after death, its implications for radiocarbon dating, and similar implications for the radioisotope dating of fossil wood and shells.

**Bone Composition**

Living bone tissue includes numerous live bone cells, blood vessels, and a mineralized mixture called bone matrix, which lies between the bone cells and blood vessels. The bone cells called osteoblasts secrete bone matrix. Osteoblasts are called osteocytes after they have secreted bone matrix on all sides and have become enclosed in it. The tiny space in the matrix that each osteocyte inhabits is called a lacuna (Eurell, 2004).

The bone matrix that osteoblasts secrete consists mainly of the protein collagen and the mineral hydroxyapatite (also spelled “hydroxylapatite” or “hydroxy apatite”). Hydroxyapatite is a form of calcium phosphate that is bonded to hydroxide ions (OH\(^-\)). Its chemical formula is Ca\(_5\)(PO\(_4\))\(_3\)(OH). That chemical formula changes as a result of the CO\(_2\) that the nearby cells release as metabolic waste. The body’s aqueous internal environment converts the CO\(_2\) into bicarbonate (HCO\(_3^-\)) and carbonate (CO\(_3^{2-}\)). In the mineral component of bone matrix, that carbonate replaces so many of the phosphate and hydroxide ions in hydroxyapatite that the chemical formula of the mineral must be rewritten as Ca\(_5\)(PO\(_4\))\(_3\)(OH, CO\(_3\)). This altered mineral is called bioapatite, carbonate hydroxyapatite, dahlrite, or simply bone mineral (Hedges & Millard, 1995; Berna et al., 2004; Pfretzschner, 2004; Wings, 2004; Keenan et al., 2015; Kendall et al., 2018). Radiocarbon is present both in the collagen and in the carbonate of bone matrix.

**Bone Diagenesis & Fossilization**

Diagenesis is the term for physical and chemical changes to a sediment or fossil after its deposition. Bone undergoes a large amount of diagenetic change during and after burial. Bone diagenesis tends to occur in five modes: microbial activity, collagen gelatinization, permineralization, encrustation, and recrystallization.

Microbial diagenesis. During the earliest phase of bone diagenesis, microbes such as bacteria and fungi consume the bones’ organic fraction (Pfretzschner, 2004). Microbial consumption of bone cells and blood vessels leaves empty voids in lacunae and Haversian canals, where osteocytes and blood vessels had been. Under some conditions, bacteria then precipitate mineral cements such as calcite (a form of CaCO\(_3\)), pyrite (FeS\(_2\)), siderite (FeCO\(_3\)), and krunohorite (Ca(Mn,Mg)(CO\(_3\))\(_2\)) into those voids (Wings, 2004; Carpenter, 2005). The infilling of voids with minerals is called permineralization, and it contributes to fossilization (long-term preservation).

The microbial phase is often short lived. For example, in bones submerged in bodies of freshwater, microbial activity ceases after about six months (Pfretzschner, 2004). After that, most of the organic fraction of the bone is gone (Pfretzschner, 2004). Collagen gelatinization. Intermolecular cross-linking makes collagen a highly stable organic molecule (Antonio et al., 2011), but it eventually breaks down. Bacterial and fungal activity contribute to collagen decay (Kendall et al., 2018), and in small bones (e.g., those of rodents) in bodies of freshwater, the initial period of microbial activity destroys all of the collagen (Pfretzschner, 2004). Collagen lasts longer in larger bones (e.g., those of humans), which still retain 85–95% of their collagen a year after death (Pfretzschner, 2004). Following the period of microbial activity, the remaining collagen is attacked by abiotic factors that gelatinize the collagen by cutting it into shorter and shorter chains of peptides (Pfretzschner, 2004). Collagen breakdown occurs faster in hotter environments, in extremely acidic or extremely alkaline environments, and around cracks in the bone (Kendall et al., 2018).

The breakdown of collagen causes further diagenesis of the bone. Gelatinizing collagen soaks up water and swells, which generates cracks in the bone mineral (Pfretzschner, 2004). Collagen decay also releases sulfide (S\(^-\)) ions, which leads to the precipitation of iron sulfides such as pyrite onto the surfaces of voids and cracks (Pfretzschner, 2004).

Bone mineral: preservation, permineralization, encrustation, and recrystallization. The preservation of bone mineral depends on pH and the presence or absence of buffering chemicals. Bone mineral dissolves in sediments that contain calcium aluminum phosphate minerals or have groundwater with a pH below 7. It is preserved in sediments that contain calcite and carbonated apatite and have groundwater with a pH above 8.1 (Berna et al., 2004).

If the bone mineral is preserved, three subsequent modes of diagenesis predominate in bone after the collagen gelatinization phase: permineralization (infilling of voids with minerals), encrustation (growth of minerals on external surfaces and the surfaces of cracks), and recrystallization (replacement of less-stable minerals with more-stable minerals as the minerals dissolve). At this stage, all three occur by precipitation of water-dissolved ions, without microbial help. The permineralization and encrustation may involve growth of crystals of calcite (CaCO\(_3\)), other carbonates, pyrite (FeS\(_2\)), barte (BaSO\(_4\)), and other minerals (Pfretzschner, 2004; Wings, 2004). During these processes, canaliculi that once connected adjacent osteocytes may be filled in by new hydroxyapatite or pyrolusite (MnO\(_2\)), isolating lacunae from each other (Pfretzschner, 2004; Pfretzschner & Tütken, 2011).

Recrystallization involves water-mediated exchange reactions. It is particularly prevalent at external surfaces and at cracks (Pfretzschner, 2004; Pfretzschner & Tütken, 2011). Fluorination is an important example. As it trades its hydroxide for fluoride, bone mineral is converted into francolite (Ca\(_5\)(PO\(_4\),CO\(_3\))F) and is later converted to fluoroapatite (Ca\(_5\)(PO\(_4\))F). The fluorination contributes to fossilization, because it increases crystal size, which increases the stability of bone mineral (Berna et al., 2004; Kocsis et al., 2010; Kendall et al., 2018). Fossil bone of Mesozoic age always has a high fraction of francolite and fluoroapatite (Wings, 2004; Piga et al., 2011). The high stability that fluorination confers on the bone mineral in fossil bone slows down the recrystallization process but does not stop it (Berna et al., 2004; Suarez & Passey, 2014; Keenan et al., 2015). Because recrystallization continues, fossil bone has a much higher degree of recrystallization than archaeological bone does (Kendall et al., 2018).

Bone recrystallization also includes processes other than fluorination. During recrystallization, some of the calcium in bone...
mineral is replaced by iron, manganese, zinc, strontium, sodium, and uranium (Pfretzschner, 2004). Some of the phosphate in bone mineral is replaced by metal hydroxides, which may subsequently become metal oxides (Pfretzschner, 2004). The phosphate in bone mineral can also be replaced by fluoride, chloride, or carbonate (Pfretzschner, 2004). When bone interacts with carbonate-rich water, replacement of phosphate by carbonate occurs on a larger scale and can result in replacement of most of the bone phosphate with carbonate (Fernández-Jalvo et al., 2016).

Cracking increases the rate and spread of permineralization, encrustation, and recrystallization (Pfretzschner & Tütken, 2011; Pokines et al., 2018). In sufficiently moist conditions, wet–dry cycles and freeze–thaw cycles can cause cracks in bone and are especially effective at doing so on bones at the soil–air interface and especially on the exposed side of those bones (Pokines et al., 2018). In arid environments, exposed bone cracks as it dries out (Pfretzschner & Tütken, 2011).

**How New Radiocarbon Is Added to Old Bone**

The amount of $^{14}$C in bone drops as the bone loses organic material during the microbial decay phase and the collagen gelatination phase. However, the amount of $^{14}$C in bone then rises again as bone mineral gains new $^{14}$C. There are five ways that old bone mineral gains new radiocarbon: recrystallization, permineralization, encrustation, bacterial contamination, and uranium decay.

**Recrystallization, permineralization, and encrustation.** Recrystallization brings new radiocarbon into bone mineral when carbonate replaces phosphate in the crystal structure of the bone mineral. The new carbonate contains $^{14}$C, because it comes from bicarbonate and carbonate in groundwater, which are derived from dissolution of atmospheric CO$_2$, which contains $^{14}$C (Olsen et al., 2008; Zazzo, 2014).

Permineralization and encrustation by calcite and other carbonates also bring new $^{14}$C into bone. The purification process called pretreatment can remove the carbonate infillings and crusts (Zazzo & Saliège, 2011), but it cannot remove the carbonate that has been incorporated into the crystal structure of bone mineral by recrystallization.

**Bacterial contamination.** Old geological samples can accumulate new radiocarbon through the metabolic activity of recent bacteria and fungi, which take in atmospheric $^{14}$C. The presence of their cells and their organic waste adds $^{14}$C to coal samples, and methane that they excrete adds $^{14}$C to petroleum if its temperature is low enough ($\leq$77°C) to support live bacteria (Lowe, 1989; Bonvini et al., 2003; Tankersley et al., 2017). Coal and petroleum often contain enough radiocarbon to yield falsely young radiocarbon “ages” of a few tens of thousands of years (Lowe 1989; Bonvini et al. 2003). There is no reason to suppose that recent bacteria and fungi, if present on and in fossil bone, would not add $^{14}$C to it, yielding falsely young radiocarbon “ages,” as with other geological samples.

**Uranium decay.** Another way that new $^{14}$C is added to geological samples is via the radioactive decay products of uranium. Radioactive emissions from $^{238}$U add new $^{14}$C by converting certain other isotopes (e.g., $^{18}$O and $^{13}$B) into $^{14}$C (Jull et al., 1985; Bonvini et al., 2003). In addition, some of the daughter isotopes of $^{238}$U (e.g., $^{223}$Ra, $^{224}$Ra, and $^{226}$Ra) themselves emit $^{14}$C nuclei during radioactive decay (Ronan, 1997; Bonvini et al., 2003). Buried bone readily takes up uranium via groundwater (Hedges & Millard, 1995) and concentrates it, so that fossil bone usually has a higher uranium content than the surrounding sediment (Goodwin et al., 2007; Kisleva et al., 2019).

**Implications for Radiocarbon Dating of Recent Bone**

**Collagen.** The collagen in bone matrix is the material that is usually used for radiocarbon dating of bone in archaeological samples (Olsen et al., 2013; van der Plicht & Palstra, 2016). Bone collagen can be contaminated by substances in humus and other external sources, which add new $^{14}$C, yielding a falsely young radiocarbon “age.” However, pretreatment removes such contaminants. Pretreated collagen therefore yields a correct age (van der Plicht & Palstra, 2016; Cersoy et al., 2018), unless it is older than 50,000 years, the upper limit for radiocarbon dating (van der Plicht & Palstra, 2016).

**Bone mineral.** Unlike collagen, bone mineral is usually useless for radiocarbon dating, even though the carbonate that bone mineral incorporates during life contains $^{14}$C. The usefulness of bone mineral for radiocarbon dating is due to the fact that bone mineral accumulates new $^{14}$C after death, yielding a falsely young radiocarbon “age.” Calcite and other carbonate crystals that arrive via permineralization and encrustation add new radiocarbon (Zazzo & Saliège, 2011; van der Plicht & Palstra, 2016), but pretreatment can remove such crystals (Zazzo & Saliège, 2011). However, pretreatment cannot remove the new carbonate that becomes part of the crystal structure of bone mineral during recrystallization. Because that carbonate contains newly added radiocarbon, bone mineral yields a falsely young age when subjected to radiocarbon analysis. The older a sample is, the greater the difference between the actual age and the false age that results from recrystallization. The magnitude of the difference between the actual age and the radiocarbon “age” of the mineral jumps upward dramatically in samples older than about 10,000 years (Zazzo, 2014) and is hugely amplified in samples older than about 35,000 years (van der Plicht & Palstra, 2016). As a result, samples of bone mineral from bone that is tens of thousands of years old yield false “ages” thousands of years younger than the actual age of the bone, even after pretreatment (Zazzo, 2014).

There are two exceptions to the rule that bone mineral consistently yields a falsely young age. Cremated bone is an exception, because the heat of cremation recrystallizes the bone mineral into a more stable form that is resistant to further recrystallization (Olsen et al., 2013). The other exception is bone that has been preserved in arid areas that have remained arid for the duration of the bone’s presence there, because infiltration of $^{14}$C via groundwater-borne minerals doesn’t happen where there is no groundwater (Zazzo & Saliège, 2011).

**Implications for Radiocarbon Dating of Fossil Bone**

The fossil bone in Mesozoic samples suffers from problems that make attempts at radiocarbon dating pointless. First, as previously pointed out, radiometric dating of Mesozoic strata using radioisotopes other than radiocarbon shows that Mesozoic fossils are 65–251 million years old (Gradstein et al., 2004), far too old for any measurable amount of original radiocarbon to remain. Second, the collagen in Mesozoic bone has usually long since decayed away and is therefore unavailable for radiocarbon dating. Even when original collagen is present, it is millions of years too old to contain measurable amounts of original radiocarbon. Third, the processes of recrystallization, permineralization, encrustation, bacterial contamination, and uranium
decay add new $^{14}$C to old bone, causing it to yield a falsely young radiocarbon "age.”

Recrystallization. Fossil bone continues to behave as an open system and experiences recrystallization throughout its existence. Chemical analyses have confirmed that late in its existence, Mesozoic bone continues to accumulate rare earth elements (Kocsis et al., 2010) and carbonate (Piga et al., 2011; Keenan et al., 2015) and that its continued recrystallization includes the addition of new carbonate even during the recent period of erosion that exposes the bone-containing sediment (Suarez & Passey, 2014). That erosion is what enables paleontologists to visually spot the bone-containing deposit and prompts them to excavate the bones. It therefore stands to reason that any Mesozoic bone that has been found and excavated has recently accumulated new carbonate, which adds new $^{14}$C, which in turn accounts for the falsely young radiocarbon "age" that every Mesozoic bone that has been subjected to radiocarbon "dating" has yielded. As previously mentioned, pretreatment can remove carbonate that has arrived via permineralization and encrustation, but it cannot remove carbonate that has been incorporated into the crystal structure of the bone mineral by recrystallization. That new carbonate includes new $^{14}$C, yielding a falsely young radiocarbon "age.”

The two exceptions (cremation and arid environments) to the rule that bone mineral consistently yields a falsely young age do not apply to Mesozoic bone. Mesozoic bone was not cremated, nor is it typically entombed in places that are devoid of groundwater through the duration of its entombment. Although Mesozoic bones are often discovered in places that are currently arid most of the year, such places (e.g., western North America, the origin of all Mesozoic dinosaur bone that has thus far been subjected to radiocarbon “dating”) usually experience rain at some time during the year, exposing shallowly buried fossil bones to waterborne bicarbonate and carbonate ions that introduce new radiocarbon into the bone mineral through recrystallization.

All of the fossil bone that YEC teams have subjected to radiocarbon analysis has included bone mineral. Such samples are therefore useless for obtaining an accurate age by means of radiocarbon. Although at least some YEC teams subjected the fossil samples to pretreatment to remove calcite that had arrived by permineralization and encrustation (Snelling, 2008; Thomas & Nelson, 2015), pretreatment cannot remove the carbonate that has been incorporated into the crystal structure of bone mineral via recrystallization and therefore cannot remove the $^{14}$C that has arrived via that carbonate. Therefore, none of the radiocarbon "ages" that YEC teams obtained for fossil bones are the bones' true ages. Instead, all such radiocarbon "ages" are falsely young. This means that the bones that they found to yield radiocarbon "ages" of over 40,000 years (Fields et al., 1990; Helfinstine & Roth, 2007; Thomas & Nelson, 2015) are much older than 40,000 years, which contradicts their own assertion that the Earth and the ancestors of all the life-forms on it came into existence only about 6000 years ago.

Bacterial contamination. The interior of Mesozoic bone does not usually harbor bacteria, because most of its organic fraction has usually long since decayed away, leaving little for bacteria to use for food. Nonetheless, there are some cases in which Mesozoic bone is known to have harbored recent bacteria. Liquid chromatography and mass spectrometry confirmed the presence of chemicals made by recent soil-dwelling bacteria within a bone from a Cretaceous dinosaur (Asara et al., 2007). Visual inspection via microscopy confirmed the presence of bone-boring cyanobacteria on the surface of a bone from a Cretaceous mosasaur, and amplification via polymerase chain reaction confirmed the presence of bacterial DNA in the bone (Lindgren et al., 2011). Soft material from the bone of a Cretaceous turtle had the spectrographic signature of bacterial biofilm, in addition to morphological features consistent with bacterial cells and with troughs made by bacterial locomotion through biofilm (Kaye et al., 2008). The bacterial biofilm in the Cretaceous turtle bone was subjected to radiocarbon analysis and was found to contain a "greater than modern" (too young to accurately date) amount of radiocarbon, indicating that the contamination had occurred very recently (Kaye et al., 2008). As these examples show, Mesozoic bone can undergo bacterial contamination, a phenomenon that is known to introduce new $^{14}$C to geological samples, contributing to a falsely young radiocarbon "age.”

Uranium decay. Of the nine dinosaur bone specimens that were subjected to radiocarbon analysis in the YEC study by Thomas and Nelson (2015), four came from the Hell Creek Formation (Thomas & Nelson, 2015), which is uranium-rich (Kripp et al., 2009). Two came from the Lance Formation (Thomas & Nelson, 2015), which is also uranium-rich (Verstraeten et al., 2001). Also, two of the dinosaur genera that previous YEC teams subjected to radiocarbon analysis – Allosaurus and Camarasaurus (Dahmer et al., 1990; Helfinstine & Roth, 2007) – are from the Morrison Formation. The Morrison Formation is uranium-rich (Chenoweth, 1985), and dinosaur bones from it are notorious for containing large amounts of uranium (Gillette, 1994; Hubert et al., 1996). The dinosaur bone deposit at Dinosaur National Monument, the source of an unidentified dinosaur bone that was also subjected to radiocarbon analysis (Helfinstine & Roth, 2007), is also part of the uranium-rich Morrison Formation. As previously noted, $^{14}$C is one of the decay products of $^{238}$U and of some of its daughter isotopes.

Implications for Radiocarbon Dating of Fossil Wood & Shells

Fossil wood. YEC teams have reported that Mesozoic petrified, carbonized, and coalified wood yielded radiocarbon "ages" between 11,000 and 50,000 years (Helfinstine & Roth, 2007; Snelling, 2008; Thomas & Nelson, 2015). Petrified wood often retains a substantial fraction of its original organic content (Jiang et al., 2018), which at first would seem to make it conducive to radiocarbon dating if the YEC position that the wood is only a few thousand years old is correct. However, as with fossil bone, petrified wood undergoes recrystallization even millions of years after the death of the organism, often has absorbed a substantial amount of uranium, and often contains calcite and other carbonates that were not part of the original tree (Jiang et al., 2018; Kuczmow et al., 2019). Because all those factors introduce new $^{14}$C into such fossils, attempts to determine the ages of petrified wood by using radiocarbon are useless.

Similarly, carbon-containing compounds such as carbonates are introduced into coalified or partially coalified fossil wood by percolation of groundwater, infilling of fractures, recrystallization of mineral inclusions, mineralization of the wood after coalification, and meteoric processes during weathering (Yudovich, 2003; Dawson et al., 2012; Ward, 2016). Coal also absorbs and concentrates uranium (Yang, 2007; Havelcová et al., 2014), which adds new $^{14}$C as a decay product.
Mesozoic dinosaur bones are millions of years old, as demonstrated by radiometric dating with radioisotopes other than $^{14}$C. Radiocarbon in Mesozoic dinosaur bones is new, not original to the bone. Its addition to the bones yields the false appearance of a young age. The new radiocarbon in fossil bone mineral is in carbonate that is incorporated into the crystal structure of bone mineral during recrystallization and cannot be removed by pretreatment. In some cases, bacterial activity or the radioactive decay products of uranium add even more radiocarbon to the bone.

○ Conclusions

Teachers who encounter students who have been misled by YEC arguments that are based on radiocarbon in dinosaur bones are encouraged to direct such students to the information presented here. However, YEC publications have generated a plethora of other anti-evolution arguments, and it would be useful to be able to counter those as well. It is therefore worthwhile to note that there are four recent books that together refute nearly all of the YEC arguments that have been published thus far: Isaak (2007), Prothero (2007), Kane et al. (2016), and Senter (2019). Such resources could be useful for educating both teachers and students and for inoculating students against future exposure to YEC arguments.

Additionally, for students who profess loyalty to the Bible, it would be useful to know that several passages in the Old and New Testaments instruct against taking Genesis literally and therefore that the Bible itself does not support the YEC view. Such resources are reviewed in Senter (2019) and are partially reviewed in Senter (2016). It would be worthwhile for teachers to know of such resources, so as to direct students to them when appropriate. It is legal, at least in the United States, to address religious concerns that students bring up in science classes, as long as the teacher does not endorse one religious view over another (Her mann, 2013). Studies on conceptual change suggest that addressing such concerns may be effective in helping students feel comfortable accepting evolution and an old Earth if their objections to such concepts are based on religious concerns (Senter, 2017b). Such help could be a useful supplement to science-based refutations of YEC arguments such as those presented here regarding radiocarbon in dinosaur bones.

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Notes

1. The terms archaeology and palaeontology are often confused. Archaeology is the study of human material cultures. It deals with samples that are a few thousands of years old or younger. Palaeontology is the study of fossils. It deals with samples that are tens of thousands of years old or older, including samples that are millions or billions of years old. The crossover discipline of paleoarchaeology is the study of the material cultures of very ancient humans and their extinct relatives. It deals with samples that are 10,000 to 15 million years old.
