1. TOWARD A REVISED PALEOGENE GEOCHRONOLOGY

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ABSTRACT

New information has become available that requires a revision of Paleogene chronology incorporated in most current Cenozoic time scales (e.g. Berggren et al., 1985a, b). Age estimates for the limits of the Paleogene (the Oligocene/Miocene and Cretaceous/Paleogene boundaries) have not changed appreciably and remain at about 24 Ma and about 66 Ma, respectively. However, new radioisotope data indicate that boundaries of subdivisions within the Paleogene are generally younger than previously estimated, for example, the Paleocene/Eocene and Eocene/Oligocene, by about 2 to 3 m.y. We review the current status of magnetobiostratigraphic correlations and new radioisotope data, with particular reference to late Eocene—early Oligocene geochronology and provide a reassessment of the age of the Eocene/Oligocene boundary as 34 Ma. We anticipate that with concurrent work on a fundamental revision of the geomagnetic polarity sequence, a comprehensive and detailed new time scale for the Cenozoic will soon be developed.

INTRODUCTION

It is six years since we published a time scale for the Paleogene (Berggren et al., 1985a, b). All available first-order correlations between Paleogene calcareous plankton and magnetostratigraphy were compiled in Berggren et al. (1985a). Since that time there have been several additions and refinements to this data set; those relevant to late Eocene – early Oligocene geochronology are shown in Tables 1.1 (planktonic foraminifera) and 1.2 (calcareous nannoplankton). Inasmuch as we view a time scale to consist of a data set which integrates information from biostratigraphy, radioisotopes, magnetostratigraphy and sea-floor anomalies (Aubry et al., 1988), we believe that a thorough evaluation of each of these disciplines is required before any basic revision(s) can be made to the extant scale. Moreover revisions to Paleogene geochronology are but part of a more comprehensive revision to the time scale for the Cenozoic Era in which we are currently engaged. Thus we view this contribution as an interim step on the way to a fundamental revision of Cenozoic geochronology.

We review below pertinent new Paleogene radioisotopic age data with particular emphasis on those bearing on the Eocene/Oligocene boundary and provide an assessment of the current status of Paleogene geochronology.

NEW RADIOISOTOPIC DATA

A compilation of (predominantly post-1985) radioisotopic data pertinent to Paleogene geochronology is presented in Tables 1.3, 1.5-1.7 and summarized and compared with the Paleogene time-scale of Berggren et al. (1985a, b) in Figure 1.1. A number of late Eocene – early Oligocene radioisotopic dates were generated from the Marche-Umbria Basin (Italy) in connection with the research for a potential Eocene/Oligocene boundary stratotype section and point (Nocchi et al., 1986; Premoli-Silva et al., 1988). We have compiled an annotated list of those dates relevant to the boundary (Table 1.3) considered reliable by the responsible authors (Montanari, 1988; Montanari et al., 1988; Odin, et al. 1988). Of particular relevance to Paleogene geochronology is the fact that the ages obtained in the northeastern Apennines are from volcanic ashes in stratigraphic sections having (in general) both magneto- and biostratigraphy. Comparison of the magnetic

TABLE 1.1. LATE EOCENE-EARLY OLIGOCENE MAGNETOBIOSTRATIGRAPHIC CORRELATIONS
PLANKTONIC FORAMINIFERA

NAME	FAD	LAD	PALEOMAGNETIC CHRON	REFS.	REMARKS / SOURCE
1. *Acarinina*		X	mid-C17N (ref 1 or top C18N (ref 2)	1, 2	
2. *Planorotalites*		X	top C18N	2	
3. *Porticulasphaera semiinvoluta*	X		top C18N	1, 2	= P14/P15 boundary of Blow (1979). Note brief overlap of *Truncorotaloides* and *P. semiinvoluta* (Blow, 1979) vs. brief, but distinct, separation of *Acarinina* and *P. semiinvoluta* in Nocchi *et al.* (1986, Fig. 1).
4. *Morozovella spinulosa*		X	base 17N	1	
5. (*Cribrohantkenina inflata*)	X		(C16N or basal part of C15R)	3, 4	= P15/P16 boundary of Blow (1979) and Berggren & Miller (1988). Occurs between FAD of *Isthmolithus recurvus* and LAD of *P. semiinvoluta* and *T. pomeroli* in Spain (Molina, 1986; Monechi, 1986; Molina *et al*, 1986). FAD *I. recurvus* is in C16N2 (ref. 1-4) and LAD of *T. pomeroli* and *P. semiinvoluta* occur in C15R (in Contessa Highway; ref. 1-3) or C16N2 (in Massignano section; ref. 4) which suggests that FAD of *C. inflata* corresponds approximately with C16N2. FAD not considered unequivocally determined (ref. 3). Brief overlap of *C. inflata* and *P. semiinvoluta* shown in upper part of *G. semiinvoluta* Zone (= lower Zone P16 of Blow, 1979) in ref. 5.
6. *Porticulasphaera semiinvoluta*		X	C15R (base)	1-3	Located in C16N2 in Massignano section (ref. 4).
7. *Turborotalia pomeroli*		X	C15R	1-3	Located in C16N, just above LAD of *P. semiinvoluta*, in Massignano section (ref. 4).
8. *Turborotalia cunialensis*	X		C15R	2-4	Just above (i.e., younger than) LAD of *P. semiinvoluta* (ref. 2, 3).
9. *Globigerapsis index*		X	C13R	1-4, 6	Essentially coincident with LAD *Discoaster saipanensis* and LAD of *D. barbadiensis* and with lower of 3 normal "events" in C13R in Contessa Highway section (ref. 2, 3). Occurs in younger part of C13R on Kerguelen Plateau (ODP Site 748) and thus appears to be reliable, globally synchronous datum.
10. *Cribrohantkenina inflata*		X	C13R	2-4	= P16/P17 boundary Blow (1979) and Berggren and Miller (1988) and located between LAD of *G. index* and *T. cunialensis* and *Hantkenina* in mid-part C13R at Massignano (ref. 4) and just below youngest of 3 normal "events" in C13R in Contessa Highway section (ref. 2).
11. *Turborotalia cerroazulensis* (incl. *T. cocoaensis* and *T. cunialensis*)		X	C13R	1-4	Associated with youngest of 3 normal "events" in C13R in Contessa Section (ref. 2, 3) and above normal "event" = C13N2 at Massignano (ref. 4).
12. *Hantkenina* spp.		X	C13R	1-4	Located just above LAD of *T. cerroazulensis - cunialensis* and youngest of 3 normal "events" in C13R in Contessa Highway section (ref. 2, 3) and above normal "event" = C13N2 at Massignano (ref. 4).
13. *Pseudohastigerina micra* & *P. danvillensis* (> 150 µm)		X	C13R	2-4	Coincides with LAD *Hantkenina*.
14. *Pseudohastigerina* spp. (*naguewichiensis* & *barbadoensis*) (< 150 µm)		X	C12R	1-3	

Refs:
1. Berggren et al. (1985a)
2. Nocchi et al. (1986) = Lowrie et al. (1982)
3. Premoli-Silva et al. (1988): Gubbio (Contessa Section)
4. Coccioni et al. (1988): Massignano Section (Ancona, Italy)
5. Toumarkine and Luterbacher (1985)
6. Berggren (1991)

( ) = second order correlation

TABLE 1.2. CALCAREOUS NANNOPLANKTON

NAME	FAD	LAD	PALEOMAGNETIC CHRON	REFS.	REMARKS / SOURCE
1. *Isthmolithus recurvus*	X		mid-C16N2	1-4	= CP15a/CP15b boundary; located at top of C16N2 at Contessa Highway Section (ref. 1) and mid-C16N2 at Massignano (ref. 4).
2. *Cribrocentrum reticulatum*		X	mid-C16N1	3, 4	
3. *Cyclococcolithina kingii* (= *C. protoannula)*		X	mid-C15N	3, 4	
4. *Discoaster saipanensis*		X	C13 (third normal event in C13R)	1-4	Coincident with LAD of *Globigerapsis index*
5. *Discoaster barbadiensis*		X	C13 (third normal event in C13R)	1-4	Coincident with LAD of *Globigerapsis index*
6. Acme *Ericsonia obruta*			lower C13N1	2-4	
7. *Ericsonia formosa*		X	C12R (lower part, ref. 1; or top C13N, ref. 2)	1-3	
8. *Isthmolithus recurvus*		X	C12R (lower part)	1-3	
9. *Reticulofenestra umbilica*		X	C12R (lower part)	1-3	

Refs:
1. Berggren et al., (1985a)
2. Nocchi et al.,(1986)
3. Premoli-Silva et al.,(1988)
4. Coccioni et al.,(1988)

CQ = Contessa Quarry; CH = Contessa Highway; MAS = Massignano; MCA = Monte Cagnero.
* = Rb-Sr age.
\+ = Supporting date, not directly tied to magnetobiostratigraphy; not included on Figure 1.1.
() = Approximate/estimated correlation.

TABLE 1.3. ISOTOPIC AGES RELEVANT TO THE EOCENE/OLIGOCENE BOUNDARY (ITALY)

1. Montanari et al. (1988)
2. Montanari (1988)
3. Odin et al. (1988)

SAMPLE	BIOSTRAT. LEVEL	PALEOMAG. CHRON	AGE in Ma.	REMARKS	REF.
1. + MCA/84-5	Upper CP18	(base C9N)	28.0±0.7	Approximate age of 28.0 Ma considered acceptable pending 40 Ar/39 Ar laser-fusion probe analysis (Montanari et al., 1988).	1,2
2. CQ/GAR-274	Upper CP18	base C9N (= C9N.9)	28.1±0.3 27.8±0.2	Approximate age of 28.0 Ma considered acceptable pending 40 Ar/39 Ar laser-fusion probe analysis (Montanari et al., 1988).	1,2
3. + MCA/83-3	Lower CP18	(upper C12R)	31.7±0.6		1,2
4. CQ/BOB-247	Lower CP18	upper C12R (= C12R.12)	32.0±0.8	Approximately same biostratigraphic level as sample MCA/83-3 above.	1,2
5. MAS 84/1-14.7	base CP16a	mid-C13R (=C13R.62)	34.6±0.3	MAS 84/1-14.7 (Odin et al., 1988: 214) = MAS/85 -14.7 (Montanari et al., 1988: 206) = MAS/86 - 14.7 (Montanari, 1988: 218, Fig. 4B where it is listed as 34.3± 0.3 Ma).	1-3
6. MAS/84-2: 12.9	base CP15b; upper *T. cerroazulensis* Zone	base C13R (= C13R.82)	33.9±0.4 34.4±0.2*	MAS/84-2:12.9 (Montanari et al., 1988: 217) = MAS/86-12.9 on p. 218, Fig. 4A	1,2
7. MAS 84/1-7.2	CP15B	top C16N (=C16N.0)	35.3±0.7 36.3±0.4*	Same level as sample CQ/ETT-218 below.	1,2
8. CQ/ETT-218	mid-CP15B	top C16N (=C16N.0)	36.9±1.3 35.5±0.2*	Rb/Sr age (Montanari et al., 1988) considered more precise.	1,2
9a. CQ/CAT 210.5A	mid-CP15A	top C17N (=C17N.0)	36.3±0.3	Duplicate dates on same level equivalent to 153.5 m in CH section at top C17N.	1,2
9b. CQ/CAT 210.5B	mid-CP15A	top C17N (= C17N.0)	36.5±0.7		

TABLE 1.4. COMPARISON OF RECENT LATE EOCENE (C17N) – EARLY OLIGOCENE (C9N) AGE ESTIMATES OF MAGNETIC POLARITY CHRONS.

Magnetic Polarity Chron	Berggren et al. (1985 a,b)	Montanari (1988) Montanari et al. (1988) Odin et al. (1988)
	Ages in Ma	
C9N	28.15 - 29.21	~ 28 (base CN9)
C10N	29.73 - 30.33	–
C11N	31.23 - 32.06	–
C12N	32.46 - 32.90	32.0 ± 0.8 (uppermost C12R)
C13N	35.29 - 35.82	34.6 ± 0.8 (mid C13R 33.9 ± 0.4 and 34.4 ± 0.2 (base 13R)
C15N	37.24 - 37.68	–
C16N	38.10 - 39.24	35.3 ± 0.7 and 36.3 ± 0.4 (top of C16N) and 36.9 ± 1.3 and 35.5 ± 0.2 (top C16N)
C17N	39.53 - 41.11	36.3± 0.3 and 36.5 ± 0.7 (top C17N)

TABLE 1.5. RECALIBRATED NORTH AMERICAN LATE EOCENE-OLIGOCENE MAMMAL AGES (PROTHERO et al., 1982; SWISHER AND PROTHERO, 1990)

	Sample	Paleomagnetic Chron	Age in Ma (SEM) (Mean ages of multiple dates)	Remarks
1.	Roundhouse Rock Ash	C10R (Upper part)	28.59±0.32 b	Roundhouse Rock, Wildcat Ridge, Morrill Co., Nebraska.
2.	Nonpareil Ash	Lower C11N	30.05±0.09 b	Roundtop, Nebraska (just below Whitneyan/Arikareean boundary).
3	Upper Whitney Ash	C12N	30.58±0.18 b	Whitney ashes are located at Scottsbluff, Nebraska.
4.	Lower Whitney Ash	Upper C12R	31.85±0.01 b 31.81±0.03 a	"
5.	Persistent White Layer (=Glory Hole Ash)	Uppermost C13R	33.91±0.06 b	Located at Dilts Ranch, Wyoming.
6.	Lone Tree Ash J	C13R/C15N	34.48±0.08 b 34.72±0.04 a	Lone Tree Ash series located at Flagstaff Rim, Wyoming.
7.	Lone Tree Ash I	C15R	35.38±0.10 b	"
8.	Lone Tree Ash G.	C15R	35.57±0.06 b 35.72±0.03 a	"
9.	Lone Tree Ash F	basal C15R	35.72±0.11 b 35.81±0.04 a	"
10.	Lone Tree Ash B.	C16N (top)	35.92±0.01 b 35.97±0.22 a	"

^{40}Ar/^{39}Ar ages based on monitor mineral MMhb-I at 520.4 Ma.
b - biotite; a - anorthoclase.

TABLE 1.6. MISCELLANEOUS EOCENE-OLIGOCENE ISOTOPIC AGES WITH AND WITHOUT MAGNETOBIOSTRATIGRAPHIC CONTROL.

SAMPLE	BIOSTRAT. LEVEL	PALEOMAG. CHRON	AGE in Ma	REMARKS/SOURCE
1. Iversen basalt, Point Arena, Calif.	Latest Zemorrian age; CP19b	(= C6CN)	23.8 wr	K-Ar age by Turner (1970), recalculated by Miller (1981) using new decay constants.
2. ODP Site 706 (basement basalt)[t]	CP16b or CP16c (=NP21)	C13N (~ C13N.5)	33.4± 0.5$^+$ wr	Duncan and Hargraves (1990). Age estimate is a weighted mean from plateau and isochron age estimate of 4 samples; northern margin of Nazareth Bank, western subtropical Indian Ocean,13°06.85' S, 61°22.26' E, SE of Seychelles.
3. Society Ridge Core; base of 80.3-81 feet interval		(= C13R) (~C13R.75)	34.29±0.05$^+$ b	Upper Yazoo Clay (D. Dockery, III, personal communication, 1990). Society Ridge Test Hole No. 1, Hinds Co., Miss., Sec. 24, T7N R1W; SE/4; NE/4, NW/4. Mean of ^{40}Ar/^{39}Ar dates by C. S.
4a. Upper bentonite	(top) NP19/NP20 (top) P16	(= C13R) (~C13R.75)	34.4±0.3$^+$ s	Upper Yazoo Clay (undifferentiated); Satartia, 12-13 miles SSW Yazoo Miss.; SW 1/4, Sec. 31, TION, R3W (locality 3). Local. 3 is stratigraphically above the bentonite at local. 1 and 2 (see below). Dated by J.D.O.
4b. Upper bentonite	-"-	(= C13R) (~C13R.75)	34.31±0.07$^+$ s	Same bentonite as 4a. Mean of 5 ^{40}Ar/^{39}Ar dates by C. S.
5. Lower bentonite	NP19/20	(= C13R) (~C13R.75)	34.9±0.3$^+$ s	Yazoo Clay (Obradovich, pers. comm., 1989). Locality 1: SE 1/4, NW1/4, Sec. 9, T9N, R3W. Locality 2: SW 1/4, SW 1/4, Sec, 4, T9N., R3W. Localities 1 and 2 of Obradovich are of the same bentonite along unnamed creek. Dated by J.D.O.
6. North American tektites (Barbados)	*Turborotalia-cerroazulensis* Zone or youngest *G. semiinvoluta* (P15) Zone; NP20; base *Cryptoprora ornata* Zone	(=C15)	35.4±0.6$^+$ g	Glass et al., (1986). Located about 26 m below Eocene/Oligocene boundary based on LAD of hantkeninids and *T.cerroazulensis*; correlative with Chron C15 (Miller et al., 1991; cf. Berggren et al., 1985; Nocchi et al., 1986).Note that earlier K-Ar ages (34.2 ± 0.6Ma) on North American tektite field (Zahringer, 1963) are about 1 m.y. younger.
7. DSDP Site 612 tektite	PI5 (lower part); *C. ornata* Zone	(= C16N)	35.5±0.3 g	Spherule microtetikite layer just above middle/upper Eocene unconformity; Obradovich et al., 1989; dates of items 6 and 7 are essentially identical but tektites believed to be biostratigraphically separable, Miller, et al., 1991.
8. Bentonite in the Hurricane Lentil, Landrum Mbr., Cook Mountain Fm.	= *Ostrea sellaeformis* Zone (= NP16)	(=lower C18N to upper C20N)	42.0±0.8	Upper part Hurricane Lentil, lower part of Landrum Member, Cook Mountain Formation, East Bank Trinity River, Alabama Ferry locality, Houston Co., Texas (see Stenzel, AAPG, 1940, vol. 24, no. 9, p. 1663-1675). Dated by J. D. O.
9. Castle Hayne bentonite	CP13b (= NP15); P11 *Cubitostrea lisbonensis* Zone	(= lower C20R)	46.2±1.8 45.7±0.7*	Harris and Fullagar (1989). Sequence 1 of Castle Hayne Limestone.
10. DSDP Hole 516F[t]	P10 and NP15 (lower part)	C21N	46.8±0.5 b	Bryan and Duncan (1983). K-Ar determination on biotite from coarse sand in 516F - 76 - 4, 107-115 cm. Calcareous nannoplankton biostratigraphy (Barker, Carlson, Johnson, et al., 1983: 171, 248; Wei and Wise, 1989: 131) constrain this level correlated with Chron C21N (Berggren et al., 1983) to the lower (basal)) part of Zone NP15; see also Berggren et al. (1985).
11. ODP Site 713 (basement basalt)	CP13b (= NP15)	C20R	49.3±0.6$^+$ wr	Duncan and Hargraves (1990). Age estimate is a weighted mean average from plateau and isochron age estimate of 5 samples. Northern edge of Chagos Bank, Central Indian Ocean, 04°11.58' S, 73°23.65' E.
12. Montagnais impact structure 200 km south of Halifax, N.S.	NP13; P9	(=C22)	50.5± 0.8$^+$	Montagnais impact structure dated isotopically (Bottomley and York , 1988) and biostratigraphically (Aubry, et al., 1990). Additional data can be found in Jansa, et al. (1990).

TABLE 1.6 (continued)

13. Mo clay (-17 ash)	Upper part of *Wetzelliella (Apectodinium) hyperacantha* Zone (*Deflandrea oebisfeldensis* Acme)	(= C24R.33)	55.07±0.16$^+$ s	Mo clay ash series at Ejerselev (Jutland) Denmark. Knox (1984) correlated DSDP Site 550 ash sequence (in lower Zone NP10) to Danish ash series from ash layer No. -17 to top of Fur Formation (= ash No. +140). Ash No. -17 thus lies at, or extremely close to, the Paleocene/Eocene boundary. Dated by J.D.O.

K/Ar ages unless otherwise indicated.
* = Rb/Sr age
+ = ^{40}Ar/^{39}Ar age
: = basement ages

(= C13R) : no magnetostratigraphy; second order correlation through biostratigraphy.
J. D. O = John D. Obradovich
C. S. = Carl Swisher (using MMhb-I at 520.4 Ma)
s - sanidine; b - biotite; g - glass; wr - basalt

TABLE 1.7. ISOTOPIC AGES RELEVANT TO THE CRETACEOUS/PALEOGENE BOUNDARY. ALL ARE LASER-FUSION ^{40}Ar/^{39}Ar AGES ON SANIDINES IN BENTONITES MADE BY CARL SWISHER (SWISHER AND DINGUS, UNPUBLISHED DATA) UNLESS OTHERWISE NOTED (SEE ITEMS 1 AND 6).

SAMPLE	BIOSTRATIGRAPHIC LEVEL	PALEOMAG.CHRON	AGE in Ma.	REMARKS/SOURCE
1. Z coal	c. 40 cm above lowest Paleocene palynoflora and Iridium anomaly; stratigraphically highest dinosaur occurrence is 3.0 m below base of Lerbekmo Z coal	(≡ C29R)	66.1±0.5	^{40}Ar/^{39}Ar plateau age, same loc. as 2: Obradovich (1984). Recalculated from 66.0 Ma using 520.4 Ma for MMhb-I
2. Z coal	"	(≡C29R)	66.17±0.06	"Lerbekmo" Hill Creek locality; correlative with younger Z coal (item 1) (See also Lerbekmo et al., 1979). Mean of 7 dates.
3. Z coal	Bug Creek, Montana; correlative with younger Z Coal at Hell Creek.	(≡C29R)	66.14±0.01	Mean of 3 dates.
4a. Iridium bearing (lower) Z coal	3.1 m and 3.34 m above stratigraphically highest occurrence of K palynoflora and dinosaurs, respectively.	(=C29R)	66.22±0.08	Located just above iridium anomaly. Mean of 30 <u>single crystal</u> dates.
4b. Same as 4a.	"		66.26±0.06	Mean of 10 dates (multiple crystals).
5. Nevis Coal, Alberta	Within 2 m interval of palynomorphic break from (K) *Wodehouseia fimbriata* and (P) *W. spinata* Zones. Nevis coal is 4.5 m and 10.5 m above highest stratigraphic occurrence of *Triceratops* and *Tyrannosaurus* skeletons, respectively, and *Triceratops* is *ca.* 6 m below the K/P palynofloral break (Lerbekmo, et al. , 1979).	C29R	66.00±0.05	Mean of 12 dates
6. Beloc, Haiti	Directly overlying uppermost Maastrichtian limestones of *Abathomphalus mayaroensis* Zone and *Micula murus* Zone and overlain by 5-cm basal Paleocene *Guembelitria cretacea* (PO) Zone. P α Zone forms (*i.al., Parvularugoglobigerina eugubina, Eoglobigerina eobulloides*) occur within 1.1 m above top of tektite bearing unit.	C29R	64.48±0.08$^{\#}$ 65.2±0.1$^+$	Weighted mean of 23 total fusion ^{40}Ar/^{39}Ar dates on single tektites using an age of 513.9 (#) or 520.4 (+) for MMhb-1 (Izett et al., 1991; see discussion in this paper). Age estimate of 64.5± 0.1 Ma is consistent with weighted mean average of 3 total laser fusion dates on sanidine crystals from the HS bentonite in Montana of 64.57 ± 0.23 Ma at terrestrial K/P boundary. For additional stratigraphic data see Sigurdsson et al. (1991) and Maurrasse and Sen (1991). Dates are also consistent with a combined mean age of 64.68 ± 0.12 Ma for Z coal bentonite at Hell Creek, Montana (*cf.* item 3) and a correlative bentonite at Frenchman Valley, Saskatchewan (McWilliams et al., 1991).

TABLE 1.8. DATA FOR EOCENE/OLIGOCENE AGE ESTIMATE BASED ON INTERPOLATION FROM SOUTH ATLANTIC MAGNETIC ANOMALY DISTANCES (CANDE AND KENT, 1991)

ITEM	Chron	S. Atlantic Distance (Km)	Date (Ma)	Anomaly	S. Atlantic Distance (Km)
1. CQ/BOB-247	C12R.12	694.53	32.0	12	675.549
2. ODP 706	C13N.50	750.30	33.4	12R	687.792
3. MAS84/1-14.7	C13R.62	774.68	34.6	13	743.924
4, U. Yazoo.1	C13R.75	778.45	34.3	13R	756.732
5. U. Yazoo.2	C13R.75	778.45	34.4	E/O = 13R.14	760.790
6. U. Yazoo.3	C13R.75	778.45	34.3	15	785.690
7. U. Yazoo.4	C13R.75	778.45	34.9	15R	793.068
8. MAS84/2-12.9	C13R.82	780.48	33.9	16	803.444
9. NA tektites	C15N.00	785.700	35.4	16AR	808.159
10. MAS84/1-7.2	C16N.00	803.440	35.3	16B	812.224
11. CQ/ETT-218	C16N.00	803.440	35.5	16R	828.960

and biochronologically based numerical estimates for late Eocene to early Oligocene magnetic polarity chrons (Berggren et al., 1985a, b) with those based on the ages generated in the northeastern Apennines (Montanari, 1988; Montanari et al., 1988; Odin et al., 1988) (Table 1.4) reveals discrepancies between the two ranging from about 1 m.y. (Chron C9N) to 3 m.y. (Chron C16N – C17N) with younger values found in the data from the northeastern Apennines. These data suggested a need for a revision of the Eocene/Oligocene boundary (Berggren and Kent, 1988) from 36.6 Ma (Berggren et al., 1985a, b) to a value closer to 34 Ma.

Two Oligocene and one early middle Eocene calibration points were used to constrain the lower (predominantly Paleogene) part of the time scale of Berggren et al. (1985a, b). The Oligocene points were the Lone Tree Ashes J and B from Flagstaff Rim, Wyoming, dated respectively at 32.4 Ma and 34.6 Ma by Evernden et al. (1964) and correlated with Chron C12N and C13N, respectively, by Prothero et al. (1982). The supposedly long reversed magnetozone between these ashes (J and B) indicated by the K-Ar dates at Flagstaff Rim were interpreted as correlative with Chron C12R, consistent with the estimated duration of about 2.4 m.y. for Chron C12R on magnetic polarity chronologies. However, recent mean ^{40}Ar/^{39}Ar ages of 34.72 Ma (Ash J) and 35.97 Ma (Ash B) (Swisher and Prothero, 1990) (Table 1.5) made on single crystals of anorthoclase indicate that the stratigraphic section between these two ashes spans about half (1.25 m.y. vs. 2.2 m.y.) the time interval previously estimated based on the earlier K-Ar ages of Evernden et al. (1964), and that the paleomagnetic signature of the stratigraphic section spanning the 1.25 m.y. between these ashes (see items 6-10, Table 1.5) is to be correlated with Chron C15 (rather than C12; Prothero et al., 1982; or C13 as reinterpreted by Swisher and Prothero, 1990; see Prothero and Swisher, this volume). It should be noted that Montanari (1990) also reinterpreted the magnetostratigraphy of the High Plains sections based on the assumption that the earlier radioisotopic ages were correct and assigned the reversed interval between the two ashes to Chron C13R.

In similar fashion, newly obtained

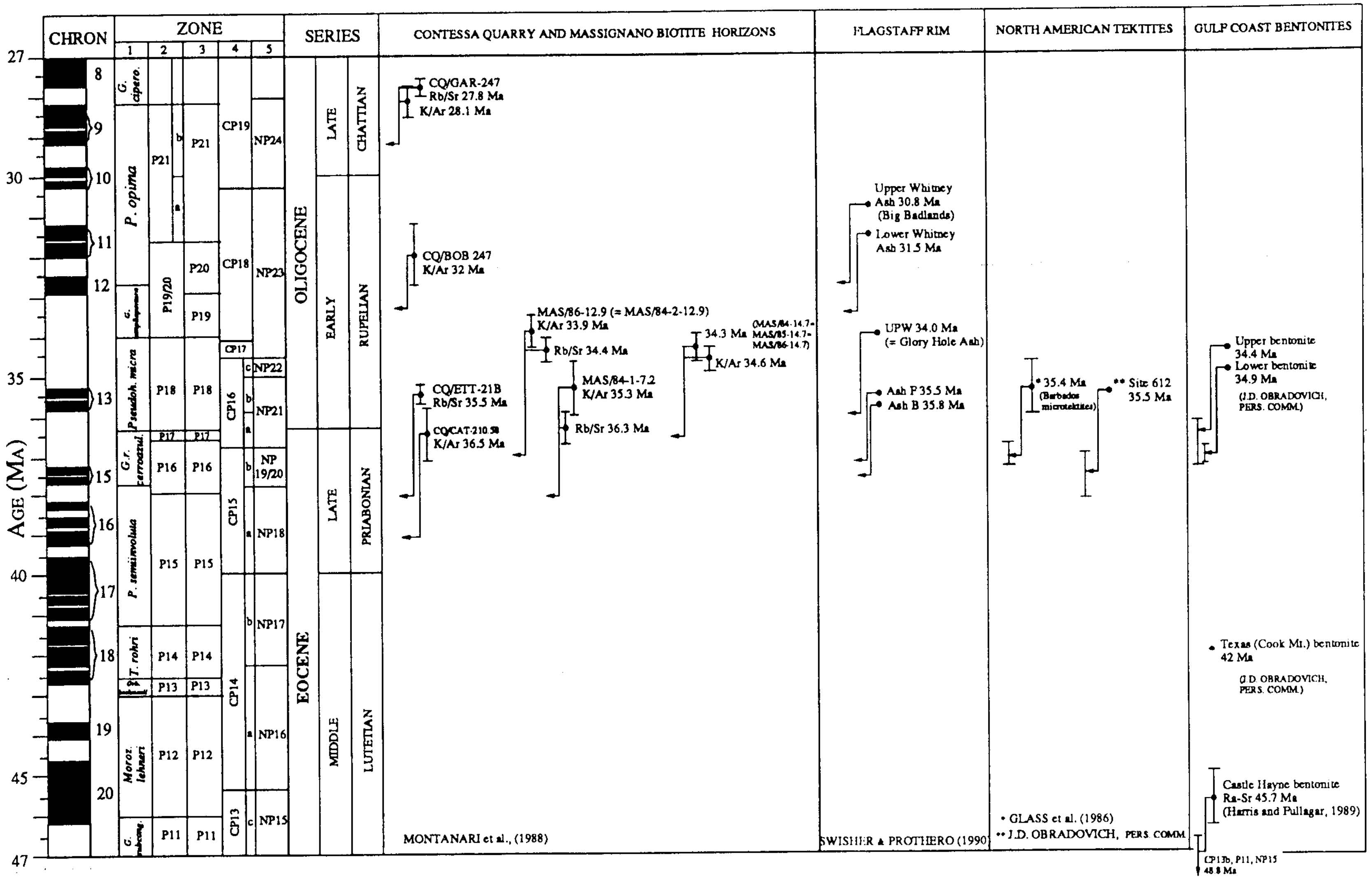


FIGURE 1.1. Magnetobiostratigraphic correlations of middle Eocene – Late Oligocene radioisotope data (Tables 1.3, 1.5, 1.6). Note that the radioisotopic data are plotted against the chronology at the left margin of the table which is that of Berggren et al. (1985 a, b). The arrows indicate the magnetobiostratigraphic position of these ages based on first or second order correlations (see text for further discussion)

$^{40}Ar/^{39}Ar$ ages on single crystals of biotite of 33.91 Ma on the Persistent White Layer (= Glory Hole Ash), just below the lower Orellan normal event and correlative with the terminal range of the titanotheres in eastern Wyoming, and of 30.58 Ma on the Upper Whitney Ash (within the upper Whitneyan normal event), suggest that the long Orellan-Whitneyan reversed interval with a duration of about 2.5 m.y. is consistent with its (re)interpretation as correlative with Chron C12R (Swisher and Prothero, 1990). The new interpretations of North American land mammal magnetobiochronology bring the terrestrial North American record more in line with the marine magnetobiochronology developed in the northern Apennines (Gubbio, Massignano), Italy (Premoli-Silva et al., 1988) and lead to a major realignment of NALM "ages" *vis à vis* marine chronostratigraphy (Swisher and Prothero, 1990).

There are a number of additional radioisotopic ages on Paleogene (primarily Eocene and Oligocene) stratigraphic levels, some of which have magnetostratigraphic, in addition to biostratigraphic, control (Table 1.6). We draw attention to several items of interest in the context of this paper.

1) A mean $^{40}Ar/^{39}Ar$ isochron age on basalt of 33.4 Ma on Chron C13N at Ocean Drilling Project (ODP) Site 706 (item 2, Table 1.6) should be compared with an age of 33.91 Ma on the Persistent White Layer (= Glory Hole Ash) in strata immediately below a normal polarity interval now identified as Chron C13N in Wyoming (item 5, Table 1.5).

2) Several single crystal $^{40}Ar/^{39}Ar$ ages between ~ 34 to 35 Ma in the upper part of the Yazoo Clay Formation of the Gulf Coast and within Zone NP19/20, and thus correlative with Chron C13R (items 3-5, Table 1.6), provide maximum ages for the Eocene/Oligocene boundary.

3) The age of 35.4 Ma on the North American tektite level at Barbados (item 6, Table 1.6) should be compared with ages of 33.9 Ma (K-Ar) and 34.4 Ma (Rb/Sr) at the base of Chron C13R in the Massignano Section (item 6, Table 1.3). The dated levels in both instances are within the *Turborotalia cerroazulensis* Zone, and again provide maximum ages for the Eocene/Oligocene boundary.

4) Ages of 46.2 Ma (K-Ar) and 45.7 Ma (Rb/Sr) on Zone NP15 in the lower Castle Hayne Formation (item 9, Table 1.6) of the Atlantic Coastal Plain and 46.8 Ma on the basal part of Zone NP15 and within a normal polarity interval identified as Chron C21N of Deep Sea Drilling Project (DSDP) Hole 516F (item 10, Table 1.6) support an age estimate of about 46^{+} Ma for Chron C21N (cf. Berggren et al., 1985a, b where Chron C21N = 48.75 to 50.34 Ma).

The early middle Eocene calibration point in the (predominantly) Paleogene part of the time scale of Berggren et al. (1985a, b) was an age estimate of 49.5 Ma for the top of Chron C21N. This was based on an interpolation from radioisotopic (K-Ar) ages on lavas and tuffs stratigraphically bracketing the top of a normal magnetozone in continental beds in the western United States correlated to a normal magnetozone in the Ardath Shale (Zone P10) in San Diego, and thence to Anomaly 21 (Flynn, 1983, a, b; 1986).

Prothero and Swisher (this volume) and work in progress by Swisher indicate that the radioisotopic dates from Wyoming used by Flynn (1986) to calibrate Chron 21N may likely be anomalously old. New $^{40}Ar/^{39}Ar$ dates on single crystals of sanidine and biotite extracted from magnetic and biostratigraphic sections in Wyoming and Texas indicate an age of 46-45 Ma for Chron C21N. The Wyoming dates used by Flynn (1986) for the correlation of Chron C21N need to be redated by single crystal methods to determine if they are anomalously old as a result of contamination from older detrital minerals.

In view of the ages of ~ 46-47 Ma for the early Chron C20R to C21N interval cited above, we regard the estimates of 49.5 Ma for the top of Chron C21N (Flynn, 1983 a, b; 1986) and the age of 49.3 Ma on ODP Site 713 basement basalt (within Zone CP13B = NP15) immediately above Anomaly 21 (item 11, Table 1.6) as anomalous in the context of this discussion.

5) The $^{40}Ar/^{39}Ar$ age of 50.5 ± 0.8 Ma on the lowest melt horizon of the Montagnais impact

structure, biostratigraphically dated as Zone NP13 and P9, late early Eocene (item 12, Table 1.6), is seen to be about 2 m.y. younger than the estimated age, 53 Ma, for this level in the time scale of Berggren et al. (1985a, b). This age is consistent with those discussed under items 4 (above) and 6 (below) indicating that the Eocene part of a revised Paleogene time scale will require an approximately 2 m.y. younger shift in values.

6) The $^{40}Ar/^{39}Ar$ plateau age of 55.1 Ma on the -17 ash of the Mo Clay sequence in Denmark (item 13, Table 1.6) provides a much needed calibration point for the early Paleogene as it lies biostratigraphically very close to the Paleocene/Eocene boundary.

7) A large number of single-crystal laser-fusion $^{40}Ar/^{39}Ar$ ages have recently been made on the Hell Creek "Z" coal and the iridium bearing (lower) Z coal of Montana (Table 1.7). The ages range essentially between ~ 66.1 and 66.3 Ma and confirm previous estimates of ~ 66 Ma (e.g., Obradovich, 1984a; Obradovich et al., 1986; chronogram in Harland et al.,, 1990) for the Cretaceous/Paleogene boundary.

A recent study by Izett et al. (1991) reported three laser fusion $^{40}Ar/^{39}Ar$ dates on a sample split of the Baadsgaard et al. (1988) sanidine from the Hell Creek Z-Coal. These authors reported a mean age of 64.56 ± 0.16 Ma for the sanidine, an age approximately two percent younger than that reported here. Approximately one percent of this age difference can be explained by different ages used for the irradiation monitor mineral, the international standard Minnesota hornblende MMhb-I. The age of MMhb-I was originally published by Alexander et al. (1978) with an age of 519.4 Ma. This age was used by Obradovich (1984b) who used MMhb-I as a monitor mineral for the calibration of his $^{40}Ar/^{39}Ar$ plateau age of 66.0 ± 0.54 on sanidine from the Hell Creek Z-Coal. In 1987, the age of MMhb-I was modified to 520.4 Ma by Samson and Alexander (1987). As such, Obradovich's age for the Z-Coal sanidine would be about 0.2% older or 66.1 ± 0.54 Ma. The mean $^{40}Ar/^{39}Ar$ age based on single crystals of sanidine reported in this paper of 66.12 ± 0.14 Ma on sanidine also collected from the Hell Creek Z-Coal is also based on MMhb-I as a monitor mineral with a published age of 520.4 Ma. and is remarkably consistent with the age of 66.1 ± 0.54 Ma obtained by Obradovich.

Izett et al. (1991) report a weighted mean of three total fusion $^{40}Ar/^{39}Ar$ dates of 64.56 ±0.16 Ma. This age is based on an age of 513.9 Ma for MMhb-I, an age the Menlo Park lab has recently adopted for the MMhb-I interlaboratory standard based on an extensive set of potassium and argon measurements on MMhb-I and in-house standard SB-3. What is curious is that although the $^{40}Ar/^{39}Ar$ ages reported by Izett et al. for Hell Creek Z-Coal appear consistent with the K-Ar ages reported by Baadsgaard et al. (1988), they are based on an age of 513.9 Ma for MMhb-I (Izett et al., 1991) while the Australian National University (ANU) reports an age of 524.2 Ma for MMhb-I (Baadsgaard et al., 1988). If an age of 520.4 Ma is used for the Minnesota standard, the Menlo Park results become 65.4 Ma, an age still approximately 1 % younger than the ages adopted here. Obviously, the age of MMhb-I has not been fully resolved at the present time. As a result, we have chosen to report our ages here based on the published age of MMhb-I of 520.4 Ma as this age is most consistent with other data used in the calibration of the current time scale of Berggren et al. (1985a, b). If a younger or even older age for MMhb-I is adopted in the future, then all time scale calibration points will have to be evaluated together, not just those at the K/P boundary.

The other percent age difference for the K/P boundary is not as easily explained. Work in progress indicates that it may also be a bias in the absolute measurement of the $^{40}Ar/^{39}Ar$ of the standard. In one interlaboratory experiment, similar raw $^{40}Ar/^{39}Ar$ ratios were obtained on the K/P sanidine, but about a percent difference for the standard Fish Canyon whose age is based on K-Ar dates and, in part, on the age of MMhb-I. The actual cause of this discrepancy has not been agreed upon at this time, but work in progress will hopefully resolve this issue. We have chosen at this time to continue to use an age of approximately 66 Ma for the K/P boundary until this interlaboratory bias is resolved.

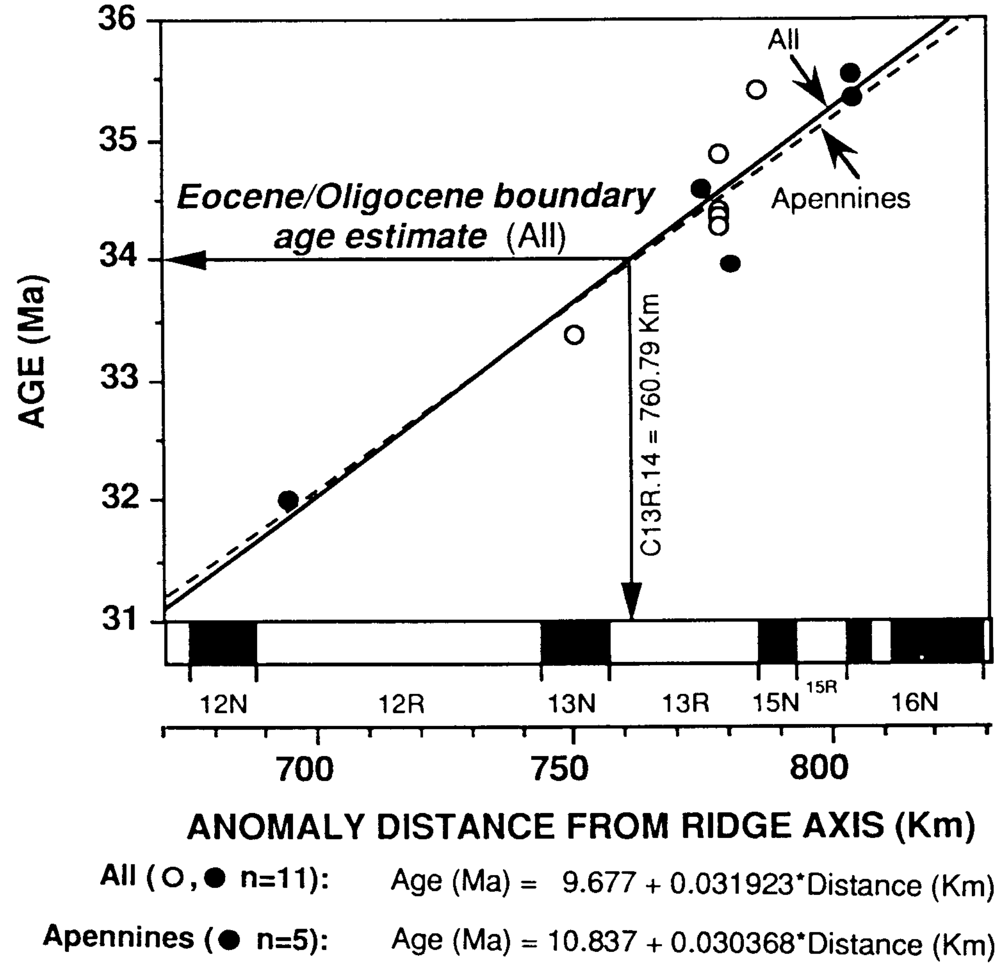


FIGURE 1.2. Estimated age of the Eocene/Oligocene boundary based on linear regression through 11 radioisotope age determinations plotted with respect to characteristic distance from ridge axis to correlative magnetic anomalies in the South Atlantic (Cande and Kent, 1991) according to magnetobiostratigraphic constraints (Table 1.8; see text for further discussion). Filled circles indicate subset of data from the Apennines (Table 1.3), open circles other data (Table 1.6).

THE EOCENE/OLIGOCENE BOUNDARY

The Eocene/Oligocene boundary has recently been stratotypified in the Massignano section (Umbro-Marche Apennines), near Ancona, Italy, where the boundary point is designated at the 19 meter level within C13R; this is 0.14 of the stratigraphic distance below the base of Chronozone C13N (=C13R.14) and corresponds to the extinction level of hantkeninids (Nocchi et al., 1986).

Data from Tables 1.3, 1.5, and 1.6 which are relevant to late Eocene–Oligocene geochronology are presented in Figure 1.1. The radioisotopic data are plotted directly to the chronologic scale at the left of the figure, whereas the arrows indicate the magnetobiostratigraphic position based on first or second order correlation. For example, the ages of 27.8 Ma and 28.1 Ma on Contessa Quarry biotites would correlate with early Chron C8R in the chronology of Berggren et al. (1985a, b). However, the dated level is within earliest Chron C9N and is seen to be about 1 m.y. younger (28 Ma vs. 29.2 Ma) than the age estimate of Berggren et al. (1985a, b). The other data are similarly plotted for each of the general areas discussed above.

Examination of the data in Tables 1.3, 1.5-1.7 and Figure 1.1 indicate that the Eocene/Oligocene boundary (= P17/P18 boundary, within Zone NP21, and within the upper

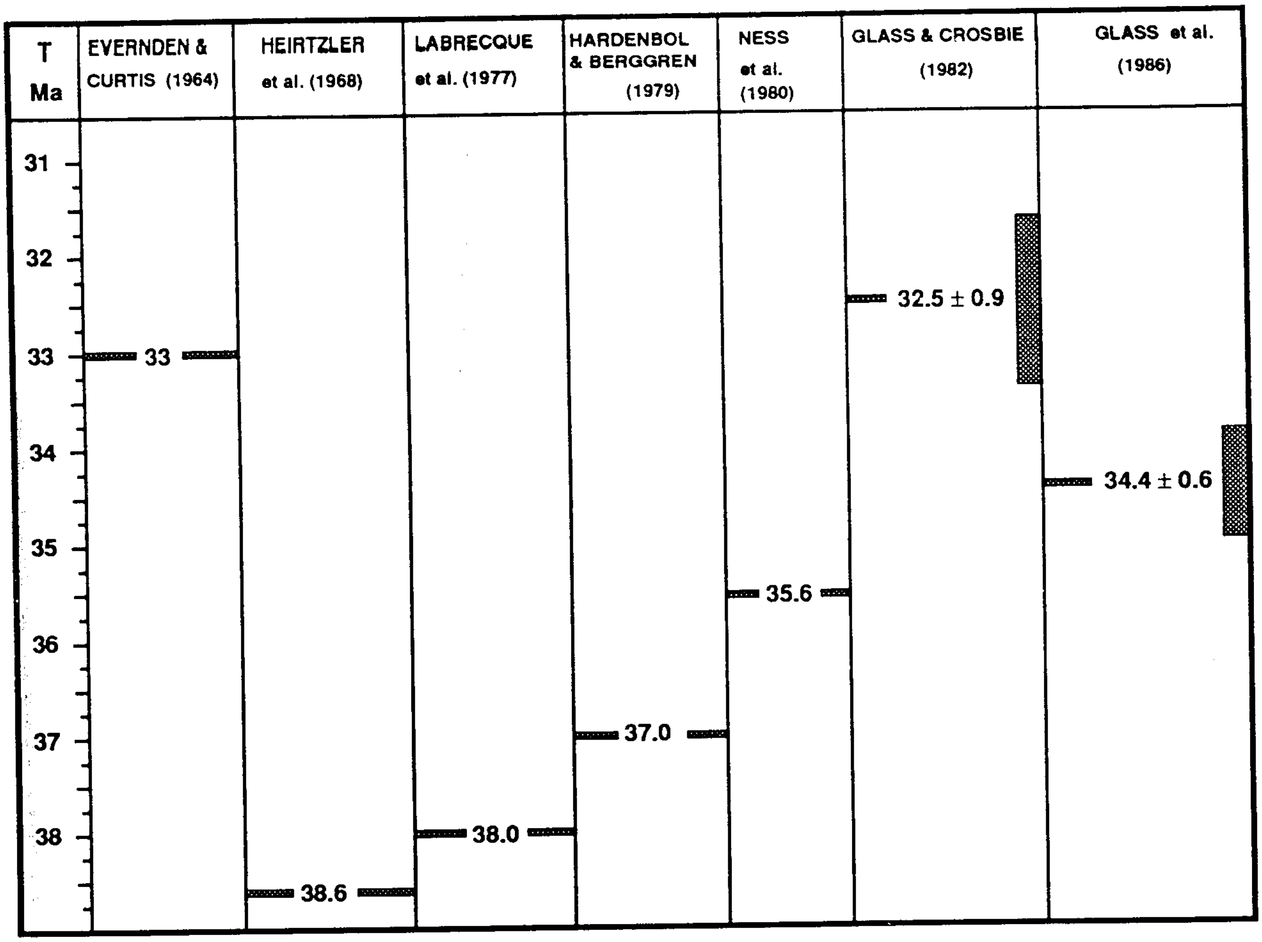


FIGURE 1.3. Historical vicissitude of the Eocene/Oligocene boundary.

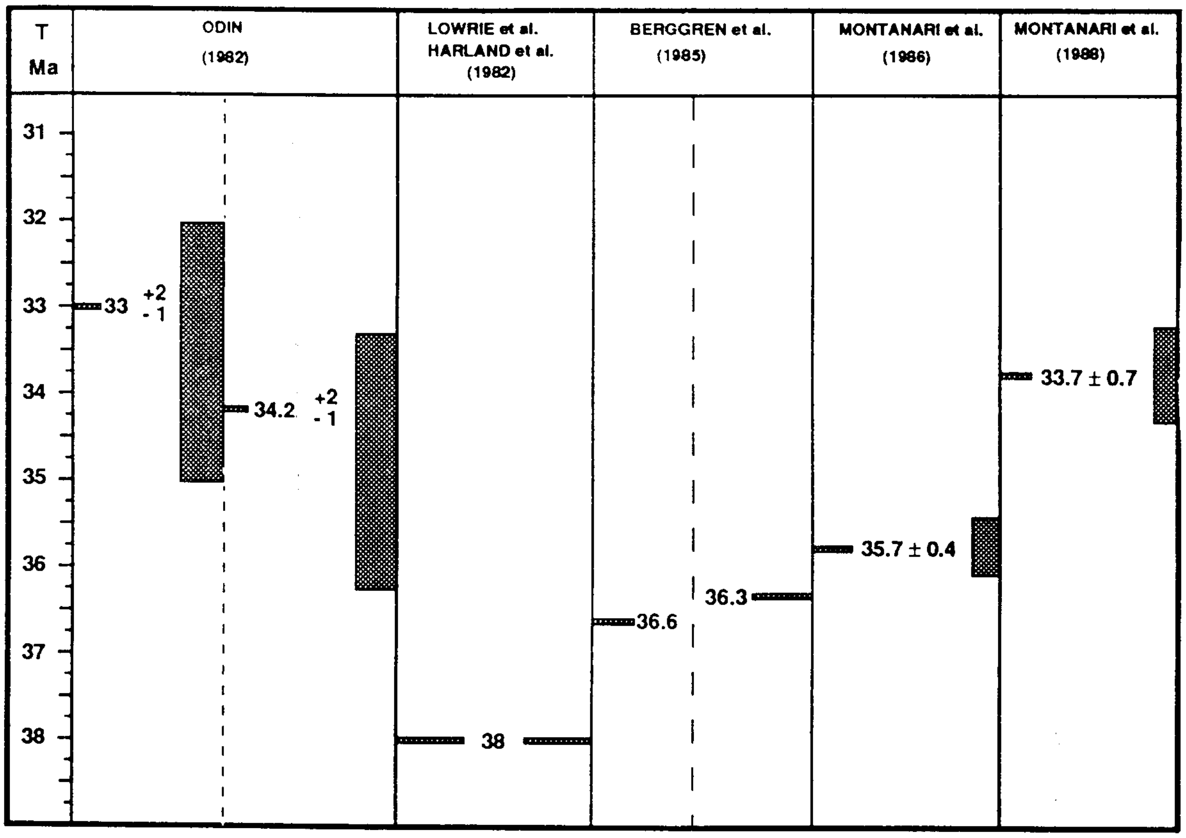
third of Chron C13R (=C13R.14) in Massignano) is bracketed by:

1) an age of 33.4 Ma on Chron C13N at ODP Site 706 (item 2, Table 1.6).

2) ages of 34.28 Ma (item 3, Table 1.6), 34.4 Ma and 34.31 Ma (items 4a and 4b, Table 1.6), and 34.9 Ma (item 5, Table 1.6) on upper Yazoo Clay bentonites of the Gulf Coastal Plain which are correlative biostratigraphically with the lower part of Chron C13R.

An estimate of 34.0 Ma for the boundary (Figure 1.2) is obtained by a linear regression on a total of 11 dates from the Apennines, North American tektites in Barbados, and bentonites from the Upper Yazoo Clay (items 4-8, Table 1.3; items 2-6, Table 1.6) plotted according to magnetobiostratigraphic constraints with respect to characteristic distance from ridge axis to correlative magnetic anomalies in the South Atlantic as revised by Cande and Kent (submitted to *Journal of Geophysical Research*). This age estimate is based on the assumption that the Eocene/Oligocene boundary occurs at C13R.14, as indicated in the magnetobiostratigraphy of the Massignano section, and that seafloor spreading was uniform in the South Atlantic over just the short interval from about anomaly 12 to Anomaly 16. A very similar age estimate (33.9 Ma) for the Eocene/Oligocene boundary is obtained if the regression analysis is performed on only the 5 dates in this interval from the Apennines (items 4-8, Table 1.3).

The estimate of 34 Ma upon which most



geochronologists now appear to agree should be contrasted with previous estimates of the age of the Eocene/Oligocene boundary (Figure 1.3) which ranged from < 33 Ma (Evernden et al., 1964; Glass and Crosbie, 1982) to > 38 Ma (Heirtzler et al., 1968; LaBrecque et al., 1977; Lowrie et al., 1982; Harland et al., 1982). In this context it is important to understand the nature of the methodologies used in obtaining these widely differing values. For example:

1) The estimate of 33 Ma by Evernden et al. (1964) was based on K-Ar ages on volcanics intercalated in mammal-bearing terrestrial sequences. However, because of the endemic nature of the North American fauna during this time interval, correlation with the standard European chronostratigraphic framework was based entirely upon stage of evolution of the mammalian faunas. Recent studies on these dated volcanics have shown that some of the earlier age estimates based on conventional K-Ar dates were too old due to contamination, while others were too young as a result of alteration (Swisher and Prothero, 1990).

2) The age estimates of 38.6 Ma, 38.0 Ma and 35.6 Ma by Heirtzler et al. (1968), LaBrecque et al. (1977), and Ness et al. (1980), respectively, were magnetochronologic estimates based on extrapolation and interpolation between direct ages or age estimates on selected magnetic polarity chrons or sea-floor anomalies. These age estimates for the Eocene/Oligocene boundary are for a level within the upper part of Chron C13R and may be found in the tables in Ness et al. (1980). The age of 38 Ma of Lowrie et al. (1982) and Harland et al. (1982) is essentially that of LaBrecque et al. (1977).

3) The age estimates of Glass and Crosbie (1982) and Glass et al. (1986) were based on sediment rate extrapolations to the biostratigraphically estimated level of the Eocene/Oligocene boundary in local sections based on K-Ar ages on the North American tektite strewn field. The age estimate of 34.4 Ma was based on a direct age of 35.4 Ma on the Barbados tektite

(see item 6, Table 1.6) which lies some 26 m below the biostratigraphically estimated position of the Eocene/Oligocene boundary.

4) The estimates of Odin (1982) are based on (predominantly) glauconite ages on upper Eocene – lower Oligocene sediments. The different age estimates reflect varying interpretations of the base of the Oligocene as equivalent to the Lattorfian/Bartonian stage boundary (34 $^{+2}/_{-1}$ Ma) or the Rupelian/Priabonian stage boundary (33 $^{+2}/_{-1}$ Ma).

5) The age of 36.6 Ma of Berggren et al. (1985a, b) was based on a linear regression through several calibration points which connected three linear segments of the sea-floor magnetic reversal sequence (see Berggren, 1986). The actual value for the Eocene/Oligocene boundary in Berggren et al. (1985a, b) should be 36.3 Ma in as much as the position of the boundary was plotted in the middle part of Chronozone C13R, rather than in the upper part of Chronozone C13R as now indicated by the Massignano section. This age estimate was based in part on the anomalously old K-Ar dates of Everden et al. (1964) (Swisher and Prothero, 1990).

6) The age estimates of 35.7 ± 0.4 Ma and 33.7 ± 0.7 Ma in Montanari et al. (1986, 1988, respectively) are based on a regression line through radioisotopic ages in the lower Oligocene and upper Eocene of the northeastern Apennines. The younger value resulted from the elimination of an age on a lower Oligocene (Chron C13N) stratigraphic level subsequently believed to be spurious. A recent estimate of 33.7 ± 0.4 Ma of Odin et al. (1991) is in substantial agreement with the age of 34 Ma we derive here for the Eocene/Oligocene boundary.

CURRENT STATUS OF PALEOGENE GEOCHRONOLOGY

The following age estimates for boundaries of the major subdivisions of the Paleogene are suggested on the basis of our assessment of current information:

Oligocene/Miocene (Chattian/Aqutanian) boundary, correlated to Chron C6CN, at about 24 Ma (e.g., item 1, Table 1.6; chronogram of Harland et al., 1990);

Eocene/Oligocene (Priabonian/Rupelian) boundary, correlated to Chron C13R.14, at 34 Ma;

Paleocene/Eocene (Thanetian/Ypresian) boundary, correlated to Chron C24R.33, at about 55 Ma (item 12, Table 1.6);

Cretaceous/Paleogene (Maastrichtian/Paleocene) boundary, correlated to Chron C29R.3, at about 66 Ma (Table 1.7).

ACKNOWLEDGEMENTS

This paper grew out of a general review of the status of Paleogene geochronology presented by one of us (WAB) at the Penrose Conference (1989). We wish to thank M.-P. Aubry for her help in biostratigraphically dating several key samples with the aid of calcareous nannoplankton and discussions on various problems associated with stratigraphic interpretation, and K. G. Miller and S. Cande for thoughtful critiques of a draft version of this paper. This research was supported by NSF grants OCE-9101463 (WAB) and OCE-8811339 and OCE-9104447 (DVK). This is WHOI Contribution Number 7777 and L-DGO Contribution Number 4817.

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