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Neogene erosion surfaces along the Andean Flank of north-central Peru

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ABSTRACT

Following the description of a series of high-level erosion surfaces in the cordilleras of central Peru (Wilson, 2011), the present study investigates several areas in the middle and lower sectors of the Andean Flank in the region between the rivers Rímac and Huarmey. Fifteen separate surfaces are recognised at intervals of ~200 m between the elevations of 200 m and 3300 m. Although some areas lack certain surfaces because of subsequent erosion, the study of a number of widely spaced areas permits the establishment of a full sequence of surfaces which, it is believed, were developed over the whole of the Andean Flank in central Peru.

It is postulated that the surfaces were developed in the stable intervals which occurred between the multiple episodes of active uplift which led to the development of the Western Cordillera as it exists today.

The individual surfaces do not show any coastward tilt and it is concluded that the uplift of this part of the Andean Flank involved a significant component of vertical movement, probably controlled by a fault system located near the coastline.

A sample of the Fortaleza Fm taken from an area where the ignimbrite overlies an erosion surface at ~1400 m has been dated at ~5.5 Ma. Much further work is required to establish the ages of the individual surfaces.

RESUMEN

Siguiendo la descripción de una serie de altas superficies de erosión en las cordilleras del Perú central (Wilson, 2011), este estudio investiga varias áreas en los sectores inferiores y medianos del Flanco Andino entre los ríos Rimac y Huarmey. Se reconocen 15 superficies individuales, a intérvalos de 200 m, entre las elevaciones de 200 m y 3300 m. Aunque unas áreas carecen de algunas de las superficies debido a erosión subsequente, el estudio de varias áreas bien separadas permite establecer una secuencia completa de superficies que, se cree, se desarrollaron através de todo el Flanco Andino en el Perú central.

Se postula que las superficies se desarrollaron en los intervalos de estabilidad tectónica que ocurrieron entre los episodios multiples de levantamiento activo, los cuales resultaron en el desarrollo gradual de la Cordillera Occidental tal como existe hoy.

Las superficies individuales no muestran ninguna inclinación hacia la costa, y se concluye que el levantamiento de este sector del Flanco Andino involucró un componente significante de movimiento vertical, probablemente controlado por un sistema de fallas ubicado cerca a la linea de costa.

Una muestra de la Fm Fortaleza tomada de un afloramiento donde la ignimbrita sobreyace a una superficie de erosión a ~1400 m ha sido datada en ~5.5 Ma. Se necesita mucho más trabajo para establecer las edades de las superficies individuales.

1. Introduction

1.1. An extended work

Wilson (2011) demonstrated the presence of a series of high-level erosion surfaces in the upper reaches of the Andes in central Peru, the surfaces giving a step-like profile to the higher parts of the Western Cordillera. While much of the lower and middle sectors of the Pacific Flank are cut by precipitous canyons devoid of recognisable erosion surfaces, the divides separating the individual drainage systems commonly include prominent subhorizontal features which can be observed when travelling up any of the main valleys. It was decided to carry out a study of a number of areas (Fig. 1) with a view to determining whether these features form a regionally coherent system of erosion surfaces. The areas were selected to provide data over a strike length of ~200 km and a range of elevations from near sea level to over 4000 m.

Schematic profiles constructed for some of the drainage divides in the Andean Flank (Figs. 1, 2) suggest that:

a) the profiles all show step-like patterns, and

b) the steps appear to occur at more or less the same elevations in the various profiles.

It was therefore decided to carry out a more detailed study of parts of the Andean Flank with a view to:

i) identifying the individual features which make up the profile of the Andean Flank;

ii) mapping their lateral extent within specific areas;

iii) confirming the regional extent of the features.

The situation is complicated by the fact that not all the erosional surfaces are found in each profile, some having been destroyed by later erosion. A further complication is the presence of isolated hills in the lower reaches of the Andean Flank, which represent outliers or remnants of surfaces which have been destroyed in the surrounding areas. Thus, while the Andean Flank does not have the form of a simple, gradually rising, stairway, it nevertheless has a general step-like profile, with the individual “steps” occurring at similar elevations along a strike length of ~200 km.

1.2. Objectives

This report forms part of an ongoing investigation into the Neogene erosion surfaces found across the Andean region of central Peru, with the overall objective of obtaining a better understanding of the Andean uplift and providing an insight into the possible mechanisms of that uplift. Ongoing studies, including a report on the eastern flank and the Subandean Belt (in preparation), suggest that the same sequence of erosion surfaces can be recognised across the whole of central Peru. This implies both a uniformity in the amounts of uplift and a synchronicity of the individual phases of uplift. While to date the investigation is facilitating the quantification of the Andean uplift, little progress has been made in dating the individual phases. This aspect will require substantial efforts in the future.

2. Methodology

2.1. Work methods

The work methods employed in this study were the same as used in previous investigations (Wilson, 2009, 2011). Detailed study was carried out on 1:100,000 topographic and geologic maps of specific areas in order to identify subhorizontal sections of the interfluves separating not only the main valleys but also the minor drainage systems within those valleys. These subhorizontal features are not completely flat and planar, but rather show gentle undulations about a mean elevation, and are separated by scarps from higher and lower surfaces.

Once identified, the features were plotted onto base maps, along with their elevations. Maps were then drawn to show the distribution of the individual surface (Figs. 3 to 9). It must be noted, however, that the surfaces are generally represented only by the remnants present in the ridge tops. The maps therefore indicate the areas in which remnants of specific surfaces occur, rather than continuous areas of those surfaces. Also, areas such as canyons, where no subhorizontal features can be recognised, have been left blank.

The study was largely office-based, but benefited from field observations made in the course of earlier work, plus specific field checking carried out as part of this investigation.

2.2. Assumptions

The assumptions made in developing the concept of a sequence of erosion surfaces characterising the Andean Flank can be enumerated as follows:

1. Each episode of uplift was followed by an interval of tectonic stability long enough to allow the development of a distinct erosion surface.
2. Following uplift, the rivers would have rapidly incised their courses until they were near sea level, after which lateral erosion would become important, particularly in the lower courses of the rivers.
3. This lateral erosion would destroy pre-existing features and lead to the formation of a new, lower, surface.
4. Surfaces initiated in separate valleys would eventually coalesce to form a laterally extensive feature close to sea level and with little internal relief.
5. It is assumed that each new surface was initiated in the coastal area and gradually extended inland.
6. The inland limit would be marked by a scarp separating the surface from older, higher, features.
7. The initiation of the next episode of uplift would abruptly terminate the development of the preceding erosion surface.
8. The process would be repeated, leading the development of the multiple erosion surfaces recognised in the Andean Flank.

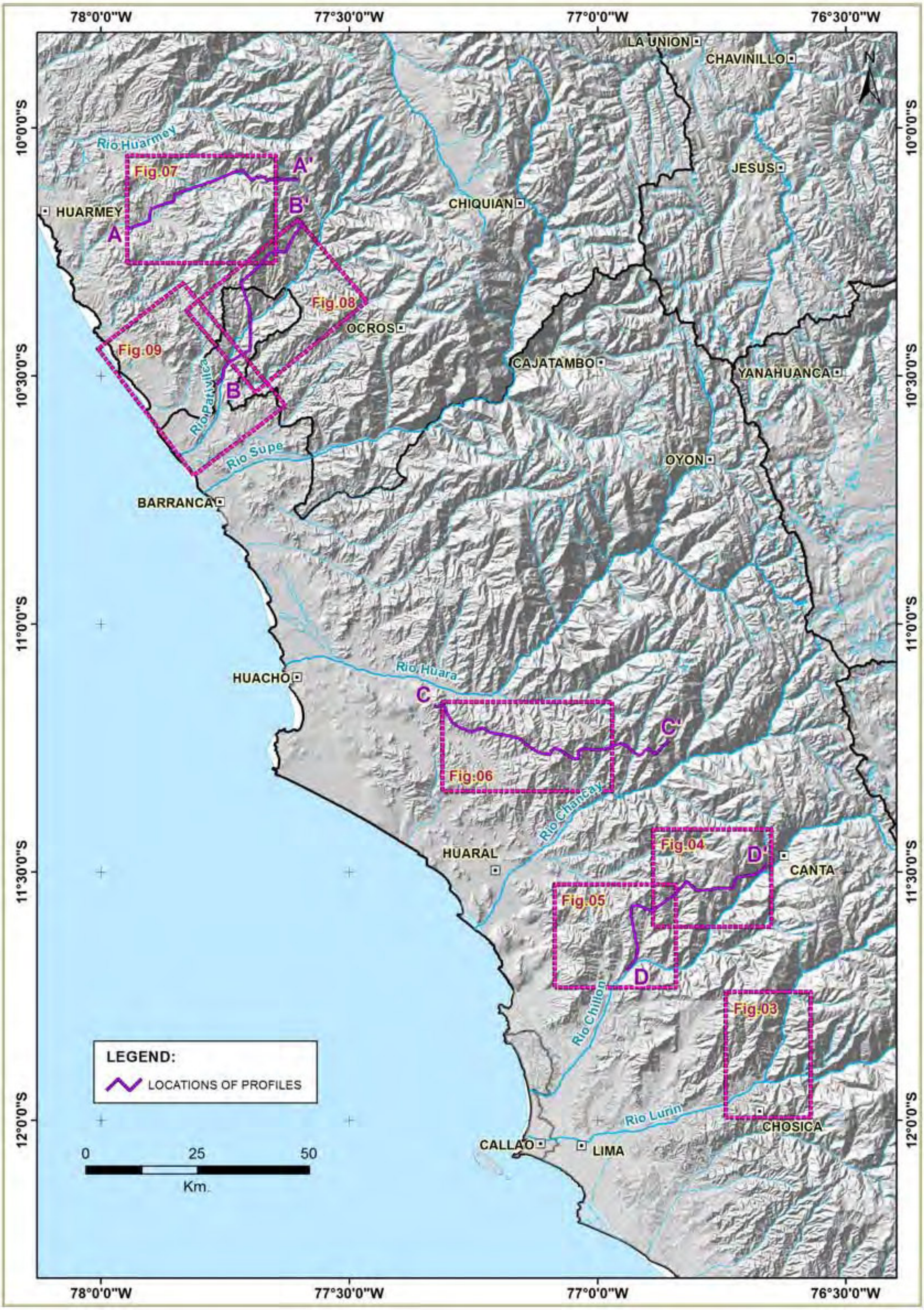
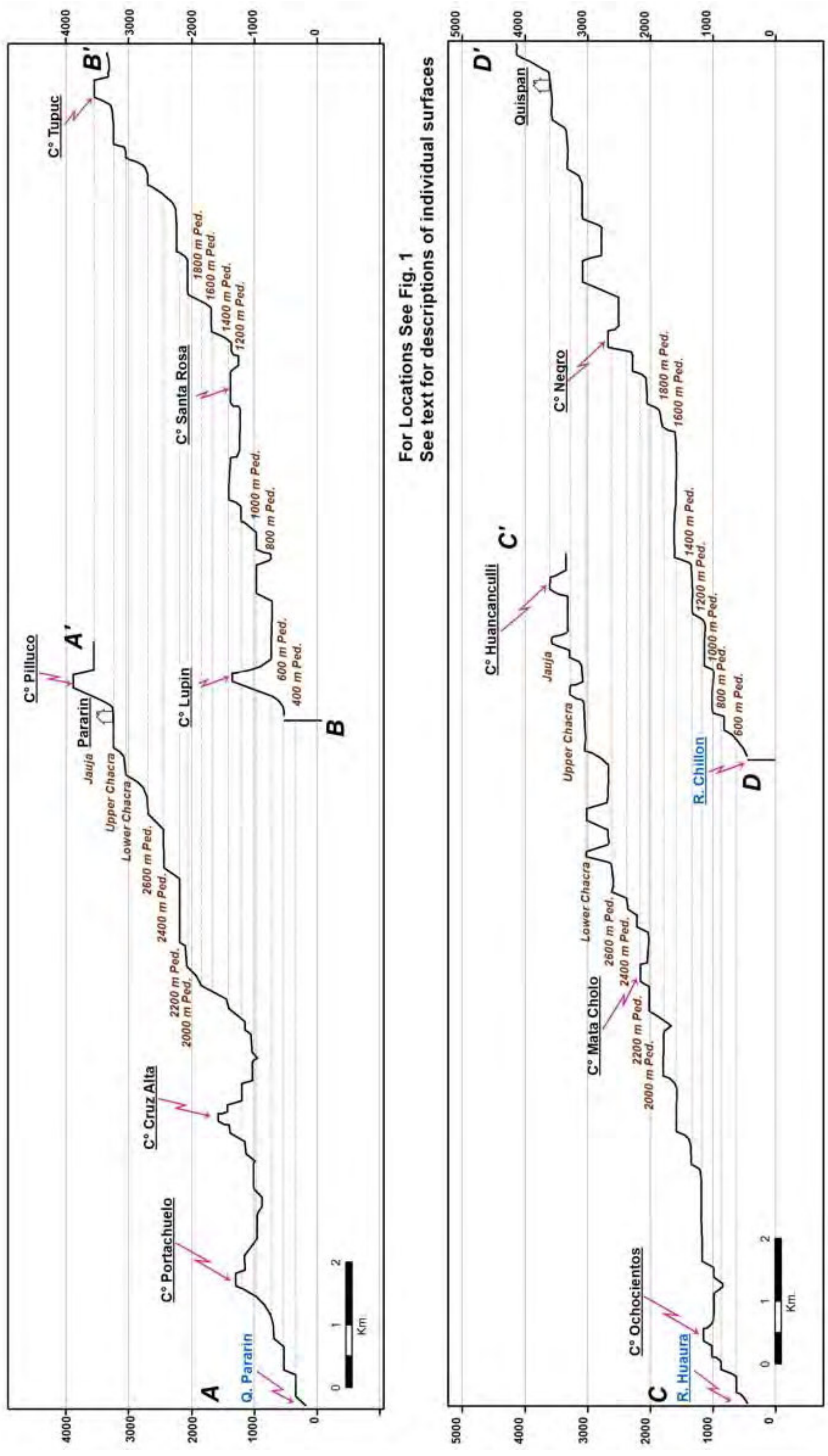


Figure 1. Location map showing the areas studied in this work.



For Locations See Fig. 1
See text for descriptions of individual surfaces

Figure 2. Schematic profiles along drainage divides in the Andean Flank.

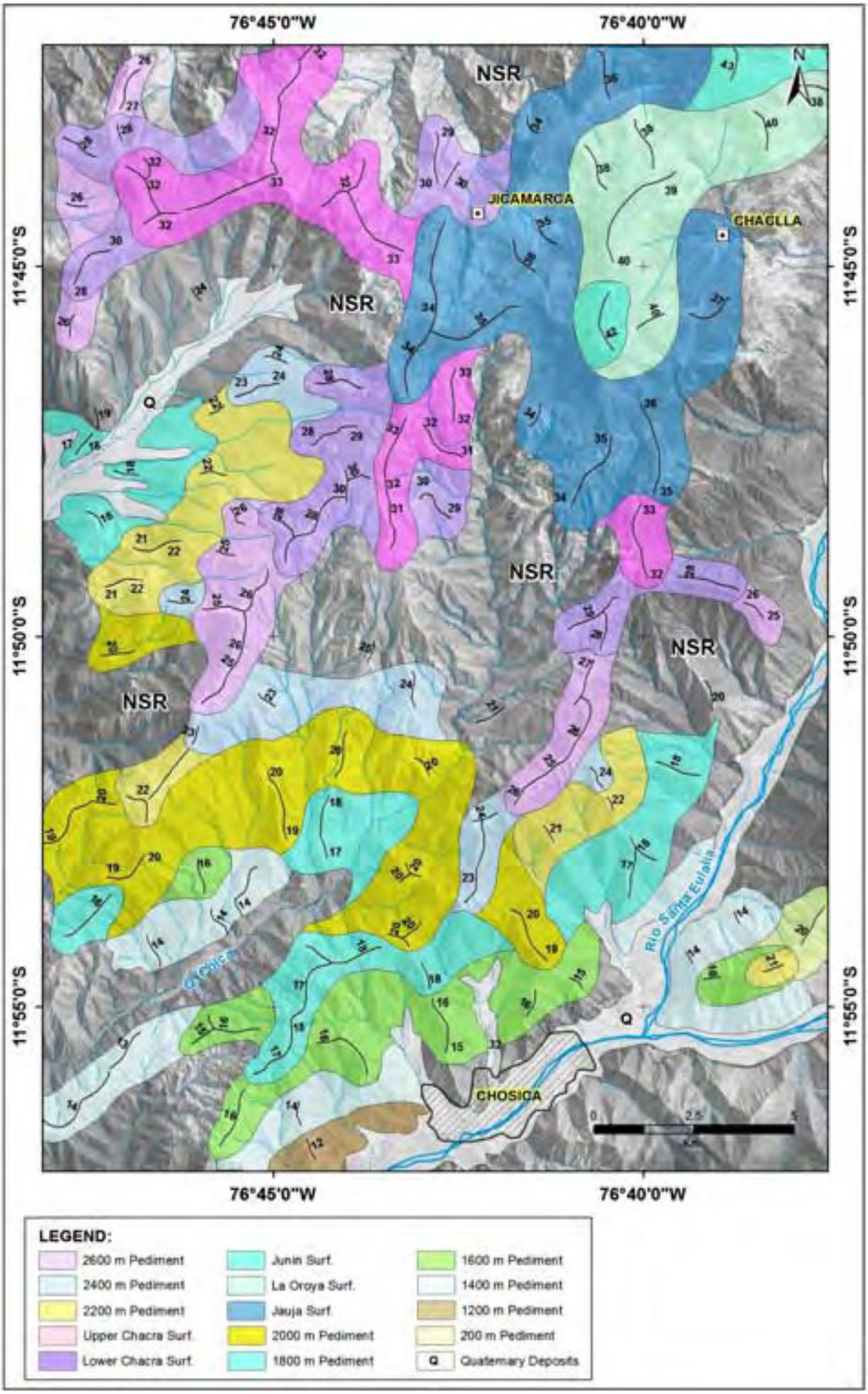


Figure 3. Map of erosion surfaces between the Río Chillón and the Río Anasmayo.

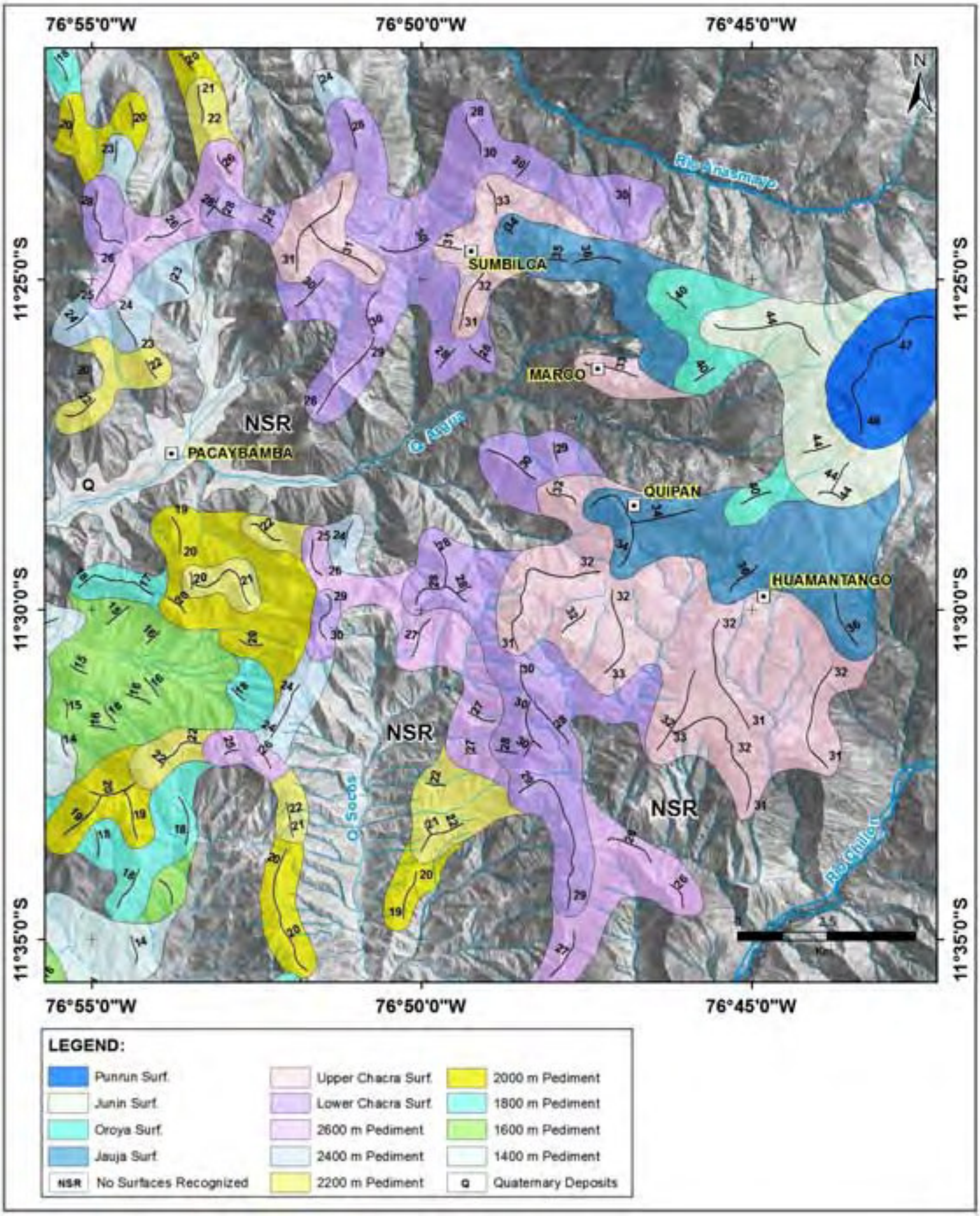


Figure 4. Map of erosion surfaces between the Río Rímac and the Jicamarca area.

3. General observations

Before considering the individual erosional features it is worth considering the Andean Flank as a whole. The following general observations can be made.

1. The high-level surfaces identified by Wilson (2011) extend into some of the study areas. They are represented in Figure 4, where the Jauja Surface forms a well-defined feature at ~3400–3600 m, while remnants of the La Oroya Surface (~3800–4000 m) and the Junín Surface (~4200–4300 m) can also be recognised. The eastern sector of the area represented in Figure 3 also contains remnants of the high-level surfaces.

2. Beneath the high-level surfaces occurs a series of erosional features extending from ~3300 m down to near sea level. The uppermost two features, which can be quite extensive, occur in the range 2800–3300 m. They are correlated with McLaughlin's (1924) Chacra Stage, and are here defined as the Upper Chacra Surface and Lower Chacra Surface.

The individual features found beneath the Chacra surfaces commonly occur as erosional benches cut into the Andean Flank and are here referred to as pediments. It is felt that it would be confusing to name the pediments after geographic locations, and it is therefore proposed to name the individual features from the approximate elevation at which they are found.

3. The surfaces have been divided into two groups, the Upper and Lower Pediments. The Upper Pediments commonly occur as narrow and discontinuous remnants of features cut into the middle section of the Andean Flank. The Lower Pediments are represented by relatively extensive and continuous surfaces found in the coastal area and the lower Andean Flank.

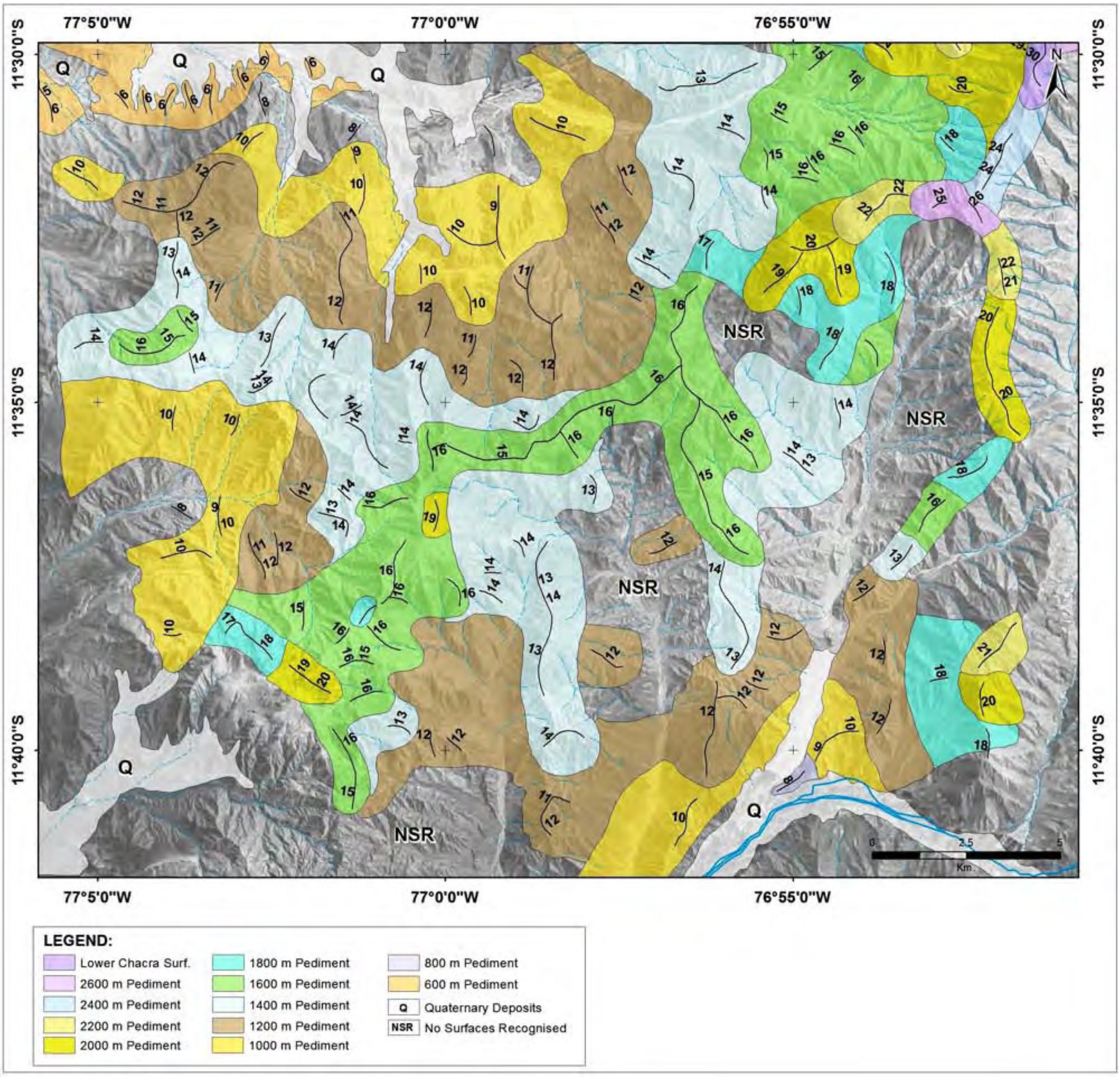


Figure 5. Map of erosion surfaces between the lower course of the Río Chillón and the Quilca area.

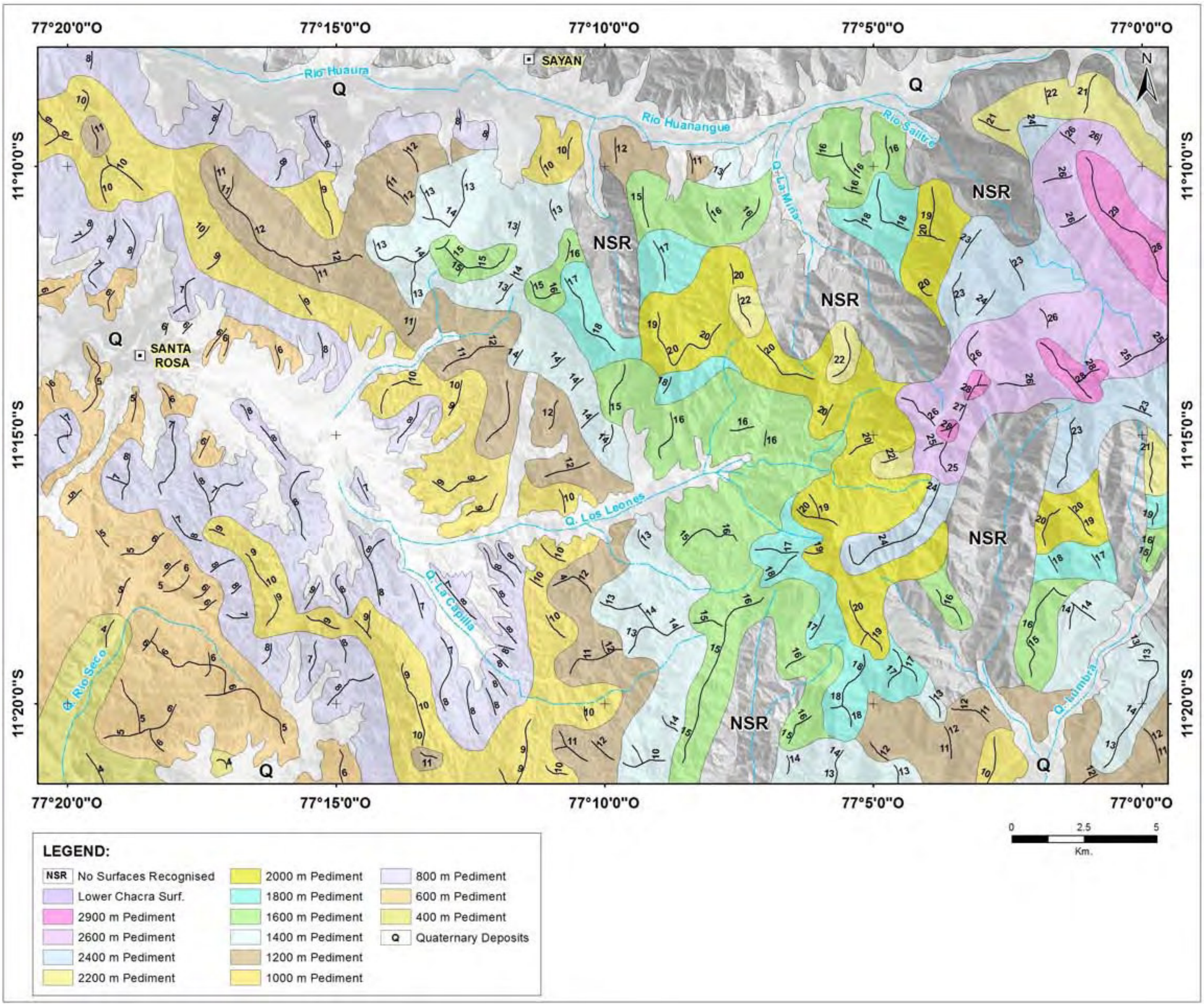


Figure 6. Map of erosion surfaces between the Río Seco and the Río Huaura.

4. It may be noted that the fragmentary nature of the Upper Pediments in some areas, and the local absence of individual surfaces, makes it difficult to recognise a coherent sequence of features in a single area. However, observations in a variety of quadrangles, as in the present study, permit the establishment of a whole series of pediments which can be recognised with reasonable confidence over a wide area. The author has thus identified, in unpublished studies, individual members of the Upper Pediments in the Casma–Santa Rosa and the Chepén–Chongoyape areas.

5. Although various of the pediments can be found extending up the main valleys, they are generally best preserved in the divides separating the drainage systems, where individual pediments can extend for distances of 10 km or more. Thus in the area south of the Río Huaura (Fig. 7), both the 1000-m Pediment and the 1200-m Pediment form divides for ~12 km and ~6 km respectively. Similarly, the Chacra surfaces also form quite extensive parts of divides (Figs. 3, 4, 8).

6. It is common to find that some interfluves contain outliers of higher surfaces which have otherwise been destroyed by erosion. Thus Figure 6 illustrates a remnant of the 1400-m Pediment almost 15 km west of the main body of this feature. These outliers are useful in confirming the previously greater extent of specific erosional surfaces.

7. A particularly interesting outlier is shown in Figure 9, where a remnant of the 1600-m Pediment rises above a variety of lower, younger, features. The outlier is ~20 km west of the main surviving part of the pediment, and lies only ~12 km from the coastline. This has significant structural implications, which are considered below.

8. In their lower courses the main rivers generally occupy narrow valleys incised into one or other of the Lower Pediments. The lower course of the Río Fortaleza is a good example, flowing through a trench ~1 km wide and ~300 m deep which has been cut into the 400-m Pediment (Fig. 9). A similar situation prevails in the lower course of the Río Huarmey (Fig. 6) and in the Río Huaura in the area west of Figure 7.

9. On following the main rivers and their tributaries upstream the depth of incision increases dramatically, being commonly in the range 1000–2000 m. The intensive erosion has led to the formation of the deep canyons which characterise the middle portion of the Andean

Flank. This process has destroyed much of the pre-existing erosion surfaces, such that in the mid-flank area they are mainly restricted to the interfluves. In Figures 3 to 9 these areas devoid of recognisable pediments have been left blank.

The deep valleys formed by the incision of the river systems were referred to by McLaughlin (1924) as the Canyon Stage, which he interpreted as being the result of a major phase of uplift of the Andean Block. It now appears that in fact the canyons were formed by the cumulative incision resulting from multiple phases of erosion, which are represented by separate pediments in the distal portions of the valleys.

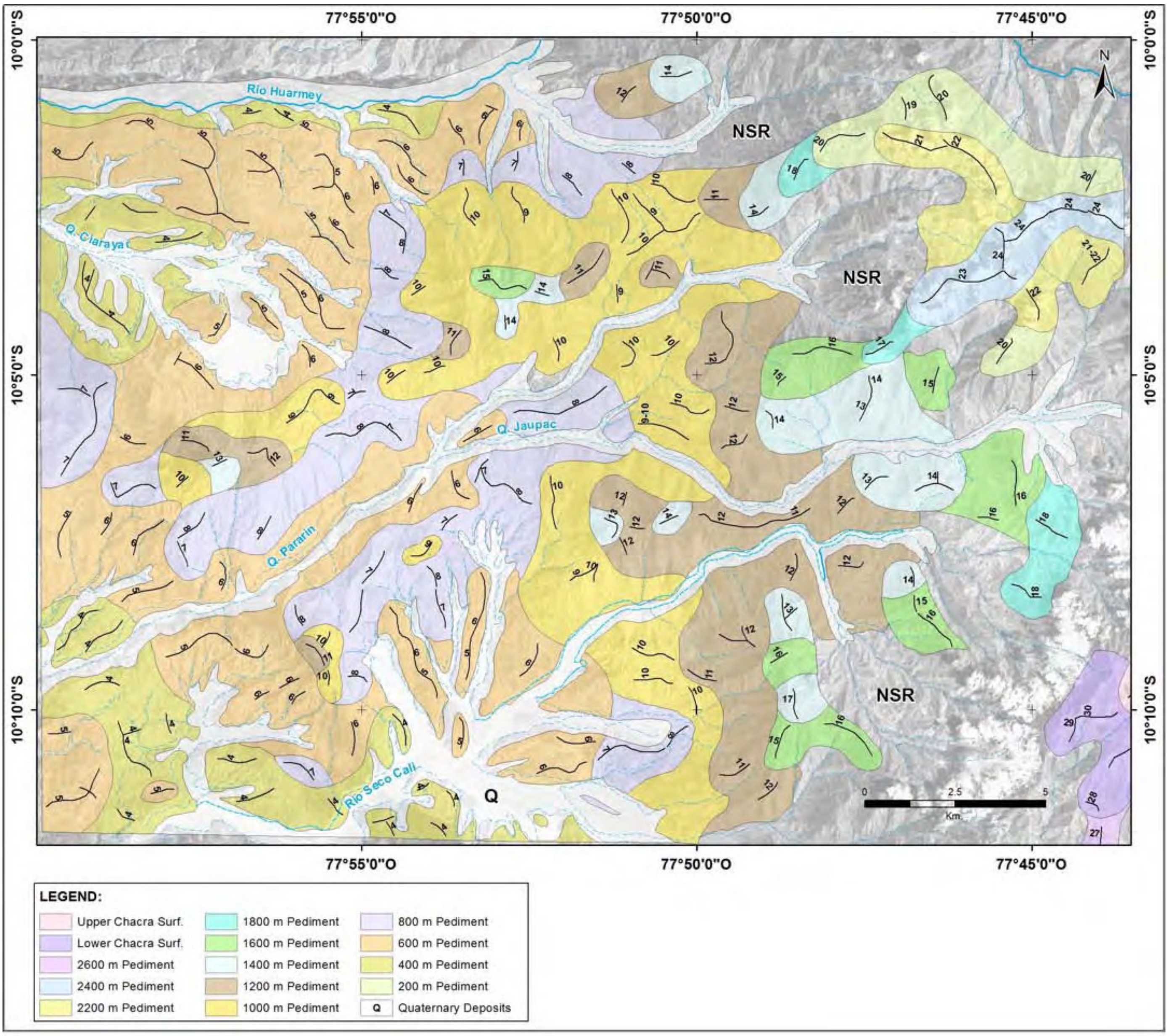


Figure 7. Map of erosion surfaces between the Río Seco (Cali) and the Río Huarmey.

4. Erosion surfaces

McLaughlin (1924) recognised a series of erosional benches along the flanks of the main valleys forming part of the Atlantic drainage in central Peru, though without precisely defining their elevations. The features were named the Chacra Stage because of the concentration of farms (*chacras*) associated with them. The current study shows that comparable surfaces also occur in the Pacific flank, and in fact comprise two separate features named here as the Upper and Lower Chacra surfaces.

There now follows a description of the individual erosional features recognised in the study area.

4.1. Chacra surfaces

4.1.1. Upper Chacra Surface

This feature comprises a gently undulating surface in the range 3100–3300 m, and with an average elevation of ~3200 m. It is particularly well developed in the Huamantango area on the north flank of the Río Chillón (Fig. 3), where it forms a 5 km-wide platform which is the site of many small farms. The surface is separated by scarps from both the Jauja Surface and the Lower Chacra Surface.

The Upper Chacra Surface is also preserved in interfluves near Sumbilca (Fig. 3), near Jicamarca (Fig. 4), and in the flanks of quebrada Shanan (Fig. 8), where it is represented by subhorizontal ridge tops separated by scarps from the adjacent features.

The surface has also been recognised in the upper reaches of the Fortaleza valley, where it is partially covered by ignimbrites.

4.1.2. Lower Chacra Surface

This surface is also well represented in the northern flank of the Chillón valley (Fig. 3), where it occurs as a series of concordant ridge tops at 2800–3000 m. The feature is normally separated by scarps from the Upper Chacra Surface and the 2600-m Pediment, though the lower limit is commonly a profound scarp falling more than 1000 m to the current river level.

The Lower Chacra Surface shows the same general characteristic elsewhere in the study area, where it occurs as subhorizontal ridge tops in several interfluves (Figs. 3, 4). Although the individual ridge tops rarely exceed 5 km in length, the presence of outliers at 2800–3000 m confirms the previously greater extent of the surface (Figs. 3, 7).

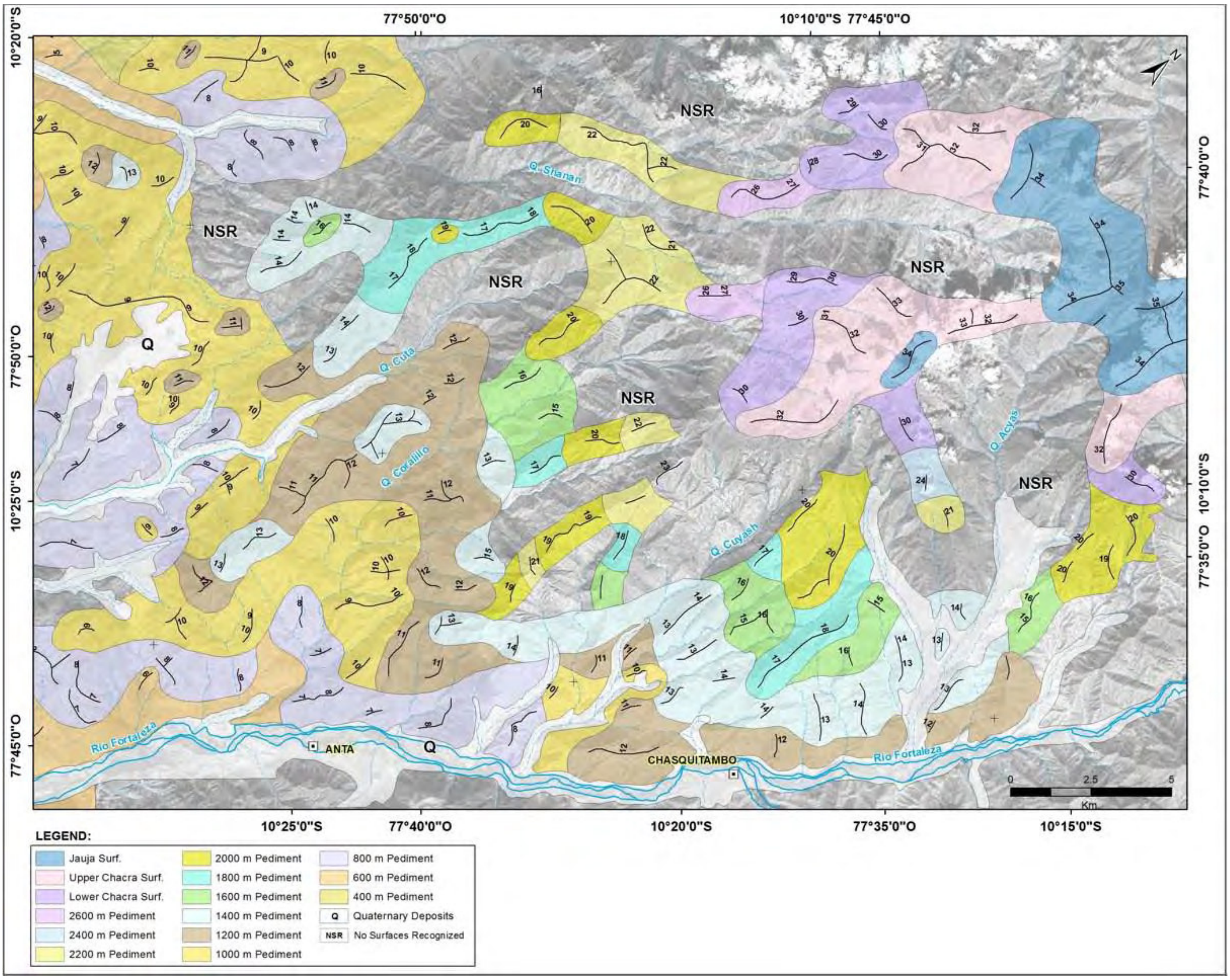


Figure 8. Map of erosion surfaces between the Río Fortaleza (Chasquitambo) and the quebrada Shanan.

4.2. Upper Pediments

The Upper Pediments are made up of six erosional features occurring in the range ~1500–2700 m. They are found mainly in the interfluves of the mid-Andean Flank and also occur as benches in the main river valleys. While most of the pediments are reasonably well preserved in the study area, some have been largely destroyed by later erosion. Despite occurring in restricted areas, these pediments are separated by scarps from adjacent features, and merit being considered as separate entities. Moreover, reconnaissance suggests that they occur in many other areas of the Andean Flank.

The individual features can be described as follows:

4.2.1. 2600-m Pediment

The 2600-m Pediment occurs as a defined feature in the interfluves illustrated in Figures 3 and 4, where it forms a series of subhorizontal ridge tops at ~2500–2700 m. In Figure 3 the ridge tops extend for 4–5 km and form a clearly defined “step” between the Lower Chacra Surface and the 2400-m Pediment, from which they are separated by scarps. Similar relationships can be observed in Figure 4. The 2600-m Pediment is also quite well preserved in the eastern sector of Figure 7, where it surrounds isolated remnants of the Lower Chacra Surface. Here again, the feature is separated by scarps from the adjacent pediment.

The 2600-m Pediment is poorly represented in the mid-Andean Flank covered by Figure 8, but can nevertheless be recognised in the interfluves bounding the quebrada Shanan.

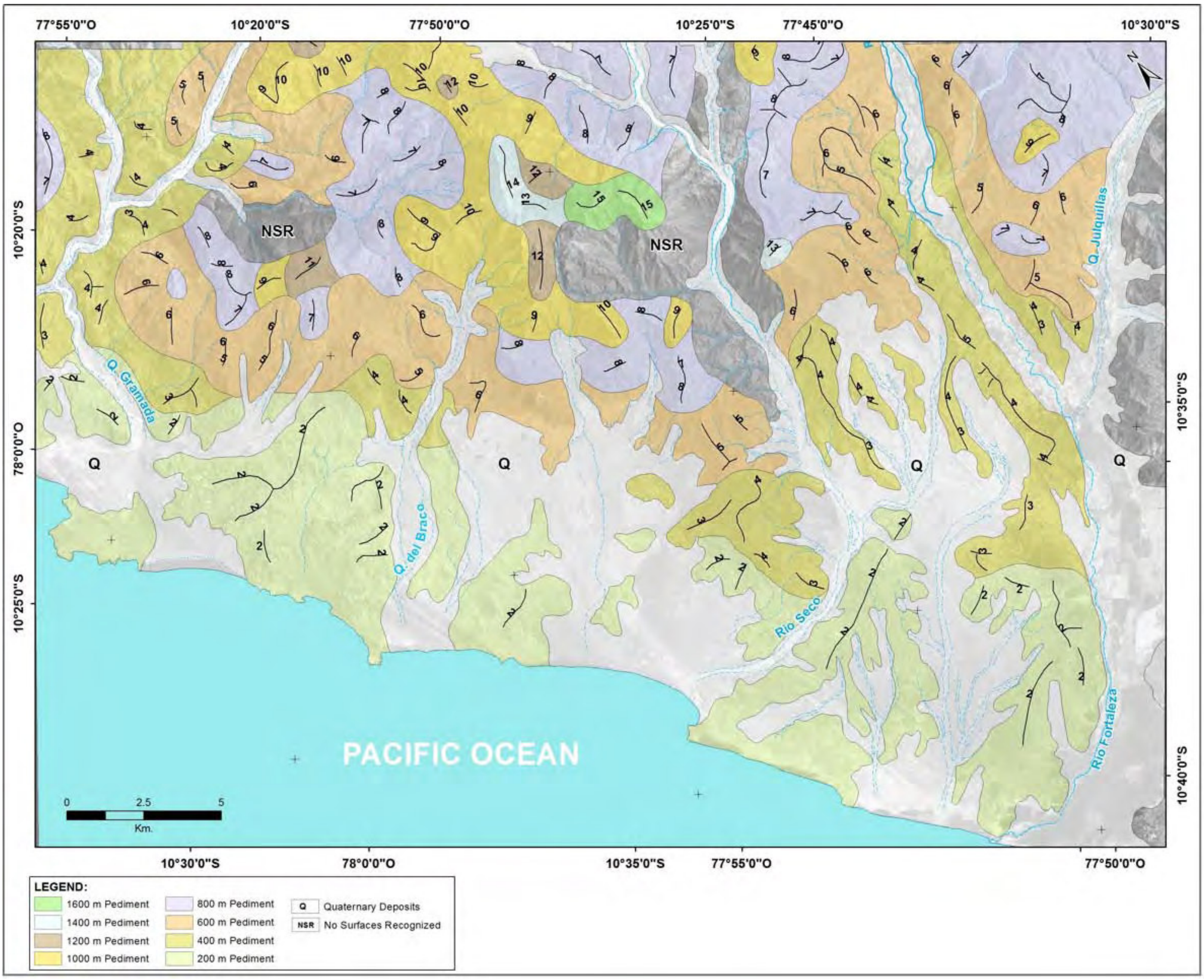


Figure 9. Map of erosion surfaces between the lower course of the Río Fortaleza and the quebrada Gramadal.

4.2.2. 2400-m Pediment

This pediment is best preserved in the area covered by Figure 7, where it is represented by a series of ridge tops in the range 2300–2400 m. These features form a defined “step” between the 2600-m Pediment and lower features, from which they are separated by scarps.

The 2400-m Pediment is less well preserved elsewhere in the study area, being represented only by a number of small remnants (Figs. 3, 4, 6, 8). These remnants nevertheless show the same characteristics as the more extensive areas of the pediment, and indicate the previously widespread development of the feature prior to subsequent erosion.

4.2.3. 2200-m Pediment

This pediment is not well preserved in the study area, though enough remnants remain to confirm that it forms a separate feature in the Andean Flank. The pediment occurs in the area covered by Figure 7, where ridge tops at 2100–2200 m form an erosional bench separated by scarps from the 2000-m and 2400-m pediments. A comparable situation is represented in Figure 8, where ridge tops at 2100–2200 m form step-like features extending for ~5 km in the interfluves bounding quebrada Shanan. In this case the 2400-m Pediment has been completely eroded, such that the 2200-m Pediment directly abuts the 2600-m Pediment.

The pediment is poorly preserved elsewhere in the study area, though it can be recognised in Figures 3, 4, 5, and 6, where it shows the same characteristics as outlined above. The area south of Río Huanangue (Fig. 6) is noteworthy in containing a number of “islands” of the 2200-m Pediment rising above the 2000-m Pediment, illustrating the previously greater extent of the feature.

4.2.4. 2000-m Pediment

Within the study area the 2000-m Pediment is best preserved in the southern limit of the Río Huanangue drainage (Fig. 6), where for a distance of ~10 km the divide is formed by a surface at 1900–2000 m. The feature is separated by scarps from a number of lower and higher pediments.

Remnants of the pediment are also recognised in the areas represented in Figures 3, 4, and 8, where they generally form step-like features at 1900–2000 m in the divides separating elements of the drainage systems.

The area represented in Figure 5 is interesting in that isolated ridge tops at 1900–2000 m are found ~15 km west of the nearest sizeable remnant of the pediment, again indicating a more widespread development of the feature in the past.

4.2.5. 1800-m Pediment

Scattered throughout the study area are subhorizontal ridge tops and erosional benches at 1700–1800 m, clearly separated by scarps from adjacent features, and which are here referred to as the 1800-m Pediment. A good example occurs in the area between quebrada Colca and the Rímac valley (Fig. 4), where the pediment forms the divide for a distance of over 5 km and is separated by scarps from the 1600-m and 2000-m pediments.

Comparable situations can be observed in the Fortaleza valley and on the southern flank of the Shanan valley (Fig. 8), where once again this pediment forms sections of divides several kilometres in length. Elsewhere the pediment is preserved only as small and commonly isolated remnants.

The previously greater extent of the pediment is indicated by the presence of an outlier at the head of quebrada Inocentes (Fig. 5), ~16 km west of other remnants of the feature.

4.2.6. 1600-m Pediment

This pediment is present throughout the study area, but is best preserved in the areas covered by Figures 5 and 7. Thus it occurs as a clearly defined erosional feature on the south flank of the Huamangue valley and also in the Andean Flank (Fig. 7), being represented by a series of concordant ridge tops at 1500–1600 m, which are separated by scarps from both the 1400-m and the 1800-m pediments. In the southern sector of Figure 7 the pediment forms a divide between two minor drainage systems over a distance of 5–6 km.

A similar situation is revealed in Figure 5, where the 1600-m Pediment forms an interfluve extending for ~15 km. Small, scarp bounded remnants of older, higher pediments rise above the 1600-m Pediment, which is itself separated by scarps from a variety of lower features.

It is also noteworthy that the westernmost remnants of the 1600-m Pediment in Figure 5 lie only ~15 km from the beach.

Elsewhere in the study area the pediment is represented by erosional benches at 1500–1600 m on the flanks of valleys. These benches can be small and/or isolated (Figs. 6, 8), though elsewhere they can occupy more extensive areas of the valley flanks, as in the case of the Rímac (Fig. 4).

4.3. Lower Pediments

The Lower Pediments comprise seven erosional terraces ranging in elevation from near sea level to ~1400 m and are quite well preserved in the lower Andean Flank. They are found as sets of concordant ridge tops in the flanks of the main valleys and their tributaries, and also in the divides separating the drainage systems. They can be described as follows.

4.3.1. 1400-m Pediment

This feature is well represented in the area covered by Figure 5, where it occurs in divides separating the Chillón and Chancay drainages. It forms an E-W-trending section of the main divide, and also occurs as a subhorizontal ridge top immediately west of quebrada Quilca (Fig. 5). In both cases the ridge tops lie in the range 1300–1400 m for 7–10 km and are separated by scarps from the 1600-m Pediment and the 1200-m Pediment.

The 1400-m Pediment is also quite well preserved in the Huaura valley immediately south of Sayán, where it is again represented by a group of concordant ridge tops at 1300–1400 m (Fig. 7). The pediment also occurs as an erosional terrace cut into the Andean Flank and now reduced to a narrow remnant (Fig. 6). Outliers of the pediment occur up to 15 km west of the main body of the feature (Figs. 8, 9).

4.3.2. 1200-m Pediment

This pediment is well developed in the southern flank of the Huaura valley, where it is preserved as a more or less continuous ridge top lying at ~1100–1200 m for ~5 km (Fig. 7). To the east the pediment is separated by a scarp from the 1400-m Pediment. The lower limit is a scarp leading down to the 1000-m Pediment, as can be seen to the north of Santa Rosa and in the area of quebrada Los Leones (Fig. 7).

The pediment also occurs as an erosional terrace preserved in parts of the Andean Flank (Figs. 6, 8), with the same characteristics as seen in the Huaura valley. It is quite well represented south of Quilca (Fig. 5), where concordant ridge tops at 1100–1200 m occur in a belt 4-5 km wide. The pediment is also recognised in the Fortaleza valley and forms the divide between the quebradas Cuta and Coralillo for several kilometres (Fig. 8).

Outliers of the 1200-m Pediment occur at up to 12 km west of its main area of preservation, for example in the coastal belt north of the Río Fortaleza (Fig. 9).

4.3.3. 1000-m Pediment

The best example of this pediment in the study area is found on the south side of quebrada Los Leones (Fig. 7), where it forms a more or less continuous ridge top at 900–1000 m for a distance of ~2 km. It is separated by a scarp from the 1200-m Pediment to the west, while the lower limit is a scarp separating the feature from a quite extensive area characterised by ridge tops at 700–800 m (Fig. 7).

The pediment is also well preserved in the area north of the Río Fortaleza (Fig. 9), where it forms part of the divide between the quebrada Gramadal and Río Seco valleys, and shows the same characteristics as in the Los Leones area..

The 1000-m Pediment also occurs as a well-defined feature in the Andean Flank, being particularly well preserved in parts of the areas covered by Figures 6 and 8.

4.3.4. 800-m Pediment

This pediment occurs as a defined erosional feature which penetrates up the main river valleys and their tributaries, and marks the beginning of a phase of incision which further accentuated the existing drainage pattern. Good examples of the 800-m Pediment can be found in the Huaura valley (Fig. 4) and in the Fortaleza valley (Figs. 8, 9). In both cases the pediment forms a bench between the river flood plains and higher surfaces, locally abutting directly against the 1200-m Pediment. Further downstream in the Fortaleza valley, it is separated by a scarp from the 600-m Pediment.

The pediment is also present in the quebrada Los Leones area, where it is represented by an abundance of ridge tops at 700–800 m (Fig. 7). In the upstream section of the quebrada, the ridges are almost buried by Quaternary alluvial material, though further downstream they can be seen to be separated from the 600-m Pediment by a scarp.

The relationship between the 800-m and the 600-m pediments is well displayed in the more distal portion of the Fortaleza valley (Fig. 9), where there is clear separation of the two features. A similar situation can be observed in the Río Seco–Calli area in the southern sector of the area covered by Figure 6, where 3 km-long, subhorizontal ridge tops at 500–600 m terminate abruptly against the 800-m Pediment.

4.3.5. 600-m Pediment

This feature occurs in the river valleys as an erosional bench at 500–600 m. It is particularly well developed on the south flank of the Huarmey valley (Fig. 6), where it forms a plateau-like feature ~8 km in width. The upper limit is a defined scarp separating it from higher surfaces, while the lower limit is a scarp which drops down to an area characterised by ~400-m ridge tops.

The 600-m Pediment extends southwards from the Huarmey valley, parallel to the coast and extending ~7-10 km inland, until it reaches the Fortaleza valley, where an extension reaches for some distance up the valley (Fig. 9). In these areas the pediment maintains the same general characteristics as in the Huarmey valley, with abundant concordant ridge tops at 500–600 m bounded by scarps both above and below.

Finally, the pediment occurs in the Santa Rosa area (Fig. 6), where there is a quite large area occupied by concordant ridge tops at ~600 m.

4.3.6. 400-m Pediment

Although this feature is not widely preserved in the study area, it can nevertheless be clearly recognised in the lower courses of some of the river valleys, being incised by the current river systems. Thus it occurs in the lower Fortaleza/Río Seco valleys (Fig. 9), where it is represented by a series of linear ridges at elevations of 300–400 m which terminate quite abruptly against the 600-m Pediment. The lower limit is a scarp separating the feature from the 200-m Pediment.

A similar situation can also be observed in the quebrada Gramadal area (Fig. 9).

The 400-m Pediment occurs as a narrow erosional bench between the channel of the Río Huarmey and the higher ground to the south (Fig. 6), and can be observed on both flanks of the valley downstream of the area covered by Figure 6.

A similar pattern is seen in the Huaura valley to the west of the area covered by Figure 7, where a bench at 300–400 m can be clearly observed on both sides of the river, as illustrated in the 1:100,000 topographic map of the Huaral (23-i) sheet.

4.3.6. 200-m Pediment

Within the study area this feature is recognised only in the area north of Paramonga (Fig. 9), where it occupies a ~5 km-wide belt extending inland from the beach. The pediment comprises an erosional bench at 100–200 m cut into the volcanics of the Casma Group. The inland boundary is a scarp separating the feature from the 400-m Pediment, while the seaward boundary is a discontinuous cliff system.

The pediment has been incised by the existing rivers, both those with a permanent flow, *e.g.* the Río Fortaleza, and those with only an intermittent discharge, *e.g.* the Río Seco and quebrada del Braco. The river channels are 150–200 m-deep and up to several kilometres wide, and have a partial infill of conglomeratic alluvial debris.

Outside of the study area, the 200-m Pediment can be observed in the area covered by the Casma sheet, bevelling bedrock on both sides of the Panamerican Highway to the south of the Río Samanco, and is also quite well developed along the coastal strip in the area covered by the Huarmey geological sheet.

5. Correlations

The general correlation of the surfaces identified in this study with the features found elsewhere in the Andean Flank of central Peru is illustrated in Figure 10. The suggested correlations are based on the average elevations and general characteristics of the various features, and should be regarded as provisional until their lateral continuity can be established.

It is noteworthy that there appears to be a broad correlation of erosional features recognisable from Ica into northern Peru. The main difference established by this report is the subdivision of the major features recognised by Myers (1976) and Wilson (2009), leading to a more detailed picture of the morphology of the Andean Flank.

The general situation can be described as follows:

1. Although Myers (1976) considered his Cochapunta Surface as part of the Puna Surface, it is now clear that it in fact corresponds to the Jauja and Chacra surfaces of this study. Similarly, the Huamandioja Surface of the Ica region occurs at the same elevation and has the same characteristics as the Lower Chacra Surface, while the Trigopampa Surface includes both the Upper Chacra and the Jauja Surfaces.

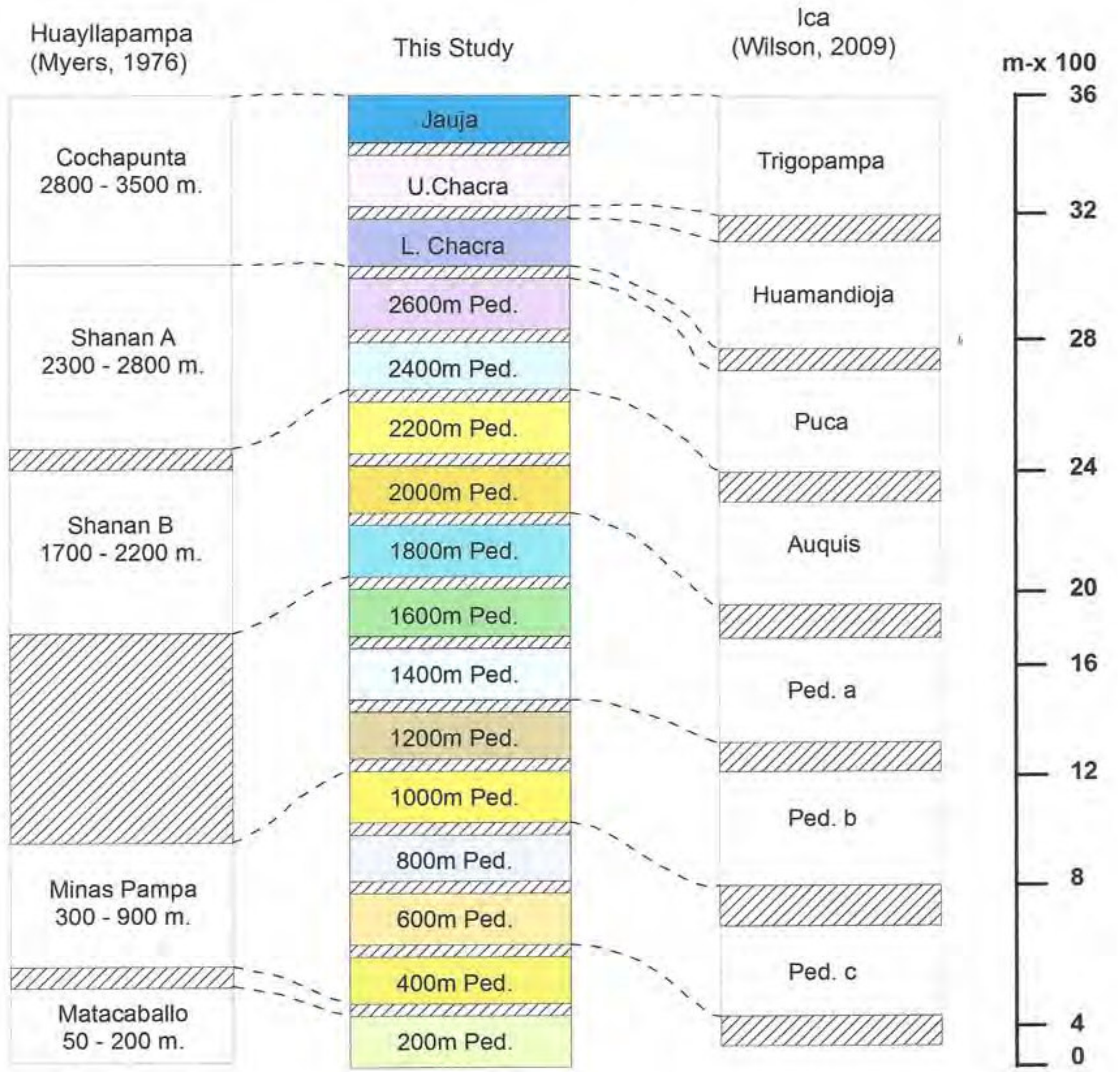


Figure 10. General correlation of erosion surfaces in the Andean Flank of south-central and north-central Peru.

2. Myers' (1976) Shanan A Surface corresponds to the Puca Surface of Ica (Wilson, 2009), and to the 2400-m and 2600-m pediments of this study.

3. The Shanan B feature correlates broadly with the Auquis Surface of Ica, and can be clearly differentiated in the study area into the 1800-m, 2000-m, and 2200-m pediments.

4. Myers (1976) did not recognise any mappable surfaces between ~900 m and ~1700 m, largely because the pediments established in that interval in the study area are poorly preserved in the area covered by the Huayllapampa geological sheet. Nevertheless, with the benefit of having examined a larger area, the 1200-m, 1400-m. and 1600-m pediments can be recognised in the Huayllapampa area.

5. The Minas Pampa Surface at 300–900 m (Myers, 1976) can be subdivided into the 400-m, 600-m, 800-m. and 1000-m pediments, while the Matacaballo Surface corresponds directly to the 200-m Pediment.

Pediments a, b, and c of the Ica region (Wilson, 2009) are provisionally correlated, on the basis of their similar elevations, with the surfaces lying between 1800 m and 600 m in this study area.

6. Ages of the erosion surfaces

The ages of the erosion surfaces described above remain to be established. Meanwhile, the current state of our knowledge can be summarised as follows:

1. Two samples of the Fortaleza ignimbrite have been dated using the ^{40}Ar-^{39}Ar method. The analytical data are

given in the Appendix and indicate ages of ~5.5 Ma for both samples.

One sample was obtained at 1454 m on the west flank of Cerro Uchu Uchu (Huayllapampa sheet: N 8873150, W 219725), in an area where the ignimbrite mantles an erosion surface at ~1400 m. The surface, its back scarp, and the ignimbrite covering can be clearly seen from the Llacllín road near to its junction with the main highway. This outcrop forms the current downstream limit of the Fortaleza Formation.

Myers (1976) quoted a K-Ar date of ~5.8 Ma for a sample of the Fortaleza Fm from an unspecified locality, but probably in the same general area as our sample.

It can be concluded that the 1400-m Pediment predated ~5.5 Ma

2. The other sample of the Fortaleza Fm was obtained at 3774 m on the northern flank of Cerro Inca Huagansa (Chiquián sheet: N 8875780, W 2444299), near the eastern limit of the Río Fortaleza drainage. As this sample is also dated at ~5.5 Ma it appears that the Fortaleza Fm may be the result of a single episode of ignimbrite activity. The relationship of the Fortaleza Fm to the underlying erosion surfaces will be examined in a separate paper.

3. The Jauja Surface is recognised in the northern flank of the Fortaleza valley (Fig. 8) and is quite well developed in the upper reaches of the valley, where it is locally mantled by the Fortaleza Fm. Wilson (2009) estimated the age of the surface in central Peru at ~8 Ma on the basis that it is mantled by the Rumihuasi tuff dated at ~7.3 Ma (Mégard, 1984).

Unpublished studies by the writer in the Santa valley support this general age. Thus in the area immediately south of the village of Parón (Carhuaz sheet) the crest of Cerro Huandoy is an erosional feature cut into Cretaceous sediments at 3400–3600 m and which is correlated with the Jauja Surface. The feature is cut by a N-S fault which juxtaposes the Cretaceous sediments against the Yungay tuff. The latter has been dated at 6.4–7.8 Ma (Cobbing et al., 1981) and at ~7.1 Ma (Wise & Noble, 2003).

These data confirm that the Jauja Surface is older than ~7 Ma, and an estimate of ~8 Ma seems reasonable as a minimum age, though it would not be surprising if further work suggested a slightly greater age.

It may also be mentioned that elsewhere in the Santa valley the Yungay tuff has been bevelled by elements of the Chacra surfaces. Thus in the southern sector of the Corongo sheet, the village of Huaripampa sits on an erosional feature cut into the Yungay tuff at 2800–2900 m, and which is correlated with the Lower Chacra Surface, which must therefore have a maximum age of ~7 Ma.

If, as suggested above, the Jauja Surface (~3600 m) formed at ~8 Ma and the 1400-m Pediment at ~5.5 Ma, it implies an average rate of uplift of almost 0.9 mm/yr, without taking into account the pauses required to allow for the development of the intervening erosion surfaces. In contrast, the average rate of uplift implied for the interval between the Jauja Surface (~3600 m, ~8 Ma) and the Puna Surface (~4800 m, ~16 Ma) amounts to ~0.15 mm/yr. Similarly, the average rate between the formation of the 1400-m Pediment (~5.5 Ma) and the present-day sea level amounts to ~0.25 mm/yr.

The above average rates of uplift are based on very limited data and should be used with great caution. Nevertheless, even if the assumed ages of the surfaces are significantly in error (for example if the 1400-m Pediment and the Jauja Surface are respectively ~6 Ma and ~9 Ma), the average rates of uplift would still be much greater than those which apparently characterised the time intervals before and after formation of those surfaces.

An accelerated rate of uplift in the interval ~8–5.5 Ma, and the attendant increase in erosion, could possibly explain the relatively poor preservation of the Upper Pediments (1600–2600 m) in many areas.

The reason for any acceleration of uplift in the time frame mentioned above remains to be resolved. It could be a result of a temporary increase in the rate of convergence. Alternatively, it may be noted that the interval partly coincides with the subduction of the Nazca Ridge beneath the Andean Belt in northern Peru, and it can be speculated that the rate of uplift was affected by this event.

7. Structural considerations

7.1. Geometry of the Andean uplift

In parts of southern Peru, the Andean Flank can be observed to be a tilted surface leading up to the Altiplano. McLaughlin (1924) and Myers (1976) both assumed that a similar situation had prevailed in central Peru, with the uplift having been achieved as a result of tilting about an axis located near the present coastline. Nevertheless, Wilson (2011) observed that in central Peru the Puna Surface is essentially horizontal for tens of kilometres west of the crest of the Western Cordillera, and suggested that the Andean uplift could have involved significant faulting along the coastline. The current study confirms that significant faulting must have occurred near the coastline for the following reasons:

1. No significant tilt can be recognised in the erosional surfaces observed in this study. Thus there are several examples of outliers occurring 10–15 km west of the main body of a specific surface, yet occurring at the same elevation, implying that there has been no significant tilting since the formation of that surface. A good example occurs in Figure 5, where an outlier of the 2000-m Pediment occurs 15 km southwest of other remnants of the feature, yet at the same elevation. A tilt of only 2 % over that distance would imply a difference of ~300 m in elevation. The fact that the fragments of the 2000-m Pediment are united by a more or less continuous remnant of the 1600-m Pediment provides further support to the concept that tilting was not a major element in the Neogene uplift of the Andean Flank in central Peru

2. On the other hand, the outliers suggest that fault controlled uplift has been a significant mechanism. Thus it would be difficult to explain the presence of an outlier of the 2000-m Pediment (Fig. 5) at only 17 km from the coast as a result of tilting. In fact, there has been historical faulting near the beach in the Chancay area.

It can be concluded that, while some tilting may have occurred, the uplift of the Andean Block in the study area involved a significant amount of faulting near to the coastline. No post-Puna Surface faulting has been recognised within the Andean Flank itself.

7.2. Mechanics of the Andean uplift

The precise nature of the mechanics controlling the uplift of the Andes in central Peru remains to be established. It is clear, however, that any preferred tectonic model has to explain:

a) the fact that the episodes of uplift were apparently simultaneous and involved the same amount of vertical displacement across the whole Andean Block in central Peru, and

b) the fact that, following the development of the Jauja Surface, most of the subsequent episodes resulted in individual uplifts of ~200 m. While the uniformity of the amount of uplift does not necessarily imply a similar degree of uniformity in the periodicity of the episodes of uplift, it is nevertheless an important characteristic of the Andean uplift.

Some of the potential mechanisms can be summarised as follows:

1. During the Neogene, crustal thickening led to the gradual formation of a ~55 km-thick root beneath the Western Cordillera (Fukao & Yamamoto, 1989). The development of this root must have led to the progressive rise of the Western Cordillera in the course of the Neogene. The area is now in isostatic equilibrium.

However, the Eastern Cordillera does not appear to have a root and is not in isostatic equilibrium (Fukao & Yamamoto, 1989), yet has been uplifted to virtually the same elevation as the Western Cordillera. Crustal thickening therefore cannot be the only mechanism involved in the uplift of the Andean Belt.

2. The Andean uplift in central Peru may also be a response to plate convergence, with the whole of the Andean Block having been uplifted as a single tectonic unit within a regional compressive regime caused by the opposing pressures generated by the Nazca Plate and the Brazilian Shield.

Under this scenario the episodic nature of the phases of uplift could be explained as a result of the rapid release of pressures which had slowly accumulated within the Andean Block as a result of plate convergence. Thus the phases of uplift may have been triggered by the accumulated pressures having reached a critical level, the time required to achieve that level being a function of the varying rates of plate convergence.

In the case of the Western Cordillera, it is suggested that the uplift generated by the development of the root system was occurring in a regional compressive regime, and that the timing and amount of specific episodes of uplift were in fact controlled by the mechanism outlined above.

With regard to the Eastern Cordillera, it is suggested that its uplift is a direct consequence of the pressures generated as a result of the plate convergence outlined above. Work in progress by the author indicates that the Eastern Cordillera has the same sequence of erosion surfaces as are found in the Western Cordillera, supporting the concept that the whole Andean Block was subjected to episodic uplift controlled by plate convergence.

10. Conclusions

The current study allows us to reach the following general conclusions.

1. The high-level erosion surfaces were followed by the development of fifteen separate features ranging in elevation from ~100 m to ~3300 m.

2. The surfaces reflect a Neogene structural history dominated by multiple phases of episodic uplift, each phase commonly producing ~200 m of uplift.

3. The surfaces were formed by fluvial erosion in the intervals between the phases of active uplift.

4. There is no sign within the study area of any deformation having accompanied the uplift, nor is there any evidence of coastward tilt of the individual surfaces.

5. The uplift probably involved a significant amount of faulting in the near-shore area.

6. Although much work needs to be done, it seems possible that one of the main mechanisms of the Neogene uplift was the convergence of the Nazca Plate and the Brazilian Shield, each phase of uplift being triggered by the accumulated pressures within the crust having reached a critical level.

7. It is critically important that further age data are acquired for the individual surfaces. Apart from the Puna Surface (dated at ~16 Ma), there is little firm information on dates. The Jauja Surface is considered to have a minimum age of ~8 Ma, and the 1400-m Pediment can be dated at more than ~5.5 Ma, with the ages of the intervening features being little more than guesses.

Appendix

Two samples of the Fortaleza ignimbrite, denominated GD-4 and GD-6, were analysed at the University of Nevada at Reno, USA, using the ^{40}Ar-^{39}Ar method. The analyses were funded by Cía. de Minas Buenaventura and were supported at the University of Nevada by Prof. Donald Noble. The full information on these two samples is as follows:

GD-4. This sample was obtained from near the base of the ignimbrite on the west flank of Cerro Uchu Uchu, at an elevation of 1454 m (Huayllapampa sheet: N 8873150, W 219725).

The material consisted of greyish, partially welded tuff with phenocrysts of quartz, feldspar, and occasional biotite, and included fragments of pumice and quartzite. The biotite was separated and subjected to analysis. The analytical data are included in Table 1 and can be summarised as follows:

plateau age:	5.57 ± 0.09 Ma;
isochron age:	5.15 ± 0.20 Ma.

GD-6. This sample was obtained from a block at the base of a cliff formed by the Fortaleza Fm on the northern flank of Cerro Huagasa. It proved impossible to obtain a sample from the outcrop itself, despite strenuous efforts at a number of places. The sample was obtained above the main road to Conococha/Huaraz at an elevation of 3774 m (Chiquián sheet: N 8875780, W 244299).

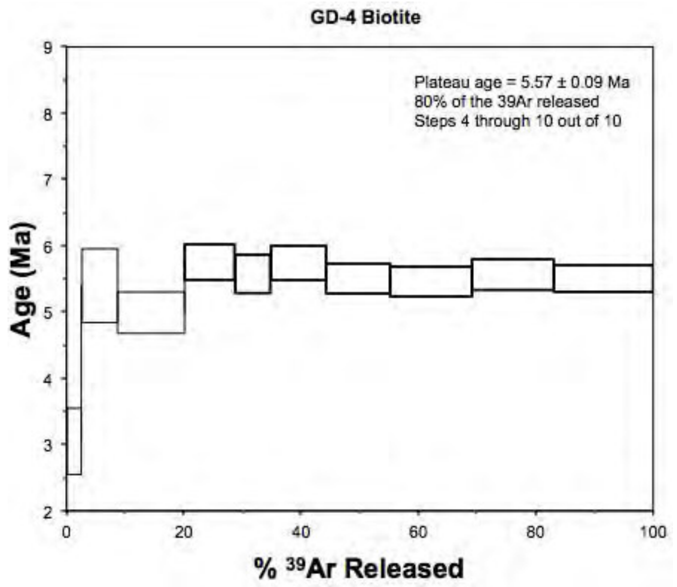
The Fortaleza Fm at this locality consists of a very hard, strongly welded tuff containing phenocrysts of quartz, feldspar, and rare biotite, as well as subangular fragments of quartzite. The analytical data on the biotite separated from the sample are included in Table 2 and can be summarised as follows:

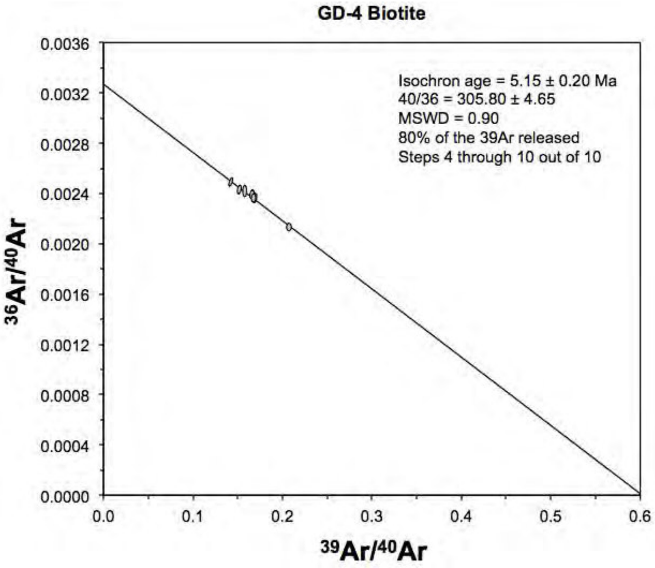
plateau age: 5.30 ± 0.07 Ma;
isochron age: 5.35 ± 0.04 Ma.

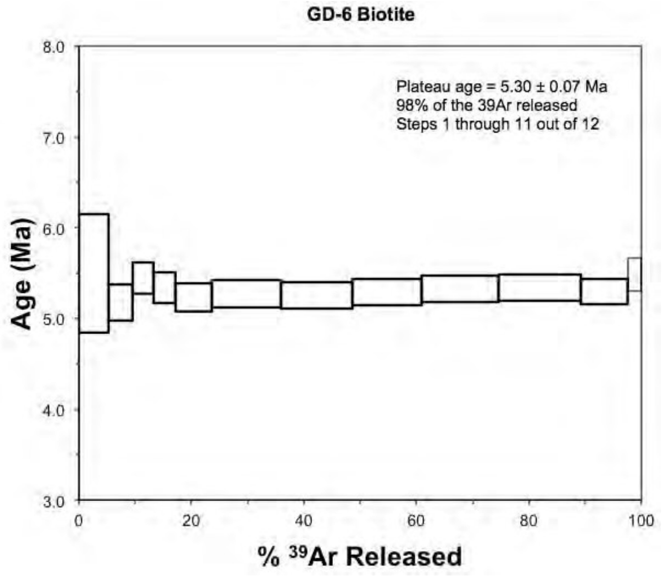
Prof. Donald Noble regards this as an accurate age for this part of the Fortaleza Fm (e-mail communication, 17 July, 2015).

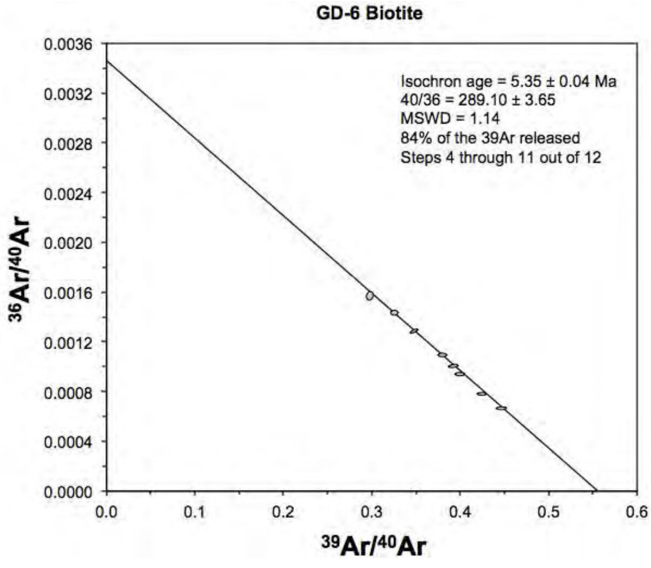
Discussion of age data. Myers (1976) also mentioned a K-Ar age of 5.84 ± 0.2 Ma obtained on a biotite phenocryst from a sample from the Fortaleza Fm. Although the precise location of this sample was unclear, it was probably obtained from one of the downstream outcrops of the unit in the area covered by the Huayllapampa sheet, and therefore close to GD-4.

While there is not an absolute concordance of the ages derived for the Fortaleza Fm, it is nevertheless clear that the ignimbrites accumulated during a restricted time interval. Thus although the formation may comprise more than one discrete flow, it appears to represent a single brief volcanic episode.









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