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Comparative Study of Miocene Fission-Track Chronology and Magneto-Biochronology

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ABSTRACT

Fission-track ages of zircon crystals from 15 Miocene tuff layers in central and northeast Honshu, Japan have been determined. Ten of the sample horizons are controlled by biostratigraphic data of either calcareous nannoplankton or planktonic foraminifera, or both. A comparison between the fission-track ages and the magneto-biostratigraphic constraints shows that the Anomaly 5-Chron 11 correlation is better than the Anomaly 5-Chron 9.

Key words : Miocene, fission-track dating, magnetic anomaly, magnetostratigraphy, biostratigraphy.

1. INTRODUCTION

The correlation of Middle and Late Miocene geomagnetic reversal sequences between the marine magnetic anomaly patterns and the magnetostratigraphy of sediment sections has been a controversial topic for the past 15 years. There are two correlation models : the Anomaly 5-Chron 9 model (Ryan *et al.*, 1974 ; Theyer and Hammond, 1974) and the Anomaly 5-Chron 11 model (Foster and Opdyke, 1970 ; Hsü *et al.*, 1984 ; Berggren *et al.*, 1985). The two models differ in the correlation method of Chrons 7 through 14 (Fig. 1). The maximum difference in the numerical age of a biostratigraphic datum level between the two models is about 2 m.y. (20%). This problem has been unsolved, owing mainly to the lack of reliable isotopic ages calibrating magneto-biostratigraphic time-scales.

In this work, fission-track zircon ages and biostratigraphic data have been compared in Miocene sections in central and northeast Honshu, Japan, in order to determine which alternative correlation model is correct. These sections seem to be ideal for the purpose, because (a) they commonly contain tuff layers of which isotopic ages can be obtained and (b) biostratigraphic data of calcareous nannoplankton and planktonic foraminifera are available.

Fission-track zircon dating is an ideal method for dating tuff layers in sediment sections, because (a) zircon is highly resistant against weathering and (b) possible contamination from detrital crystals can be checked by grain-by grain analysis.

In fission-track dating, however, there are methodological problems, e.g., data collection procedure, age calibration constant, and statistical procedure, which should be cautiously considered when reliable ages are desired.

With discussions on these problems, the following processes have been performed in this study : (a) adoption of the 2π Population c_W corrected procedure (Suzuki, 1984 ; Kasuya, 1986) ; (b) determination of zeta values for three standard dosimeter glasses using the Fish Canyon Tuff age standard zircon ; and (c) data selection according to the χ^2-test proposed by Galbraith (1981).

Procedural terminology used in this paper is after Suzuki (1984).

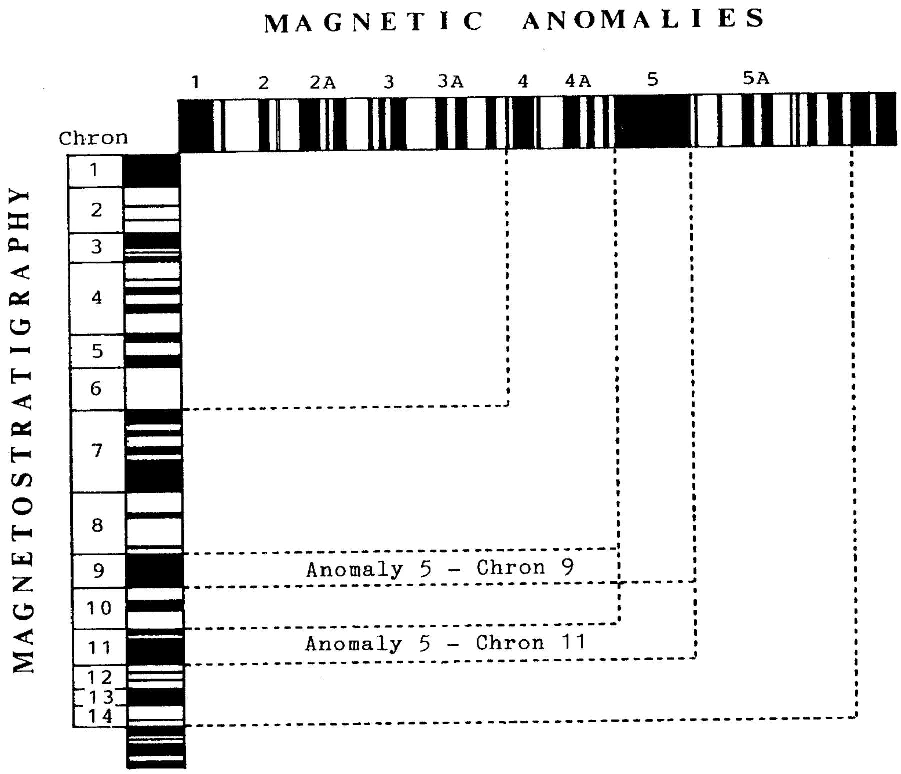


Fig. 1. Correlation of the marine magnetic anomaly pattern (Anomalies) to the magnetostratigraphy of deep-sea sediments (Chrons). The magnetic anomalies are after Berggren *et al.* (1985). The magnetostratigraphy is based on pinton cores from DSDP Site 62 (Ryan *et al.*, 1974). The Anomaly 5-Chron 9 and Anomaly 5-Chron 11 models differ in the correlation method of Chrons 7 through 14.

2. EXPERIMENTAL

A. Material

The Fish Canyon Tuff zircon (Naeser *et al.*, 1981), the most popular age standard for fission-track dating, was used in this study. A $^{40}Ar/^{39}Ar$ biotite plateau age of 27.8 ± 0.2 Ma (Hurford and Hammerschmidt, 1985) has been adopted as the reference age of the Fish Canyon Tuff.

Zircon concentrates of unknown age were separated from silicic tuff layers in Miocene sections in the Sendai, Karasuyama, Takasaki, Hiki, and Boso areas (Fig. 2). Approximately 100 hand samples were collected from these sections, but only 15 samples were considered suitable for dating. The locations of the dated samples are given in Table 1. Kasuya (1987MS) presented maps and columnar sections showing the collection sites and stratigraphic positions of these samples. Ten of the 15 sample horizons are controlled by biostratigraphic data of either calcareous nannoplankton or planktonic foraminifera, or both (Table 2); these data all indicate geological ages of the Middle and Late Miocene.

Three standard glasses, i.e., SRM 961, 962 (Carpenter and Reimer, 1974), and CN 1 (Hurford and Green, 1983), were used as neutron fluence dosimeters. Low-U Brazilian muscovite was used as an external detector for induced fission-tracks of the zircons and standard glasses.

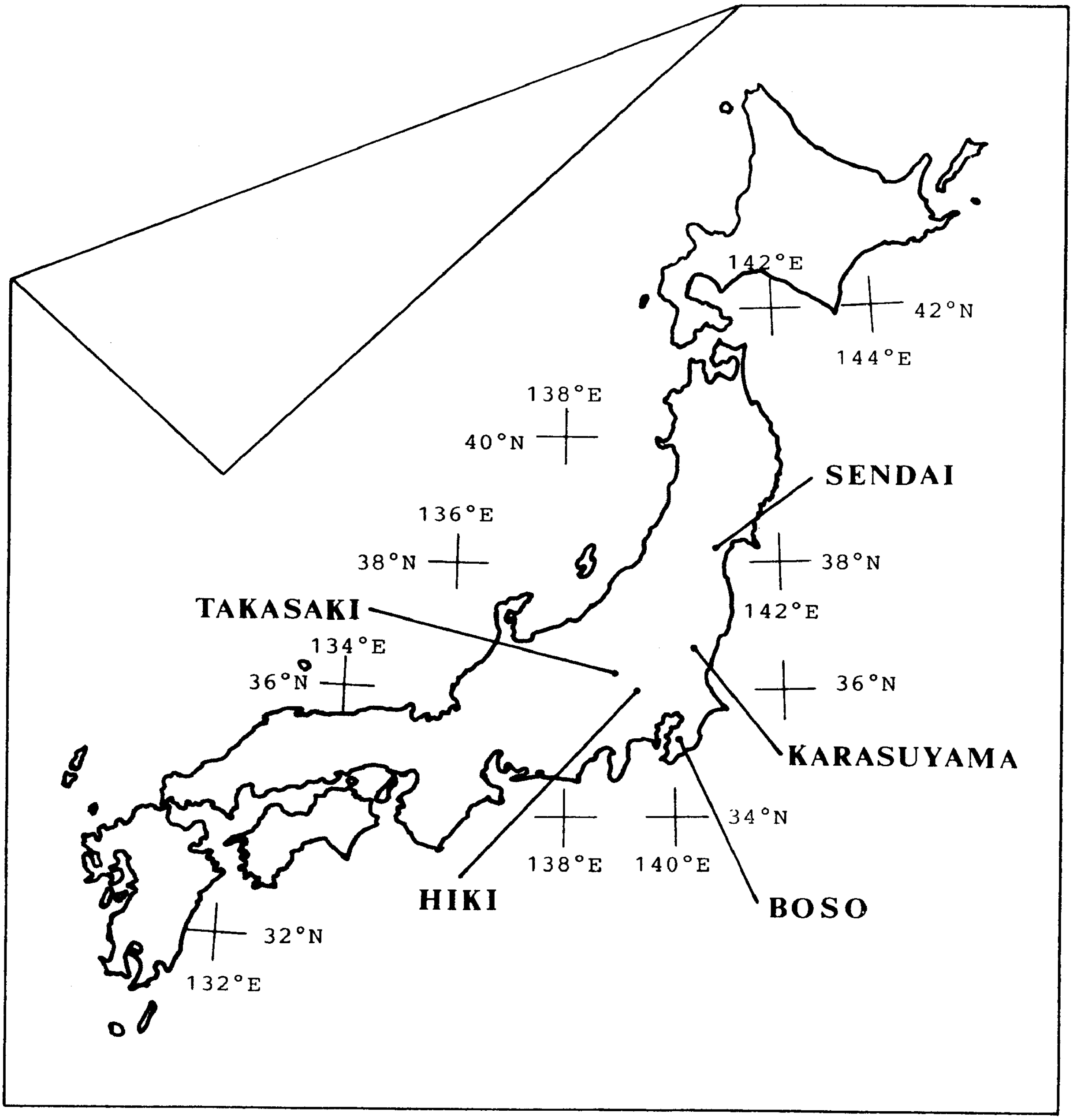


Fig. 2. Map showing the locations of areas where fission-track ages and biostratigraphic data were compared.

B. Experimental procedure

The 2π Population c_W corrected, originally suggested by Suzuki (1984), was adopted in this study (Fig. 3). The advantages of this procedure are described in Sect. 4 A.

Zircon grains were separated into aliquots A and B. After the irradiation (Irradiation 1) of the zircons in aliquot B, the zircons in the two aliquots were etched simultaneously under the same condition. Then, on external surfaces of the zircons, spontaneous tracks were counted in aliquot A, whereas spontaneous and induced tracks were counted in aliquot B. Next, the zircons in aliquots A and B were sealed with muscovite detectors and irradiated (Irradiation 2) again. After etching the muscovite detectors, induced tracks of

Table 1. The collection sites of the zircon samples studied.

Sample	Sample location (Longitude; Latitude)	Formation	Key bed	Reference
F	37°36'40"N; 106°42'17"W	Fish Canyon Tuff		Naeser et al. (1981)
SE 1	38°14'32"N; 140°49'44"E	Shirasawa F.		
SE 2	38°14'55"N; 140°48'53"E	Tsunaki F.		
SE 3	38°14'44"N; 140°48'22"E	Tsunaki F.		
SE 4	38°13'03"N; 140°47'24"E	Hatatate F.	Ht10	Oda and Sakai (1977)
KA 1	36°38'44"N; 140°06'50"E	Oogane F.	Og25	Sakai (1986)
KA 2	36°38'00"N; 140°06'47"E	Oogane F.	Og1	Sakai (1986)
TA 1	36°17'13"N; 138°55'27"E	Haraichi F.	Bb	Takayanagi et al. (1978)
TA 2	36°16'52"N; 138°55'25"E	Haraichi F.	Kt	Takayanagi et al. (1978)
HI 1	36°00'01"N; 139°21'14"E	Iwadono F.	I-12	Koike et al. (1985)
HI 2	36°00'54"N; 139°20'11"E	Iwadono F.	I-8	Koike et al. (1985)
HI 3	36°01'18"N; 139°20'16"E	Iwadono F.	I-1	Koike et al. (1985)
BO 1	35°11'28"N; 140°08'31"E	Kiyosumi F.	Ky21 (HK)	Nakajima et al. (1981)
BO 2	35°10'10"N; 140°00'42"E	Amatsu F.	Am78 (OK)	Nakajima et al. (1981)
BO 3	35°10'09"N; 140°00'41"E	Amatsu F.	Am76	Nakajima et al. (1981)
BO 4	35°09'41"N; 140°00'42"E	Amatsu F.	Am40	Nakajima et al. (1981)

Table 2. Biostratigraphic constraints on the horizons of samples. The samples are arranged according to biostratigraphic order.

Sample	Biostratigraphic control	Biozones Calc.nannopl.	Foram.	Reference(s)
BO 1	Below FAD of *Discoaster asymmetricus* Above LAD of *Discoaster berggrenii*	NN12-NN13		Honda (1981MS) Oda et al. (1983)
BO 2	Below LAD of *Discoaster quinqueramus* Above FAD of *Discoaster quinqueramus*	CN9		Honda (1981MS) Oda et al. (1983)
BO 3	Below LAD of *Discoaster quinqueramus* Above FAD of *Discoaster quinqueramus*	CN9		Honda (1981MS) Oda et al. (1983)
BO 4	Below LAD of *Catinaster calyculus* Above FAD of *Catinaster calyculus*	CN7b		Honda (1981MS) Oda et al. (1983)
KA 1	Below LAD of *Discoaster hamatus* Above LAD of *Cyclicargolithus floridanus*	CN5b-CN7		Honda (1981MS)
TA 1	45m above FAD of *Globigerina nepenthes*		N14	Takayanagi et al. (1978)
KA 2	Below FAD of *Catinaster coalitus* Above LAD of *Sphenolitus heteromorphus*	CN5		Honda (1981MS)
TA 2	Below FAD of *Catinaster coalitus* Above LAD of *Cyclicargolithus floridanus* Below FAD of *Globigerina nepenthes* Above FAD of *Sphaeroidinellopsis subdehiscens*	CN5b	N13	Honda (1981MS) Oda et al. (1983) Takayanagi et al. (1978)
SE 4	Below LAD of *Cyclicargolithus floridanus* Above LAD of *Sphenolithus heteromorphus*	CN5a		Honda (1981MS) Oda et al. (1983)
HI 3	With *Praeorbulina glomerosa* and *Orbulina universa*		N9	Matsumaru and Matsuo (1981)

FAD = first appearance datum; LAD = last appearance datum.
NN zones after Martini (1971).
CN zones after Okada and Bukry (1980).
N zones after Blow (1969).

the zircons in the two aliquots were counted in the muscovite detectors.

Thermal neutron irradiations were carried out at the TRIGA MARK II nuclear reactor of St. Paul's University, Japan with the standard dosimeter glasses sealed with muscovite detectors. The zircons were etched in a eutectic KOH-NaOH melt (Gleadow *et al.*, 1976) at 240°C for 11.0 to 16.5 hr. The muscovite detectors were etched in 50% hydrofluoric acid at room temperature for 15 to 25 min. Fission-tracks were counted at 1000× magnification in transmitted light under Nikon Optiphoto and Olympus Vanox microscopes with dry objectives.

A fixed counting area was assigned for each zircon grain within a sample. In most samples, sufficient numbers of tracks were counted to make final fractional uncertainty in age (ρ_T/T) less than 10%.

3. CALCULATION

A. Age calculation

A fission-track age (for $T < 10^8$ yr) is given by the following equation (Fleischer *et al.*, 1975):

$$T = \zeta(\rho_S/\rho_I)\rho_D \tag{1}$$

where

$$\zeta = \frac{\sigma I}{B\lambda}\frac{R_I}{R_S}\frac{\eta_I}{\eta_S}, \tag{2}$$

$$B = \rho_D/\phi, \tag{3}$$

ρ_S = spontaneous track density,

ρ_I = induced track density,

ρ_D = induced track density in muscovite detector of a dosimeter glass,

σ = thermal neutron fission cross section for ^{235}U,

I = isotopic ratio $^{235}U/^{238}U$,

λ = decay constant for spontaneous fission of ^{238}U,

R_I = range of the induced fission fragments,

R_S = range of the spontaneous fission fragments,

η_I = etching efficiency of induced tracks,

η_S = etching efficiency of spontaneous tracks,

ϕ = thermal neutron fluence.

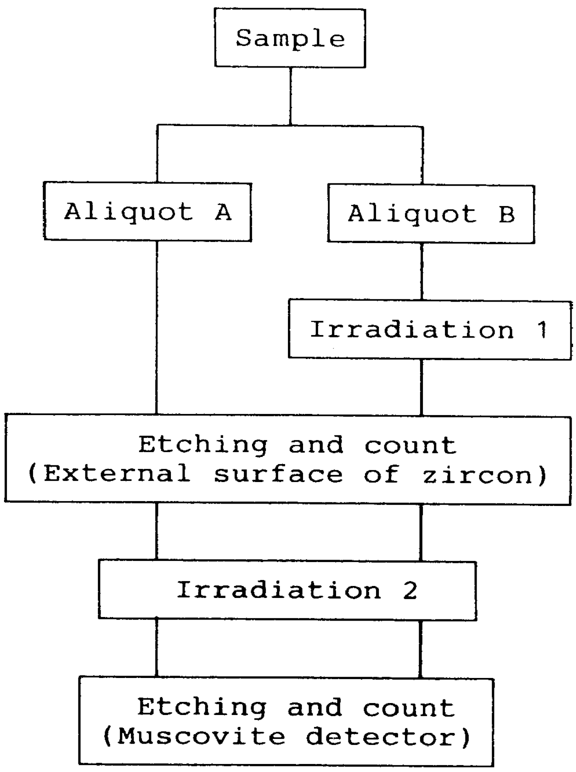


Fig. 3. Schematic representation of the 2π Population c_W corrected procedure. On the external surfaces of zircon, spontaneous tracks are counted in aliquot A, whereas spontaneous and induced tracks are counted in aliquot B. Induced tracks of zircon in the two aliquots are also counted in muscovite detectors.

The zeta calibration method (Hurford and Green, 1982) was executed in this study in order to avoid uncertainties connected with neutron fluence dosimetry and spontaneous fission decay constant of ^{238}U.

In the 2π Population c_W corrected, a zeta factor for a dosimeter glass related to Irradiation 1 is given by

$$\zeta_I = T_S(\rho_I/\rho_S)(1/\rho_{DI}) \tag{4}$$

where

$$\frac{\rho_S}{\rho_I} = \frac{\sum N_{ZA}/\sum N_{MA}}{\sum N_{ZB}/\sum N_{MB} - \sum N_{ZA}/\sum N_{MA}}, \tag{5}$$

T_S = reference age of standard,

ρ_{DI} = induced track density in muscovite detector of a dosimeter glass related to Irradiation 1,

N_{ZA} = number of tracks in each zircon of aliquot A,

N_{MA} = number of tracks in muscovite detector for each zircon of aliquot A,

N_{ZB} = number of tracks in each zircon of aliquot B,

N_{MB} = number of tracks in muscovite detector for each zircon of aliquot B.

An error in ζ_I, or σ_ζ, can be evaluated from

$$\sigma_\zeta = \zeta_I\{(\rho_S/\rho_I+1)^2(1/\sum N_{ZA} + 1/\sum N_{ZB} + 1/\sum N_{MA} + 1/\sum N_{MB}) + 1/\sum N_{DI} + (\sigma_{TS}/T_S)^2\}^{1/2} \quad (6)$$

where

$\sum N_{DI}$ = number of tracks in muscovite detector of a dosimeter glass related to Irradiation 1,

σ_{TS} = error in reference age of standard.

The fission-track age equation in the 2π Population c_W corrected then becomes

$$T = \zeta_I(\rho_S/\rho_I)\rho_{DI}. \quad (7)$$

An error in T, or σ_T, can be evaluated from

$$\sigma_T = T\{(\rho_S/\rho_I+1)^2(1/\sum N_{ZA} + 1/\sum N_{ZB} + 1/\sum N_{MA} + 1/\sum N_{MB}) + 1/\sum N_{DI} + (\sigma_\zeta/\zeta_I)^2\}^{1/2} \quad (8)$$

Error equations (6) and (8), which have been verified by the Montecarlo method, are written by assuming that Poisson errors are applicable to the fission-track counts and by approximating Poisson distributions to Gaussian distributions. All the errors reported in this paper represent one standard deviation.

B. Statistical procedure

The χ^2-test proposed by Galbraith (1981) was applied to the fission-track data in aliquots A and B to check a possible departure from the Poisson model. If the value of χ^2 is unacceptable, non-Poisson variation factors, e.g. contamination of zircon grains of different ages, are presumably affecting the data (Green, 1981). To avoid erroneous results caused by non-Poisson variations, fission-track data were completely rejected when the χ^2-test showed that the data of aliquots A or B, or both are highly heterogeneous to reject a null hypothesis at 5% level.

4. RESULTS AND DISCUSSION

All the fission-track data accepted in this study are given in Table 3. The zeta values and fission track ages are listed in Tables 4 and 5, respectively.

A. Data collection procedure

Spontaneous fission-tracks can be counted either on external or internal surfaces of zircon. The reasons for adopting external surfaces in this study are: (a) identification of fission-tracks on external surfaces is easier since there are no short tracks; (b) etching properties of fission-tracks on external surfaces are more homogeneous; and (c) external (contamination) effect is negligible in considerably higher uranium content minerals such as zircon. Reasons (a) and (c) were previously pointed out by Gleadow (1981).

Among various procedures using external surfaces, the present author adopted the 2π Population c_W corrected because of the following advantages: (a) spontaneous and induced tracks in zircon are etched and counted under identical conditions; (b) difference in uranium content of zircons between aliquots A and B is corrected; and (c) the Galbraith's χ^2-test can be applied to check possible departures from the Poisson model.

The zircons in aliquot B were not annealed prior to Irradiation 1, because changes in etching properties occur when zircon is annealed (Gleadow, 1981).

The main disadvantage of the 2π Population c_W corrected is the larger Poisson error caused by increase in number of variables. This disadvantage

Table 3. Fission-track data of the samples adopted in this study. Etching time represents the condition for zircon. χ^2-test is after Galbraith (1981) ; DF represents degrees of freedom.

Sample : Etching time : Counting area for each grain

Aliquot A						
	Zircon		Mica			
No. of grains	ΣN_{ZA} (tr)	ρ_{ZA} ($tr\cdot cm^{-2}$)	ΣN_{MA} (tr)	ρ_{MA} ($tr\cdot cm^{-2}$)	χ^2-test χ^2	DF
Aliquot B						
	Zircon		Mica			
No. of grains	ΣN_{ZB} (tr)	ρ_{ZB} ($tr\cdot cm^{-2}$)	ΣN_{MB} (tr)	ρ_{MB} ($tr\cdot cm^{-2}$)	χ^2-test χ^2	DF
Thermal neutron dosimeters						
Irradiation 1			Irradiation 2			
Dosimeter glass	ΣN_{D1} (tr)	ρ_{D1} ($tr\cdot cm^{-2}$)	Dosimeter glass	ΣN_{D2} (tr)	ρ_{D2} ($tr\cdot cm^{-2}$)	
F-1 : 11.0 hours : 4.12×10^{-5} cm²						
39	5126	3.190×10^6	4333	2.697×10^6	36.1	38
32	6975	5.291×10^6	3639	2.760×10^6	36.8	31
SRM 961	9063	6.666×10^5	SRM 961	4257	8.264×10^5	
SRM 962	4815	5.506×10^4				
CN 1	7373	1.646×10^5				
F-2 : 11.0 hours : 4.12×10^{-5} cm²						
33	4400	3.236×10^6	4419	3.250×10^6	36.6	32
22	5582	6.158×10^6	2854	3.149×10^6	24.2	21
SRM 961	8118	1.010×10^6	SRM 961	7892	1.008×10^6	
SRM 962	6069	8.755×10^4				
CN 1	8162	2.615×10^5				
F-3 : 11.0 hours : 4.12×10^{-5} cm²						
69	8822	3.103×10^6	7578	2.666×10^6	75.0	68
51	15181	7.225×10^6	5372	2.557×10^6	53.9	50
SRM 961	7311	1.492×10^6	SRM 961	4257	8.264×10^5	
SRM 962	5816	1.209×10^5				
CN 1	6137	3.610×10^5				
SE 1 : 15.2 hours : 2.06×10^{-5} cm²						
63	597	4.600×10^5	2925	2.254×10^6	64.2	62
45	1656	1.786×10^6	1943	2.096×10^6	49.6	44
SRM 961	2430	9.721×10^5	CN 1	4300	3.071×10^5	
SE 2 : 15.0 hours : 2.06×10^{-5} cm²						
48	254	2.569×10^5	2787	2.819×10^6	60.5	47
54	1107	9.951×10^5	3140	2.823×10^6	59.4	53
SRM 961	2430	9.721×10^5	CN 1	11186	7.509×10^5	
SE 3 : 15.3 hours : 2.06×10^{-5} cm²						
43	831	9.381×10^5	3459	3.905×10^6	50.3	42
31	1940	3.038×10^6	2346	3.674×10^6	30.9	30
SRM 961	2430	9.721×10^5	SRM 961	3272	1.258×10^6	
SE 4-1 : 15.2 hours : 2.06×10^{-5} cm²						
80	587	3.562×10^5	4139	2.512×10^6	65.8	79
65	1328	9.918×10^5	3206	2.394×10^6	48.3	64
SRM 961	2430	9.721×10^5	CN 1	11186	7.509×10^5	
SE 4-2 : 16.5 hours : 2.06×10^{-5} cm²						
33	195	2.868×10^5	1123	1.652×10^6	31.6	32
12	464	1.877×10^6	470	1.901×10^6	7.0	11
SRM 961	6382	2.383×10^6	CN 1	6656	5.929×10^5	
KA 1 : 11.5 hours : 3.09×10^{-5} cm²						
52	2166	1.348×10^6	4555	2.835×10^6	54.9	51
37	3751	3.281×10^6	3138	2.745×10^6	33.4	36
SRM 961	5060	6.487×10^5	SRM 961	4257	8.264×10^5	
KA 2 : 14.0 hours : 4.12×10^{-5} cm²						
56	1423	6.168×10^5	2328	1.009×10^6	65.2	55
34	2146	1.532×10^6	1428	1.019×10^6	23.6	33
SRM 961	5060	6.487×10^5	SRM 961	9063	6.664×10^5	

TA 1-1 : 11.5 hours : 4.12×10^{-5} cm^2						
59	2738	1.126×10^6	8645	3.556×10^6	57.9	58
43	4994	2.819×10^6	6357	3.588×10^6	46.4	42
SRM 961	3790	6.423×10^5	CN 1	3199	2.990×10^5	
TA 1-2 : 11.5 hours : 4.12×10^{-5} cm^2						
59	2857	1.175×10^6	4641	1.909×10^6	64.9	58
42	5556	3.211×10^6	3586	2.072×10^6	47.1	41
SRM 961	5060	6.487×10^5	SRM 961	9063	6.664×10^5	
TA 2-1 : 13.5 hours : 4.12×10^{-5} cm^2						
59	1859	7.648×10^5	5402	2.222×10^6	56.6	58
52	3807	1.777×10^6	4758	2.221×10^6	60.7	51
SRM 961	3790	6.423×10^5	CN 1	3199	2.990×10^5	
TA 2-2 : 14.0 hours : 4.12×10^{-5} cm^2						
48	1259	6.366×10^5	2089	1.056×10^6	34.7	47
46	2911	1.536×10^6	2097	1.106×10^6	41.5	45
SRM 961	5060	6.487×10^5	SRM 961	9063	6.664×10^5	
HI 1 : 12.5 hours : 2.06×10^{-5} cm^2						
38	1056	1.349×10^5	2044	2.611×10^6	46.3	37
38	4086	5.220×10^6	1832	2.340×10^6	40.3	37
SRM 961	7311	1.492×10^6	CN 1	4322	1.943×10^5	
HI 2 : 12.5 hours : 4.12×10^{-5} cm^2						
51	1266	6.025×10^5	2705	1.287×10^6	44.9	50
47	4436	2.291×10^6	2301	1.188×10^6	38.5	46
SRM 961	7311	1.492×10^6	CN 1	4322	1.943×10^5	
HI 3 : 12.5 hours : 2.06×10^{-5} cm^2						
66	2119	1.559×10^6	3950	2.905×10^6	67.0	65
40	4691	5.693×10^6	2424	2.942×10^6	35.9	39
SRM 961	7311	1.492×10^6	SRM 961	4257	8.264×10^5	
BO 1-1 : 14.8 hours : 2.06×10^{-5} cm^2						
30	111	1.796×10^5	804	1.301×10^6	33.5	29
20	346	8.398×10^5	518	1.257×10^6	20.1	19
CN 1	6158	1.720×10^5	SRM 961	8192	9.204×10^5	
BO 1-2 : 15.0 hours : 2.06×10^{-5} cm^2						
41	171	2.025×10^5	1315	1.557×10^6	32.5	40
26	422	7.879×10^5	765	1.428×10^6	26.0	25
SRM 961	8540	6.426×10^5	SRM 961	3034	9.479×10^5	
BO 2-1 : 15.0 hours : 3.09×10^{-5} cm^2						
58	575	3.208×10^5	2833	1.581×10^6	51.3	57
53	1400	8.549×10^5	2131	1.301×10^6	56.3	52
SRM 961	8540	6.426×10^5	SRM 961	3034	9.479×10^5	
BO 2-2 : 16.5 hours : 4.12×10^{-5} cm^2						
55	392	1.730×10^5	5036	2.222×10^6	54.3	54
24	2115	2.138×10^6	2295	2.321×10^6	28.0	23
SRM 961	6382	2.383×10^6	CN 1	6656	5.929×10^5	
BO 3-1 : 16.0 hours : 4.12×10^{-5} cm^2						
63	290	1.490×10^5	3600	1.849×10^6	60.8	62
48	909	6.129×10^5	2532	1.707×10^6	34.2	47
SRM 961	4257	8.264×10^5	CN 1	12171	6.441×10^5	
BO 3-2 : 16.5 hours : 3.09×10^{-5} cm^2						
45	204	1.467×10^5	2456	1.766×10^6	44.8	44
16	725	1.466×10^6	862	1.744×10^6	12.6	15
SRM 961	6382	2.383×10^6	CN 1	6656	5.929×10^5	
BO 4-1 : 15.0 hours : 4.12×10^{-5} cm^2						
31	204	1.597×10^5	1797	1.407×10^6	37.1	30
25	392	3.806×10^5	1361	1.321×10^6	24.9	24
SRM 961	8540	6.426×10^5	CN 1	10948	6.742×10^5	
BO 4-2 : 16.5 hours : 4.12×10^{-5} cm^2						
119	628	1.281×10^5	5448	1.111×10^6	106.9	118
62	2461	9.634×10^6	2739	1.072×10^6	62.5	61
SRM 961	6382	2.383×10^6	CN 1	6656	5.929×10^5	

Table 4. Zeta values for standard dosimeter glasses. Zeta values and their errors were obtained from equations (4) and (6), respectively, using the Fish Canyon Tuff age standard zircon.

Dosimeter glass	Sample	ζ_1 values ($yr \cdot cm^2 \cdot tr^{-1}$)	
SRM 961	F-1	25.9 ± 2.0	26.5 ± 0.8
	F-2	26.5 ± 1.7	
	F-3	26.6 ± 1.1	
SRM 962	F-1	313 ± 24	320 ± 10
	F-2	306 ± 20	
	F-3	328 ± 13	
CN 1	F-1	105 ± 8	107 ± 3
	F-2	103 ± 7	
	F-3	110 ± 4	

can be recovered, however, by counting a large number of zircon grains.

Suzuki *et al.* (1984) suggested that the effect of irradiation on etching properties of zircon are notable when the track density ratio (ρ_S/ρ_I) is less than 1/30. In this study, every ρ_S/ρ_I value was controlled so as to exceed 1/11 ; under this condition, no differences in the etching properties of fission-tracks in zircons were observed between aliquots A and B. Therefore, the following equation is most probably satisfied :

$$R_S\eta_S = R_I\eta_I \tag{9}$$

Hence, equation (2) is rewritten as

$$\zeta = \sigma I/B\lambda. \tag{10}$$

Thus we can obtain zeta values independent of the etching efficiency of tracks in zircon.

The counting efficiency for external surfaces of zircon ($\eta_{EStotal}$; Suzuki, 1984) is defined by the ratio of etching efficiencies (external surfaces of zircon versus muscovite detector). It is given by

$$\eta_{EStotal} = \frac{\zeta_2\rho_{D2}}{\zeta_1\rho_{D1}}(\Sigma N_{ZB}/\Sigma N_{MB} - \Sigma N_{ZA}/\Sigma N_{MA}) \tag{11}$$

where

ζ_2 = zeta value of a dosimeter glass related to Irradiation 2,

ρ_{D2} = induced track density in muscovite detector of a dosimeter glass related to Irradiation 2.

Table 5. Fission-track zircon ages of tuff layers in Miocene sections in central and northeast Honshu, Japan. Ages and their errors were obtained from equations (7) and (8), respectively. The samples are arranged in stratigraphic order for each area.

Area	Sample	Age (Ma)	
SENDAI	SE 1	8.1 ± 0.7	
	SE 2	9.0 ± 1.0	
	SE 3	10.5 ± 0.8	
	SE 4-1	13.4 ± 1.2	13.4 ± 1.0
	SE 4-2	13.5 ± 1.7	
KARASUYAMA	KA 1	11.4 ± 0.8	
	KA 2	11.8 ± 1.0	
TAKASAKI	TA 1-1	11.5 ± 0.7	11.4 ± 0.5
	TA 1-2	11.3 ± 0.7	
	TA 2-1	12.8 ± 0.9	13.0 ± 0.7
	TA 2-2	13.2 ± 1.2	
HIKI	HI 1	11.9 ± 0.8	
	HI 2	12.7 ± 0.8	
	HI 3	15.2 ± 0.9	
BOSO	BO 1-1	4.8 ± 0.8	5.0 ± 0.5
	BO 1-2	5.3 ± 0.7	
	BO 2-1	7.6 ± 0.7	6.3 ± 0.4
	BO 2-2	5.8 ± 0.4	
	BO 3-1	6.3 ± 0.6	6.6 ± 0.5
	BO 3-2	6.9 ± 0.7	
	BO 4-1	11.1 ± 1.7	9.5 ± 0.6
	BO 4-2	9.3 ± 0.6	

The values of $\eta_{EStotal}$ for the studied samples are plotted against ρ_S in Fig. 4. Counting efficiency varies widely between 0.6 and 1.0 from sample to sample. Since the efficiency of revealing and counting tracks depends on various parameters (Wagner, 1981), it is difficult to find, for each sample, the specific conditions under which an ideal $\eta_{EStotal}$-value of 1.0 can be obtained.

The correction of uranium-content difference between zircons in aliquots A and B is not effective if ρ_S is too low, because the error in age becomes much more influenced by the Poisson variation than by the uranium-content variation (Hayashi, 1981). If ρ_S is too high, on the other hand, it becomes difficult to count a mixture of spontaneous and induced tracks in aliquot B. Thus this author suggests that the following range for ρ_S is required for applying the 2π Population c_W corrected :

$$5\times10^4\ tr\cdot cm^{-2} \leqq \rho_S \leqq 5\times10^6\ tr\cdot cm^{-2}. \tag{12}$$

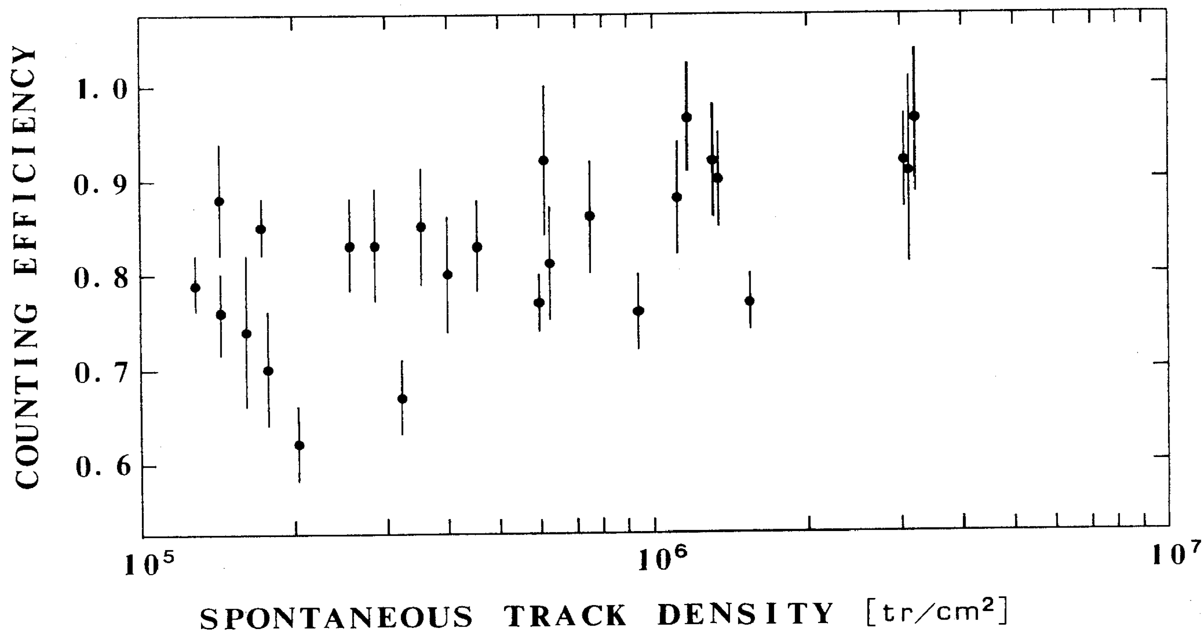


Fig. 4. Counting efficiency ($\eta_{EStotal}$) versus spotaneous fission-track density (ρ_S) for the samples studied. Counting efficiency is given by equation (11).

Since this range covers most Miocene zircons, the 2π Population c_W corrected is especially suitable for Miocene zircon dating. All the samples adopted in this study satisfy equation (12).

B. Zeta values

Zeta values for SRM 961, 962, and CN 1 were determined three times for each glass with varying neutron fluence. In all glasses the three determinations were in agreement within the Poisson counting error limits. Thus, a weighted mean zeta value was calculated for each glass (Table 4).

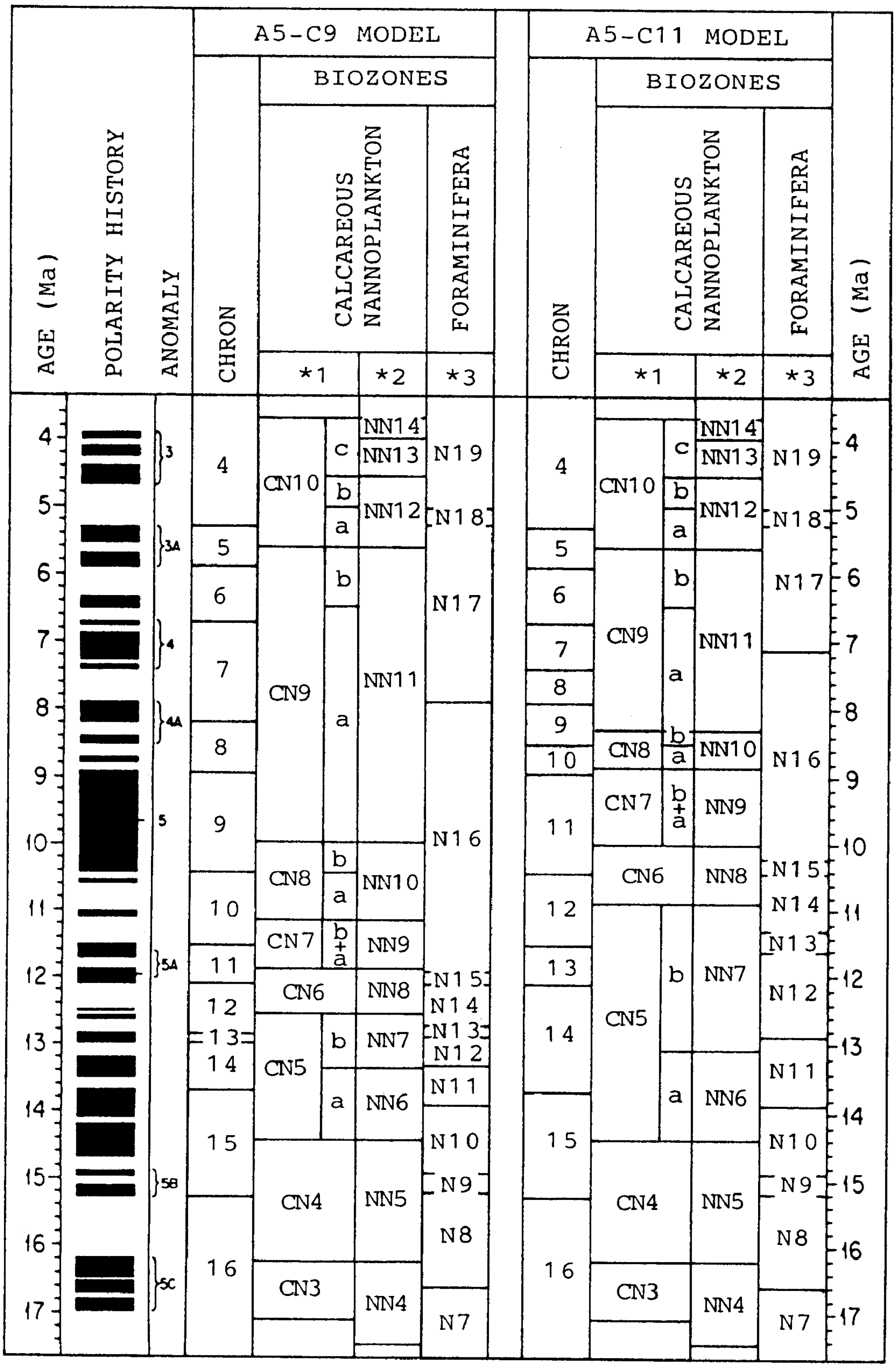
The zeta value of a dosimeter glass varies widely among workers: e.g. 310 to 382 yr•cm^2•tr^{-1} for SRM 612 (Green, 1985). As SRM 962 and SRM 612 are made of the same base material (Carpenter and Reimer, 1974), the two glasses are supposed to have the same zeta value; 320 yr•cm^2•tr^{-1} was used in this study.

These discrepancies in the zeta values among workers were resulted from differences in data collection procedures, observation conditions, and track identification criteria. Dating results can be reliable, however, as long as these conditions are kept constant.

C. Fission-track ages

Fission-track ages of the samples are summarized in Table 5, arranged in stratigraphic order within each sample area. Repeated analyses of the same sample in all cases show consistent age results within the Poisson error; thus weighted mean ages were calculated for these samples.

The consistency of repeated determinations, as well as the monotonic decrease in measured age upward through each stratigraphic section, provides confidence that these ages give a good estimate for the time of eruption and deposition of the volcanic products. This confidence is also supported by (a) agreement between the fission-track ages and biostratigraphic order (Fig. 6) and (b) agreement on the age of the Baba Tuff (sample code: TA 1) between a fission-track age of 11.4±0.5 Ma given in this study and a K-Ar biotite age of 11.6±0.4



*1 After Okada and Bukry (1980)
*2 After Martini (1971)
*3 After Blow (1969)

Fig. 5. Magneto-biochronologic scales for the Middle and Late Miocene. The numerical scale of polarity history and the Anomaly 5-Chron 11 model follow Berggren *et al.* (1985), except for the chron nomenclature, which is after Opdyke (1972). The Anomaly 5-Chron 9 model is a modification of the Anomaly 5-Chron 11 model.

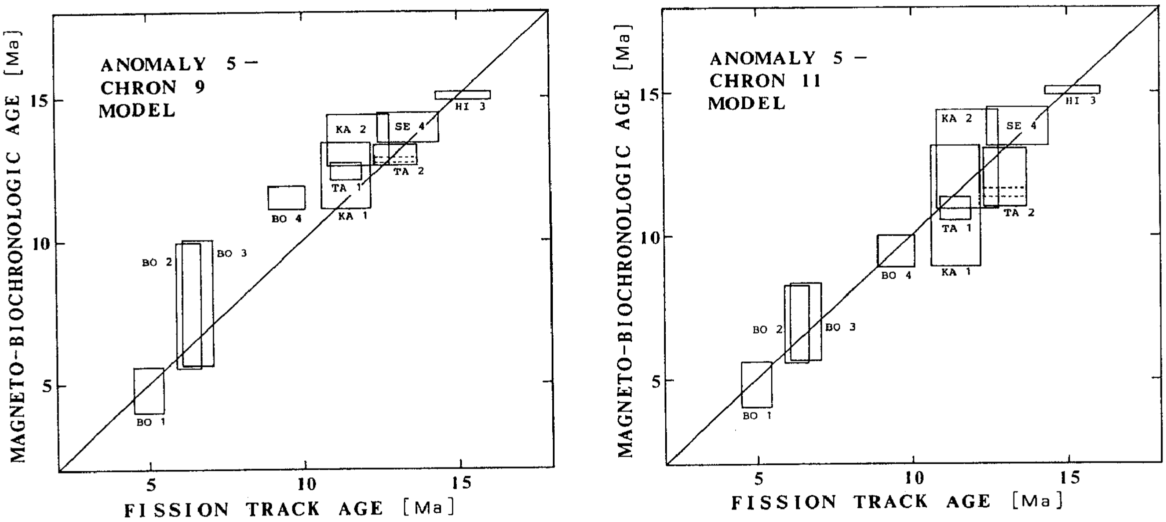


Fig. 6. Fission-track ages plotted against magneto-biochronologic age constraints. For TA 2, solid and broken lines represent biostratigraphic controls based on calcareous nannoplankton and planktonic foraminifera, respectively. The fit of the plotted data to the diagonal line in the Anomaly 5-Chron 11 model is better than that in the Anomaly 5-Chron 9 model.

Ma given by Shibata *et al.* (1979).

The data selection using the Galbraith's χ^2-test validiates Poisson error estimation. Several data, which were not adopted in this study, were rejected by the χ^2-test. The author infers that this disqualification is mainly due to the contamination of detrital zircons in the samples, because these samples tend to provide anomalously old ages.

D. Anomaly 5 correlation

Berggren *et al.* (1985) presented a magneto-biochronologic scale based on the Anomaly 5-Chron 11 correlation model. A Middle and Late Miocene segment of their scale, together with a scale based on the Anomaly 5-Chron 9 correlation model, is shown in Fig. 5; the latter scale is similar to the one proposed by Ryan *et al.* (1974). The two scales in Fig. 5 differ only in the Anomaly-Chron correlation.

We can estimate from Fig. 5 the numerical ages of a given datum level through the two correlation models. Relations between the fission-track ages (Table 5) and the magneto-biochronologic ages (derived from Table 2 and Fig. 5) for the two models are shown in Fig. 6. Though the magneto-biochronologic ages of 10 to 13 Ma are rather older than the fission-track ages in the Anomaly 5-Chron 9 model, the plotted data fit well to the diagonal line in the Anomaly 5-Chron 11 model. Therefore, the Anomaly 5-Chron 11 correlation is preferable.

Magneto-biochronologic scales are primarily constructed in low latitudes. The fission-track ages were not directly compared with magnetostratigraphy in this study. Therefore, the choice of the Anomaly-Chron correlation models depends on the assumption that each biostratigraphic datum level adopted in this study is synchronous between low latitudes and Japan. This assumption is supported by the stratigraphic consistency of the datum levels between the two regions. Close scrutinies (e.g. Johnson and Nigrini, 1985), however, have found significant non-synchroneities for numerous microfossil datum levels within and between latitudinal zones. The above-mentioned assumption, therefore, needs to be cross checked by magnetostratigraphic correlation in future.

The numerical polarity time-scale in Fig. 5 is based on a marine magnetic reversal sequence controlled by isotopic ages (Berggren *et al.*, 1985). The reason for adopting this time-scale here is that it is based on the most reliable calibration points available at present. McDougall *et al.* (1984) proposed a polarity time-scale that significantly differs from the Berggren *et al.*'s in numerical ages of anomaly boundaries ; e.g., the age of the older boundary of Anomaly 5 is 11.1 Ma in the former scale, whereas 10.4 Ma in the latter. The Anomaly 5-Chron 11 correlation is still preferable, however, even if we adopt the McDougall *et al.*'s time-scale.

Datum levels may be directly connected to magnetic anomalies in future, by accumulating biostratigraphic data of sediments directly upon sea-floor basement basalt. If that work is established, the fission-track chronology now presented will then contribute to the selection of the alternative magnetic anomaly time-scales.

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