MAGNETIC STRATIGRAPHY OF THE LATE EOCENE LA PORTE FLORA, NORTHERN SIERRAS, CALIFORNIA

DONALD R. PROTHERO[1], ANNA THOMPSON[2] AND SYLVANA DESANTIS[1]

[1] Department of Geology, Occidental College, Los Angeles, CA 90041;
[2] Department of Biology, Feather River College, 570 Golden Eagle Avenue, Quincy, CA 95971

Abstract—The La Porte flora, from a tuff bed disconformably overlying old hydraulic mining excavations in the Ione Formation near the town of La Porte, Plumas County, California, is a famous fossil assemblage originally described in 1935. It yields about 41 species of fossil plants that suggest a relatively warm late Eocene mean annual temperature of about 22-24°C, and 1650 mm of average annual precipitation. Even though it considered one of the youngest Eocene floras before the early Oligocene cooling event, its age is constrained only by a questionable potassium-argon date of 34.275 Ma on the La Porte tuff at the top of the section. We sampled the entire 40 m of Ione Formation below the tuff, as well as the La Porte tuff itself. Most samples produced a single stable component of remanence held largely in magnetite, based on the low-coercivity response of the samples in alternating field demagnetization, and the lack of remanence above the Curie temperature of magnetite. The entire 40 m of section was reversed in polarity, with only a minor normal overprint on a few samples. The Ione formational mean direction was D = 186.6, I = -57.8, k = 5.4, α_{95} = 16.5, which is antipodal to the Eocene pole, and not significantly rotated or translated. Based on radiometric dates of 45 Ma on ashes in the Ione Formation elsewhere in the region, we correlate the Ione section at La Porte with Chron C20r (43-45.1 Ma). If taken at face value, the radiometric date would correlate the La Porte Tuff with Chron C13r (33.7-34.9 Ma), or very latest Eocene in age. However, if the La Porte ash date is suspect then the La Porte flora might be between 37 Ma (tropical Kummerian stage) and 35 Ma old (beginning of Goshen-type stage) and possibly then aligns with Chron C15r (35.1-35.3 Ma) or Chron C16r (36.3-36.5). This could better explain the discrepancies between the La Porte flora and other latest Eocene Goshen-type floras, and make the La Porte flora transitional between typical Chalk Bluffs floras and late Eocene Goshen-type floras.

INTRODUCTION

The La Porte flora is an important late Eocene flora first monographed in detail by Potbury (1935). In her original paper, she documented 41 species assigned to 34 genera (Table 1). Potbury (1935) carefully interpreted the ecological and climatic signatures in the flora using a variety of analyses. Based on the modern climatic preferences of the nearest living relatives of La Porte fossil species with clear modern affinities, Potbury (1935) considers the climate at La Porte to be intermediate between a warm temperate and a tropical climate with a MAT between 20-28°C and an MAP of 800-2500 mm. Another analysis employed by Potbury (1935) was comparison of leaf characters such as size (36% specimens > 10 cm in length), and leaf margin analysis (70% species entire margined vs. 30% species non-entire margined), and the presence of drip-tips (33% of species) versus the same leaf characteristics in two modern forests: a rain forest (Costa Rica) and a tropical lowland forest (Panama). From this, Potbury (1935) inferred that the La Porte flora represented a mean annual temperature of 24°C (range 22-28°C) and a mean annual precipitation of 1650 mm (range 800-2500 mm). This is not too far from the estimates of 19-23°C MAT from CLAMP methods by Wolfe et al. (1992, 1994, 1998). A preliminary leaf margin analysis of a much larger collection of fossils from the La Porte site supports these estimates (Thompson, unpublished data). Though the flora is dominated by angiosperms, Potbury (1935) described the cycad genus *Zamia*, the conifer *Cephalotaxus* (preliminary revision to *Amentotaxus*) (Taxaceae) as well as a fragmentary fern species. Some fossil genera and species with modern New World affinities include *Quercus suborbicularia* (oak), *Ulmus* (elm), *Persea* (laurel), *Liquidambar*, *Ilex* (holly) and *Meliosma goshenensis*. Fossil genera and species with Old World affinities include *Cinnamomophyllum* (laurel), *Quercus nevadensis* (oak) and the palm *Sabalites*. Based upon comparison to the nearest living relative of the fossil species, Potbury (1935) considered the flora to encompass about 46% tree species, 41% species representing small trees and shrubs, and 13% of species representing vines. In a typical tropical rainforest biome, leaves from vines make up about 40% of the canopy leaves and up to 90% of leaves show the presence of drip tips. Because the La Porte has only 13 % of vine species and only 33% of the species have drip tips, Potbury (1935) found that the La Porte flora represents an intermediate flora between a tropical lowland and an angiosperm-dominated warm temperate forest.

More recent studies concur with these conclusions. The La Porte flora is variously described as a notophyllous, broad-leaved, evergreen forest (Leopold et al., 2008) or a thermophyllic, broad-leaved, evergreen forest (Myers, 2003). In general, the La Porte is considered a Goshen-type flora (Myers, 2003; Retallack et al., 2004; Leopold et al., 2008). Wolfe (1981) recognized a separate paleobotanical stage between the Kummerian and Angoonian floras that comprises the time between 35 Ma to the Eocene/Oligocene boundary (Myers, 2003). Goshen-type floras are thought to represent the transition between tropical, evergreen floras (Kummerian) and temperate, cool, deciduous (Angoonian) floras (Retallack et. al., 2004), consistent with Potbury's (1935) interpretation of the La Porte flora.

STRATIGRAPHY

In the La Porte area (Fig. 1), the section consists of the lower 35 m of Ione Formation (Fig. 2), also known as the "auriferous gravels," which were heavily mined by hydraulic methods about a century ago (Allen, 1929; Garside et al., 2005; Creely and Force, 2007). Most of the area around the locality consists of abandoned mine diggings, so very little pristine landscape is left, although a lot of forest has regrown in the century since the mining. Originally, these deposits of "auriferous gravels" were deposited in the La Porte/Gibsonville paleochannel of the northern branch of the Tertiary Yuba River (Garside et al., 2005, p. 17, fig. 8).

TABLE 1. Updated comparison of the La Porte flora with other Eocene floras.

La Porte genera and/or species	Kummerian-indicator taxa (Retallack et al., 2004)	Goshen-indicator taxa (Retallack et al., 2004)	Goshen	Chalk Bluff
Cinnamomum aerodromum				x
Cinnamomum dilleri				x
Cornus kelloggii				x
Ficus		x		
Ficus goshensis (67)			x	
Ilex oregana			x	
Laurophyllum merrillii (42)		x		
Liquidambar californicum (12)		x		x
Lonchocarpus (5)	x			
Meliosma goshensis		x	x	
Ocotea eocernua			x	x
"Persea" praelingue (8)	x			x
Persea pseudo-carolinensis				x
Quercus nevadensis (14)	x			x
Quercus suborbicularia				x
Platanus (17)	x			
Rhamnidium chaneyi				x
Alnus (64)	x	x		
Sabalitis rhapifolius				x
Smilax goshensis			x	
Tabernaemontana (88)		x		
Ulmus pseudo-fulva				x
Overlap with La Porte	4 $_{x1}$	5$_{x2}$	5	12

Distribution of La Porte species and Kummerian-indicator taxa, Goshen-indicator taxa (Retallack et al., 2004) as well as the Goshen and Chalk Bluff Floras (Potbury, 1935). Note that the La Porte does not have any of the Goshen-type indicator fossils: *Allophylus wilsoni, Meliosma aesculifolia* and *Staphylea kinnetti*. X1, X2 – The genus *Alnus* has a range from the Kummerian across the Goshen-age floras and was not counted in the overlap with the La Porte species. Numbers in parentheses refer to the numbers assigned by Retallack et al. (2004).

Goshen-type floras span a narrow geological range between 35 Ma the Eocene/Oligocene boundary at 33.9 Ma and that the Goshen-type indicators do not significantly overlap with Kummerian and Angoonian indicators (Myers, 2003).

The La Porte flora comes from the La Porte Tuff, a massive rhyodacitic laharic ash deposit that filled channel incisions near the top of the section. The La Porte Tuff has been given a wide range of age interpretations. Potbury (1935) considered the flora to be no older than upper Eocene, based on geological correlation with the Chalk Bluff Flora (clay lenses interbedded with gravels), which was then considered middle Eocene (MacGinitie, 1941). Stratigraphically the position of the La Porte is above the Chalk Bluff Flora because the La Porte Tuff disconformably overlies a thick layer of carbonaceous shales and gravels (Potbury, 1935). Furthermore, based on floral and faunal correlation, the Chalk Bluff flora today is dated at 52-49 Ma (early Eocene: Wing and Greenwood, 1993; Hren et al., 2008). Tiffney and Haggard (1996) note the presence of *Mastixia* fruits in the auriferous gravels of Upper Dutch Diggings, a mining locality within miles of the hydraulic mining site of the La Porte flora. They considered them very latest Eocene in age because they were found below the ash-filled channel of the Upper Dutch Diggings. Myers (2003) discusses the presence of *Maginitea* in the La Porte flora (Doyle et. al, 1988); however, as Myers notes, it is uncertain whether the fossils originated from the La Porte tuff or possibly from an older fossil deposit below the tuff similar to the deposit of the *Mastixia* fruit from the auriferous gravels of the Upper Dutch Diggings. Elsewhere *Maginitea* is not known from deposits younger than 38 Ma (Myers, 2003).

Evernden and James (1964) and Dalrymple (1964) obtained K-Ar dates on the La Porte tuff of 33.4 Ma, but with the recalibration of the K-Ar decay constants, that date is 34.275 Ma (Dalrymple, 1979). Wolfe (1992) gave K-Ar dates of 33.1 Ma and 33.3 Ma for the La Porte tuff. Some more recent studies however have questioned the old Evernden and James (1964) K-Ar dates in general (Myers, 2003; Retallack et al., 2004; Leopold et al., 2008) or the K-Ar dates assigned to the La Porte specifically (Myers, 2003), but the flora has been treated in recent studies to be a latest Eocene (Myers, 2003) or earliest Oligocene (Leopold et al., 2008) flora. A recent study of northern Sierra Nevada ignimbrites suggests that the La Porte Tuff does not correlate with any of the other nine units sampled, which were dated between 31.2 and 28.7 Ma. Based on geochemical analysis, Cassel et al. (2009) indicate that the La Porte tuff

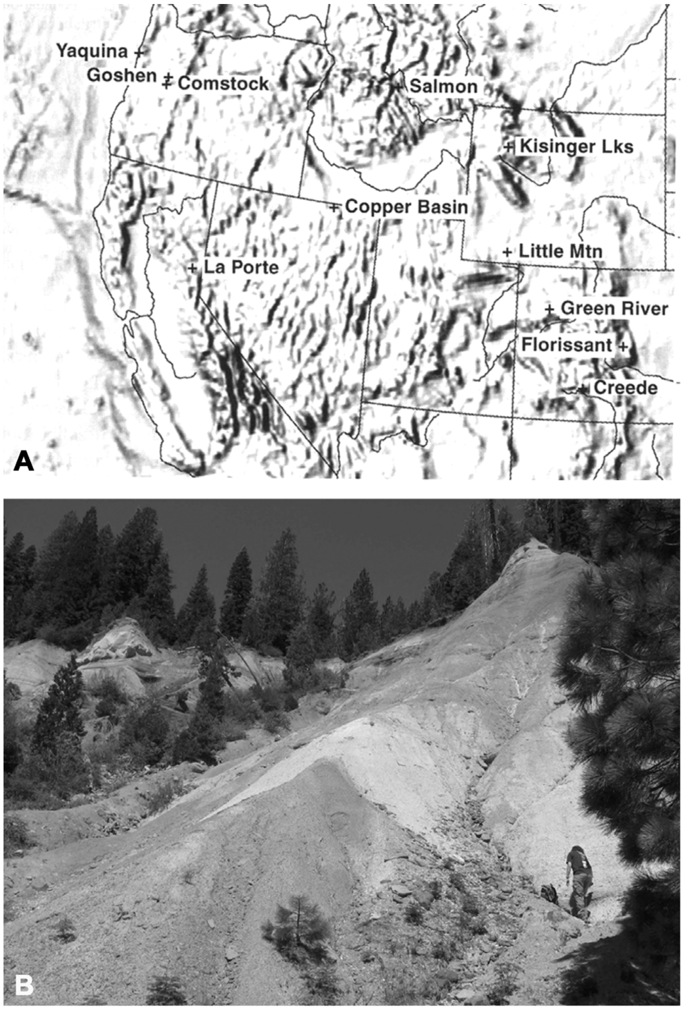

FIGURE 1. **A**, Index map showing location of La Porte and other Eocene paleofloras mentioned in the text (modified from Wolfe et al., 1998, fig. 1). **B**, Photograph of exposures, showing route of section. Site 1 is at the base where the photographer was standing; student assistant on site 2; site 3 halfway between site 2 and top; site 4 is the ash bed that caps the section. Photo by D.R. Prothero.

perhaps was part of an earlier phase of ignimbrite volcanism. Cassel et al. (2009) also consider the La Porte tuff to be a significantly reworked and well-sorted deposit and conclude that the tuff did not originate from the ash fall deposits (31-23 Ma) of the western Nevada Sequence of Faulds et al. (2005).

In summary, the La Porte flora appears to be considerably younger than 49 Ma and older than 31 Ma, though because of K-Ar age dating the flora has been treated as either latest Eocene or earliest Oligocene (K-Ar age estimates between 34.274 and 33.4 Ma). Because its likely age is close to the Eocene-Oligocene boundary (33.9 Ma, according to Gradstein et al., 2004), correctly interpreting this flora is crucial to fully understanding the timing of the Eocene-Oligocene climate deterioration. As several recent studies have indicated, cooling at the end of the Eocene or the beginning of the Oligocene is evident from the paleobotanical record, but because of poor age control the rate and timing of the climate change is still uncertain (Myers, 2003; Retallack et. al., 2004; Leopold et al., 2008; Prothero 2008). In addition, the La Porte flora has been widely used as evidence for paleoelevation of the Sierras in the Eocene, and by extension, other high-altitude Eocene floras like Florissant in Colorado (Wolfe et al., 1998). In this paper we attempt to more accurately assess the age of the La Porte flora by magnetic stratigraphy.

METHODS

In May 2009, we sampled the only complete exposures of the Ione Formation beneath the fossil-bearing tuff (Fig. 2), located in old hydraulic mining spoil piles just south of Highway 120, about a mile southwest of the town of La Porte. The actual section was taken in the center of Section 29, T21N R93, La Porte 7.5-minute quadrangle, Plumas County, California (longitude = W109°56.430', latitude = N32°57.582'). Four paleomagnetic sites (6-8 samples per site) were taken from 10 m intervals spanning 40 m of section, thus covering all the Ione Formation exposed in the area. Samples were taken as oriented blocks of rock with simple hand tools, and then wrapped and carried back to the laboratory. There they were sub-sampled into core-sized cylinders using sandpaper, or if the sample was too crumbly, casts into disks of Zircar aluminum ceramic in a magnetically shielded room. The samples were then analyzed on a 2G Enterprises cryogenic magnetometer with an automatic sample changer at Occidental College. After measurement of natural remanent magnetization (NRM), the samples were demagnetized in alternating fields (AF) of 2.5, 5.0, 7.5 and 10.0 mT (millitesla) to prevent the remanence of multi-domain grains from being baked in, and to examine the coercivity behavior of each specimen. AF demagnetization was followed by thermal demagnetization of every sample at 50°C steps from 100 to 630°C to get rid of high-coercivity chemical overprints due to iron hydroxides such as goethite, and to determine how much remanence was left after the Curie temperature of magnetite (580°C) was exceeded.

Results were plotted on orthogonal demagnetization ("Zijderveld') plots. Mean directions for each sample were then analyzed using Fisher (1953) statistics, and classified according to the scheme of Opdyke et al. (1977).

RESULTS

Orthogonal demagnetization ("Zijderveld") plots of representative samples are shown in Figure 3. In nearly every sample, there was a single component of remanence that was pointed south and up at NRM, indicating that the sample is of reversed polarity. There was no high-coercivity component (shown by the large drop of intensity in the first three AF demagnetization steps in Fig. 3), so there appears to be little chemical remanence due to iron hydroxides, such as goethite. Overprinting was not significant, since nearly all the samples showed a single component of remanence that was pointed south and up. The remanence appears to be held in magnetite, since intensity declined rapidly through thermal demagnetization, and vanished above the Curie temperature of magnetite and no remanence was left at 600°C (Fig. 3).

Since only reversed polarities were obtained, a reversal test for stability was not possible. However, reversed mean ($D = 186.6$, $I = -57.8$, $k = 5.4$, $\alpha_{95} = 16.5$, $n = 18$) is antipodal to the cratonic pole for the Eocene (Diehl et al., 1983), so the remanence is a primary or characteristic remanence, and overprinting has apparently been removed (Fig. 4).

All four sites were reversed in polarity (Fig. 2). Their site statistics are given in Table 2. All sites were statistically significant, i.e., separated from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). The entire basal 35 m of the section apparently represents one continuous reversed polarity magnetozone within the Ione Formation. The La Porte tuff, which disconformably overlies the Ione Formation, is also reversed in polarity.

DISCUSSION

As shown in Fig. 5, if the K-Ar dates between 34.275 to 33.4 Ma are correct, the La Porte tuff and flora would correlate with the youngest part of Chron C13r (33.7-34.9 Ma, using the magnetic polarity time scale of Gradstein et al., 2004). Based on the new calibration of the Eocene-Oligocene boundary at 33.9 Ma (Gradstein et al., 2004), the La Porte tuff and flora would be very latest Eocene or possibly very earliest Oligocene in age. In this case it is very close in age to the Goshen flora south of Eugene, Oregon, which is dated at 33.4 Ma, and yields a MAT

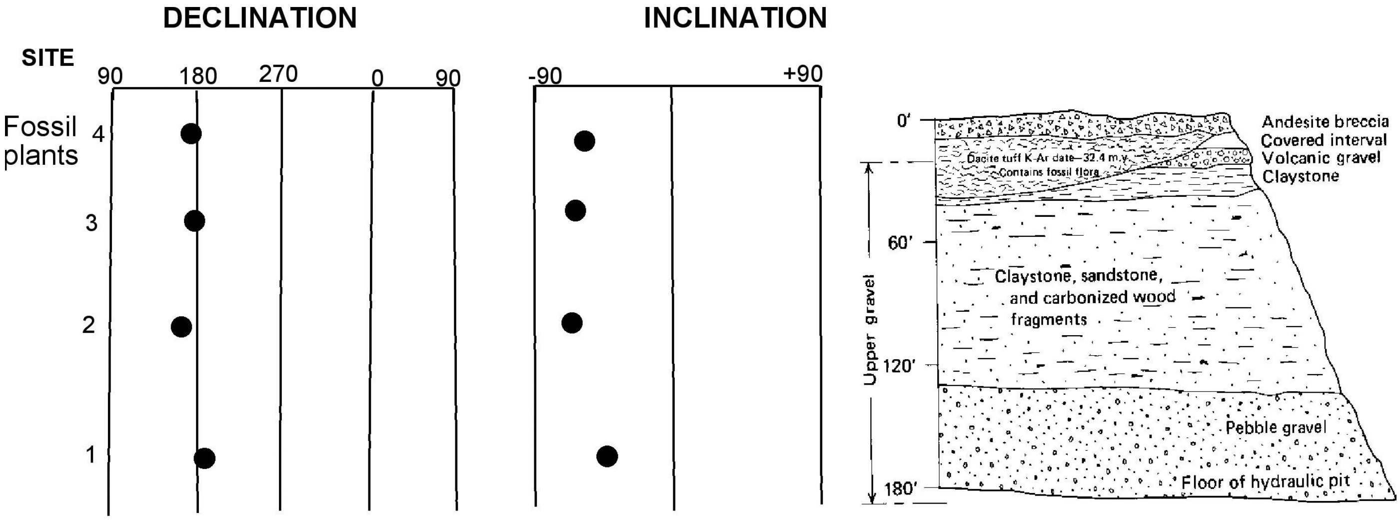

FIGURE 2. Lithostratigraphy and magnetic stratigraphy of the Ione Formation at La Porte. Declination and inclination of magnetic sites are shown. Solid circles are sites that are statistically removed from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). Lithostratigraphy after Yeend (1974, fig. 15).

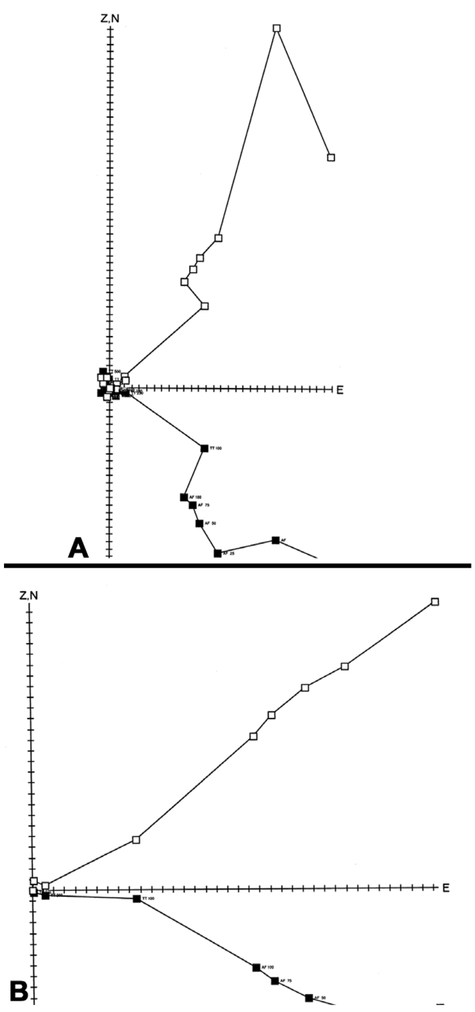

FIGURE 3.Orthogonal demagnetization ("Zijderveld") plots of representative samples. Solid squares indicate declination (horizontal component); open squares indicate inclination (vertical component). First step is NRM, followed by AF steps of 2.5, 5.0, 7.5, and 10.0 mT (millitesla), then thermal steps from 100 to 630°C. Each division equals 10^{-6} emu.

estimate of 19.7°C, slightly cooler than the La Porte flora (Retallack et al., 2004). It would be very close in age to the Florissant flora of Colorado, which is dated at 34.07 ± 0.1 Ma and gives a MAT estimate of 11-18°C, considerably cooler than Goshen or La Porte (Leopold et al., 2008; Prothero, 2008). It would also be close in age to the Steamboat flora from the Warner Range in northeastern California, not far from La Porte. The magnetic stratigraphy of this flora is currently under study in our laboratory (Upton and Prothero, 2009), but it is estimated at 34-35 Ma in age, and yields a MAT of 17.1°C, close to Goshen and much cooler than La Porte (Myers, 2003). Thus, the La Porte flora represents the warmest assemblage from this period in the western United States, warmer than the flora from Goshen, Oregon, or the Steamboat flora of northeastern California, and considerably warmer than the interior Florissant flora, Colorado.

Floristically, a comparison between the La Porte and the Florissant floras reveals no overlap at the species level (Leopold et al., 2008) and very little overlap at the generic level. Ecologically, the La Porte flora represents a warm, subtropical, angiosperm-dominated, evergreen lowland forest, but the Florissant is a warm-temperate, decidedly deciduous highland flora with many conifer species and some unexpected associations such as fan palms together with conifers such as *Picea* (Leopold et. al., 2008). Historically, the Florissant flora is considered to have been preceded by the much warmer and lower in elevation middle Eocene Green River flora (41% species overlap: Leopold et al., 2008). The Goshen and La Porte floras share five species (Table 1; Potbury, 1935) and the La Porte is generally considered to be a Goshen-type flora (Myers, 2003; Retallack et al., 2004; Leopold et al., 2008), which represents the transition between tropical, evergreen floras (Kummerian) and temperate, cool, deciduous (Angoonian) floras (Retallack et. al., 2004) on the West Coast. However, it is important to note that not only is species overlap with the actual Goshen flora low (5 species), the La Porte also has only five of the Goshen-type indicator species (Table 1; Retallack et al., 2004) and is missing all three species that are particularly considered Goshen-type indicators (*Allophyllus wilsonii*, *Meliosma aesculifolia*, *Staphylea kennettii*: Myers, 2003). Furthermore, the La Porte flora has a 29% species overlap (12 species) with the geographically close Chalk Bluff Flora (Table 1; Potbury, 1935). This comparison could in the future change by taxonomic revisions (Wing and Greenwood, 1993; Leopold et al., 2008), but as it is directly based on the original work of Potbury (1935), the overall pattern of the La Porte floristically sharing many more species with the Chalk Bluff flora rather than the Goshen flora itself or Goshen-type indicator species should be considered valid. Also striking is that though the La Porte and the Florissant floras do not

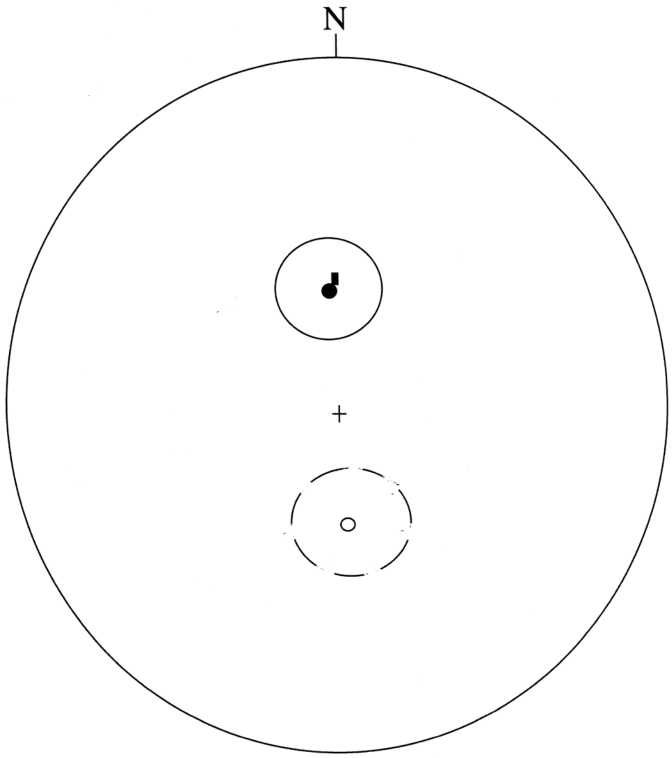

FIGURE 4. Stereonet of means of all sites. Solid square shows location of Eocene cratonic pole. Open circle and dashed line indicate mean of reversed samples (upper hemisphere projection). Solid circle shows projection of reversed mean into lower hemisphere. The reversed mean is antipodal to the Eocene pole within error estimates, so the directions are primary and overprinting has been removed.

TABLE 2. Paleomagnetic data from the La Porte section. Sites 1-3 were taken in the Ione Formation. Site 4 is the La Porte tuff. **N** = number of usable samples analyzed; **DEC** = mean declination; **INC** = mean inclination; **K** = precision parameter; α_{95} = ellipse of 95% confidence around the mean.

SITE	N	DEC	INC	K	α_{95}
1	6	199.8	-42.9	4.5	36.4
2	7	161.0	-65.3	8.7	24.0
3	6	183.9	-65.0	4.2	42.5
4	8	177.7	-50.0	4.3	40.1

have any species overlap, the older Chalk Bluff and Green River floras do share especially temperate genera such as *Acer*, *Cedrela*, *Platanus* and *Salix* with each other and the Florissant flora (Tidwell, 1998, chart 3).

This suggests that there was a time when many temperate genera disappeared from the California coast after the middle Eocene and only migrated back into the area during the Oligocene and after the climate had considerably cooled (Leopold et al., 2008). This further suggests that most likely there had to have been a time of climate warming between the Chalk Bluff flora and the La Porte flora that culled the more temperate and deciduous elements in the California coastal lowlands. In interior regions like Colorado these temperate and deciduous elements may have been retained at higher elevations and/or higher latitudes during this warming period, which could explain their presence in the highland Florissant flora. Myers (2003) has inferred a climate cooling prior to 38.5 Ma because in the interior Pacific Northwest thermophyllic forms such as *Macginitiea* appear to go regionally extinct and thermophyllic elements in later floras such as the Goshen-type Cedarville flora are neither abundant nor diverse. This cooling was followed by a warming trend starting around 37 Ma which ushered in the Goshen-type floras (35 Ma to the Eocene-Oligocene boundary) (Myers, 2003) on the West Coast and eventually produced the much higher elevation but still relatively warm Florissant in the interior of the West Coast by 34.07 Ma.

This leaves two distinct possibilities for the age of the La Porte flora:

1. The K-Ar dates are correct and the La Porte correlates with the youngest part of Chron C13r (33.7-34.9 Ma) and must be very latest Eocene or very earliest Oligocene in age. This scenario suggests that there was rapid climatic cooling in the early Oligocene on the West Coast as is consistent with the global record because evidence of some cooling is already seen in the transition to the earliest Oligocene Goshen flora (Prothero, 2008). This scenario could also explain the low species overlap between the La Porte and the Goshen floras; however, it would not provide an explanation why the La Porte can only very generally be considered a Goshen-type flora or why the La Porte floristically is much more similar to the much older Chalk Bluff flora.

2. We must also consider the possibility that the K-Ar dates are incorrect, especially since a recent study found the La Porte tuff to be significantly re-worked and extremely crystal-poor (Cassel et al., 2009). Considering the close floristic affinity of the La Porte flora with the Chalk Bluff flora as well as the fact that the La Porte flora is not a very typical Goshen-type flora, leaves the possibility that the La Porte is between 37 Ma (beginning of tropical Kummerian stage: Myers, 2003) and 35 Ma old (beginning of Goshen-type stage) and possibly then correlates with Chron C15r (35.1-35.3 Ma) or Chron C16r (36.3-36.5: Gradstein et al., 2004). As the La Porte flora also does not contain very many Kummerian indicator species (Table 1; Retallack et al., 2004) its age may be very close to 35 Ma. This would make the La Porte a very early Goshen-type flora and this may explain why the La Porte shares so many species with the older Chalk Bluff flora and does not share many species with floras yet to come, like the Goshen. As the La Porte is warmer than the Florissant, Steamboat, and Goshen floras, this may also indicate that climate cooling started well before the Eocene/Oligocene boundary (Retallack et al., 2004).

In several places, the Ione Formation “auriferous gravels” yield floras such as the Chalk Bluff flora (MacGinitie, 1941). The Chalk Bluff flora was considered middle Eocene by MacGinitie (1941) but is now generally considered to be between 49-52 Ma (Wing and Greenwood, 1993; Hren et al., 2009), based on faunal and floral correlation. The marine portion of the Ione Formation crops out nearby at the western flank of the Sierras (Lindgren, 1894; Allen, 1929; Pask and Turner, 1952; Gilliam, 1974). It yields a relatively non-diagnostic molluscan fauna said to be younger than Domengine stage (Creely and Force, 2007), which would place it between 47-37 Ma in the middle Eocene (Prothero, 2001).

The constraints on the age of the Ione Formation are even less precise. The best dates are 38.9 ± 1 Ma for an overlying ash from the gold-bearing section at North Columbia, California (Yeend, 1974, p. 1), and a tuff date of 45 Ma interbedded with the Ione Formation in the San Juan Ridge Mine (Pease, 1997). Based on the latter date, we correlate the Ione reversed magnetozone at La Porte with Chron C20r (43-45.1 Ma). Thus, there seems to be a hiatus of about 11 million years in the disconformity between the Ione Formation and the incised La Porte tuff, if the original La Porte ash dates are taken at face value.

However, based on the scenarios above, it is possible that the Chalk Bluff floras may be closer in age to the 38.9 Ma date than the 45 Ma year date or the even older date of 49-52 Ma. Wing and Greenwood (1993) note an ‘anomalous’ result in that the coastal and more southerly Chalk Bluff flora has a lower MAT (14.2-17°C) than more interior, northerly localities around 50-52 Ma, but attribute this ‘anomaly’ to the possibility of inaccurate taxonomic sorting. However, we propose that the Chalk Bluff flora may not be anomalous, but actually younger than 49-52 Ma. If the floristic overlap between the Chalk Bluff and the La Porte correctly indicates a period of warming between the two floras

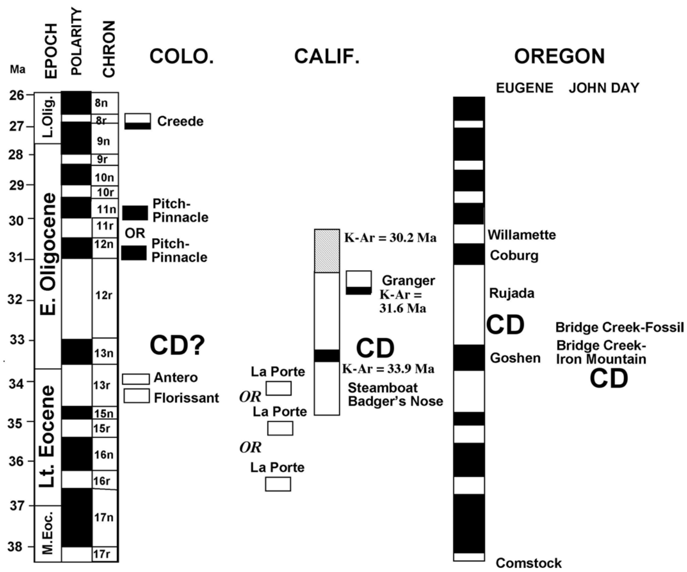

FIGURE 5. Correlation of the La Porte Ione Formation paleomagnetic section, based on the dates and age constraints discussed in the text. Time scale after Gradstein et al. (2004). Figure modified from Prothero (2008, fig. 7), where the paleofloras and their age constraints are discussed in detail.

during which the more temperate elements were culled and if there was a cooling prior to 38.5 Ma that added more temperate species to California coastal environments, it would date the Chalk Bluff flora sometime around the 38.5 Ma cooling event and before the beginning of the tropical Kummerian stage (37 Ma) which is not inconsistent with a Chalk Bluff MAT of 14.2-17 °C (Wing and Greenwood, 1993). In that case, the Ione reversed magnetozone would correlate at La Porte with Chron C17r (38.0-38.2 Ma) or Chron C18r (39-40 Ma), which would make the hiatus representing the disconformity between the La Porte Tuff and the underlying Ione Formation only 2-4 m.y.

CONCLUSIONS

Magnetostratigraphic analysis of the exposures of the Ione Formation capped by the volcanic ash yielding the La Porte flora produced a section that was entirely reversed in polarity. If the dates of the volcanic ash are taken at face value, then the La Porte flora and underlying Ione Formation exposures correlate with Chron C13n (33.7-34.9 Ma), or very latest Eocene in age. However, if the La Porte ash dates are suspect (Cassel et al., 2009), then the La Porte flora might be between 37 Ma (tropical Kummerian stage) and 35 Ma old (beginning of Goshen-type stage) and possibly then aligns with Chron C15r (35.1-35.3 Ma) or Chron C16r (36.3-36.5). This could better explain the discrepancies between the La Porte flora and other latest Eocene Goshen-type floras, and make the La Porte flora more transitional between the typical Chalk Bluffs floras and the late Eocene Goshen-type floras.

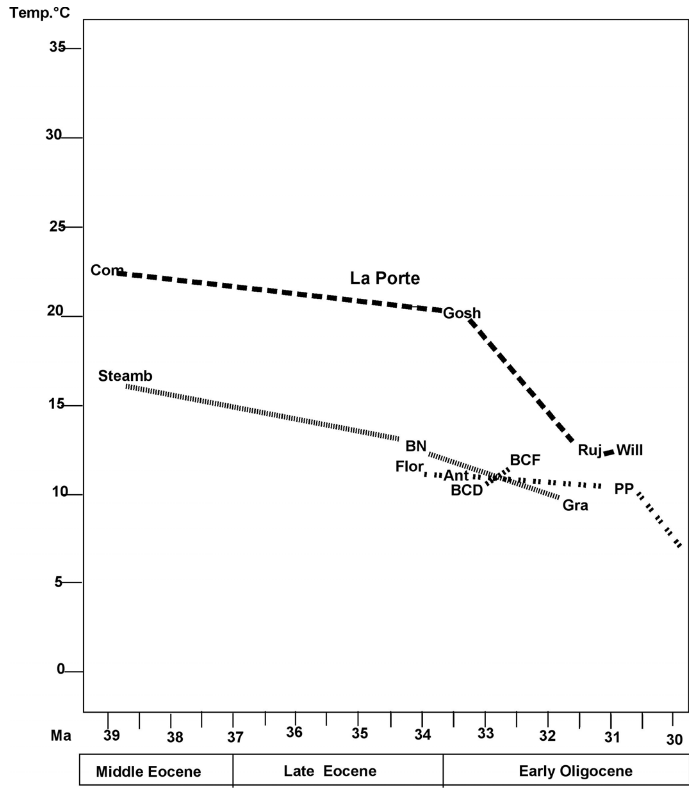

FIGURE 6. Diagram showing the change in temperature versus age as represented by the floras discussed in this paper. The abbreviations are plotted at the mean annual temperature of the flora. The coastal Oregon floras are connected by the long bold dashed lines; the Warner Range, California floras by the gray line; the Colorado floras by the light dashed line; the central Oregon floras are connected by the short dashed line. **Abbreviations: Com** = Comstock flora; **Gosh** = Goshen flora; **Ruj** = Rujada flora; **Will** = Willamette flora; **Steamb** = Steamboat flora; **BN** = Badger's Nose flora; **Gra** = Granger flora; **BCD** = Bridge Creek-Dugout flora; **BCF** = Bridge Creek-Fossil flora; **Flor** = Florissant flora; **Ant** = Antero flora; **PP** = Pitch-Pinnacle flora (modified from Prothero, 2008, fig. 9). Note that the La Porte flora plots at a warmer mean annual temperature than Goshen (if they are contemporaries) or at temperatures more appropriate to the earlier part of the late Eocene (if La Porte is older than the questionable radiometric date). See text for discussion.

ACKNOWLEDGMENTS

We thank T. Knight, E. Upton, E. Westcott, and C. Ayers for help with sampling, and V. Rutledge for help in the lab. We thank S. Bogue and J. Kirschvink for help maintaining the Occidental paleomagnetics lab. We thank G. Retallack, J. Myers, and H. Meyer for helpful comments on this paper. This research was supported by grants to Prothero by the Donors of the Petroleum Research Fund of the American Chemical Society, and by NSF grant 08-18520.

REFERENCES

Allen, V.T., 1929, The Ione Formation of California: University of California Publications in Geological Sciences, v. 18, p. 347-448.

Cassel, E.J, Calvert, A.T. and Graham, S.A., 2009, Age, geochemical composition, and distribution of Oligocene ignimbrites in the northern Sierra Nevada, California: implications for landscape morphology, elevation, and drainage divide geography of the Nevadaplano: International Geology Review, v. 51, p. 723-742.

Creely, S. and Force, E.R., 2007, Type region of the Ione Formation (Eocene), central California: stratigraphy, paleogeography, and relation to auriferous gravels: U.S. Geological Survey, Open-File Report 2006-1378.

Dalrymple, G.B., 1964, Cenozoic geochronology of the Sierra Nevada, California: University of California Publications in Geological Sciences, v. 47, p. 1-41.

Dalrymple, G.B., 1979, Critical tables for conversion of K-Ar ages from old to new constants: Geology, v. 7, p. 558-560.

Diehl, J., Beck, Jr., M.E., Beske-Diehl, S., Jacobson, D. and Hearn, C.B., Jr., 1983, Paleomagnetism of the late Cretaceous-early Tertiary north-central Montana alkalic province: Journal of Geophysical Research, v. 88, p. 10593-10610.

Doyle, J.A., Schorn, H.E., Tiffney, B.H. and Upchurch, G.R., Jr., 1988, The LaPorte flora - earliest Oligocene of north-central California: Guidebook for the 1988 meeting of the Paleobotanical Section of The Botanical Society of America, University of California, Davis, August 14-18, 1988.

Evernden, J. and James, G.A., 1964, Potassium-argon dates and the Tertiary floras of North America: American Journal of Science, v. 264, p. 945-974.

Fisher, R.A., 1953, Dispersion on a sphere: Proceedings of the Royal Society, v. A217, p. 295-305.

Gilliam, M.L., 1974, Contact relations of the Ione and Valley Springs formations in the Buena Vista area, Amador County, California [M.S. thesis]: Palo Alto, Stanford University, 180 p.

Hren, M.T., Pagani, M., Erwin, D.M. and Brandon, M., 2008, Biomarker reconstruction of the early Eocene paleotopography and paleoclimate of the northern Sierra Nevada: Geology, v. 38, p. 1-7.

Leopold, E.B., Manchester, S.R. and Meyer, H.W., 2008, Phytogeography of the late Eocene Florissant flora reconsidered: The Geological Society, Special Paper 435, p. 53-70.

Lindgren, W., 1894, Geologic Atlas of the United States, Sacramento Folio: U.S. Geological Survey, 3 p.

MacGinitie, H., 1941, A middle Eocene flora from the central Sierra Nevada: Carnegie Institution of Washington, Publication 534, p. 1-178.

Myers, J., 2003, Terrestrial Eocene-Oligocene vegetation and climate in the Pacific Northwest; *in* Prothero, D.R., Ivany, L.C. and Nesbitt, E.A., eds., From greenhouse to icehouse: the marine Eocene-Oligocene transition: New York, Columbia University Press, p. 171-188.

Opdyke, N.D., Lindsay, E.H., Johnson, N.M. and Downs, T., 1977, The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of Anza-Borrego State Park, California: Quaternary Research, v. 7, p. 316-329.

Pask, J.A. and Turner, M.T., 1952, Geology and ceramic properties of the Ione Formation, Buena Vista area, Amador County, California: California Division of Mines, Special Report 19, p. 1-39.

Pease, R.C., 1997, Geology and mineralization of the San Juan Ridge Mine Tertiary gravel deposit; *in* Lawler, D., ed., Northern Sierra Region, California, Geological Field Trip Guidebook, June 14-15, 1997: Northern California Geological Society, p. 1-9.

Potbury, S., 1935, The La Porte flora of Plumas County, California: Carnegie Institute of Washington, Publication 465, p. 29-81.

Prothero, D.R., 2001, Chronostratigraphic calibration of the Pacific Coast Cenozoic: a summary: Pacific Section SEPM, Special Publication 91, p. 377-394.

Prothero, D.R., 2008, Magnetic stratigraphy of the Eocene-Oligocene floral transition in western North America: Geological Society of America, Special Paper 435, p. 71-87.

Retallack, G.J., Orr, W.N., Prothero, D.R., Duncan, R.A., Kester, P.R. and Ambers, C.P., 2004, Eocene-Oligocene extinctions and paleoclimatic change near Eugene, Oregon: Geological Society of America, Bulletin 116, p. 817-839.

Tidwell, W.D., 1998, Common fossil plants of western North America, second edition: Washington, D.C., Smithsonian Institution Press, 386 p.

Tiffney, B.H. and Haggard, K.K., 1996, Fruits of the Mastixioideae (Cornaceae) from the Paleogene of western North America: Review of Palaeobotany and Palynology, v. 92, p. 29-54.

Upton, E. and Prothero, D., 2009, Magnetic stratigraphy of Eocene-Oligocene plant localities in the Warner Range, northeastern California: Geological Society of America, Abstracts with Programs, v. 41, p. 123.

Wing, S.L. and Greenwood, D.R., 1993, Fossils and fossil climate: the case for equable continental interiors in the Eocene: Philosophical Transactions of the Royal Society London B, v. 341, p. 243-252.

Wolfe, J.A., 1981, A chronologic framework for Cenozoic megafossil floras of northwestern North America and its relation to marine geochronology: Geological Society of America, Special Paper 184, p. 39-47.

Wolfe, J.A., 1992, Climatic, £oristic, and vegetational changes near the Eocene/Oligocene boundary in North America *in* Prothero, D.R. and Berggren, W.A., eds., Eocene-Oligocene climatic and biotic evolution: Princeton, Princeton University Press, p. 421-426.

Wolfe, J.A., 1994, Tertiary climatic changes at middle latitudes of western North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 108, p. 195-205.

Wolfe, J.A., Forest, C.E. and Molnar, P.E., 1998, Paleobotanical evidence of Eocene and Oligocene paleoaltitudes in midlatitude western North America: Geological Society of America, Bulletin 110, p. 664-678.

Yeend, W.E., 1974, Gold-bearing gravel of the ancestral Yuba River, Sierra Nevada, California: U.S. Geological Survey, Professional Paper 772, p. 1-43.