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PALAEOMAGNETIC STRATIGRAPHY OF PLIOCENE CONTINENTAL DEPOSITS OF THE BOLIVIAN ALTIPLANO

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Abstract

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Fluvio-lacustrine post-Miocene deposits of the Bolivian Altiplano have been sampled in 400 m of section in the La Paz and Ayo Ayo basins in order to provide a magnetostratigraphic scheme for chronostratigraphic interpretations. Stable characteristic components were isolated after stepwise AF or thermal demagnetizations. The directions of cleaned magnetization were compared to the normal and reverse dipole field directions at the site. The plot of the mean directions calculated for each stratigraphic level define successive magnetozones which can be identified on the standard geomagnetic polarity scale with the help of the K/Ar ages obtained on tuff layers. The deposition of the middle and upper part of the La Paz Formation covers the Gauss epoch. The Gauss/Matuyama (2.48 Ma) and the Gilbert/Gauss (3.4 Ma) limits are located in the top and the middle of the formation. The occurrence of the first glacial/interglacial oscillation can be placed in the early Matuyama (ca 2.2 Ma) in agreement with the oxygen isotopic record from the equatorial ocean.

Introduction

The Altiplano plateau at 4000 m spreads between the Western and the Eastern cordillera of the Andes. The La Paz basin (Bolivia) situated at 16°30'S, 68°W (Fig.1) was cut in the Altiplano by a regressive erosional phase during the Late Pleistocene related to the setting of the upper hydrologic basin of the Amazon. First reported by Troll and Finterwalter (1935), the lacustrine, fluvial and glacial deposits were described in detail by Dobrovolny (1962). The stratigraphy was recently reinterpreted by Servant (1977) and Ballivián et al. (1978).

The first chronological data obtained on the post-Miocene deposits (5.5 Ma) results from K/Ar analyses on a tuff layer (Toba Umala) underlying the deposits in the Umala and Ayo Ayo basins, 100 km south from La Paz (Evernden et al., 1977). This can be considered as a maximum age since remains of Pliocene mammals were discovered at Ayo Ayo, in the lower part of the Umala Formation, correlatable to the La Paz Formation (Hoffstetter, 1971), and at La Paz in the lower part of the La Paz formation (Villarroel, 1978). The K/Ar age was recently confirmed on a correlatable tuff layer near the base of the La Paz Formation called Toba Cota Cota: the age given by Servant et al. (1988) is 5.5 ± 0.02 Ma.

Stratigraphy and recent chronological data

The lower sequence (La Paz Formation sensu stricto) is more than 500 m thick, and can be

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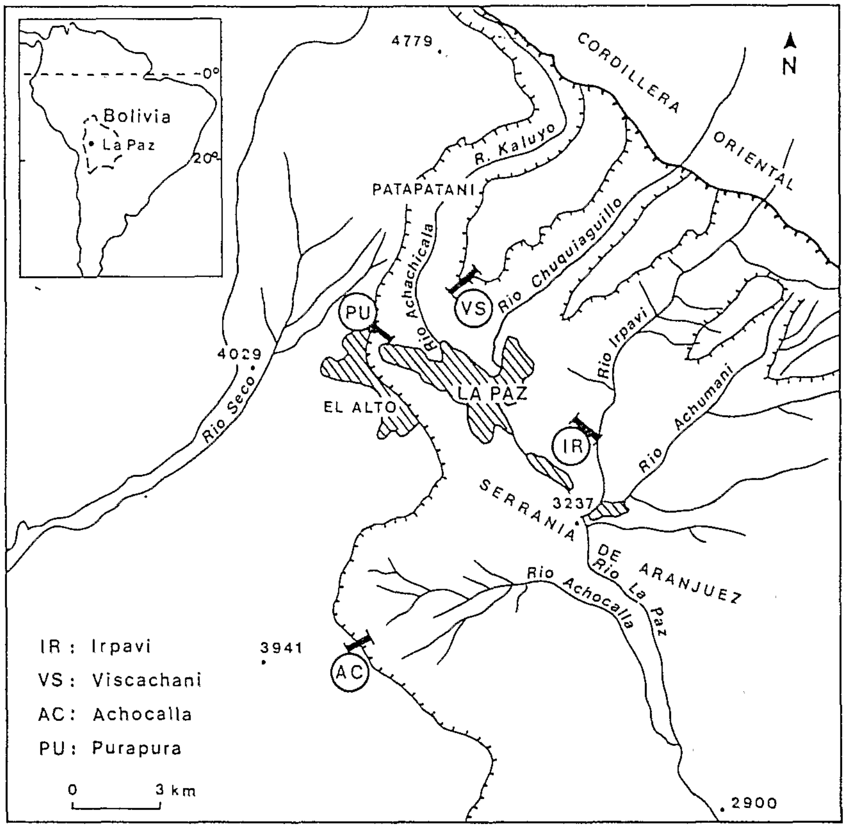

Fig.1. Geographical situation of the La Paz Basin and sampling localities.

described at successive outcrops (Figs.2 and 6). It consists of lacustrine silty and clayey beds interlayered with fluvio-lacustrine sandy and gravelly layers. The sediments are grey, often lightly coloured in yellow (silts) or green (clays). Some clayey levels are brightly coloured (red, white or black).

In the upper part of this sequence, a white bed (2–12 m thick) was recognized as a tuff (Toba Chijini, sometimes presenting an ignimbritic facies), which was formerly reported as overlying the La Paz Formation (Dobrovolny, 1962) but can clearly be observed as interbedded in the upper part of it. After unsuccessfull K/Ar dating attempts (ages ranging from 0.5 to 11 Ma), two coherent ages were finally obtained by K/Ar analyses on biotite by MacIntyre (quoted in Clapperton, 1979): 3.27 ± 0.14 and 3.28 ± 0.13 Ma. Other ages now available are 2.8 ± 0.1 Ma at Ayo Ayo and 2.8 ± 0.1 at La Paz (Lavenu et al., 1988).

Above the Chijini tuff, the La Paz Formation is enriched with conglomeratic units. The upper part of the formation is affected by a major discontinuity (erosional phase) overlain by fluvio-glacial or glacial deposits: till (50–100 m thick) of the Calvario glaciation on which lies a thick (100–200 m) interglacial conglomeratic bed (Purapurāni Formation). A second tuff layer (Toba Sopari) can be observed in the upper valley of the Rio Kaluyo (North from La Paz) interlayered between the Calvario till and the Purapurani conglomerates. Dobřovolny (1962) did not differentiate this tuff from the Chijini tuff and considered the lowest till older than the Chijini tuff but he noted that in other sections of the basin, the Chijini tuff directly overlies the La Paz Formation. Clapperton (1979) also claimed to have

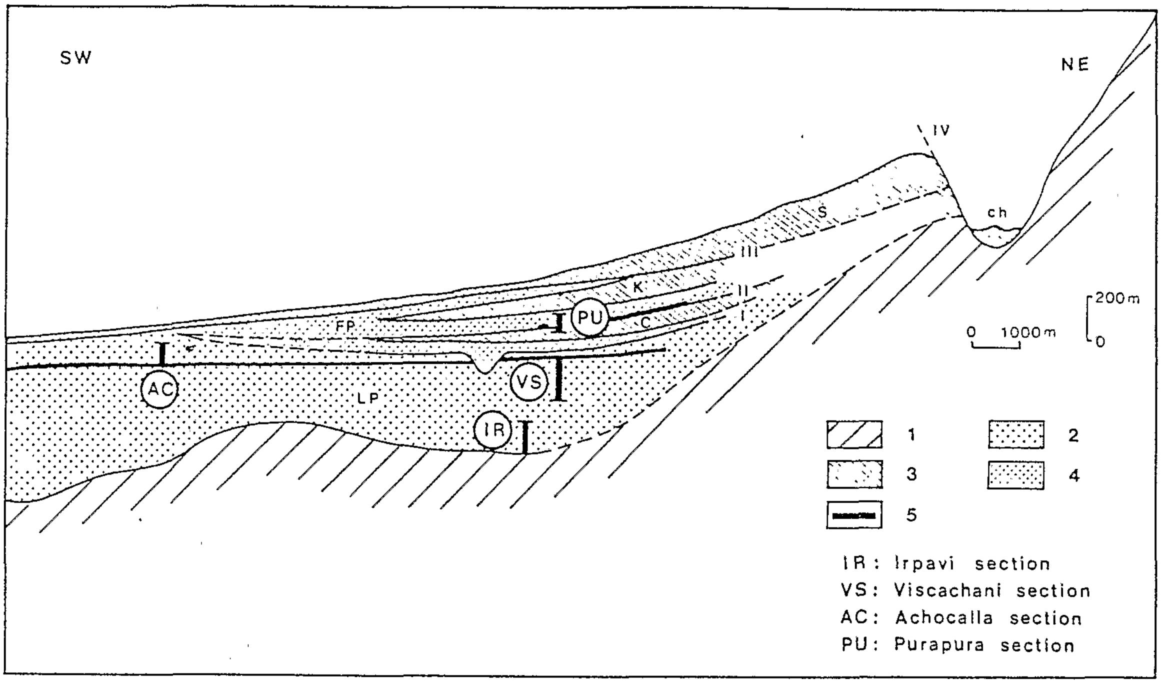

Fig.2. Summary stratigraphy of the post-Miocene deposits of the La Paz basin. *1* = Paleozoic or Cretaceous basement. *2* = La Paz formation s.s. *3* = Tills. *4* = interglacial conglomerates. *5* = tuff layers. *LP* = La Paz. *C* = Calvario. *FP* = Purapurani formation. *K* = Kaluyo. *S* = Sorata. *Ch* = Choqueyapu. *I–IV* design the erosional phases.

observed glacial deposits below the Chijini tuff. Following stratigraphical arguments and using the ages provided by McIntyre in Clapperton (1979) Clapperton dated this glacial phase prior to 3.2 Ma. However, Clapperton did not present any precise description or stratigraphic log to support his arguments. All the clear and complete sections of the Basin clearly show that the Chijini Tuff not only overlies the La Paz formation, but is interlayered in its upper part (note that Clapperton's new section is situated between the Capellani section and the Viscachani section of Ballivian et al., 1978) This problem is further complicated by contradictory K/Ar ages obtained on the Sopari tuff: 2.7 ± 0.1 and 2.8 ± 0.1 Ma (remarkably consistent with the ages of the Chijini tuff) on two samples from the Kaluyo valley and 1.6 ± 0.1 Ma on one sample from the Chuquiaguillo valley. However, the observation of multiple inclusions of granitic materials (pebbles) in the outcrops of the Kaluyo valley suggests that old biotites might have been integrated in the dated samples and so falsify the results. As such inclusions were not observed in the Chuquiaguillo valley, the age obtained from this site might be considered as more reliable than the other two.

Other successive tills can be observed in the upper part of the Kaluyo valley attributed to the Kaluyo, Sorata and Choqeyapu glaciations. These tills are separated by interglacial deposits, erosional phases and palaeosoils.

Magnetostratigraphic study

Magnetostratigraphic investigations of post-Miocene deposits from Bolivia were successfully carried out by MacFadden et al. (1983) on the Quaternary Tarija Formation (south Bolivia). The palaeomagnetic investigations of the La Paz Formation were initiated by Servant in 1981: specimens were tested for the intensity and stability of the remanence at the LGQ. A complete sampling program was carried out in May 1984 on five different sections of the La Paz basin (Figs.2 and 6).

(1) The IRPAVI section (Fig.6a), 120 m thick, comprises the bottom part of the La Paz Formation: 41 levels were sampled. Unfortunately, the link with the middle and upper part of the formation could not be determined until now.

(2) The VISCACHANI section (Fig.6b), about 210 m high, comprises the middle and upper part of the La Paz Formation (Chijini tuff included) and the Calvario till. However, for reasons of accessibility, the levels above the Chijini tuff could not be sampled. Twenty-nine levels were sampled in the 170 m below the tuff.

(3) The levels above the Chijini tuff were sampled in the basin of the Rio Achocalla (tributary to the La Paz basin) (Fig.6c). Twelve levels were sampled in a 80 m section called Achocalla.

(4) Rare and thin clayey layers could be sampled in the Calvario till and in the Purapurani interglacial complex (Pura Pura section, Fig.6d). The scarcity of the subsampled levels is due to the difficulty of finding fine-grained layers and safe sampling sites.

(5) Finally, the upper tuff (Toba Sopari) were sampled in the high valley of the Rio Kaluyo.

As close correlations were shown between the Laz Paz formation at Laz Paz and the Umala formation at Ayo Ayo, a sampling was also carried out on rare suitable layers in the latter: 6 levels were sampled in an 18 m section from clayey and silty layers and one level from the overlying tuff (unnamed); 14 m of unsampled section separate the sampled sedimentary layers from the tuff.

The stratigraphy presented here results from the observations made during the sampling, the description of the sampled levels and the data presented by Balliviàn et al. (1978).

Sampling technique: the magnetic north direction was marked on the horizontal surface of each block. Two or three blocks per level were collected on a total of about 100 levels. In general 4–6 cubes (8 cm^3) were cut for each level with a rotary saw, but a few of the laminated clayey levels only provided one or two specimens each.

Palaeomagnetic analyses

Measurements were made with a Balanced Fluxgate Spinner Magnetometer (Molyneux, 1971) connected to a microcomputer (Tucholka and Tessier, 1987). Natural Remanent Magnetization (NRM) intensities range from 0.5 to 20 mA m^{-1} (1 milliAmpere/meter = 1 microGauss). The highest values (0.25 A m^{-1}) are recorded in the tuff layers. The NRM values are not plotted on the figures because uncleaned remanent magnetizations are not representative; furthermore, characteristic remanent magnetizations were isolated at different thermal steps providing a large and meaningless spectrum of intensity values.

Susceptibility measurements were carried out with a Bartington MS2 meter; the values range from 5 to 200×10^{-5} SI units (Fig.6a–c); the highest values ($> 80 \times 10^{-5}$ SI) have not been recorded in the tuff layers but in the silty and clayey layers of the Irpavi section.

The uncleaned NRM directions seem to be strongly influenced by the present-day field. Viscosity tests (Thellier and Thellier, 1959) were carried out on the levels of the Irpavi section. The specimens (1 per level) were set in a normal field (X north; Z down) for 6 days; the magnetic moment $M1$ was measured; the specimens were then reset in a reverse field (X south; Z up) for 6 days; the moment $M2$ was measured. The rate of viscosity, $(M1 - M2/M1 + M2) \times 100$, varies from 2 to 45% (Fig.6a). As the viscous remanent magnetization acquired on a few million years could be strong enough to hide the characteristic remanent magnetization, stepwise demagnetizations were applied. Twin pilot specimens taken from each level were submitted to alternating field (AF) and/or thermal demagnetization at respectively 5–100 mT or 50–650°C. The AF demagnetization was performed with a Schonstedt GSD −1 demagnetizer. High temperature treatments were made in a furnace protected by a triple magnetic shield: proper cooling was insured by pulsed air circulating in the shielded cooling unit. The median destructive field generally lies between 10 and 50 mT and half of the initial intensity is removed between 150° and 300°. In some levels, less than 10% of the initial intensity remained after heating at 600°C suggesting a small contribution of high blocking temperature minerals. Progressive inductions of isothermal remanent magnetizations (IRM) show that the saturation is nearly acquired after application of a 0.2 T field (Fig.3); the coercivity of remanence ranges from 20 to 35 mT. This suggests the major contribution from pseudosingledomain (1–13 μm) grains of magnetite in the NRM.

Comparative analysis of the orthogonal plots revealed that thermal demagnetization (Fig.4) gives more accurate results than AF. The 300°C step was retained for the routine demagnetization as it insures a sufficient removal of the secondary magnetization and leaves a residual magnetization strong enough to be accurately measured.

The individual directions, retained after treatment, were each compared to directions corresponding to normal and reverse dipole fields at the site (resp. Dec = 360°, Inc = −30°; Dec = 180°, Inc = 30°). As the sedimentation rates could be high enough to allow a record of medium to long period palaeosecular variation, the vectors lying inside a 50° arc around these directions are considered as normal or

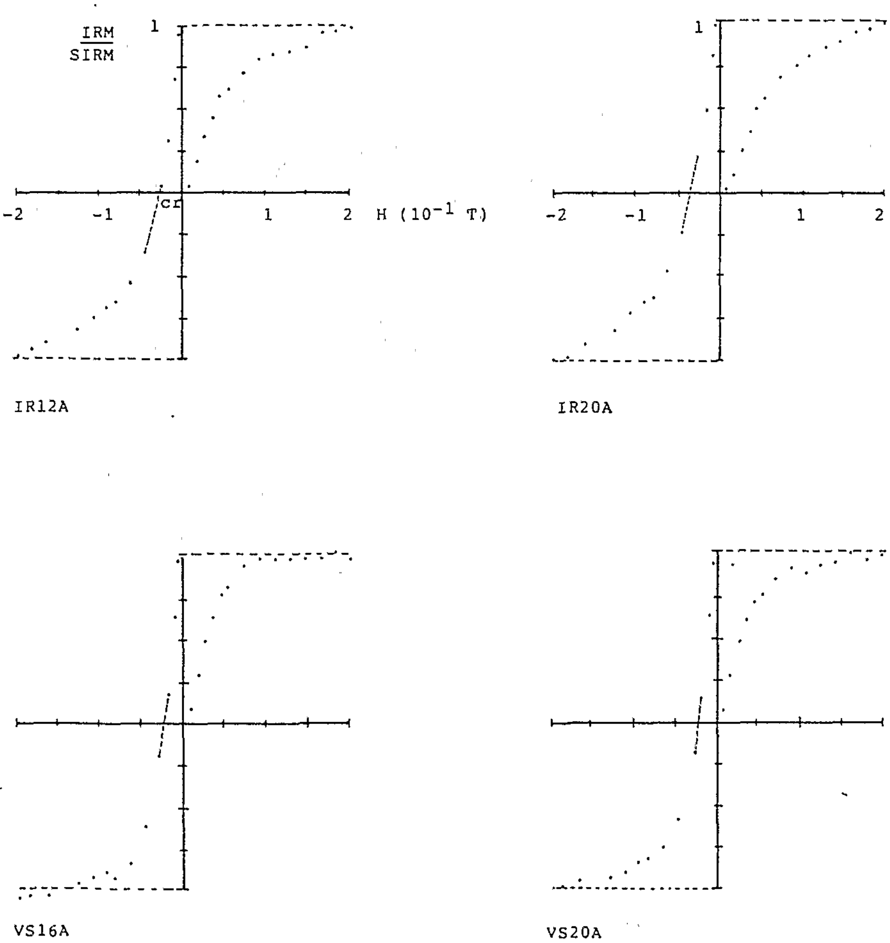

Fig.3. Acquisition of Isothermal Remanent Magnetization and back field *IRM* (−0.2 to 0.2 T). The saturation magnetization *SIRM* is not reached for specimens *IR12A* and *IR20A* but is completely acquired before 0.2 T for specimens *VS16A* and *VS20A*. The coercivity of remanence (*cr*) ranges around 25, 30 mT.

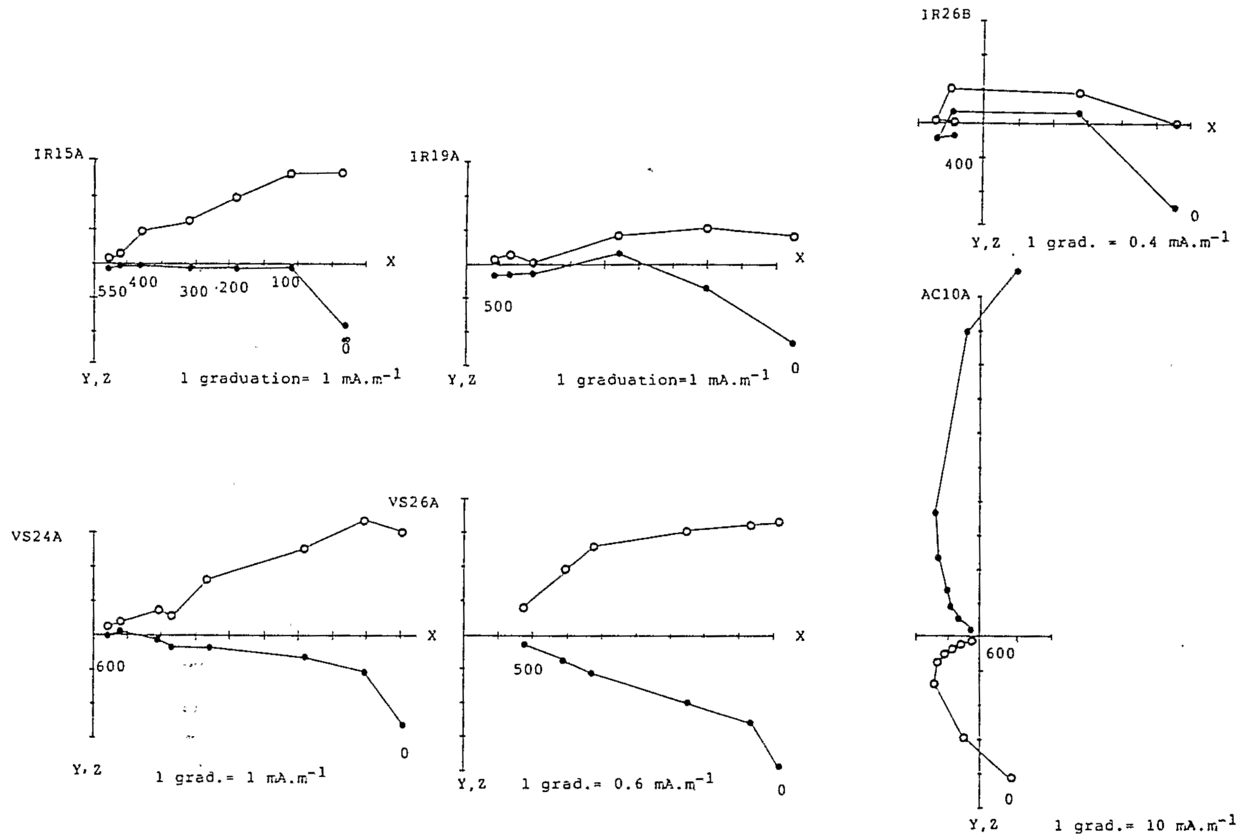

Fig.4. Orthogonal projection of the magnetic vectors during thermal demagnetization. The thermal steps are indicated in °C. For *IR15A*, *IR19A*, *VS24A* and *VS26A* the normal component is stable. For *IR36A* and *AC10A*, the reverse magnetization appears after elimination of spurious normal components (200 to 400°C).

reverse; the directions lying outside this 50° arc are considered as intermediate. When intermediate directions occur from the same level as reverse directions the former are interpreted as due to incomplete removal of the VRM: they are rejected for polarity interpretation.

The cleaned directions are plotted on a stereographic projection (Fig.5) and the statistical parameters are given in Table I for each section. The mean inclinations of the reverse groups do not reach the dipole field inclination (30°) which confirms that, in some cases, small secondary components still persist. It was noted that weak NRM intensity and strong viscosity rates were generally associated with reversed characteristic magnetizations while stronger NRM intensity and weaker viscosity rates were associated with normal characteristic magnetizations. This is explained by the addition of vectors of opposite direction in the first case and of the same direction in the second case.

TABLE I

Statistical parameters for each section

		Dec.(°)	Inc.(°)	N	α 95	K
Irpavi	Normal	0	−26	87	4.1	13.5
	Reverse	179	15	40	7.2	9.2
Viscachani	N	3	−25	29	4.8	15.8
	R	168	13	16	12.9	6.9
Achocalla	N	8	−34	12	12.9	9.0
	R	178	27	20	10.9	7.9
Ayo Ayo	N	15	−48	2		
	R	175	35	16	11.5	10

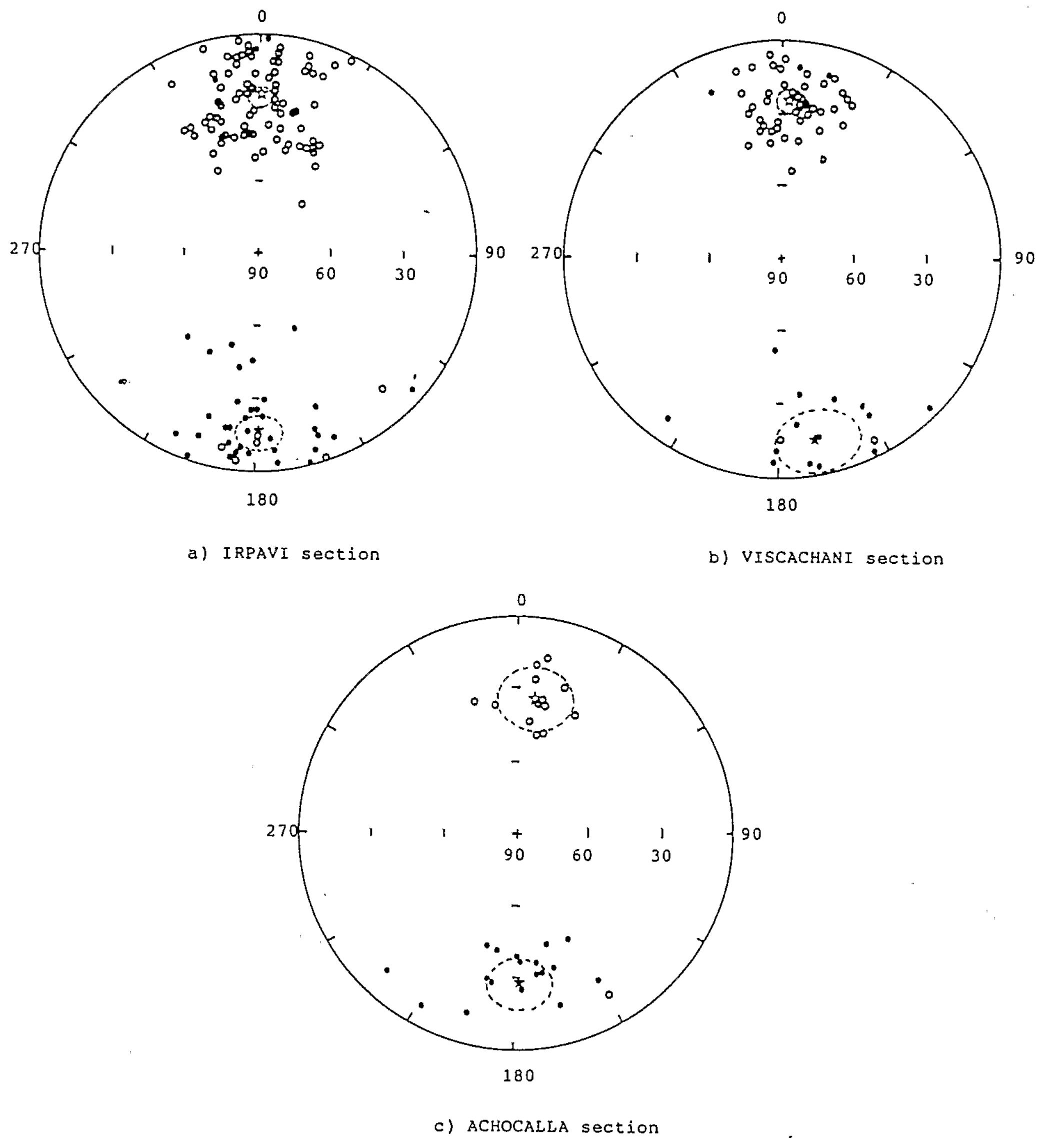

Fig.5. Stereographic projection of the individual vectors after 300°C treatment (the characteristic magnetizations). For each section normal and reverse groups clearly appear. Black dots are vectors pointing downward (positive inclination) and white dots are pointing upward (negative inclination). Stars represent the mean direction of each group, the ellipse drawn around the stars are the projection of the cone of confidence at 95%.

Magnetostratigraphic interpretation

The mean directions, calculated from all the individual cleaned directions retained at each level, are plotted along the stratigraphic logs in Fig.6a–d. The changes in polarity are clearly deduced from the declination record while the sign of the inclination at such a low latitude is affected by the medium to long period palaeosecular variation. The succession of polarity zones is given for each separate stratigraphic section. The limits of the magnetozones are arbitrarily set midway between two sites of opposite polarity. The normal and reverse magnetozones are respectively labelled *N* and *R*, followed by an integer. As the Irpavi section cannot be directly connected with the others, the magnetozones were labelled *I*(Irpa-

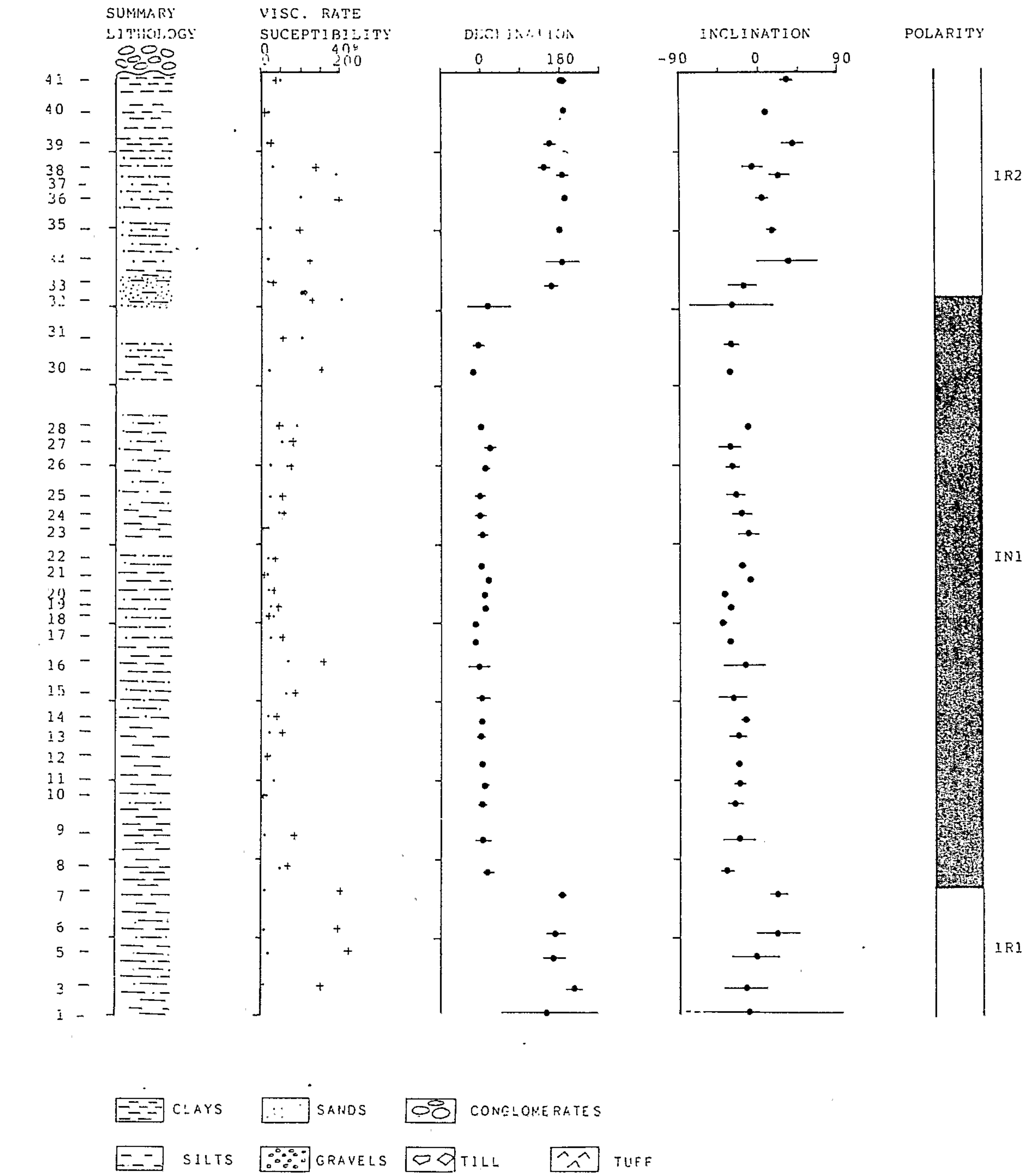

Fig.6a. For explanation see p. 340.

vi) *R* and *IN*. The zone *IR1* is defined in the first 18 m (5 sites), the *IN1* zones extends to 75 m (24 levels); for reason of cohesion of the sediment, site 29 did not provide any reliable specimen and 8 m remain uncovered. Zone *IR2* comprises the upper 30 m of the section (12 sites).

The Viscachani section starts with a reverse

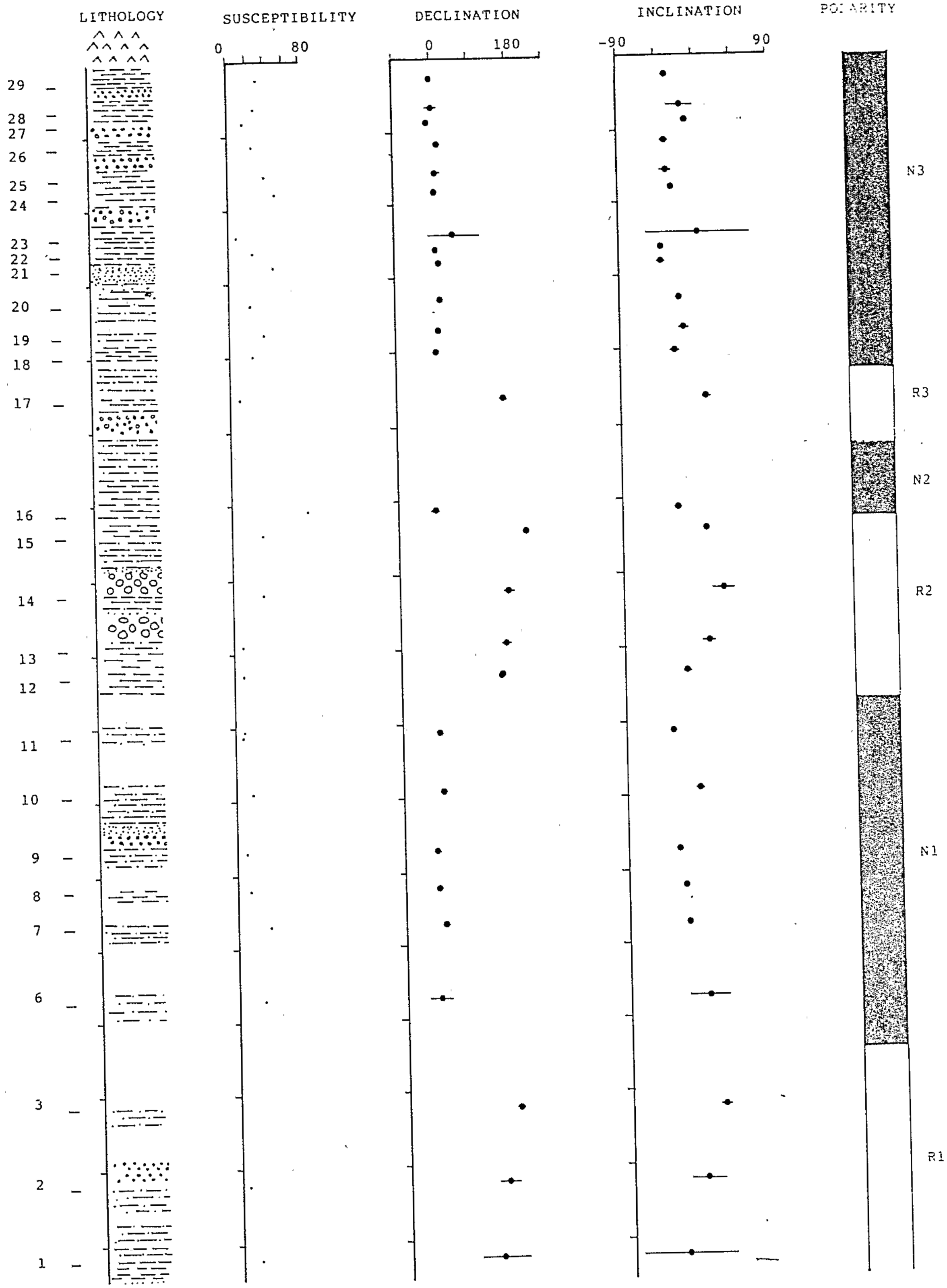

Fig.6b. For explanation see p. 340.

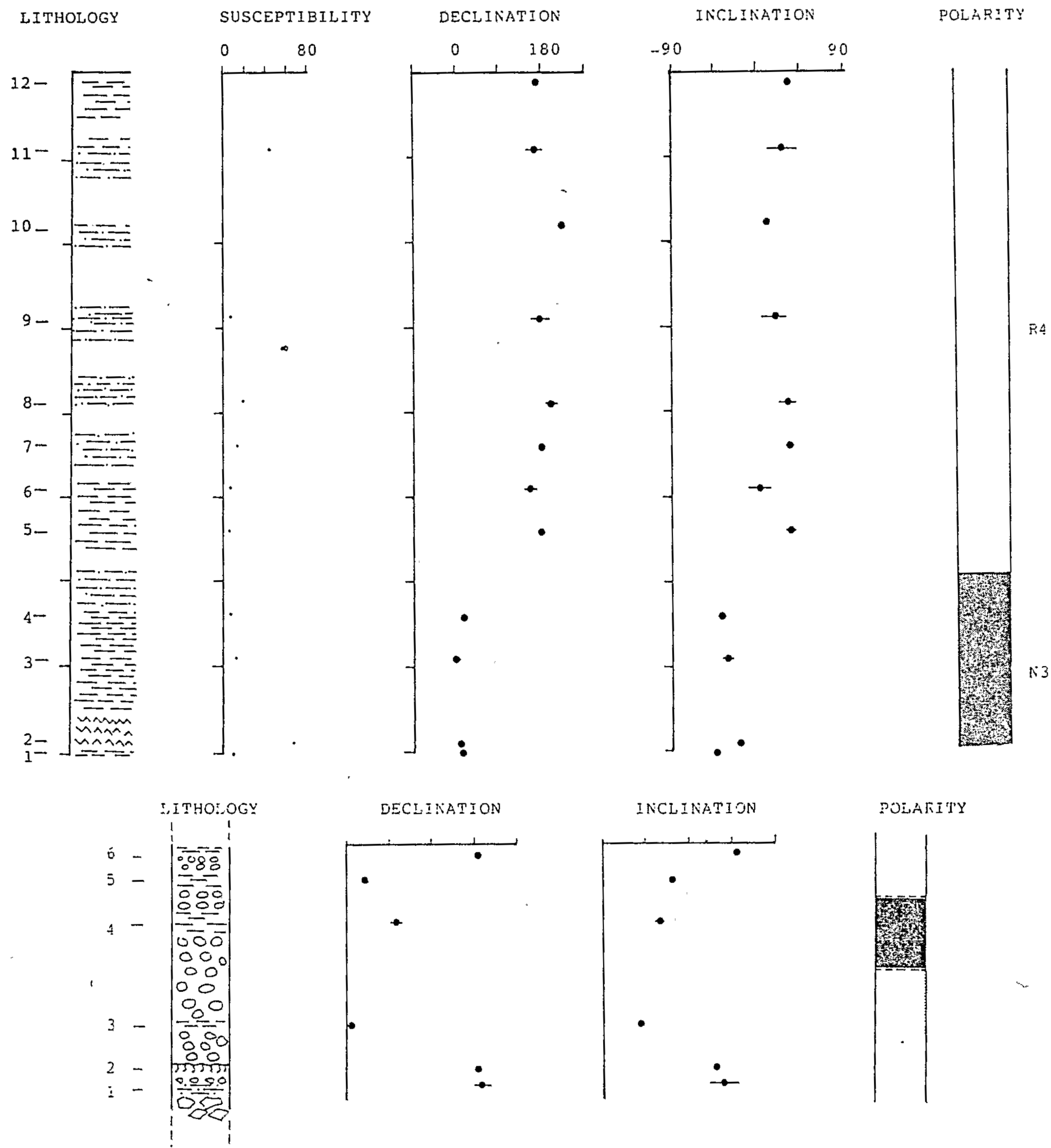

Fig.6. Summary lithology, viscosity rates (if available), susceptibility (SI units) average declination and inclination (degree) at each level; α95 is given by the horizontal bars or integrated in the size of the point. The magnetostratigraphic interpretation is given as a succession of normal (black) and reverse (white) magnetozones. Vertical intervals are 10 m. a. Irpavi section (see p. 338). b. Viscachani section (see p. 339). c. Achocalla section (p. 340, upper). d. Purapura section (p. 340, lower).

zone *R1* (30 m, 3 sites) followed by zone *N1* (50 m, 6 sites). Zone *R2* is defined on 22 m at 4 sites, a thin normal zone *N2* is defined at one site only but the polarity is firmly established by a highly stable normal magnetization on the 3 specimens from two different blocks. Zone *R3* is also defined at 1 site by 3 specimens. The 43 uppermost meters of the section represent a normal polarity zone (*N3*, 11 sites) if we except site 23 which shows a large standard deviation; the weak residual remanence (<0.5 mA m^{-1}) may have been covered by the background noise of the magnetometer.

The sequence sampled on the Viscachani section ends just below the tuff; it is completed on the Achocalla section (Fig.6c): normal polarity zone *N3* covers the Chijini tuff and 20 m above it (2 sites). The polarity scale of the La Paz formation ends with zone *R4*, recorded by 60 m of lacustrine sediments. The fluviatile conglomerates at the top of the formation could not be sampled. In the Calvario till and the Purapurani conglomerates, the sampling was restricted because of the lack of suitable lithologies. One site in the middle of the till carries reversed directions. The 30 m sampled in the interglacial conglomerates (Fig.6d) present a reverse polarity interrupted by a normal polarity recorded on two sites.

Finally, the four specimens of the Sopari tuff (Kaluyo valley) present a very high intensity (2 A m^{-1}), significantly different from the intensity of the Chijini tuff (0.2 A m^{-1}), in spite of identical susceptibility values (ca 100×10^{-6} SI units). The declinations before cleaning are significantly deviated from the normal dipole declination ($D = 300°$). A cleaning at 40 mT was necessary to change the declination to 330°. At this stage, the intensity equals 3% of the initial intensity. It is thus reasonable to conclude that a high secondary magnetization was superimposed on the original one. The position of the sampled tuff section in the Kaluyo valley suggests the possibility of a lightning effect. The paleomagnetic data do not provide an argument to differentiate the two tuff layers.

The six levels sampled from the Umala Formation at Ayo Ayo present a well-defined reversed polarity while the overlying tuff is of normal polarity (directions and statistical parameters are listed in Table I). The faunal arguments tend to associate this reverse magnetization to zone *IR1* of the Irpavi section while the normal polarity of the tuff is in agreement with the normal polarity of the Toba Chijini and/or the Toba Sopari.

Correlation to the standard geomagnetic polarity time scale and chronological implications

Palaeontological arguments and radiometric datings already cited suggest a Pliocene age for the bottom of the lacustrine formation, and a middle Pliocene age 2.7–3.2 Ma for the Chijini tuff, e.g. the upper part of the formation. On this basis, the magnetostratigraphic results of the La Paz formation can be compared to the standard geomagnetic polarity time scale (GPTS) of the last 5 Ma (Mankinen and Dalrymple, 1979). The polarity succession *N1* to *N3* is remarkably identical to that recorded during the Gauss epoch. The *R1*/*N1* boundary can be interpreted as the Gilbert/Gauss boundary (3.4 Ma), magnetozone *R2* and *R3* as the Mammouth (3.05–3.15 Ma) and Kaena (3.01–2.92 Ma) events and the *N3*/*R4* boundary as the Gauss/Matuyama boundary (2.48 Ma). The absence of stratigraphic connection between the Irpavi section and the Viscachani section raises the problem of the identification of the *IR1*, *IN1* and *IR2* magnetozones. The altitudinal situation (165 m below the bottom of the Viscachani section), the palaeontological arguments and the age 5.5 Ma of the tuff underlying the Pliocene fossiliferous deposits of the Umala Formation at Ayo Ayo and La Paz Formation at Cota Cota allow to place this section between 5.2 and 3.4 Ma during the Gilbert epoch.

In Fig.7, the magnetozones are plotted versus their age on the GPTS. The five chronological data respectively assigned to the polarity reversals (*R1*/*N1*, *N1*/*R2*, *N2*/*R2*, *R3*/*N3* and *N3*/*R4*) define five points *A–E*. Stable deposition rates throughout the whole Gauss epoch are suggested by the alignment of the points, in spite of slightly different slopes between *AC* and *CE*. The average value equals 17 cm per thousand years. If extrapolated, the slope of *AC* locate the bottom of the Viscachani section around 3.6 Ma. Such an extrapolation is invalid for the upper part of the formation because of the higher frequency of conglomeratic beds.

By interpolation, the Chijini tuff, located in

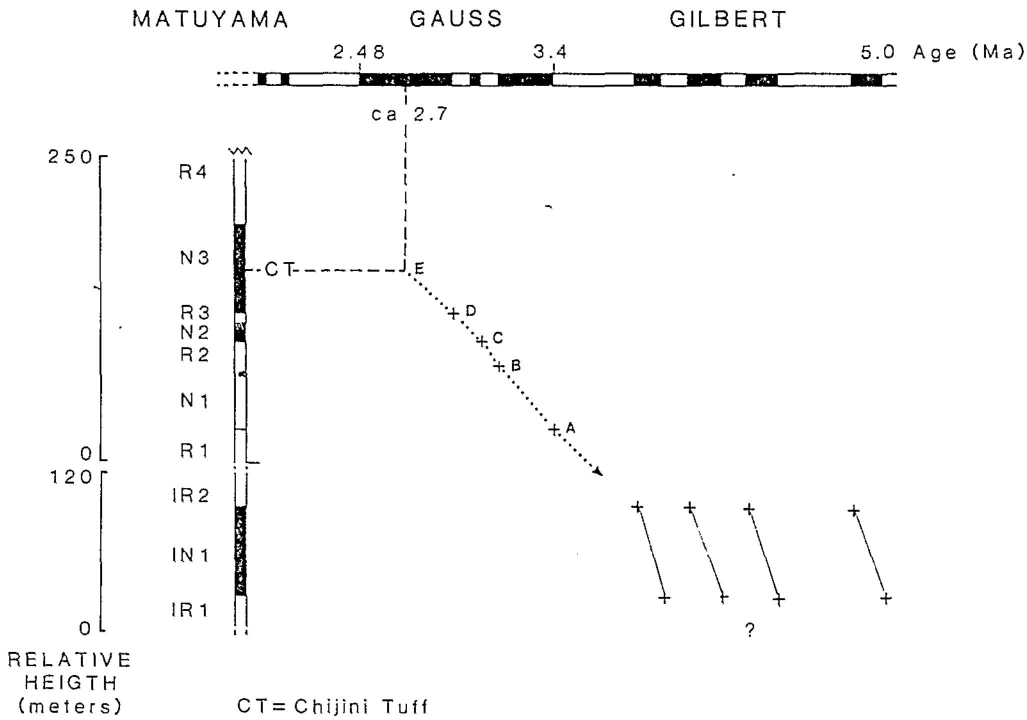

Fig.7. Magnetostratigraphic results (versus height) against the standard Geomagnetic Polarity time scale (Mankinen and Dalrymple, 1979). This representation shows the remarkable constance of the deposition rate across the middle and upper part of the La Paz formation and the high sedimentation rates implied by identification of zone *IN1* to any of the normal events in the Gilbert epoch.

the middle part of zone *N3*, can be dated around 2.7 Ma e.g. not significantly younger than the ages given by Lavenu et al. (1988; ca 2.8 Ma); on the other hand, the ages given by Mac Intyre in Clapperton (1979) (ca 3.27) are 0.7 Ma too old.

The interpretation of the succession of magnetozone *IR1*, *IN1*, *IR2* raises problems because of the lack of connection between the Irpavi and the Viscachani sections. As it is clearly older than the succession *R1* and *R4* and younger than 5 Ma (palaeontological and radiometric arguments), it must be related to part of the Gilbert epoch. Magnetozone *IN1* recorded in 75 m of lacustrine to fluviolacustrine sediments, must be related to one of the normal events in the Gilbert epoch. However, the duration of such events does not exceed about 0.15 Ma; this implies minimum values of deposition rates of ca 50 cm per thousand years e.g. three times higher than the average defined during the Gauss epoch. An alternative hypothesis would consist of an interruption of sedimentation during the reversed period separating two successive normal events.

The reverse polarity of the oldest till (Calvario till) and the Purapurani conglomerates and their position above the La Paz Formation place them in the Matuyama Epoch. The normal event, recorded in a few meters (8–15 m), must be related to one of the normal events in the early Matuyama (Reunion 1, 2 or Olduvai).

We must emphasize that, in our stratigraphic interpretation, the Sopari tuff is located at about the same position as the Purapurani conglomerates (e.g. lying on the Calvario till) and also shows a normal polarity; these two normal polarity levels may be considered as nearly contemporaneous. The possibility that these represent the Olduvai event would be in agreement with the age of ca 1.6 Ma obtained on the tuff.

The major erosional phase which affected the La Paz Formation may have also removed the tracks of eventual high amplitude climatic oscillations preceding the Calvario glacial. Consequently, this till might be related to any cold phase occurring after 2.48 Ma (Gauss/Matuyama limit) and before 1.8 Ma (Olduvai event).

Discussion

Late Neogene climatic variations recorded in the equatorial Pacific Ocean have been reconstructed by oxygen isotope stratigraphy with a time calibration provided by the magnetostratigraphy (Shackleton and Opdyke, 1976, 1977) in two sites (cores V28-239, 3°N—160°E and V28179, 4°N—140°W). These studies present the evidence of high amplitude oscillations of $\delta^{18}O$ during the late Pliocene. The authors interpret these variations of 0.75 and 1‰ as reflecting glacial phases with magnitudes at least 2/3 of the last glaciation of the upper Pleistocene. The $\delta^{18}O$ progressively increases during the whole Gauss epoch and reaches its maximum values after the Gauss/Matuyama boundary. Several maxima are then recorded between the Gauss/Matuyama boundary and the end of the Olduvai event. In an equatorial Atlantic site (DSDP site 397, 26°N—15°W) Shackleton and Cita (1979) showed that the first significant increase in $\delta^{18}O$ of Pliocene age occurs between 2 and 2.4 Ma; they interpreted it as evidence of the onset of glaciations in the Northern Hemisphere.

Hooghiemstra et al. (1984) have drawn a curve of fluctuations of forest pollen through the last 3.5 Ma, from the study of the Funza core (300 m) drilled in a sequence of tuffs and lacustrine deposits located at 2500 m near Bogota in Colombia (5°N, 75°W). In agreement with the oceanographic data, large amplitude oscillations appear around 2.4 Ma reaching their maximum between 1.9 and 1.5 Ma. Finally, the present study attests that the glacial maximum recorded in the Bolivian Andes occurred between 2.48 and 1.8 m.y. B.P.

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Lacustrine and fluviolacustrine conditions prevailed during the interval 5.5–2.48 Ma in the Altiplano basin.

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References

Ballivièn, O., Bles, J. L. and Servant, M., 1978. El Plio-Cuaternario de la region de la Paz (Andes Orientales, Bolivia). Cah. ORSTOM Sér. Géol., 10(1): 101–113.

Clapperton, C. M., 1979. Glaciation in Bölivia before 3.27 Myr. Nature, 277: 375–377.

Dobrovolny, E., 1962. Geologia del valle de la Paz. Publ. Min. Minaspetrol. Bol., 3, 153 pp.

Evernden, J., Kreg, S. and Cherroni. C., 1977. Potassium–argon ages of some Bolivian rocks. Econ. Geol., 72: 1042–1061.

Hoffstetter, R., Martinez, C., Munoz-Reyes, J. and Tomasi, P., 1971. Le gisement d'Ayo Ayo (Bolivie), une succession stratigraphique Pliocène–Pléistocène datée par des mammifères. C.R. Acad. Sci., 273: 2472–2475.

Hooghiemstra, H., 1984. Vegetational and climatic history of the high plain of Bogota, Colombia: a continuous record of the last 3.5 million years. In: Diss. Bot., 79, 368 pp.

Lavenu, A., Bonhomme, M. G., Vatin-Perignon, N. and De Pachtère, P., 1988. Neogene magmatism in the Bolivian Andes (between 16° and 18°S). Part I: numerical stratigraphy (K/Ar) and tectonics. J. South Am. Earth Sci., 1(2): in press.

MacFadden, B. J., Siles, O., Zeitler, P., Johnson, N. M. and Campbell, K. E., Jr., 1983. Magnetic polarity stratigraphy of the middle Pleistocene (Ensenadan) Tarija formation of southern Bolivia. Quat. Res., 19: 172–187.

Mankinen, E. A. and Dalrymple, G. B., 1979. Revised geomagnetic polarity time scale for the interval 0–5 m.y. B.P. J. Geophys. Res., 84: 615–625.

Molyneux, L., 1971. A complete results magnetometer for measuring Remanent Magnetization of rocks. Geophys. J.R. Astron. Soc., 24: 429–433.

Servant, M., 1977. Le cadre stratigraphique du Plio-Quaternaire de l'Altiplano des Andes tropicales en Bolivie. Rech. Fr. Quat. Bull. Assoc. Fr. Etud. Quat., 50: 324–327.

Servant, M., Sempéré, T., Argollo. J., Bernat, M., Ferraud, G. and Lo Bello, P., 1989. Morphogenèse et soulèvement de la cordillère orientale des Andes centrales de Bolivie au Néogène. C.R. Acad. Sci. Paris, in press.

Shackleton. N. J. and Cita, M. B., 1979. Oxygen and carbon isotope stratigraphy of benthic foraminifera at Site 397: detailed history of climate changes during the late Neogene. In: Initial Reports of the Deep Sea Drilling Project, 47. U.S. Government Printing Office, Washington, D.C., 1, pp. 433–445.

Shackleton, N. J. and Opdyke, N. D., 1976. Oxygen isotope and palaeomagnetic stratigraphy of Pacific core V28-239, late Pliocene to latest Pleistocene. Geol. Soc. Am. Mem., 145: 449–464.

Shackleton, N. J. and Opdyke, N. D., 1977. Oxygen isotope and palaeomagnetic evidence for early Northern hemisphere glaciation. Nature, 270: 216–219.

Thellier, E. and Thellier, O., 1959. Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique. Ann. Geophys., 15: 285–376.

Troll, C. and Finterwalter, R., 1935. Die Karten der Cordillera Real und des Talkessel von La Paz (Bolivien) und die Diluvialgeschichte der zentralen Anden. Petermanns Mitt., 81: 393–399.

Tucholka, P. and Tessier, J., 1987. Interfacing the DIGICO Fluxgate Spinner magnetometer to an Apple IIE microcomputer. Geophys. J.R. Astron. Soc., 89: 705–712.

Villarroel, C., 1978. Revalidacion y redescription de *Posnanskytherium desaguaderoi* Liendo, 1943; Toxodontidae (Notoungulata) del Plioceno superior Boliviano. Rev. Serv. Geol. Bol. 16.