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Fission Track Dating and Paleomagnetic Study of the Cenozoic Continental Deposits at Salla, Bolivian Andes

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INTRODUCTION

One of the most important fauna of South American extinct vertebrates occurs in continental deposits of the Salla-Luribay basin, located about 70 km southeast of La Paz, Bolivia (Fig. 1). This fauna is famous for containing *Branisella*, the oldest primate fossil known from South America. The Salla fauna has been accepted as correlative with the Deseadan of the South American land mammal age (Hoffstetter, 1968). Based on K-Ar dating of the type section in south Argentine, the Deseadan is assumed the lower Oligocene (Marshall et al., 1977). Direct age assignment of the Salla fauna, however, has been uncertain. In this paper, we

Fig. 1 Index map.

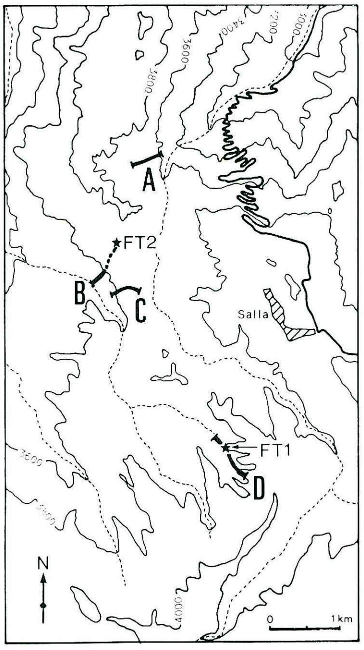

Fig. 2 Map showing sampling localities for fission track dating and paleomagnetism in Salla area.

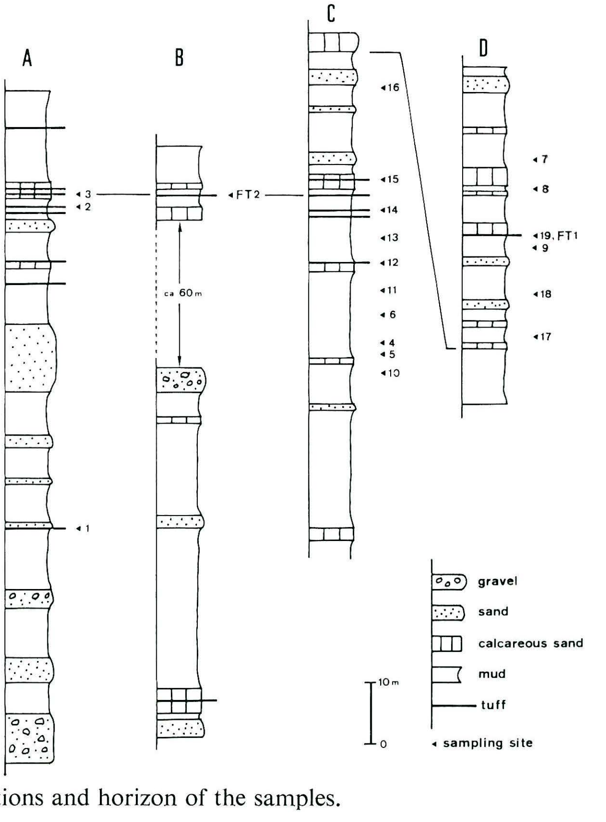

Fig. 3 Columnar sections and horizon of the samples.

present the first contribution on absolute age estimation of the fauna based on fission track dating and paleomagnetism of the deposits in the Salla area.

GEOLOGICAL SETTING AND SAMPLING

The Salla-Luribay basin is a typical place where the Tertiary sedimentary debris piling up in the Altiplano are well exposed. In the valleys west of Salla, an observable sequence is more than 500 m thick, consisting of fossiliferous mudstones of red color, grey to white sandstones and gravels. Some sections contain tuff layers, most of which are composed of fine volcanic ashes. The volcanic ashes intercalated in mud layers appear primary air-falls. Secondarily reworked volcanic materials were observed in some sandstones or gravel beds. It is suggested that the sediments in the Salla area were formed in lacustrine, swamp, or fluvial condition. The area was presumably in tropical forests on lowlands, which might be preferred by primates, in the Paleogene time. Then it was elevated to the present hight of the Altiplano, about 3500 to 4000 m above the sea level, involved in the Andean orogeny (James, 1971). Nevertheless, structural attitude of the strata around Salla is rather simple. The sediments are nearly horizontal in most parts except for some zones close to faults.

Samples for fission track dating and paleomagnetic study were collected at four localities shown in Fig. 2. At each locality, the stratigraphic section was measured. The columnar sections and horizons of the samples are shown in Fig. 3. These sections are correlated each other by using characteristic key beds, that is, tuff layers or calcareous sandstones. This correlation seems undoubted because the strata are almost continuously cropped out over the surveyed area.

FISSION TRACK DATING

Fission track dating was carried out cn two tuff beds; the upper tuff were collected at locality D (Sample name: FT1), and the lower one, which is continuously traceable almost through the surveyed area, was collected at locality D (FT2). From each tuff layer, a bulk ash sample of about 2.5 kg was obtained. Because the tuff layers are intercalated in muds, composed of fine volcanic ash, and characterized by a massive non-laminated lithology, it seems evident that these units were originated from air-fall and then accumulated in still water. Most of zircon crystals extracted from both of the bulk samples had euhedral shapes and unworn surfaces. This fact suggests that these zircons were not secondarily reworked grains but primary crystals simultaneously formed with the volcanic ashes.

The dating was carried out by T. Danhara of Kyoto Fission-Track Ltd., following the single grain (grain by grain) and re-etch method on external surfaces of zircons. This method was described in detail by Tokuhashi et al. (1983). A population of zircons was first mounted in a polyhexafluoroethylene (PFE) sheet with an external surface of crystals exposed. The zircons were etched in a vapor of 48% HF and concentrated H_2SO_4 at at 220°C. Thermal neutron irradiation was made with the TRIGA II reactor at Musashi Institute of Technology. The neutron dose was measured with NBS glass SRM612 and an external detector of muscovite. Spontaneous and induced fission tracks were counted on the same surface of single zircons.

Individual grain ages were obtained for 33 zircons from the sample FT1 and for 36 zircons from FT2. Experimental data and results are shown in Table 1 and 2. The fission track ages

Table 1a. Result of fission track dating of zircons (1).

Sample name: FT1
Locality D, Salla, Bolivia
Analyst: T. Danhara

Grain number	Spontaneous tracks	Induced tracks	Age (Ma)
1	46	37	34.8
2	163	93	48.0
3	98	53	51.7
4	78	35	62.3
5	30	22	38.1
6	49	31	44.2
7	158	103	42.9
8	47	18	73.0
9	48	29	46.3
10	62	45	38.5
11	24	14	47.9
12	48	25	53.7
13	100	40	69.9
14	41	20	57.3
15	82	56	40.9
16	37	15	68.9
17	96	91	29.5
18	20	13	43.0
19	74	49	42.2
20	120	54	62.1
21	157	68	64.5
22	77	36	59.8
23	34	20	47.5
24	128	90	39.8
25	290	85	95.4
26	127	37	95.9
27	49	25	54.8
28	55	33	46.6
29	59	30	55.0
30	26	9	80.8
31	149	52	80.0
32	17	7	67.9
33	41	25	45.8
Total	2630	1362	

Age based on total number of counted tracks: 54.0 Ma
Error in age (2s): 2.6 Ma
Spontaneous-fission decay constant for U^{238}: 7.03×10^{-17}/yr
Neutron dose: $4.69\times10^{14}/cm^2$

calculated by the analytical procedure of Naeser et al. (1979) are: 54.0±2.6 Ma for FT1, and 52.0±2.1 Ma for FT2.

PALEOMAGNETISM

Samples for magnetic measurements were collected from red mudstones or tuff layers at 19 sites (Fig. 3). At each site, three samples were obtained with independent orientation using a magnetic compass. An effort was made to excavate outcrops to obtain fresh material, because most cliffs were deeply weathered. Tilt of the strata was measured on each outcrop.

The samples were cut into 2 cm cubes and mounted in plastic cases in the laboratory. Some samples, however, were so fragile that they were broken during transportation or sample preparation. Natural remanent magnetization (NRM) of the samples were measured with

Table 1b. Result of fission track dating of zircons (2).

Sample name: FT2
Locality B, Salla, Bolivia
Analyst: T. Danhara

Grain number	Spontaneous tracks	Induced tracks	Age (Ma)
1	49	22	62.2
2	38	18	59.0
3	76	33	64.3
4	49	45	30.4
5	160	65	68.8
6	30	16	52.4
7	36	15	67.0
8	109	39	78.1
9	60	34	49.3
10	23	14	45.9
11	53	21	70.5
12	20	7	79.9
13	23	13	49.5
14	91	37	68.7
15	59	24	68.7
16	57	43	37.1
17	54	26	58.1
18	18	11	45.7
19	69	19	102
20	28	16	48.9
21	37	32	32.3
22	63	20	88.1
23	44	23	53.5
24	48	34	39.5
25	49	48	28.5
26	114	90	35.4
27	16	9	49.7
28	26	11	66.1
29	33	13	71.0
30	47	28	46.9
31	40	20	55.9
32	46	38	33.8
33	18	17	29.6
34	19	20	26.6
35	37	16	64.6
36	30	14	59.9
Total	1769	951	

Age based on total number of counted tracks: 52.0 Ma
Error in age (2s): 2.1 Ma
Spontaneous-fission decay constant for U^{238}: 7.03×10^{-17}/yr
Neutron dose: $4.69 \times 10^{14}/cm^2$

a cryogenic magnetometer (ScT, C-112) at Kyoto University. Stability of the NRM was examined through experiments of alternating field (AF) and thermal demagnetization.

Fig. 4 shows typical magnetic behavior of pilot specimens during progressive AF and thermal demagnetizations. As shown in the figure, magnetic vectors are linearly depressed toward the origin in response to the progressive demagnetization. Significant changes of magnetic directions were not observed in both of AF and thermal experiments. The thermal demagnetization revealed that NRM of these specimens mainly consist of two components probably carried by titanomagnetite and hematite. The two components, however, seem to have the same magnetic direction. Because this direction was also inseparable with that ob-

Table 2. Summary of fisssion track results from Salla.

Sample Code	Mineral	ρ_s tracks/cm²	tracks	ρ_i tracks/cm²	tracks	Φ neutrons/cm²	tracks	T Myr	±2s Myr	Number of grains	s* %	U ppm
F T 1	Zircon	1.39×10^6	2630	0.721×10^6	1362	4.69×10^{14}	1095	54.0	2.6	33	2.2	77
F T 2	Zircon	1.09×10^6	1769	0.583×10^6	951	4.69×10^{14}	1095	52.0	2.1	36	2.6	62

$*s/100 = [\{\sum(Ni-\overline{Ni})^2\}/n\,(n-1)]^{1/2}/\overline{Ni}$

Table 3. Paleomagnetic results from Salla area.

Site	Locality	Dm	Im	N	A95	k	P	PHI	LMD
8	D	95.9	65.6	2	31.4	65.3	I	−16.3	−23.4
9	D	−16.6	−20.4	2	36.9	48.0	N	72.6	−137.3
14	C	−9.6	−37.6	3	14.3	75.5	N	80.1	177.8
12	C	−30.1	−54.3	3	21.7	33.5	N	57.9	163.2
6	C	149.1	34.0	3	34.9	13.5	R	−60.6	14.8
4	C	−135.6	18.9	3	22.2	31.8	I	−46.3	198.5
5	C	−27.9	−41.9	3	17.5	50.7	N	63.0	−177.3
10	C	143.8	23.4	2	29.9	71.7	R	−54.7	25.5
3	A	−42.6	−48.2	2	10.8	535.6	N	49.5	177.3
2	A	−19.2	−36.2	2	7.0	1275.3	N	71.6	−170.5

Dm and Im: mean declination and inclination in degree
N: number of specimens
A95: radius of 95% confidence circle
k: precision parameter (Fisher, 1953)
P: polarity (N: normal, R: reversed, I: intermediate)
PHI and LMD: latitude and longitude of VGP position
Mean direction of seven sites (9, 14, 12, 6, 5, 10, 3):
Dm = −27.2, Im = −42.9, A95 = 12.1, k = 25.8, R = 6.76714.

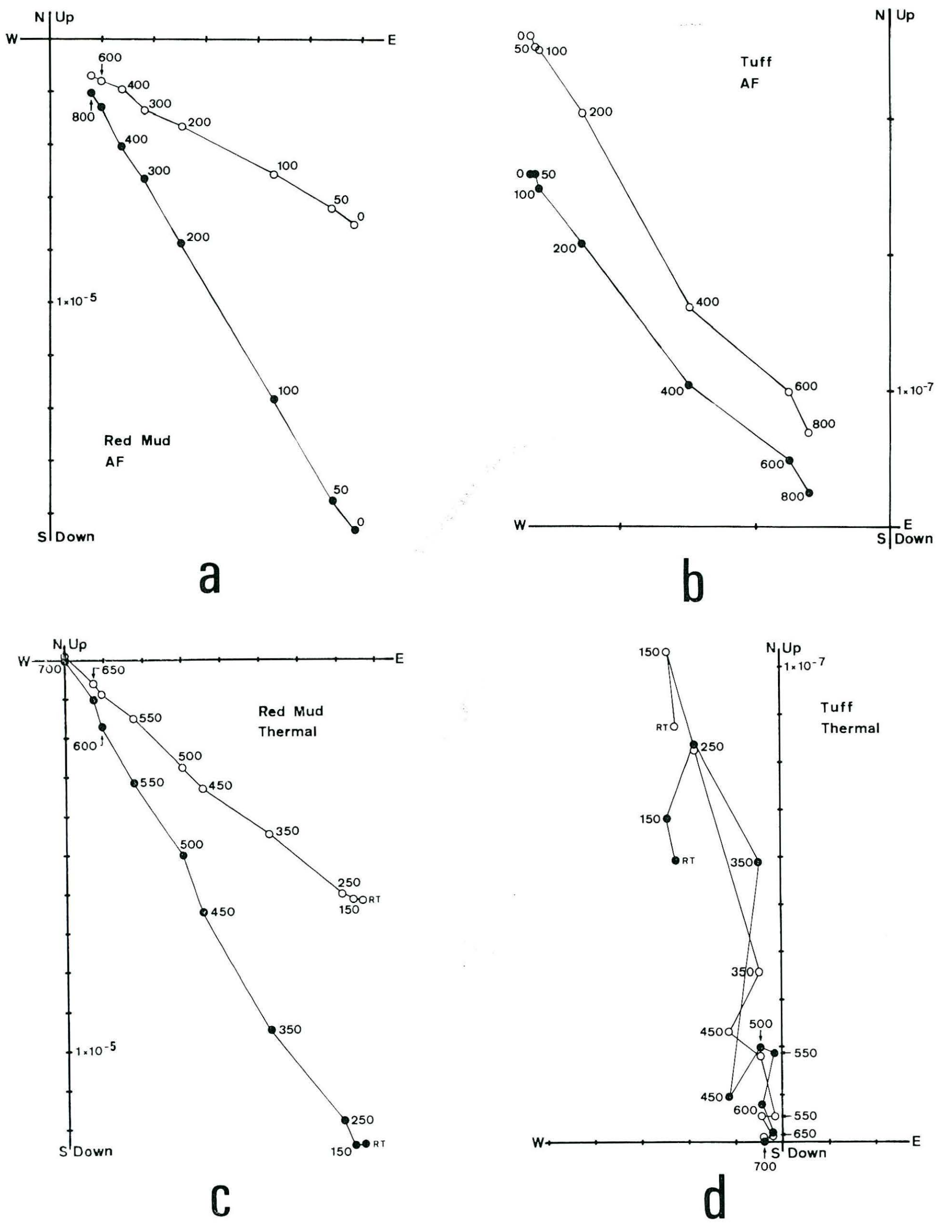

Fig. 4 Behavior of remanent magnetization during progressive AF (a, b) and thermal (c, d) demagnetization.

served after AF demagnetization, other samples were routinely demagnetized in peak AF of 100 Oe.

As represented in Table 3, mean magnetic directions were obtained just for 10 sites. For other sites, available samples numbered less than 2, or they showed highly dispersed magnetic directions. The site mean directions, shown on an equal-area plot in Fig. 5a, are classified into the normal and reversed polarity, while two sites appear to be magnetized in intermediate

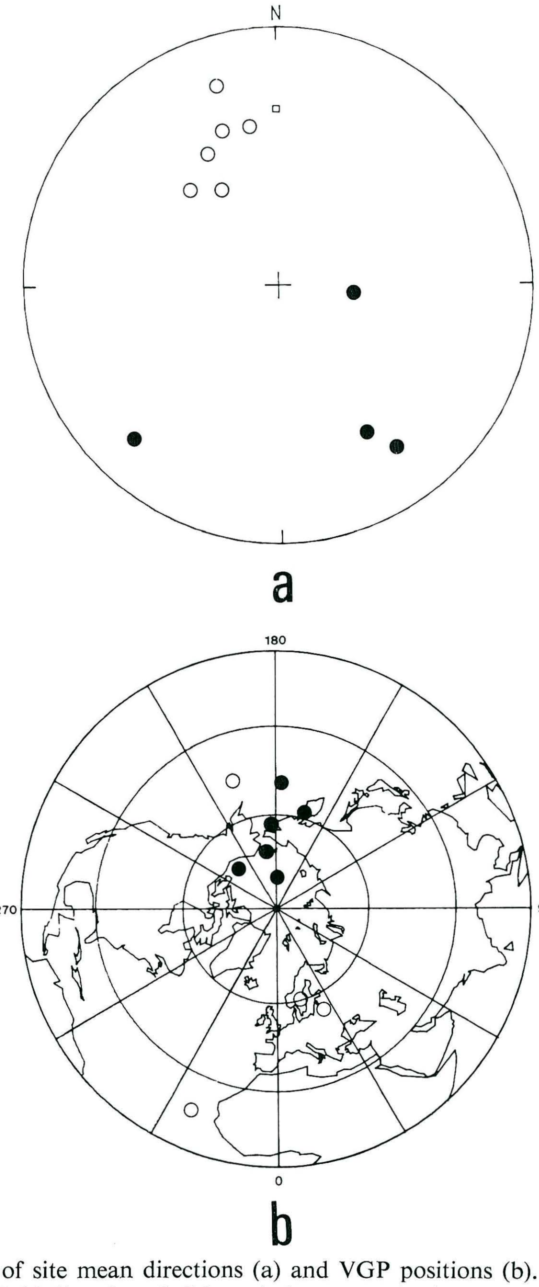

Fig. 5 Equal-area plot of site mean directions (a) and VGP positions (b). The square shows the geocentric axial dipole field direction. Solid symbols are on the lower (northern) hemisphere, and opeo symbols on the upper(southern) hemisphere.

directions. It should be noted that the magnetizations in both normal and reversed polarity showed declination shift of about 25° in a counterclockwise sense relative to the present north. Consequently, virtual geomagnetic poles (VGP's) are plotted away from the present geographic poles (Fig. 5b).

DISCUSSION

Fission track dating on the two tuff layers gave the early Eocene ages, 52 Ma and 54 Ma. The dated zircon grains seemed to be essential crystals of the ashes, and the two tuffs provided almost concordant ages. These facts suggest that the fission track dates are acceptable as the age of the volcanism and subsequent deposition. Thus, the deposits in the Salla area is suggested much older than the age accepted for the Deseadan, to which the Salla fauna was correlated (Hoffstetter, 1968).

Absolute age of the Deseadan was estimated by Marshall et al. (1977), based on K-Ar dating of the Patagonian type section in south Argentina. Their K-Ar dating, however, was concentrated on basaltic rocks overlying the Deseadan horizons, and therefore they proposed the Oligocene age, 34 Ma, as a terminal date of the Deseadan. Consequently, it may be possible that the type Deseadan spans from Eocene to the Oligocene.

Paleomagnetic polarity data obtained in the present study is not enough to define magnetostratigraphic zonation in the Salla area. The reason is that a good many of the paleomagnetic sites were discarded mainly due to sample disintegration. It can be seen, however, that the surveyed sections has recorded magnetic reversals on at least three, or possibly on four horizons (Fig. 6). Based on the results of fission track dating, the normally magnetized horizons are suggested correlative to some of the normal polarity intervals known as Anomaly 23 and 24 (53.6–51.7 Ma; Lowrie and Alvarez, 1981). The demagnetization tests revealed that the sediments in the Salla area have fairly stable remanent magnetization. Therefore, it is expected that further paleomagnetic sampling over the entire section in the Salla-Luribay basin will establish magnetic polarity zonation and its correlation to the polarity time scale.

Besides the magnetostratigraphic purpose, the present paleomagnetic data serves as a tec-

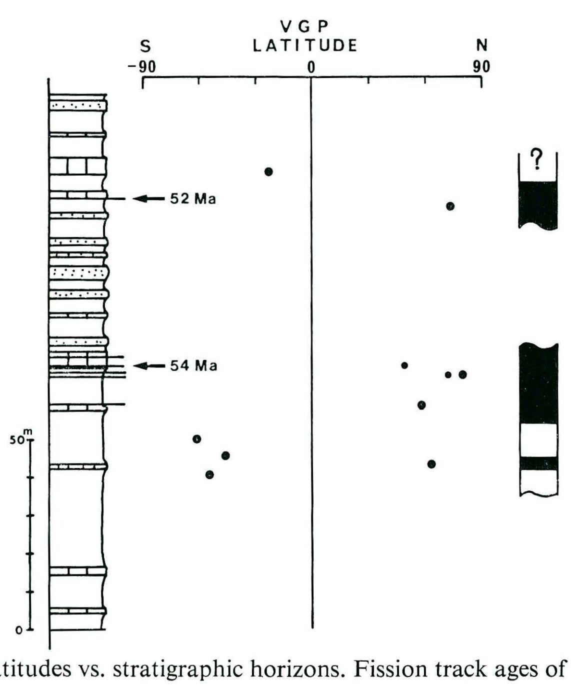

Fig. 6 Plot of VGP latitudes vs. stratigraphic horizons. Fission track ages of two tuff layers are also shown.

tonic indicator. As mentioned before, magnetic directions of the five normal and two reversed horizons are deflected counterclockwise about 25°. The mean inclination of the seven sites (horizons) is −42°, which is not significantly different from that of the axial dipole field at the present latitude of Salla (I = −31° at 17°S). In comparison with the standard apparent polar wonder path (APWP) of stable South America (Vilas, 1981), this result suggests a counterclockwise rotation about 25° of the sampling area against the stable craton of South America. Recently, Heki et al. (1983) made a systematic paleomagnetic study in the Central Andes, and showed that the Peruvian block was rotated counterclockwise with respect to the stable part of South America including the Andes in Chile. Thus, they confirmed that the Arica deflection, a sudden change of the trend of the coastline and mountain chains near the Peru-Chile border (Fig. 1), was caused by an oroclinal bendng. The paleomagnetic data from Salla suggests that the sampling area was a part of the Peruvian block, and that the bending occurred later than about 50 Ma.

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