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Supplement DR1 - Background Geology for Florissant Formation

OVERVIEW OF PUBLISHED DESCRIPTIONS AND INTERPRETATIONS OF FLORISSANT PALEO-LAKE DEPOSITS

Geological Setting

Florissant Fossil Lagerstätte: Description, Origin, Location, Stratigraphy, and Age

The late Eocene Florissant Formation is a fossil Lagerstätte that contains extremely well preserved fish and bird specimens and paleobotanical, insect, and other invertebrate assemblages from the lacustrine facies; mammal fossils from the associated fluvial deposits; and giant petrified trees preserved in a volcanic lahar. The lake has been interpreted as a lahar dammed fluvial drainage in which biological remains accumulated and were preserved in fine detrital and pyroclastic sediments (Evanoff et al., 2001). This deposit has extraordinary biologic diversity and records a period of gradual global cooling that followed the Paleocene-Eocene thermal maximum, as described by Prothero (1994, 2004, 2008) and Zachos (2001). The fossil diatom flora of the Florissant Formation is a unique record in non-marine diatom biochronology, being the most diverse pre-Neogene assemblage on record, with the first-appearance of 14 fresh-water genera (Benson and Kociolek, 2012; Benson et al., 2012). A compilation of diatom fossils from Clare's Quarry, augmented by the published records of several additional Florissant sites, yielded 33 genera, a number that exceeds by 20 any other known freshwater diatom-bearing deposit from the Eocene and older (Benson and Kociolek, 2012; Benson et al., 2012). In addition, the Florissant diatom flora consists of taxa with decidedly modern affinities, allowing for reasonable, although cautious, interpretations of paleo-habitats extrapolated from autecology of modern analog taxa (or nearest living relatives) to the fossil taxa.

The fine volcanic lahars and coarse volcanic rubble that dammed the Florissant fluvial drainage were generated by periodic eruptions of the Guffey volcano, part of the Thirty-nine Mile volcanic field southwest of the modern areal extent of the Florissant Formation (Epis and Chapin, 1974; Evanoff et al., 2001; Meyer, 2003).

The Florissant Formation is known from a relatively small area in the vicinity of the town of Florissant in Teller County, Colorado (Fig. 1). Exposures of these deposits are limited to scattered roadcuts that penetrate the subsurface and to slopes of hills and ridges that roughly flank the present-day creek drainages northwest and south of the town of Florissant (Fig. 2). Principal fossil sites are located within the Florissant Fossil Beds National Monument, established in 1969, which is to the south of Florissant on County Highway 1.

The Florissant "lake beds," initially described by Cross (1894) and mapped by Wobus and Epis (1978), were interpreted as Eocene and Oligocene in age, respectively. These deposits were later described as the Florissant "Formation" by Evanoff et al. (2001) in which he included, but distinguished, the interbedded strata of fluvial and volcanic processes from those of lacustrine origin. In keeping with on-going research and recent literature on the Florissant Fossil Beds National Monument, the host unit for this study is herein referred to as the Florissant Formation or the Florissant lake beds. Evanoff et al. (2001) divided the formation into seven informal subunits on the basis of local lithologic characteristics, relative position as to elevation, and limited stratigraphic control. Among these lithologic subunits are shales, mudstones, pumice conglomerates, and granite gravel conglomerates. Of the subunits named, three are lacustrine in origin and were designated "upper shale," "middle shale," and "lower shale." In general, each of the three lake shale subunits contains laminated shales, mudstones, coarse volcanic tuffs, and volcanic ash (Evanoff et al., 2001).

The late Eocene age of the Florissant Formation is established on the basis of (1) sanidine crystals in the "upper shale" tuffs and "middle shale" cap rock provide a mean $^{40}Ar/^{39}Ar$ radiometric age of 34.05 ± 0.08 Ma (McIntosh and Chapin, 2004), and (2) brontotheres and *Mesohippus* teeth and bones consistent with the North American Mammal Age (NALMA) of Chadronian from the fluvial facies (Prothero, 2004; Worley, 2004; Worley-Georg and Eberle, 2006; Lloyd et al., 2008) that places the deposit into late Eocene.

Florissant Topography, Climate, and Elevation Inferred from Paleobotany

On the basis of terrestrial paleobotanical evidence, the Florissant paleo-lake has been interpreted as a high-elevation, low-relief intermontane lake (Gregory and Chase, 1994; Evanoff et al., 2001) with a warm, temperate to subtropical climate (Meyer, 2003; Leopold and Clay-Poole, 2001). Mean annual temperature estimates range from 12.8 ± 1.5 to 17. 5°C from leaf morphology and autecology of nearest living relative (NLR) (Leopold and Clay-Poole, 2001; Meyer, 2003; and Boyle et al., 2008). These values indicate that it is unlikely that Florissant lake would have experienced any period of icing over.

A mean annual precipitation of 72 ± 31 cm with 57 ± 16 cm during the growing season is estimated from leaf morphology (Gregory and McIntosh, 1996). Meyer (2003) gives a range of 50-80 cm of annual rainfall with most of it occurring during the growing season in the late spring and early summer and a distinct dry season. Integrated leaf and pollen records suggest that the area experienced moderate summer rainfall and mild, dry winters (Leopold and Clay-Poole, 2001).

Estimates of paleo-elevation for the vegetated slopes surrounding the paleo-valley from MacGinitie (1953) (using the NLR method) range from 300 to 900 m. Studies based on lapse rates with temperature decreases of 1°C per 1,000 m of elevation gain produce a range from 1,900 to > 4,100 m (Meyer, 2003) for the paleo-elevation of Florissant. If the genus-based WAPLS estimate of 14.7°C is used for MAT with previous leaf morphology estimates of late Eocene sea-level temperature, an estimate for Florissant paleo-elevation would fall within the range of ~1,600 to 2,800 m (Boyle et al., 2008).

Estimates of Areal Extent, Lake Type, and Duration of Florissant Lake System

There are conflicting views among investigators as to the size and geometry of the paleo-lake; consequently, also as to the original position and nature of the shoreline. While some believe the lake was limited to the present-day topographic extent (Evanoff et al., 2001; Meyer, 2003), others conclude that the lake was larger than present-day topography would suggest (MacGinitie, 1953; McLeroy and Anderson, 1966). Meyer 's (2003) estimates of approximately 30 km^2 (18.6 mi^2) for the areal extent of the lake uses the generalized dimensions of 1.5 km width and 20 km length as indicated by the Wobus and Epis (1978) map. Meyer (2003) further states that the present-day outcrop area of the Florissant Formation indicates that there has been minimal structural change in this area since the Eocene. MacGinitie (1953, p. 4) states, “The present outline of the (Florissant) beds is due to complex faulting and subsequent erosion, and does not represent, in any sense, an old lake margin.” Additional evidence for faulting includes studies by Niesen (1969), and Hanneman et al. (1996).

The paleo-lake was interpreted by McLeroy and Anderson (1966) as permanently stratified with no mixing of top and bottom waters. This conclusion was based on exposures of "middle shale" and "lower shale" characterized by the preservation of laminations, the absence of evidence of scour or bottom turbulence, and the exclusion of benthic organisms. The absence of benthos, the presence of pyrite, and the excellent fossil leaf and insect preservation attest to the likelihood that the hypolimnion was consistently anoxic and, therefore, inhospitable to bottom feeders and infauna (McLeroy and Anderson, 1966). Permanent stratification would have occurred as a result of either lack of turbulent mixing or density instabilities that are insufficient to mix vertically adjacent water masses (Cohen, 2003). It was recognized by McLeroy and Anderson (1966), that many modern subtropical lakes experience some overturn despite the apparent minimal seasonal temperature fluctuations.

The duration of Florissant lake is estimated as 2,500–5,000 years on the basis of extrapolations from counts of diatomaceous laminae from “middle shale” sites in the Florissant Formation (McLeroy and Anderson, 1966). Alternative estimates for the lake duration are calculated using the 35-36.5 Ma radiometric age of the lower member of the Thirtynine mile Andesite (McIntosh and Chapin, 2004) that is credited with having dammed the drainage to form the lake (Epis and Chapin, 1974). If the initial development of the Florissant lake occurred at 35-36.5 Ma, the earliest lake sediments would have been deposited as much as one million years before the origin of the dated tuffs from the "middle shale" and the "upper shale" Florissant units. This would extend the estimate of the duration of the lake system, now represented only by the preserved and exposed Florissant beds, to at least one million years, and possibly to as much as 2.45 million years.

Source of Volcanic Tuffs in Florissant Deposits

Ver Straeten (2007) observed that volcanogenic sediments in the ancient Florissant lake beds are of three basic types: simple, coarse-to fine-grained, normally graded beds, of probable airfall origin; medium to coarse pumiceous beds of airfall or riverine input; and mixed volcanogenic/detrital sediment of riverine origin.

The central Colorado volcanic field, consisting of at least 10 late Eocene and Oligocene (38–29 Ma) eruptive centers, dispersed pyroclastic material over approximately 22,000 km^2 in the southern Rocky Mountains (McIntosh and Chapin, 2004). Despite proximity of Florissant lake to this generally contemporaneous volcanic activity, the specific eruptive centers that sourced the ash and tuff beds within the Florissant Formation have not been conclusively identified. The Guffey/Thirtynine Mile volcanic field (36.5–35 Ma) is a remnant of the central Colorado volcanic field. Although the Florissant paleo-valley is within the Guffey/Thirtynine Mile volcanic field, the 34.05 Ma mean age of the Florissant tuffs is inconsistent with any of the dated ignimbrites in the region (McIntosh and Chapin, 2004). The Guffey/Thirtynine Mile volcanic products pre-date the volcanic tuffs in the "upper shale" and "middle shale" of the Florissant by at least one million years.

Additionally, the Florissant tuffs from the "middle" and "upper shales" are compositionally inconsistent with the Guffey andesites and the ignimbrites of the Thirty-nine Mile volcanic field (McIntosh and Chapin, 2004). The feldspar phenocrysts of the Florissant tuffs are dominantly plagioclase and those of the Guffey/Thirty-nine mile field are dominantly sanidine (McIntosh and Chapin, 2004). The work by McIntosh and Chapin (2004), therefore, shows that the Guffey/Thirtynine mile field is not a likely source for the dated Florissant tuffs.

Evidence of Tectonic Activity

Although the tectonic history of the Florissant valley is not well understood, faults have been delineated that suggest that (1) there was faulting in the Florissant lake valley prior to and during the deposition of the lake shales (MacGinitie, 1953); and (2) there was post-depositional normal faulting that created a patchwork of lake sediment remnants preserved in grabens (MacGinitie, 1953; McLeroy and Anderson, 1966; Niesen, 1969; Epis and Chapin, 1974; Steven, 1975; and Evanoff et al., 1992).

Additional support for tectonic readjustment within the Florissant valley is provided by shallow seismic refraction and reflection surveys conducted over several areas within Florissant Fossil Beds National Monument (Hanneman et al., 1996). The geophysical data differentiate valley-fill sediments from the Proterozoic Pikes Peak Granite that forms the valley basement and surface exposures bordering the Florissant outcrops on east and west flanks of the valley. One east-west seismic line that transects Niesen's (1969) F-2 north-south trending fault on the east side of the Florissant valley near the south branch of Grape Creek indicates down-to-the-west displacement preserving a thickened wedge of Tertiary valley-fill truncated on the east by granite in a steeply up-thrown fault block in the subsurface.

Conditions for Extraordinary Macrofossil Preservation

As interpreted by McLeroy and Anderson (1966), the excellent macrofossil preservation in the Florissant lake beds is attributed to a minimal transport distance, early burial, burial in extremely fine sediments, accumulation in an anoxic setting, and lack of disturbance by physical or biological agents. These observations strongly support deposition in a relatively deep-water position within an isolated hypolimnion.

Biofilm entrapment has been introduced as an additional mechanism accounting for the excellent macrofossil preservation in the lake beds at Florissant (Harding and Chant, 2000, O'Brien et al., 2002, and O'Brien et al., 2008). Observations suggest that biofilm from planktic diatoms and bacteria acted as trapping agents for leaves and insects. The biofilm encased leaves formed floating mats that were protected from degradation prior to sinking into an anoxic hypolimnion, where they became buried in fine sediments.

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