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FISSION TRACK AGES AND SEDIMENTARY PROVENANCE STUDIES IN PERU, AND THEIR IMPLICATIONS FOR ANDEAN PALEOGEOGRAPHIC EVOLUTION, STRATIGRAPHY AND HYDROCARBON SYSTEMS

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Abstract
Reconnaissance fission track dating was carried of 33 samples collected from the Bagua-Santiago, Huallaga, Urubamba-Camisea and Alto Manu areas. We present preliminary results and conclusions, pending further data analysis. Track length distributions suggest that many samples underwent prolonged residence in the partial annealing zone, with long cooling histories, and only some samples pass a Chi^2 test, so in most cases a “fission track age” does not date a particular geological event. In these samples, discrete age populations can be distinguished which indicate differing grain resistance to track annealing, a function of grain chemistry Cooling history modeling of grain ages and track lengths and, possibly, data on the chemistry (e.g. Cl/Fl/OH content) of apatite grains is required. Preliminary interpretation of the data is possible, even in the absence of thermal modeling. In particular the zircon grain ages which have generally not been deeply enough buried to have been reset, and we can distinguish inherited and syn-deposition (airfall or reworked young volcanic) components which give us several new absolute ages, including a new 68.5 Ma direct age for the “Vivian sandstone” at Pongo de Mainique Oligocene and Early Miocene ages for strata about 2.5 km above the Cretaceous. The apatite data suggest a 25 Ma age for initial uplift at the rear of the Santiago and Huallaga Basins, Late Miocene rejuvenation of uplift between the Bagua and Santiago Basins, coincident with formation of the frontal Campanquiz Anticline, and a slightly older age for the unroofing of the frontal thrusts in the Huallaga Basin. Apatite data from the Machu Picchu area indicate rapid unroofing at ca. 1 km/Ma since the Late Pliocene, younger than the thin-skinned thrusting in the Camisea area and probably driven by the same post-thrusting thick-skinned deformation which caused the uplift of the Shira and Vilcabamba Cordilleras. Thrusting in the Camisea area is dated as Late Miocene to Pliocene in age. Apatite ages in the Mipaya and Coñec areas are mostly detrital and partially annealed but still reveal an influx of volcanic material coincident with the Middle Oligocene volcanic flare-up in the arc to the west, consistent with changes in sediment provenance from sedimentary to mixed metamorphic/volcanic. The data provide valuable insights into the timing of deposition, burial, deformation and uplift, and can be used to improve our understanding of petroleum systems in the Peruvian foreland basins.

Introduction
There are few published fission-track studies on Peruvian rocks (e.g. Garver et al., 2005; Kontak et al., 1990; Laubacher and Naeser, 1995; Naeser et al., 1991; Wipf, 2006) and only short study (Aleman and Marksteiner, 1993) which even addresses the foreland fold-thrust belt. None of the studies on Eastern Cordillera or Subandes rocks report grain age or track length data, and the results are difficult to interpret. This study contributes a full suite of grain age and track length data from samples collected in several different basins, which will contribute to sediment provenance and dating studies, and to thermal models of sediment burial and exhumation, all important to understanding foreland petroleum systems.

Apatite and zircon fission track ages have been obtained from 33 samples in the Bagua-Santiago, Huallaga, Urubamba-Camisea and Alto Manu areas collected between 1994 and 1996. Apatite and zircon yield proved a challenge, possibly due to intense weathering or diagenetic alteration, and much larger samples than expected were required even from apparently fresh granitoids and metamorphic rocks. In all, apatite ages were obtained from 32 samples from all traverses, and zircon ages were obtained from 7 samples collected between Pongo de Mainique and Mipaya along the Rio Urubamba.

Initial analysis was carried out in the late 1990s by Geotrack, by Shari Kelley at New Mexico Tech, and by John Murphy at the University of Wyoming, all using the external detector method (Gallagher et al., 1998 provides a good review of analytic methods and statistical analysis of the results), and provided individual grain ages and track length data. The data are currently being reanalysed, using software not available to me at that time, to use combined grain age and track length data to assess burial and cooling histories, and to statistically separate detrital from reset grain age populations. The ages reported here are “central ages” from samples as a whole, and grain population ages determined using radial plots because they reveal statistically valid that cannot be seen on age-frequency histograms. A brief preliminary summary of the ages and possible implications is presented in this paper and results of thermal modeling will be presented in the near future.

Fig. 1 — Location map for samples dated in this study

Outline of results

Bagua-Santiago traverse
Samples were collected from "Marañon complex" basement immediately west of the Santiago Basin, and from Cenozoic samples in the Nazareth area, from the Pongo de Huaracayo, from the west limb of the Pongo de Manseriche and from outcrops along the oil pipeline across the Cordillera Campanquiz. Apatite ages were obtained from nine samples.

Western Santiago results are summarized in Figure 2. Sample 250, ca. 500-1000 m below the Pozo shale, has an estimated depositional age of 45-55 Ma. The very tight track length distribution is characteristic of very rapid uplift (Gallagher et al., 1998) and so the well-defined ca. 25 Ma age can reasonably be interpreted as dating the uplift of the thin-skinned anticline at the rear of the Santiago Basin, which detached at either the base of the Pucara limestone or a base-Sarayaquillo evaporite. Sample 289 comes from "Marañon Complex" schist from some 40 km to the southwest. Geologic maps (Ingemmet Aramango quadrangle 11-g) show basement unconformably overlain by Pucara limestones which were folded by "Jurua" deformation and bevelled flat before the deposition of the Cretaceous. The skew track length distribution is characteristic of slower rise through the partial annealing zone (PAZ), and indicates that basement here probably only ramped significantly above regional during latest Late Miocene time, coincident with growth of the frontal Campanquiz Anticline.

Pongo de Huaracayo results are summarized in Figure 3. Track length distributions are complex, and indicate prolonged cooling. Thus, careful thermal history modeling will be required. The samples were collected about 1000 m and 2000 m below the Pozo shale and were mostly likely deposited during the Late Paleocene or early Eocene. Cretaceous and Paleocene-Eocene age populations may be detrital but possibly slightly reset, preserved in the most annealing-resistant grains. I have studied numerous thin sections and several heavy mineral separates from this area (Kennan, 2006). The lowest samples contain abundant volcanic detritus, while the higher samples contain mostly metamorphic material. Volcanic clasts do not reappear until immediately below the Pozo shale, where white airfall tuff is also found. Based on a comparison with the regional geology we assign absolute ages as ca. 55 Ma for the lower volcaniclastic sandstones and breccias (samples 491, 492) just above "Huchpayacu" red sands and shales, ca. 45 Ma for the base of the metamorphic dominated unit (samples 489, 490) and ca. 35 Ma for the Pozo tuff.

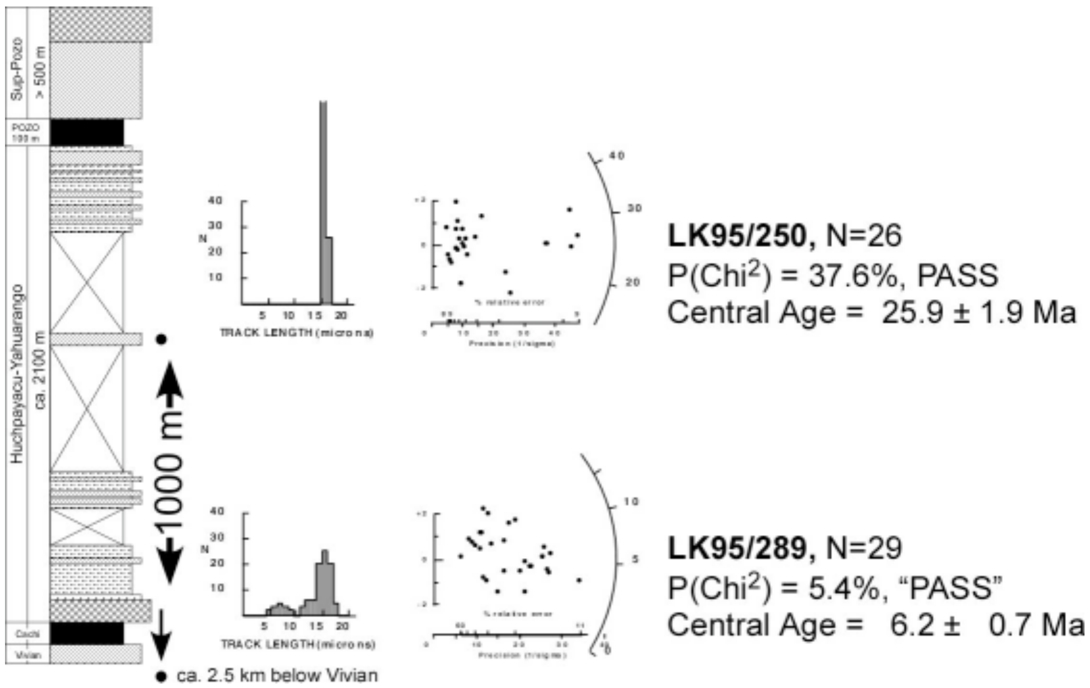

Fig. 2 — Western Santiago Basin apatite data

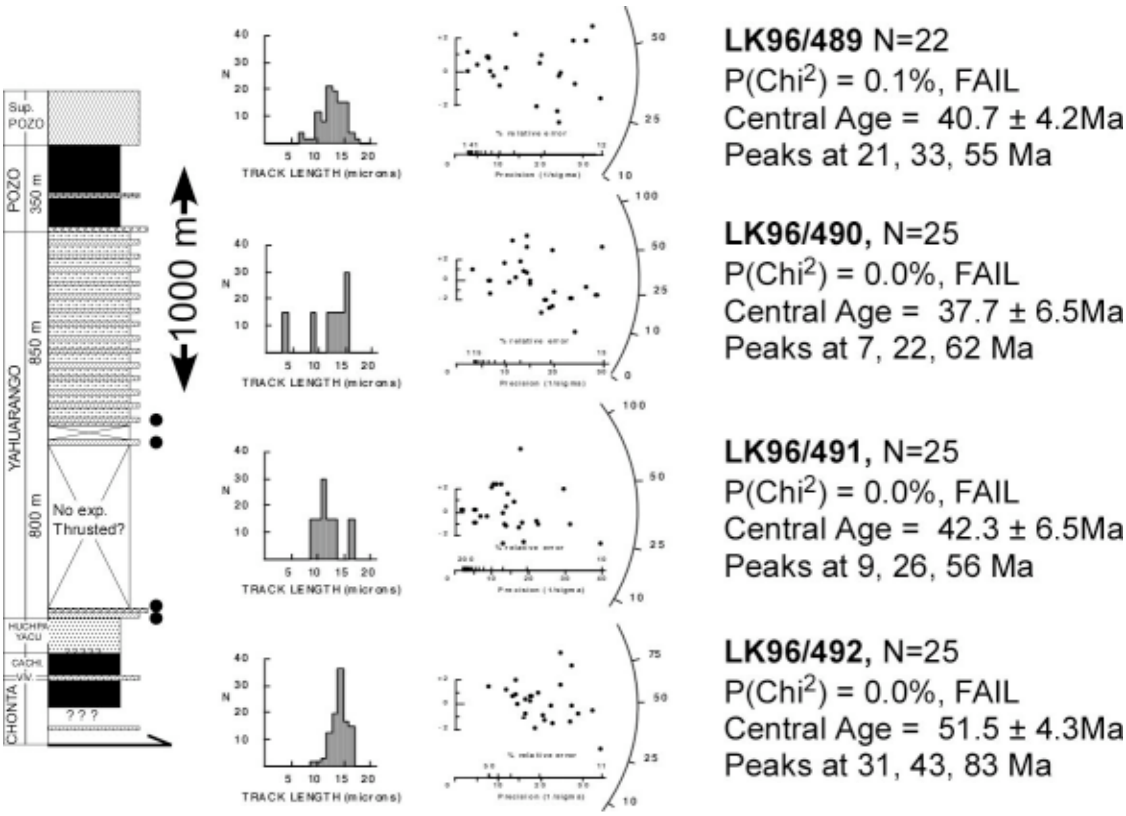

Fig. 3 — Central Santiago Basin, Pongo de Huaracayo, apatite data

We speculate that Late Oligocene and Early Miocene populations in all samples may indicate a cooling event broadly similar to that recorded in sample 250 to the west, but that the Paleogene section was never buried by more than about 3 km, insufficient to totally reset the apatite ages. Aleman and Marksteiner (1993) report an event of about this age from samples collected within the Cretaceous, but give no further details. Late Miocene age populations probably reflect the uplift of the least annealing-resistant grains through the PAZ, coincident with the cooling of samples collected from the Campanquiz Anticline.

Results from Pongo de Manseriche and Cordillera Campanquiz are summarized in Figure 4. Here too, track lengths suggest prolonged residence in the PAZ, with the oldest ages, also possibly preserving detrital late Cretaceous through Paleocene-early Eocene ages. Thin sections show abundant evidence for reworked tuff, so the 38 Ma age population in sample 449 may be partially reset from grains of about 55 Ma (the sample is from the "Casa Blanca" sandstone as mapped by Ingemmet, but is a red volcaniclastic sandstone with abundant airfall tuff and lapilli beds, broadly similar to the samples at sites 491, 492 at Huaracayo). Sample 449 is the deepest sample from this area, and most likely to have been more or less completely reset. It's pronounced 6 Ma peak, with a relatively tight track length distribution suggests that unroofing of the Cordillera probably during the Late Miocene, similar to the age inferred by Aleman and Marksteiner (1993) from Cretaceous samples.

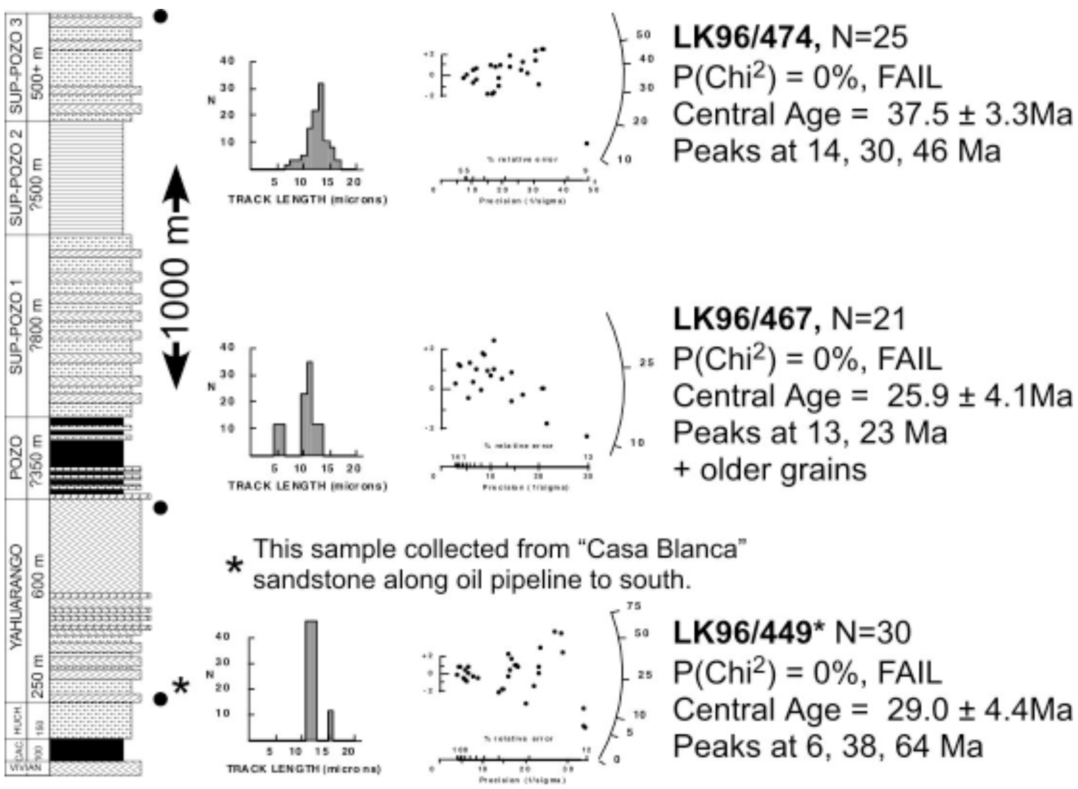

Fig. 4 — Eastern Santiago Basin, Pongo de Manseriche, apatite data

Huallaga traverse
Six samples were collected from the axis of the Saposoa Syncline near Juanjui, from the hangingwall anticline of the Ayomayo backthrust, and along the Tarapoto-Yurimaguas Road just above the Chazuta and Shanusi thrusts (e.g. Hermoza et al., 2005).

The Saposoa Syncline is extraordinarily deep, estimated from my own field measurements (Figure 5) to contain at least 9 km of post-Cretaceous sediment (similar to the seismic interpretation and measurements of Hermoza et al., 1995). Sample 339 comes from the conglomeratic sandstones at the base of Ipururo Formation about 3500 m above the Cretaceous, to which ca. 12-15 Ma age is usually assigned and sample 336 from the uppermost Ipururo about 7500 m above the Cretaceous, just below the Plio-Pleistocene Juanjui conglomerates. Maximum burial is estimated at ca. 5000-6000 m and 2000 m for samples 339 and 336, respectively.

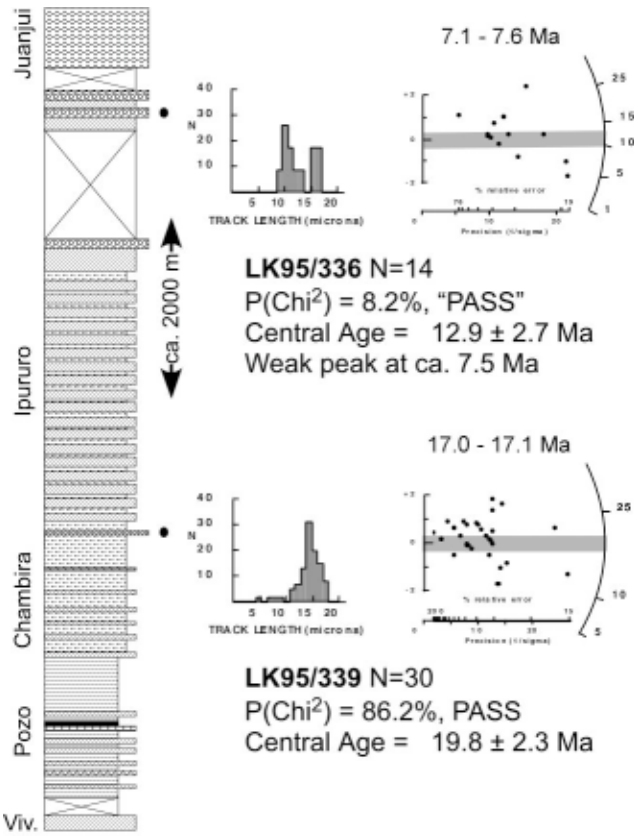

Fig. 5 — Semi-schematic log, Saposoa Syncline, western Huallaga Basin

Sample 339 has a well-defined ca. 20 Ma age and a relatively tight track length distribution. However, the more or less parallel strata on the flanks of the Bellavista Anticline show no indication of growth at this time, and seismic lines (e.g. Hermoza et al., 2005) show no angular unconformities. Thus, we suggest that this is an inherited detrital age and that only moderate annealing may have taken place. Although deeply buried, the cover is young and has probably pushed the PAZ deeper than normal. We suggest that the Early Miocene age reflects uplift of the metamorphic core of the Eastern Cordillera not far to the west, and with a typical exhumation-transport lag time of ca. 5 Ma from cooling to basin, supports the assigned ca. 15 Ma stratigraphic age.

Sample 336 has a less well-defined ca. 13 Ma age, with a weak peak at ca. 5 Ma and a broad track length distribution. As with sample 339 we suggest that the grain ages are inherited, again supporting the very young Pliocene age usually assigned to the base of the Juanjui Formation.

362 was collected from uppermost Sarayaquillo Formation red beds on the steeply-east-dipping forelimb of a minor thrust within the Chazuta thrust sheet, about 7 km east of the Ayomayo backthrust and above the Chazuta footwall ramp. No detrital ages are preserved and all apatites were completely reset. The relatively tight track length distribution and 9-13 Ma age population is consistent with moderately fast uplift through the PAZ, ramping out of the deep syncline west of the Chazuta thrust during the latest Middle Miocene.

East of Tarapoto (Figure 6), ages were obtained from the Upper Sarayaquillo red beds immediately above the long-offset Chazuta Thrust, and from the same stratigraphic level just above the Shanusi Thrust, about 4 km below the Chazuta Thrust, with relatively minor offset in this area. All apatites were fully annealed by Middle Miocene time and there are no inherited detrital ages. Track length distribution is complex and, clearly, more thermal modeling is required to elucidate the timing of thrusting in more detail. Older age peaks of late Middle Miocene age suggest the strata may have been within the PAZ but cooling by that time, while younger ca. 5-6 Ma peaks are a maximum age for the passage of the least annealing-resistant grains through the PAZ. This age range is consistent with the 40-50 Ma offset on the Chazuta Thrust taking place over no shorter an interval than the Late Miocene, given ca. 10 km/Ma as the maximum rate of foreland shortening in the Central Andes, and given the thrust took up all Subandean shortening while it was active. Thus, we might not expect a particularly sharp unroofing episode. Thin-skinned shortening was brought to an end by reactivation of the Tiraco Dome.

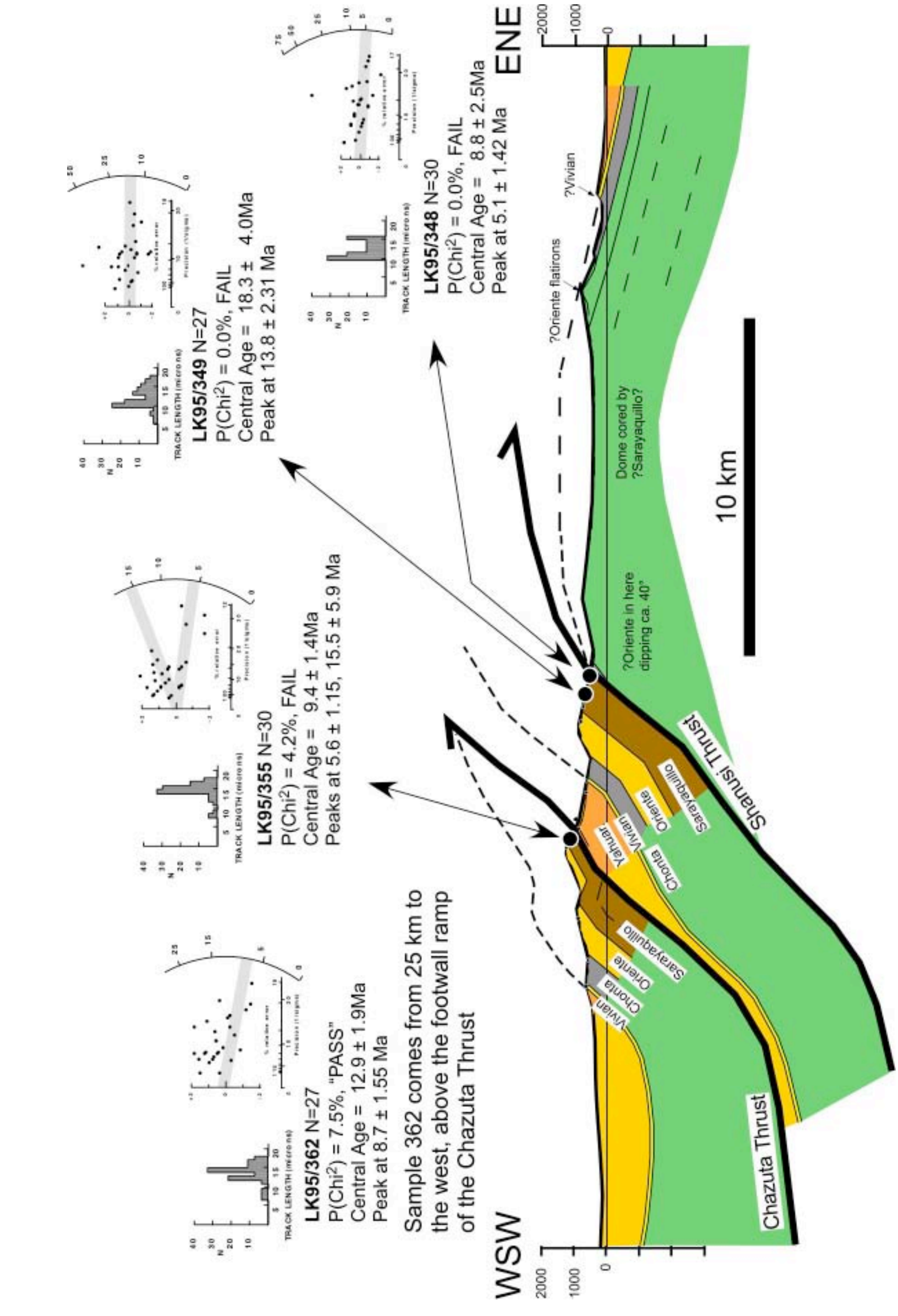

Fig. 6 — Ayomayo and Tarapoto area apatite data

Urubamba traverse — Machu Picchu

In 1995 we collected samples from the ca. 250 Ma Machu Picchu granite near Aguas Calientes and along the railway to Quillabamba (Figure 7). Samples we collected over an elevation range of 1500-4500 m to attempt to measure exhumation rates in the area, but only two samples, from 2100 m and 3100 m, yielded sufficient apatite. In both cases, there were a significant number of zero-age grains. Unfortunately, these two samples are separated by only 1000 m and no apatite was obtained at the elevation extremes of the transect, thwarting the original intention of plotting age versus elevation to define long-term exhumation rate.

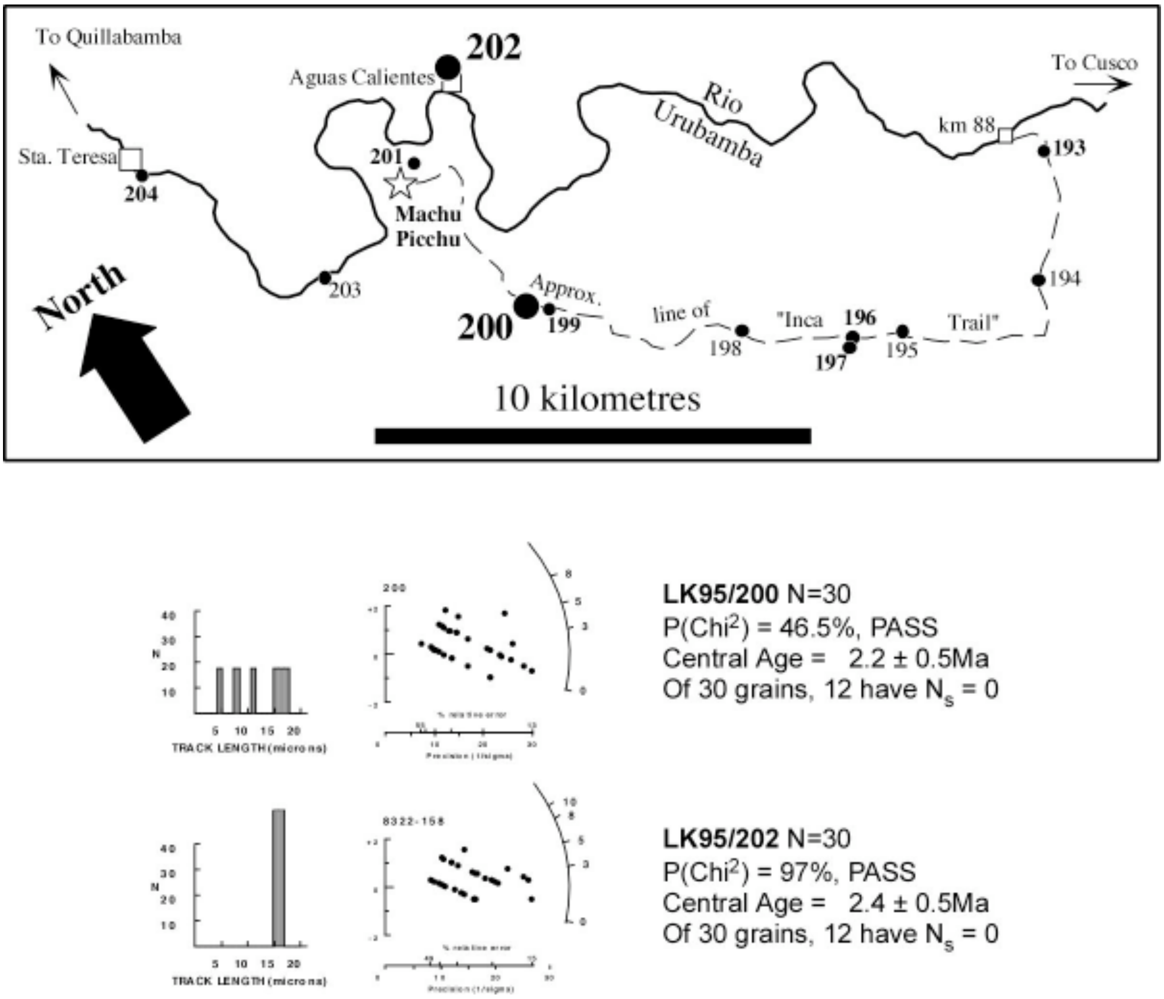

Fig. 7 — Machu Picchu area location map and apatite data

These two data points do however, suggest extremely young rapid exhumation of > 1 km/Ma during the Late Pliocene and Pleistocene. This is certainly consistent with the apparently juvenile, deeply incised topography in the Machu Picchu area. The uplift is significantly younger than the age of thin-skinned thrusting in the Camisea area (see below), and probably occurred above thick-skinned, basement cored structures similar to the Vilcabamba and Shira ranges.

Urubamba traverse — Pongo de Mainique area

Four samples were collected from the “Vivian” or Tonquini sandstone, and from Cenozoic strata immediately north of the Pongo up to 2000 m above the Cretaceous (Figure 8). Zircons and apatites were dated from all but the lowest Cenozoic sample.

The Tonquini sandstone (sample LK94/URU16), at the mouth of the Pongo, is interpreted as a transgressive blanket sand burying a scoured surface on top of slightly older shales and sands, with a transitional relationship to overlying strata. The zircon data (Figure 8) provide a direct estimate of stratigraphic age of this unit, with 15 out of 20 grains defining a sharp 68.5 ± 3.18 Ma peak (Figure 8), and the remainder being reworked, with Mitu or Ambo ages. Most of the young grains were subhedral to subrounded so some transport is implied, and the age indicated is a minimum.

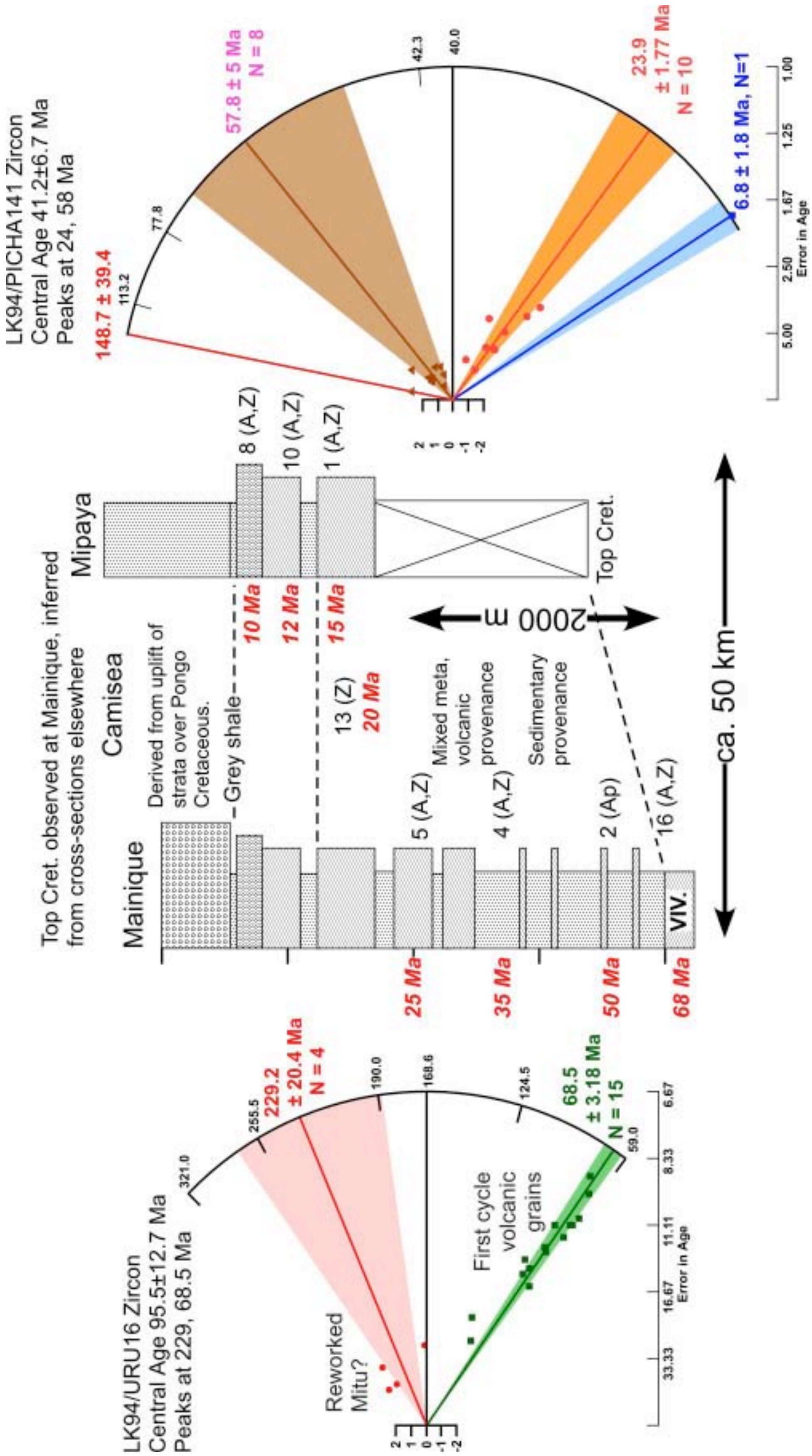

Fig. 8 — Summary logs, stratigraphic ages (red italics) for the Pongo de Mainique and Mipaya area. Selected radial plots show detrital zircon age peaks which constrain depositional age

Apatites from the same sample give a central age of 19.6 ± 6.2 Ma, but do not define a single age population. Peaks of 99.3 Ma and 9.5 Ma are interpreted as inherited (annealing-resistant grains) and exhumation (non-resistant grains). Track length distribution is broad and exhumation can only be tied to a late Middle Miocene through Late Miocene interval.

Sample LK94/URU2 comes from ca. 900 m above the top Cretaceous. Apatites give a central age of 77.5 Ma and pass a Chi^2 test, but the ages can also be decomposed into a population of 53 ± 6.9 Ma and assorted older grains with large individual errors. Track length distribution is broad, and these are interpreted as reworked and detrital. We cannot assess the relative effects of exhumation and transport time lag, and of partial annealing, but the 53 Ma peak is close to probable stratigraphic age.

Sample LK94/URU4 comes from ca. 1250 m above the top Cretaceous. Zircons give a 256.9 ± 27.7 Ma central age and fail a Chi^2 test. Grain age populations show that all the zircons were reworked from late Jurassic, Permo-Triassic and Mississipian rocks. Apatites give a 51.4 ± 9.7 Ma central age, and pass a Chi^2 test. There is a very sharp age peak at ca. 45 ± 5 Ma, consistent with the probable later Paleogene age of deposition, and also a significant number of Late Cretaceous grains.

Sample LK94/URU5 comes from ca. 2000 m above the top Cretaceous, not far above a marked transition from brick red shales and subordinate sands, to light brown, locally pebbly, sandstones. Apatites give a 32.3 ± .7 Ma central age, and fail a Chi^2 test, although track length distribution is tight. There are apatite age peaks at 24.7 ± 2 Ma and 120.2 ± 42 Ma. The latter are clearly reworked and indicate that the sample was never fully annealed and therefore not buried below the base of the PAZ (ca. 4-5 km). Burial depth is estimated at not more than 2500 m from the author's field data and published cross-sections (e.g. Gil, 2002) and the sample may never have passed much below the top of the PAZ. The Late Oligocene peak and tight track length distribution is consistent with a detrital origin, rapid uplift in the sediment source area. Zircons from the sample give a 122.6 ± 23.7 Ma central age, fail a Chi^2 test, and show age peaks at 54 ± 4, 121 ± 15 and 279 ± 26 Ma, all reworked. Probable age of deposition is about 20-25 Ma, coincident with resurgent Andean deformation and volcanism. Thin sections and heavy mineral separates show that metamorphic clasts and minerals become more abundant above this sample, possibly reflecting deep unroofing of the Eastern Cordillera since the Late Oligocene.

About 1500 m above sample LK94/URU5, we note the presence of a distinctive conglomerate and grey shale package, which we correlate with exposures in the Mipaya area, and for which we estimate a latest Middle Miocene to earliest Late Miocene age. This is overlain in turn by a yellow conglomerate with mostly reworked Cenozoic clasts which we suggest is syntectonic and derived from Cenozoic strata which once buried the Pongo de Mainique structure, deposited in a piggyback basin between the Pongo de Mainique and the rising frontal structures in the Camisea-Mipaya area.

Urubamba traverse — Camisea-Mipaya area
A single sample, LK/URU13, was collected near the confluence of the Rios Urubamba and Camisea, at about 2000-2500 m above top Cretaceous (poorly-constrained). Published seismic lines suggest a position immediately below the frontal blind backthrust, and a stratigraphic position similar to the Mipaya samples. Only zircons were recovered, and these gave a 112.7 ± 17.7 Ma central age which fails a Chi^2 test. There are grain age peaks at 166 ± 9, 76 ± 6 and 47 ± 7.5 Ma and a single young outlier at 19.1 ± 4.71 Ma. Again, the youngest grain is euhedral.

Sample LK/PICHA1, a grey friable medium sandstone, about 3 km southeast of the Mipaya well, lies about 2200 m above top Cretaceous in the hangingwall of the frontal blind backthrust. Zircons give a central age of 41.2 ± 6.7 Ma, fail a Chi^2 test, and have well-defined grain age peaks at 56 ± 5 (N = 8) and 24 ± 2 (N = 10), and single-grain outliers at 229.5 ± 59 Ma, 148 ± 39 and 6.8 ± 1.8 Ma, none of which may be statistically significant. Apatites give a central age of 30.2 ± 3.4 Ma, fail a Chi^2 test, and have age peaks at 14 ± 6 and 31 ± 8 Ma. The stratal thickness to the northeast of the sample is no more than ca. 1500 m, so it seems unlikely that these grains have been buried deep enough to anneal. Thus, the 14 ± 6 Ma peak may be detrital and indicate deposition during the late Middle Miocene. If so, the 24 Ma zircon peak would have to comprise reworked, slightly older, material and the single 6.8 Ma zircon would have to be of no significance.

Sample LK/URU10, about 10 km northwest of the Pagoreni well, lies about 2300 m above top Cretaceous. Zircons from URU10, a brown slightly pebbly sandstone about 1500 m above top Cretaceous, give a central age of 48 ± 6.3 Ma, fail a Chi^2 test, with grain age peaks at 104 ± 17, 48 ± 5, 27 ± 3 and 17 ± 4. The youngest zircons are all euhedral. The latter two peaks are defined by only 2 grains each, but error bars are relatively small. Apatites give a central age of 38.5 ± 4.5 Ma and also fail a

Chi^2 test. Age peaks occur at 40.3 ± 6 and 16 ± 4 Ma. Track length distribution is tight and only slightly skew. We interpret the young, essentially identical zircon and apatite peaks as a detrital, tuff input aged 15-16 Ma. Grain shapes indicate little or no rounding, and depositional age is probably Middle Miocene, consistent with the age inferred for sample PICHA1 nearby.

Sample LK/URU8 comes from a distinctive sand and conglomerate package, immediately below a grey clay bed, possibly bentonitic. Zircons give a central age of 80.9 ± 9 Ma, fail a Chi^2 test. The largest grain age peak is at 90.5 ± 7 Ma (10 grains), with smaller populations at 55 ± 14 and 38 ± 8 Ma and a few older outliers. Apatites give a central age of 45.5 ± 9.8 Ma, fail a Chi^2 test and have well-defined age peaks of 98 ± 14, 25 ± 10 and 13 ± 3 Ma. The overlying section is mixed sand and clay and estimated to be no more than ca. 1000 m thick where bedding returns to the horizontal about 1 km to the north, so the apatite ages are also clearly detrital. We estimate time of deposition at ca. 10 Ma, or earliest Late Miocene. Thin sections and heavy mineral separates show a distinct change in provenance, with volcanic apatites and hornblendes much more abundant, possibly coming from the Eastern Cordillera (Cusco, Crucero areas). Thus, we correlate the conglomerate and grey marker bed with similar facies described from the Madre de Dios Basin (Acre conglomerate and 9 Ma Cocama tuff, Campbell et al., 2001).

Coñec traverse

The southernmost transect consists of a series of samples collected along the Rio Alto Manu between Pongo de Coñec and the Pantiacolla Anticline. Of these, 8 samples from upper Cenozoic strata in the Palotoa Syncline (Ingemmet usage, Pilcopata quadrangle 26-j), where the author's structural data indicate a Cenozoic thickness of ca. 7000 m. The stratigraphic divisions shown are the author's own, with a lower 2600 m thick brick-red unit of clays, calcretes and subordinate sands, a middle 2500+ m thick brown unit comprising claystones, siltstones and significant medium-coarse sandstone, and an upper 1300+ m thick unit comprising mostly coarse sandstones and conglomerates. Thin bentonites are present close to the base of the lower unit, and we estimate an age of ca. 55 Ma for these. The presence of Paleogene charophytes up to 2000 m above the Cretaceous indicates that the Paleogene here is substantially thicker than farther southwest, where only 80 m of Huayabamba Formation is reported from the Candamo well (Hermoza, 2004). There is a very marked influx of detrital volcanic material at the base of the middle unit, for which we estimate an age of not older than 32 Ma (the oldest Oligocene tuffs in the Cusco area) and possibly as young as ca. 27 Ma (when tuffs become more widespread). Metamorphic clasts derived from the Eastern Cordillera are also present, increasing in abundance upwards. We correlate this middle unit with the Quendeque Formation in the Inambari region, the base of which is dated at 29 Ma (Hermoza, 2004). A distinctive 10 m thick grey clay with very abundant leaf fossils is present in the upper unit at about 6300 m above the Cretaceous, which may be equivalent to the Late Miocene marine-influenced beds of this age elsewhere in the Central Andean foreland basin (e.g. Hovikoski et al., 2005, 2007). The upper unit has an extraordinarily mixed provenance, with reworked Cenozoic sandstones, Paleozoic sandstones and slates, probable Paleozoic metamorphic rocks, ignimbrite clasts, and common granitoid cobbles not seen in the lower and middle units. As in the Rio Urubamba section, we interpret this upper section as syntectonic, coincident with the initiation of foreland deformation. The upper part of the section may be equivalent to the Mazuko Formation of Hermoza (2004).

The fission track results obtained, from apatites only, are summarized in Figure 9. No apatites were recovered from samples in the lower unit. All the samples fail a Chi^2 test and comprise multiple grain-age populations. Sample LK95/152 was buried by up to ca. 4000 m and probably entered the PAZ, annealing some apatites. The other 6 samples were probably not buried by more than ca. 2000 m and are likely to preserve entirely detrital apatite ages. All but the deepest sample show a significant content of Cretaceous grains. There no grain age populations of Paleogene age; all are Early Miocene or younger. This is consistent with an origin from reworked tuffs of this age, as seen in thin section and heavy mineral data. The ages obtained are consistent with the depositional ages inferred above through comparison with other sections studied nearby, and indicate a Middle Miocene age for the upper part of the middle unit, and a Late Miocene age for the upper unit. The youngest ages were obtained from the highest sample and may indicate reworking of Pliocene tuffs such as those at Arco-Aja (Laubacher et al., 1988). The author is not aware of any published direct fission-track dating of uplift from deeper Cretaceous or older samples in the Manu-Madre de Dios area.

Principal conclusions

Fission track studies are a valuable tool for dating uplift and exhumation, and an underused method for direct dating of detrital grains. The results of this study reveal that "fission track ages" from most samples cannot be simply interpreted as dating discrete geologic events. Most samples contain several age populations and track length distributions suggest complex, possibly multiphase, cooling histories.

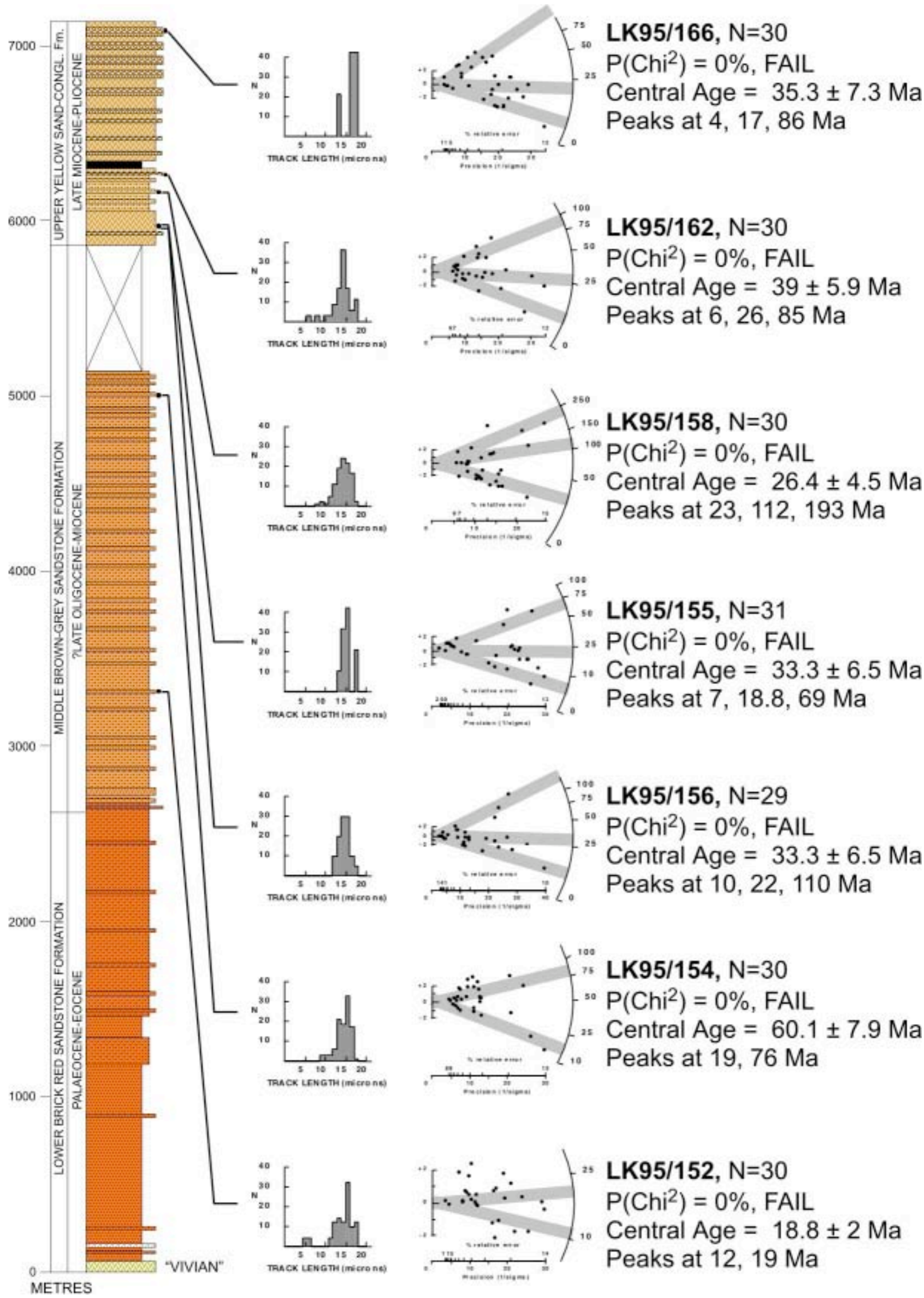

Fig. 9 — Summary of apatite ages from the Rio Alto Manu.

Most of the samples analysed in this study were collected from the Santiago, Huallaga, Ucayali and Madre de Dios Basins, with the aim of testing the ability of grain age populations in samples to provide direct dates for sedimentation and information on the exhumation and cooling history of sediment source regions, and fission track dating was complimented with structural, stratigraphic, petrographic and heavy mineral data. Some of the samples collected were deeply enough buried to reveal something of the exhumation histories of the samples themselves.

The study, although at a reconnaissance level, shows that fission track dating of detrital grains in sandstones can extract stratigraphic ages even where well-defined tuffs are not present. Reworked tuff-derived grains can yield a direct date, and other ages provide minimum stratigraphic ages. Thus, the method can be applied to samples collected throughout measured stratigraphic sections, and not only from discrete tuff beds, which are rare in the foreland. The study also showed that ideally detrital zircons and apatites should be obtained from the same sample, especially where no other age constraints are available, since a combination of age types can distinguish detrital and uplift ages for a given sample. Where possible track length data should be assessed for individual grains, allowing thermal modeling of the histories of individual grain age populations, which in turn can be used to assess something of the exhumation history of sediment source areas rather than the sample being analysed.

The method can be applied to both field and well samples and is relatively cost effective, in that most samples collected can yield useful information, something not the case when looking for microfossils in challenging foreland settings, and the results from a single sample can provide information on several different geologic aspects of petroleum systems modeling.

The results provide direct estimates of the age of “Vivian” sandstones and overlying Cenozoic strata in the southern Ucayali and northern Madre de Dios Basins, and reveal the exhumation history of the Eastern Cordillera and foreland fold-thrust belt structures in all four areas studied. The results compliment those of other regional studies (such as Gil, 2002 and Hermoza, 2004) with relatively little overlap. Analysis of the data is ongoing, and this study is a significant contribution to our understanding of the Peruvian foreland, with application to structural, stratigraphic and petroleum systems problems.

The results of this study, when integrated with others, clearly show that a Paleogene foredeep was better developed in the Ucayali Basin and further north, than in the Madre de Dios. The southern arm of the Paleogene foredeep was either non-existent or lay within the now deeply-eroded and deformed eastern part of the Eastern Cordillera as in Bolivia (Kennan et al., 1995; Kennan, 2006), where it is preserved in only a few large syncline axes. Andean shortening, uplift, exhumation and sediment transport restarted at about Early Oligocene time, coincident with an upsurge in volcanic activity after a hiatus lasting between 10 Ma (northern Peru) and 20 Ma (southern Peru). This event was almost synchronous, dated at between 32 and 27 Ma all the way from Ecuador to southern Bolivia.

Cooling ages from frontal structures, and direct dates on detrital grains in adjacent sediments indicate that deformation reached the present-day Subandean mountain front during the Late Miocene. Thin-skinned shortening may have stopped during the Pliocene in the Huallaga and Ucayali Basins, where older fold-thrust belts are disrupted by thick-skinned uplifts. Extremely young exhumation ages from the Machu Picchu area indicate that thick-skinned deformation continues to propagate to the south. The ages from the Machu Picchu area are the youngest, to our knowledge, obtained in the Central Andes and indicate an extremely high (> 1 km/Ma) rate of Pliocene-Pleistocene exhumation and erosion rate in that area.

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