Oligocene calibration of the magnetic polarity time scale

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ABSTRACT

Magnetostratigraphic studies of the Oligocene White River Group in Wyoming, Colorado, Nebraska, and the Dakotas yield a radiometrically dated polarity stratigraphy that provides mid-Tertiary calibration points for the magnetic polarity time scale. Anomaly 12-13 reversal is bracketed by dates of 32.4 and 34.6 m.y., in best agreement with the time scale of LaBrecque and colleagues. The magnetostratigraphy also helps calibrate the Oligocene North American land mammal "ages" and allows correlation with the European marine microfossil zonation. This correlation suggests that the age of the Eocene-Oligocene boundary is 37.0 m.y., contrary to younger dates obtained from glauconites and microtektites.

INTRODUCTION

The picturesque badlands of the Oligocene White River Group of the High Plains are among the best known and most fossiliferous continental Tertiary rocks in North America. The White River Group crops out in many continuous, thick, and well-exposed sections and is thus well suited to detailed magnetostratigraphic study. Paleomagnetic correlation of the White River Group with the magnetic polarity time scale is particularly important because the time scale is at present calibrated by direct radiometric dates for only the past 13 m.y. (Harrison and others, 1979). Other calibration points have been supplied by indirect means, chiefly biostratigraphic correlations (Lowrie and Alvarez, 1981). As a result, the dates of most Tertiary and Mesozoic polarity events have been supplied by interpolation and extrapolation. A considerable controversy over the many conflicting versions of the time scale has arisen (Lowrie and Alvarez, 1981; Ness and others, 1980; Butler and others, 1981; Butler and Coney, 1981). Some of these time scales differ by as much as 5 m.y. in their placement of Paleogene polarity events [for example, compare Lowrie and Alvarez (1981) with Ness and others (1980)]. Attempts to constrain the interpolation of the magnetic polarity time scale have been made (Berggren and others, 1978), but only one direct association of mid-Tertiary magnetostratigraphy with absolute dates was published (Testarmata and Gose, 1979) prior to this paper. The White River Group, with its abundant fossils, continuous sections spanning almost 10 m.y. of the Oligocene Epoch, and numerous radiometric dates (Emry and others, 1983), provides some much-needed mid-Tertiary calibration points for the magnetic polarity time scale.

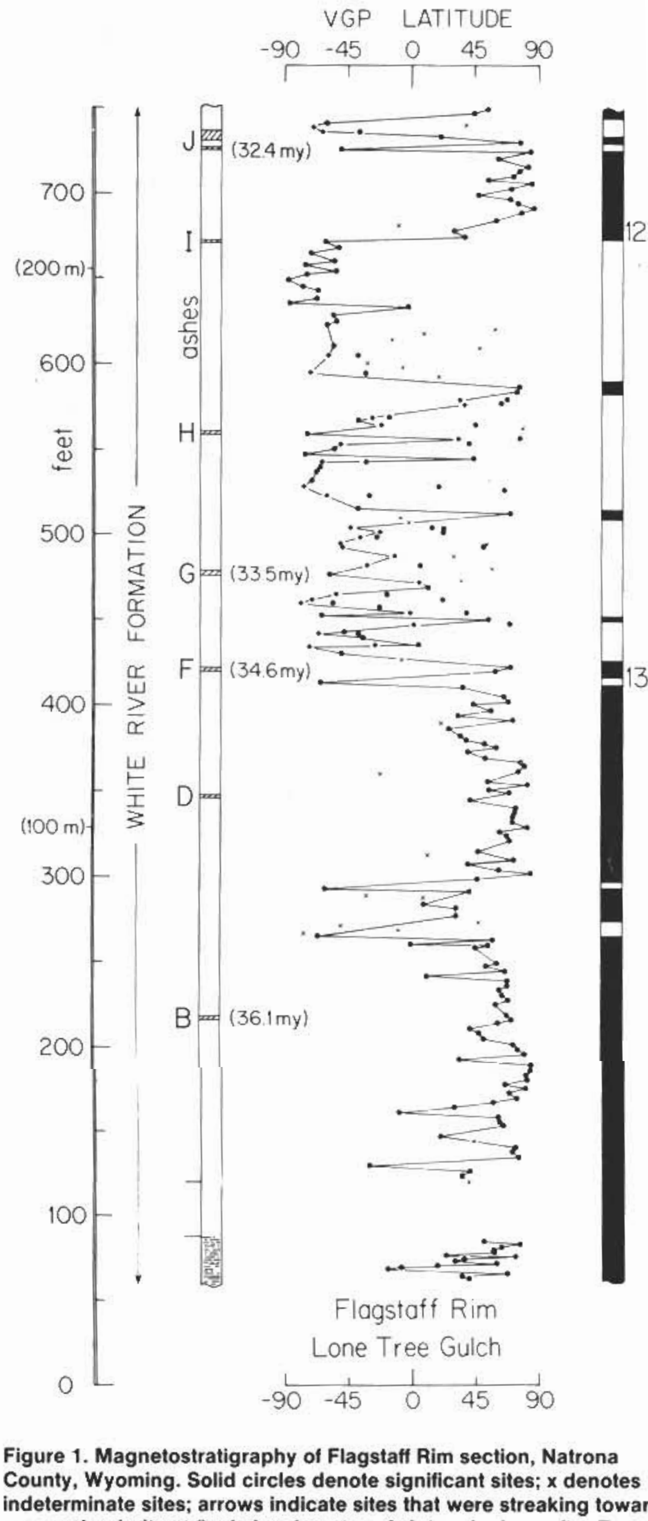

Figure 1. Magnetostratigraphy of Flagstaff Rim section, Natrona County, Wyoming. Solid circles denote significant sites; x denotes indeterminate sites; arrows indicate sites that were streaking toward reversed polarity at final cleaning step. Ash terminology after Emry (1973).

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itself is consistent with a structural trough of the dimensions suggested by the seismic data, the volcanics serving as a density excess (Hinze and others, 1975). Contacts between the volcanic rocks and the interfingered clastic rocks should provide excellent acoustic contrasts for generating the relatively strong reflections evident on the seismic sections. Furthermore, extensive volcanic flows may be expected to exhibit the relatively good continuity seen on the flanks of the trough, assuming minimal posteruptive faulting. Fowler and Kuenzi (1978) postulated that interfingered clastic and volcanic rocks would occur primarily on the flanks of the central rift structure, again consistent with the more pronounced reflections on the flanks. Lack of reflector continuity in the central part of the trough could be attributed to disruption by volcanic feeders penetrating upward in the central graben, more intensive graben faulting, or more uniform lithology lacking the requisite acoustic contrasts. The flexure on the north flank and the associated structural bench suggest high-angle block faulting (for example, Brown and others, 1980), although unequivocal fault offsets in the layered sequence itself are difficult to identify. There is no clear correlation on the COCORP seismic sections between Keweenawan structures and features in the overlying Paleozoic strata; however, data quality is too poor to rule out the possibility that small offsets in the lower Paleozoic section may be related to offsets or downwarps in the underlying rift.

Very little can be said about the identity of the isolated event at 6.5 s (20 km) of line 2. It may or may not be related to the overlying rift-fill units, and it could be due to any of several geologic structures, such as a small mafic intrusion, a "tuned" layer segment, focused energy from a small fold, or even fortuitous imaging conditions. The nature of the crust beneath the layered basement reflections is also uncertain. It could be pre-Keweenawan continental basement or, if rifting had proceeded as far as envisioned by Fowler and Kuenzi (1978), mafic material representing transition to oceanic crust.

If the lithostratigraphic identifications outlined above and shown in Figure 3 are correct, the upper Keweenawan clastic sequences would appear to be substantially more extensive than the underlying middle Keweenawan volcanics. This relationship fits well with the evolutionary model proposed by Fowler and Kuenzi (1978) in which volcanics are deposited in an initially narrow rift valley and are later covered by more extensive fluvial and marine deposits when the incipient rift fails and founders.

SUMMARY AND CONCLUSIONS

Reflectors beneath the Paleozoic sedimentary rocks of the central Michigan Basin most likely correspond to Keweenawan clastic and volcanic rock deposited in and over a late Precambrian rift. The seismic section defines at least two distinct Precambrian units: an upper, more poorly layered, zone of considerable extent, probably consisting of upper Keweenawan clastics (red-bed sandstones grading down into conglomerates) and a lower sequence of strong, layered reflections most likely composed of lower Keweenawan volcanics interbedded with clastics. This lower volcanic sequence appears to fill and define a narrow (60 km) trough that correlates spatially with the mid-Michigan gravity high. The gravity high is consistent with dense mafic rocks filling the trough defined by the seismic section. Sharp flexures, structural benches, and relatively steep dips in the volcanic layering suggest that subsidence was controlled by fault-block motions consistent with horst and graben tectonics.

There is no unequivocal evidence on these sections that Precambrian structure was reactivated to deform the overlying Paleozoic strata, but poor data quality may be obscuring such relationships. Lower crustal and Moho reflections were not observed. In spite of these new details of Precambrian structure, the fundamental problem of the Michigan Basin itself—what caused it to subside more than 600 m.y. after activity in the underlying rift presumably ceased—remains unresolved. However, these initial surveys are relatively short compared with the dimensions of the basin; it may be that even longer deep seismic traverses must be completed before the appropriate structures come into focus.

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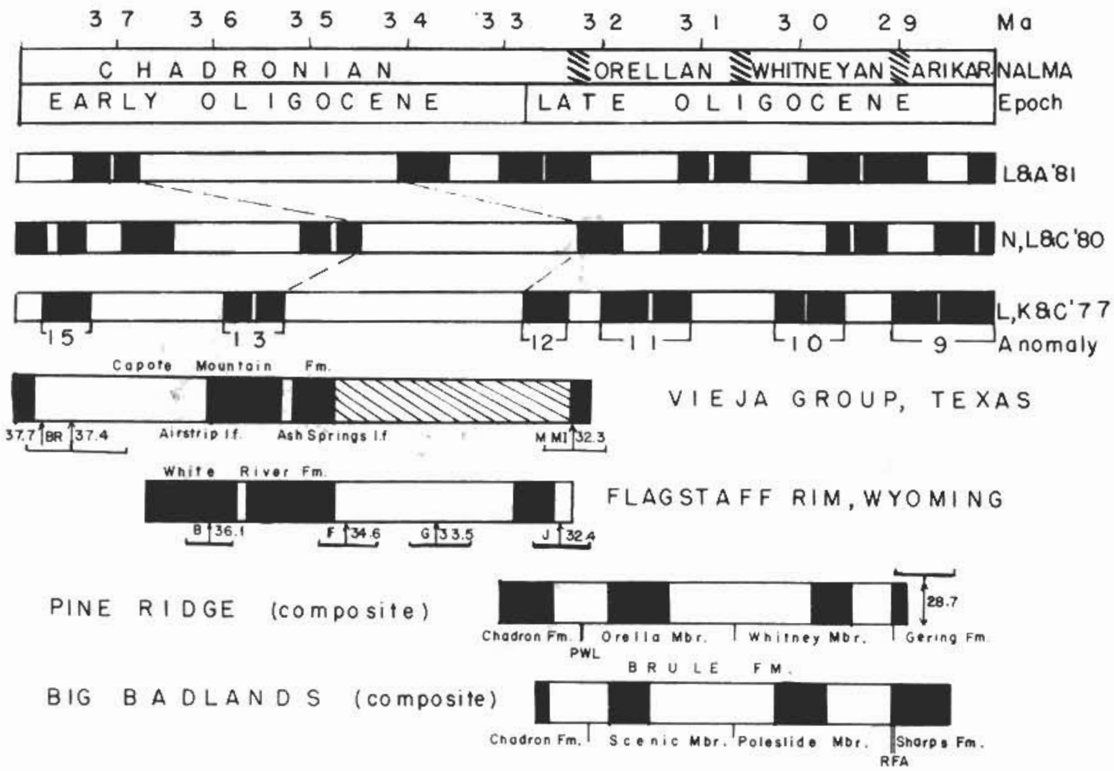

Figure 2. Correlation of Oligocene rocks with magnetic polarity time scale. Radiometrically dated ashes shown in geochronological position, with error bars indicating uncertainties. Three different versions of time scale (Lowrie and Alvarez, 1981; Ness and others, 1980; LaBrecque and others, 1979) are compared to show variation in placement of Oligocene polarity events. Hachured bars indicate indeterminate polarity. BR = Bracks Rhyolite; MMI = Mitchell Mesa Ignimbrite; NALMA = North American land mammal "ages"; RFA = Rockyford Ash; PWL = Persistent White Layer.

MAGNETOSTRATIGRAPHY

This report is a combination of two studies that were undertaken independently by Denham and Farmer at Flagstaff Rim, Wyoming, and the South Dakota Big Badlands, and by Prothero in eastern Wyoming, Colorado, Nebraska, South Dakota, and North Dakota. We sampled 2,260 m of section at 0.8- to 1.7-m intervals, resulting in 1,813 sampling horizons (sites) and 3,418 individual magnetic samples. This resulted in a magnetostratigraphic section for the Chadronian rocks at Flagstaff Rim, Wyoming, and more than 20 separate sections of mid-Oligocene (late Chadronian–Orellan–Whitneyan–early Arikareean) rocks in the Dakotas, Nebraska, Colorado, and Wyoming. Both thermal and alternating field demagnetization were employed to isolate a characteristic component of remanence carried by some form of titanomagnetite. Full details of our sampling and laboratory procedure, the magnetic behavior of the samples, and our magnetostratigraphic interpretations are presented elsewhere (Prothero and others, 1982; Prothero, 1982).

Figure 1 shows our polarity interpretations of the Flagstaff Rim section, Natrona County, Wyoming (Emry, 1973). The Flagstaff Rim section has a long reversed interval at the top that is bracketed by potassium-argon dates on biotite (Evernden and others, 1964; Emry, 1973) of 32.4 and 34.6 m.y. B.P. These dates are corrected for the new decay constants (Dalrymple, 1979) but have no published error estimates. However, most other Oligocene radiometric dates usually have uncertainties of about ± 0.7 m.y. Only one part of the Oligocene magnetic polarity time scale has a reversal approaching this length—the anomaly 12-13 reversal, 2.4 m.y. long (LaBrecque and others, 1979). The anomaly 13-15 reversal was only 1.6 m.y. long. There is no evidence of a hiatus within the Flagstaff Rim sequence that might cause some polarity intervals to be missed. Given the distinctive length of the anomaly 12-13 reversal, there seems to be no more reasonable interpretation of the long sequence of reversed rock between the 32.4 and 34.6 m.y. B.P. dates at Flagstaff Rim.

These polarity-zone identifications are corroborated by the Eocene-Oligocene magnetostratigraphy of the Vieja Group of Trans-Pecos Texas (Testarmata and Gose, 1979). The Vieja section has been correlated with Flagstaff Rim as follows: the Airstrip local fauna is correlatable with faunas below Ash B, and the Ash Springs local fauna with faunas near Ashes F and G (Emry and others, 1983). The Vieja sequence is also bracketed by radiometric dates (corrected for the new constants of 32.3 ± 0.7 and 37.4 ± 1.2 m.y., in agreement with the biostratigraphic correlations.

The magnetostratigraphy of the Vieja Group was difficult to interpret, and our interpretation (Fig. 2) differs from that of Testarmata and Gose (1979, Fig. 7). Testarmata and Gose (1979) found a long reversed interval above the Bracks Rhyolite which they interpreted to be the anomaly 12-13 reversal. If the biostratigraphic and radiometric ties between Flagstaff Rim and the Vieja Group are correct, then this reversal cannot be anomaly 12-13, but must be the reversed interval between anomalies 13 and 15. The anomaly 12-13 reversal in the Vieja Group was apparently lost in a long zone of indeterminate polarity (shown in the hachured pattern in Fig. 2). The composite Vieja–Flagstaff Rim pattern thus spans the entire Chadronian (early Oligocene) and runs from anomaly 12 to anomaly 15.

The later Oligocene composite sections (Fig. 2) have no reliable radiometric dates (R. J. Emry, personal commun.) and are intercorrelated biostratigraphically (Prothero, 1982). They can also be tied to the Flagstaff Rim section on biostratigraphic grounds. Several mammalian taxa known from the highest fossiliferous levels at Flagstaff Rim also occur in the Chadron Formation at the base of the Pine Ridge. These taxa include *Cylindrodon* sp., *Titanotheriomys veterior, Ischyromys parvidens, Yoderimys* sp., *Palaeolagus temnodon, Megalagus brachyodon, Leptomeryx speciosus, Leptotragulus profectus, Poebrotherium eximium,* and *Eotylopus reedi* (Prothero, 1982). Oreodonts from the Flagstaff Rim area have been interpreted as the direct precursors of typical Orellan *Merycoidodon* and *Miniochoerus.* Titanotheres are also known above Ash J, and also occur below and above the Persistent White Layer of the Pine Ridge area. The strong biostratigraphic ties between Flagstaff Rim and the Pine Ridge Chadron indicate at least some overlap between them. Unfortunately, the Flagstaff Rim section is virtually barren above Ash G, except for fragmentary titanothere remains. Our most reasonable interpretation is that the normal zones at the top of Flagstaff Rim and the base of the Pine Ridge are the same event, anomaly 12. This is corroborated by the lack of a long anomaly 12-13 reversal at the base of the Pine Ridge and Big Badlands sections. The Orellan normal zone would then be anomaly 11, and the Whitneyan normal zone anomaly 10. The base of the overlying Arikaree Group (Gering and Sharps Formations) begins at the base of anomaly 9 in our interpretation. The base of the Gering is dated at 28.7 ± 0.7 m.y. B.P. (Obradovich and others, 1973).

CALIBRATION OF THE MAGNETIC POLARITY TIME SCALE

The composite magnetostratigraphic pattern for the Oligocene rocks of North America appears to span anomalies 9 through 15 of the magnetic polarity time scale. Radiometric dates on this sequence best agree with the time scales of LaBrecque and others (1979), particularly in the dates of 32.4 m.y. B.P. just above anomaly 12, 34.6 m.y. B.P. just above anomaly 13, 36.1 m.y. B.P. in anomaly 13, and 37.4 m.y. B.P. just above anomaly 15 (Fig. 2). The error on these radiometric dates is great enough that we cannot reject the time scale of Ness and others (1980). However, it does not fit all four dates given above as well as the time scale of LaBrecque and others (1979). The recently published time scale of Lowrie and Alvarez (1981) can be rejected for the Oligocene. It predicts an interval of reversed polarity between 34.6 and 36.1 m.y. B.P., where we find predominantly normal polarity.

BIOSTRATIGRAPHY

Correlation of the land sections with the magnetic polarity time scale, in turn, gives estimated ages and durations for the Oligocene North American land mammal "ages," where radiometric dates are not available. Using the time scale of LaBrecque and others (1979), our correlations are shown in Figure 3. Magnetostratigraphic calibration of the North American land mammal "ages" also makes correlation with the marine faunas possible for the first time. Lowrie and others (1982) and Poore and others (1982) have presented a biostratigraphic zonation of planktonic foraminiferans and calcareous nannofossils tied directly to their magnetostratigraphy (Fig. 3). The Eocene-Oligocene boundary falls between anomalies 13 and 15; in the time scale of LaBrecque and others (1979), this is about 36.5 to 37.0 m.y. B.P. Thus, the Chadronian encompasses the latest Eocene, all of the Rupelian (early Oligocene), and the early Chattian. The Orellan, Whitneyan, and early Arikareean are also correlated with the Chattian. Further work in the Arikareean should determine how much of it is late Oligocene in age. It was once considered early Miocene.

Our correlations agree well with the age of the Eocene-Oligocene boundary given by Hardenbol and Berggren (1978). Some (Armentrout, 1981; Odin, 1978; Harris, 1979; Fullagar and others, 1980; Glass and Crosbie, 1982) have placed the Eocene-Oligocene boundary at about 32.0 m.y. B.P. This discrepancy is mostly due to the reliance on anomalously young glauconite dates, which are notoriously unreliable (Thompson and Hower, 1973; Berggren and others, 1978). Glauconite is known to be very susceptible to alteration, yielding minimum ages. The maximum ages of glauconites (Berggren and others, 1978; Hardenbol and Berggren, 1978) suggest an age of 37.0 m.y. for the Eocene-Oligocene boundary. The basalt dates given by Armentrout (1981) cannot be directly tied to the marine planktonic zonation and therefore cannot be used as direct evidence for a younger age of the Eocene-Oligocene boundary. Dates on the North American microtektite layer (Glass and Crosbie, 1982) also suggest a younger age for the Eocene-Oligocene boundary. We are not sure why this is so, but it should be investigated further before it is accepted.

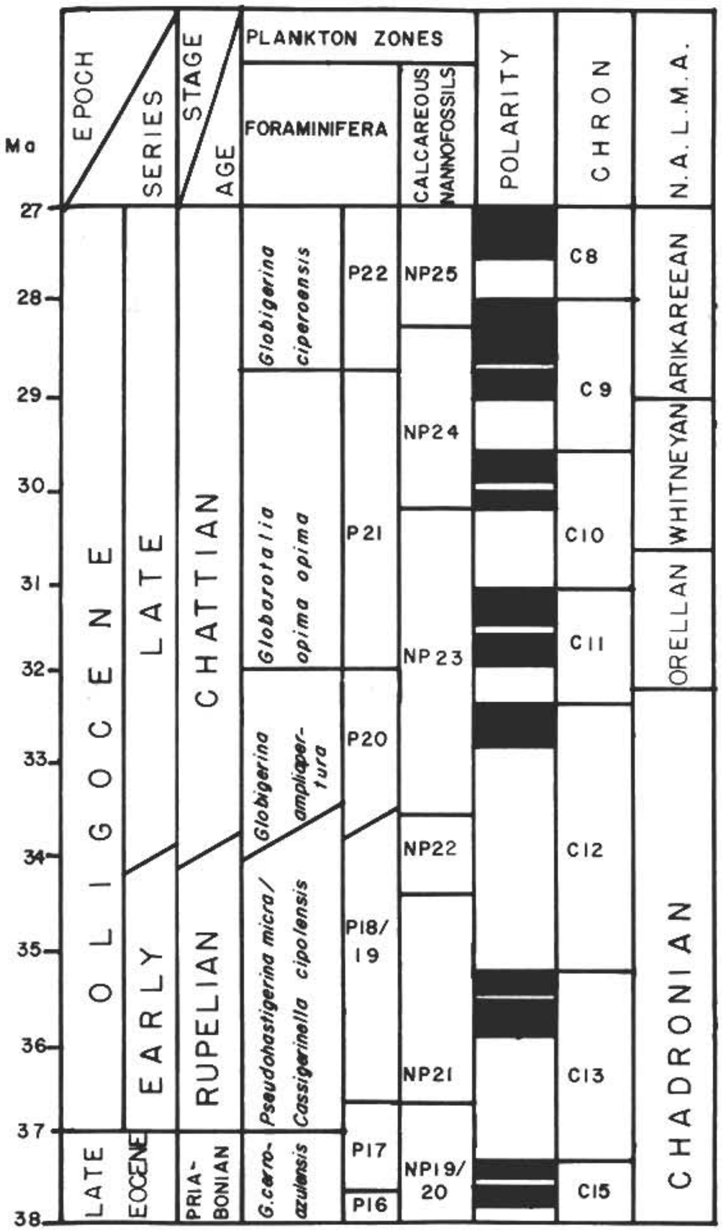

Figure 3. Correlation of North American magnetostratigraphy and mammalian biostratigraphy with European marine sections from Gubbio, Italy (Lowrie and others, 1982), modified with data from Deep Sea Drilling Project Site 522 (Poore and others, 1982). N.A.L.M.A. = North American land mammal "ages."

CONCLUSIONS

Magnetostratigraphy of the White River Group in Nebraska, Wyoming, Colorado, and the Dakotas gives a radiometrically dated polarity stratigraphy for the Oligocene. Combined with the magnetostratigraphy of the Vieja Group of Texas, the land magnetic record best fits the magnetic polarity time scale of LaBrecque and others (1979). Using this time scale, the North American land mammal "ages" are calibrated as follows: Chadronian—32.4 to at least 37.7 m.y. B.P.; Orellan—30.7 to 32.4 m.y. B.P.; Whitneyan—29.0 to 30.7 m.y. B.P. Correlation with the European marine sections by magnetostratigraphy suggests an age of 37.0 m.y. for the Eocene-Oligocene boundary. This contradicts younger dates for this boundary based on glauconites and microtektites.

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Reviewer's comment

This paper will stimulate many additional investigations of geochronology relating to the Oligocene.

Internally consistent pattern of seismicity near Charleston, South Carolina

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ABSTRACT

An improved velocity model for the meizoseismal area of the 1886 Charleston earthquake was used to relocate current seismicity, which showed marked separation into clusters. The relocated hypocenters and composite focal plane solutions were compared with available geophysical data to interpret their tectonic significance and possible association with the 1886 earthquakes. There is a distinct velocity discontinuity at a depth of about 10 km, where Vp increases from 5.9 to 6.45 km/s. The relocated hypocenters and composite focal plane solutions delineate two main source zones lying at different depths. The shallower zone, at 4 to 8 km depth and collinear with the Ashley River, is herein named the Ashley River seismogenic zone. The composite focal plane solution suggests reverse faulting on a steeply dipping northwest-striking fault with the southwest side upthrown. This zone is also associated with aeromagnetic and gravity anomalies. The deeper zone, at 9 to 13 km, suggests a right slip on a fault extending N26° E from east of Ravanel to Jedburg, a distance of more than 25 km, and dipping steeply to the west-northwest. Its location and extent are similar to the so-called Woodstock fault. Examination of geomorphic data suggests that there may be some ongoing tectonic uplift and subsidence in the area. The inferred P axes from fault-plane solutions are oriented S60° W. Firsthand accounts of the 1886 earthquakes suggest that two source areas were active in 1886 and the months that followed; I postulate that the two zones of current seismicity are coincident with the 1886 source areas.

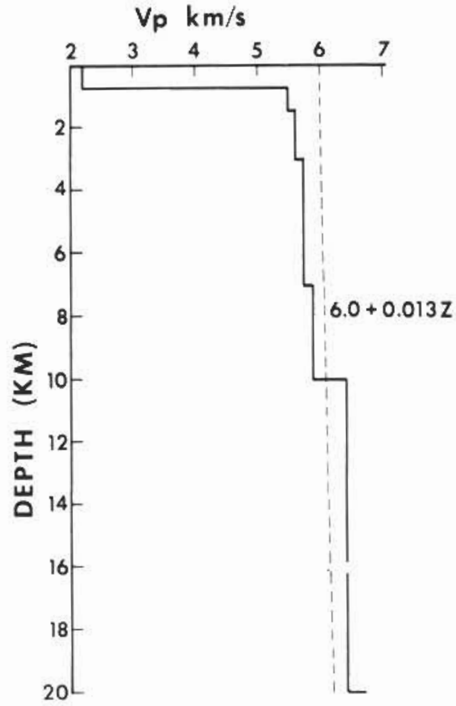

Figure 1. New layered velocity model compared with old gradient model (dashed line; Tarr and others, 1981).

INTRODUCTION

The largest earthquake known to have occurred in the eastern one-third of the United States struck Charleston, South Carolina, in 1886, and smaller earthquakes have occurred in the area from at least 1698 to today (Dutton, 1889; Bollinger, 1977; Bollinger and Visvanathan, 1977; Tarr, 1977; Nuttli and others, 1979; Rhea, 1981). The cause of that intraplate seismicity remains unknown, partly because calculated epicenters and depths of small earthquakes have not defined a spatial pattern clear enough to form the basis of a structural interpretation. I attempt here to define such a pattern of seismicity.

A multidisciplinary study of the tectonics and seismicity in the Charleston area (Rankin, 1977) began with the installation of a seismographic network in 1974. This led to the first instrumental location of earthquakes in the Charleston area. A preliminary result of the seismicity studies was the delineation of three zones of seismicity in the Coastal Plain at Middleton Place, Bowman, and Adams Run (Tarr, 1977; Tarr and others, 1981). Although specific tectonic features responsible for the seismicity were not identified because of an inexact velocity model, the epicentral locations suggested that the current seismicity (1974–1980) was occurring near the location of the 1886 event.

My improved velocity model for the meizoseismal area of the 1886 earthquake (Talwani, in prep.) is a layered model, in which lateral heterogeneity is accounted for in station corrections. I have used it to relocate the current seismicity. The new locations and composite focal plane solutions were analyzed, and the preliminary results are presented here.

VELOCITY MODEL

Following the deployment of the 10-station South Carolina Seismographic Network in 1974, seismic activity was located in the vicinity of Middleton Place, about 20 km northwest of Charleston. In 1977 the number of stations was increased to 16, with a 7-station mininet near Middleton Place (Tarr and others, 1981). Data are recorded on analog tape, which allows for the precise timing of phase arrivals. The hypocenters were located by using a velocity gradient model (Fig. 1). Station corrections were estimated to improve travel-time residuals and to account for lateral heterogeneity. This model does not allow for changes in lithology with depth, which may be associated with abrupt changes in seismic velocity.

To locate the hypocenters more accurately, a new layered velocity model was obtained, with a scheme originally developed by Crosson (1976) and modified by Ellsworth (1978). Phase data for five blasts in the Middleton Place area (Amick, 1979) and 21 well-located earthquakes with the smallest travel-time residuals were used as input. Earthquake phase data were obtained from a catalog by Rhea (1981); only P-wave phase data of Coastal Plain stations were used. The origin times and locations of the blasts were known, and they were used in the modeling. These phase data were simultaneously inverted for hypocentral coordinates, velocity structure, and station delays, using a program called VELEST (Ellsworth, 1978). The program minimizes travel-time residuals by