Regional planation surfaces provide an important datum for unravelling the tectonic evolution of a region. Those preserved at high altitudes in mountain belts are often interpreted as having formed at lower altitudes with subsequent uplift and dissection (Walker 1949; Hollingworth & Rutland 1968; Molnar & England 1990). Thus, planation surfaces may provide clues to the timing and amount of surface uplift, placing important constraints on dynamic processes in the lithosphere, if their origin and evolution are well understood. In this respect, it is important to understand both the processes that caused planation and those that lead to subsequent dissection.

In this paper we describe the geomorphology and geological context of high altitude erosion surfaces which are preserved in a vast region, up to 600 km long and 100 km wide, on the eastern flank of the Bolivian Andes. Geochronological data indicate that the surfaces formed in the interval 12–3 Ma, with most surface cutting probably pre-dating c. 9 Ma. They cut across regional shortening structures of Eocene to middle Miocene age and are now at altitudes between 2000 and 4000 m. The presence of widespread horizontal remnants suggests strongly that they have not been subsequently tilted and that the relative altitudes seen today are an original feature. Deep dissection of these surfaces only occurred in the last 3 Ma. We believe that the origin and dissection of these surfaces places important constraints on the timing, amount and nature of surface uplift in the Bolivian Andes.

Servant et al. (1989) have outlined the morphology of palaeosurfaces in the central part of the Bolivian Andes, identifying distinct phases of pediment formation and fluvial dissection. However, their work lacks precise chronological data. The morphology of palaeosurfaces in the southern part of the Cordillera Oriental has been described by Gubbels et al. (1993), who also present new geochronological data constraining the timing of surface formation and dissection. We have mapped palaeosurfaces over a much wider area of the Cordillera Oriental than previous workers. Here, we integrate our own observations of surface morphology with previous work (Gubbels et al. 1993) and with new geochronological data (Kennan et al. 1995) to reach a better understanding of how the surfaces developed through time. Finally, we discuss the links between the palaeosurfaces and tectonics and, possibly, climate change in this part of the Andes.

Geological setting
The Central Andes are the result of oblique subduction, since the Cretaceous, of the Nazca (or Farallon) plate beneath the western margin of South America (Pardo-Casas & Molnar 1987). The western edge of the South American plate has been...
thickened from c. 35 km to up to c. 75 km (James 1971; Wigger et al. 1993; Dorbath et al. 1993), mainly as a consequence of tectonic shortening, with subordinate magmatic addition (Sheffels 1990; Kennan 1994; Lamb et al. 1996). Deformation in the Bolivian Andes has been active since the Eocene, accommodating overall c. 330 km of shortening (Kennan et al. 1995; Lamb et al. 1996). The Bolivian Andes are traditionally subdivided into physiographic provinces (Fig. 1) in which the geological evolution has generally been distinct throughout the Cenozoic.

The Cordillera Occidental is the active volcanic arc, consisting of spaced Miocene and Quaternary dacitic–andesitic volcanoes and thick ignimbrite sheets erupted through a sequence of poorly known older rocks (Avila 1991). Further east, the Altiplano forms a c. 200 km wide region of subdued topography at an average altitude of c. 3800 m, which has been essentially a region of internal drainage throughout the Cenozoic, confined by the Cordilleras Occidental and Oriental. Erosion of these two ranges has supplied 10 km or more of sediment to various depocentres within the Altiplano (Kennan et al. 1995, Lamb et al. 1996). East of the Altiplano, the Cordillera Oriental (Fig. 1) forms a rugged region up to 200 km wide, made up of Palaeozoic to Cenozoic strata and igneous rocks, with altitudes ranging between 2000 and 4500 m. The main phase of shortening in the Cordillera Oriental occurred prior to c. 12 Ma. Subsequent erosion resulted in the surfaces described in this paper. The eastern flank of the Cordillera Oriental drops abruptly towards the much lower Subandes. This is a thin-skinned fold and thrust belt which deforms foreland basin sediments deposited mainly after c. 10 Ma. There has been c. 140 km of shortening above a basal décollement in the last 10 Ma (unpublished oil company data, Roeder 1988; Héral et al. 1990; Baby et al. 1993; Wigger et al. 1993).

Mapping of surface remnants

Scattered remnants of palaeosurfaces are found throughout the eastern part of the Cordillera Oriental (Figs 2 and 3), west of the Subandeon fold and thrust belt, and south of the Cochabamba Lineament System (c. 17°S), extending as far south as the Argentinian border and beyond. Surface remnants are especially widespread south of Sucre (Fig. 2) where they have been previously studied (Gubbels et al. 1993). North of Sucre,
Fig. 2. Detailed map of the Cordillera Oriental showing the preserved palaeosurfaces (black). These clearly define north-south trending, flat-bottomed palaeovalleys, with regions in between up to 1000 m higher (grey). These surfaces drained towards the east into a foreland basin now deformed as the Subandes fold and thrust belt. Since c. 3 Ma they have been deeply dissected by rivers such as the Rio Pilcomayo and Rio Grande. The locations of dated tuffs or fossils, with altitude and age, are also shown (data from sources indicated in text).
individual surface remnants tend to be smaller. However, many of the key observations presented in this paper were made in this area.

We have mapped surface remnants and intervening higher areas using a combination of 1 : 250 000 Landsat Multispectral Scanner images, SPOT multispectral images, aerial photography and topographic maps. Most surface remnants have a very distinctive bright yellow colour on standard false-colour composite satellite images. This seems to correlate, in the field, with a marked reddening of both the bedrock and patchy, thin overlying gravel deposits and the ‘bright’ appearance is confined to surface remnants at altitudes of 2000–3800 m, providing an easy form of identification. Locally, the ‘bright-coloured’ covering has been removed by shallow, dendritic fluvial dissection. Surrounding slopes exposed during later dissection are less reddened in the field and much darker on all imagery, regardless of altitude.

The morphology and field relations of the surface were also examined during extensive fieldwork throughout the Cordillera Oriental, and tuffs where mantle surface remnants were collected and dated (Kennan 1994; Kennan et al. 1995). The surfaces appear in the field as benches, flat hill tops or plains cut directly across folded Palaeozoic to Cenozoic bedrock, either bare or with a thin covering of gravels, sands and interbedded tuffs. These cover sequences are generally much less than a few tens of metres thick and, in general, the bedrock planation surfaces and cover are considered together when discussing surface morphology. However, we must draw an important distinction between the time at which the surfaces were cut and the age of the cover. In many cases, several millions of years probably elapsed between surface cutting and cover deposition, and there may be no genetic link between the two. Locally, there are cover sequences up to 250 m thick, mostly as fans built up against highlands protruding above a surface.
Nomenclature of palaeosurface remnants

Previous workers have named two palaeosurfaces; the Chayanta Surface at c. 4000 m (Walker 1949; Servant et al. 1989) and the San Juan del Oro Surface at c. 3500–2850 m (Servant et al. 1989; Gubbels et al. 1993). This paper is concerned with the latter. The c. 4000 m Chayanta Surface is defined largely by a 100 km wide summit height accordance in the western part of the Cordillera Oriental (Servant et al. 1989). Its appearance in the field is often as low-gradient undulating ground, clearly cut by steeper, rugged gorges probably related to Pliocene and younger dissection (see below). Gubbels et al. (1993) considered these surfaces to be late Miocene. However, we believe they are considerably older. For instance, flat ignimbrite shields up to 15 km across overlie low-gradient, undulose topography at c. 4000 m in the Uncía-Challapata region (Fig. 2). These are as old as 21 Ma (Schneider 1985 in GEOBOL-SGAB 1992), suggesting the existence of regional early Miocene planation. The traditionally defined San Juan del Oro Surface is a combination of flat and gently undulose surfaces between c. 2850 and 3500 m, which cut across tightly folded Palaeozoic to Miocene rocks. However, our work indicates that, especially north of Sucre, there are also widespread and previously unmapped remnants of surfaces as low as c. 2000 m. These show the same general range of surface morphologies as the higher surfaces and appear to have formed in the same drainage system and yet they have not previously been mapped together with the San Juan del Oro Surface.

It is clear that a new terminology is required. We believe that the San Juan del Oro Surface, as defined by Gubbels et al. (1993), is part of a series of low-gradient fluvial drainage systems which we provisionally refer to under the umbrella term Cordillera Oriental Palaeodrainage Systems and which were responsible for planation. We assume that there has been no regional deformation of the palaeosurfaces and have therefore used the slope and height of the palaeosurfaces to reconstruct two separate palaeodrainage basins, separated by a watershed at c. 20° S (Fig. 3). The southern palaeodrainage basin seems to have had an outlet to the foreland at c. 21° S, while the much larger northern drainage basin had an outlet at c. 18° S. A major present day watershed between the Rio Grande system, draining into the Amazon, and the Pilcomayo system, draining into the Rio de la Plata, runs through the Sucre region, north of the ancient watershed. We suggest this is a result of the Pilcomayo cutting through a major highland (reaching over 4000 m) and capturing the southern part of the original northern drainage system.

Geochronological data (see below) suggest that the two drainage basins have been distinct throughout their histories. We describe the palaeodrainage systems in terms of subareas (Fig. 1), which facilitate description and generally divide the systems into upstream and downstream parts.

Southern palaeodrainage basin

Morphology and field relationships

The remains of the southern drainage basin are found between the latitudes 19.75° S and 22.25° S in a region up to 100 km wide in the Bolivian Cordillera Oriental and northernmost part of the Argentinian Puna. It comprises north–south palaeovalleys, up to c. 30 km wide and at altitudes between 3800 and 3000 m, surrounded by steep-sided highlands reaching over 4000 m (Fig. 2). There are distinct ‘palaeotributaries’ which appear to follow the present river systems such as the Rio San Juan del Oro and also the tributaries and main stem of the Rio Tumusla. The heads of these palaeotributaries are separated by gentle watersheds from each other, from low-gradient drainage into salar basins in the Argentinian Puna to the south and from the northern palaeodrainage basin (Fig. 2).

All the palaeotributaries of this palaeodrainage system appear to drop in altitude and converge to the east, at the main outlet to the sedimentary basin in which eroded debris was deposited. In the following sections, the morphology and field relations of the palaeosurfaces are described in detail for various regions (see Fig. 1).

San Juan del Oro region (Fig. 1, region 1). The southernmost parts of the southern palaeodrainage basin, near the Argentinian border, are also the most extensive and best preserved (Fig. 4). Palaeosurfaces are found either side of the Rio San Juan del Oro (Fig. 2), mimicking its U-shaped course. Low gradient (often as low as 1 in 250) plains, up to c. 2000 km² in area, are broken by discontinuous, low strike-ridges. Surfaces are generally mantled by not more than a few tens of metres of gravel and sand cover except at their margins where gravel fans are banked as steep as c. 1 in 20 and up to c. 250 m thick. Surface altitude drops from c. 3800 m at the upstream margins to c. 3400 m at the edges of the deep gorges of the Rio San Juan del Oro and tributaries. The upper reaches of these gorges are marked by dendritic drainage networks. Away from the gorges, the drainage on the surfaces is largely unincised and some parts of the surface still drain into shallow lacustrine basins. In northernmost Argentina, the plains coalesce to
Fig. 4. Photograph looking south across gorge of Río San Juan del Oro, near Villazón. Here, the palaeosurfaces lie at c. 3500 m, are cut nearly flat across underlying Palaeozoic and Cretaceous (bright) bedrock, with some upstanding strike ridges. There is a slight tilt down into the centre of wide palaeovalleys. They are either bare or mantled by only thin gravels (with some tuffs).
define a 100 km wide flat surface which merges with the Puna across a gentle watershed at c. 3800 m, near Villazón (Fig. 2).

Ayoma–Cotagaita–Camargo region (Fig. 1, region 2). Further north, in the central part of the southern palaeodrainage basin, erosion surface remnants at c. 3000–3200 m define a north–south palaeovalley running through Cotagaita, bounded by steep-sided strike-ridges of Palaeozoic to Cretaceous strata. Although relatively recent erosion has removed the few metres of brightly reflective surface (on satellite images and aerial photographs) material from many remnants, the underlying north–south structural grain has not yet had a significant influence on the developing drainage. Surface altitude drops progressively from both the northern and southern ends of this palaeovalley towards a low point near Cotagaita. A gentle watershed at c. 3500 m separates the southern part of this palaeovalley from surfaces along the Rio San Juan del Oro valley. In the northern part of the palaeovalley, now dissected by the Rio Ayoma (see Fig. 5), the surfaces cut across steeply-dipping bedrock, with little or no sediment cover over wide areas. There are no obvious sharp steps in surface height. On the upper slopes of the Rio Ayoma valley there are thin (< 50 m) and essentially flat-lying sequences of gravels which infill shallow pre-surface valleys. The tops of these sequences are planed off at the general surface level and they may represent the product of erosion during the very early stages of surface formation. Close to its upstream margins, gradients are relatively steep, reaching 1 in 40. Surface height then drops much more gradually south towards Cotagaita, with valley-parallel gradients as low as 1 in 250 on the bare bedrock surfaces. Drainage from the surfaces in the Cotagaita region must have continued east towards Camargo along the same general course as the present-day Rio Tumusla (Fig. 2), which cuts through a ridge rising to over 4000 m. There is no other possible outlet at or below 3000–3100 m.

Otavi region (Fig. 1; region 3). Just north of Otavi, the palaeosurfaces reach an altitude of c. 3450 m at the foot of a gentle east–west watershed which defines the limit between the southern and northern palaeodrainage basins (Fig. 5). Immediately south of the watershed, topographic contours drawn on the bare bedrock of the palaeosurface clearly show a moderate dip downstream and towards the centre of a palaeovalley, now occupied by the headwaters of the Rio Ayoma. North of the watershed the palaeosurfaces drop gently north from c. 3400 m with a gradient of c. 1 in 100. The watershed can be traced to the east of the Cretaceous strata of the Otavi syncline. The highest palaeosurfaces in the

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Fig. 5. Outline topographic map of a major ancient watershed, just north of Otavi, between the southern and northern palaeodrainage basins, showing detailed present-day contours and generalized contours of palaeosurface height (bold, black). Palaeovalleys are shown in light grey and intervening high areas, composed of folded Palaeozoic to Palaeogene strata, shown dark grey. Preserved surface remnants are almost entirely devoid of sediment cover. Note that palaeosurface altitude drops gently downstream and into the centre of major north–south palaeovalleys. Recent, finer topographic detail (thin contours) is the result of post-Pliocene incision of the palaeosurfaces by the present river system.
region (Avichuca Pampa, at c. 3620 m) are preserved along this part of the watershed, which never drops below c. 3500 m. Palaeovalleys drop gently to the north, towards Sucre, and to the south, towards Camargo.

*Culpina region* (Fig. 1; region 4). All the palaeovalleys within the southern palaeodrainage basin appear to have converged in the east near Culpina, east of Camargo. Here, there are widespread surface remnants at c. 3000 m, while narrow ranges rise to near 4000 m to the north and south (Fig. 2). The continuation of the drainage system beyond Culpina is not clear, though we believe that it ultimately continued into the foreland region at c. 21° S. Also, there may have been some link with drainage from the Tarija Basin, to the southeast, since at least 6.5 Ma (see below).

**Age of palaeosurface remnants, aggradation and dissection**

The age of palaeosurface formation is bracketed both by the age of deformed rocks below the surface and younger tufts and sediments which mantle the surfaces. Tufts in the Quebrada Honda lacustrine and fluvial sequences (east of Villazón), which infill shallow depressions immediately beneath surfaces south of the Rio San Juan del Oro, near the Argentinian border, have been dated between 11.96 and 12.83 Ma (MacFadden et al. 1990). These sediments, which are only a few hundred metres thick, are essentially flat-lying, and may have accumulated at a very early stage of planation. The top of the sediment sequence coincides with the level of nearby surfaces cut on bedrock. Tufts dated at 9.32 and 8.78 Ma (Gubbels et al. 1993) come from sediments overlying the surfaces in the Cotagaíta region (c. 3100 m) and near Villazón (c. 3700 m), respectively (locations shown on Fig. 2). Thus, the complete southern palaeodrainage basin, preserved at altitudes between 3800 and c. 3000 m, was formed between 12 and 9 Ma. The northern palaeodrainage basin also probably existed at this time (see below) and there must have been a major watershed between the two. Much of this watershed is still represented by steep-sided highlands rising over 1000 m above nearby surfaces. In the Otavi and Avichuca Pampa regions, however, flat surface remnants are present along the crest of the watershed suggesting that, locally, drainage cut through the highlands and one palaeodrainage system grew at the expense of the other.

The widespread presence of thin and generally undated gravel sequences, resting on the planation surfaces in the southern part of the southern palaeodrainage basin, indicates one or more limited phases of fluvial aggradation prior to dissection. This aggradation may be the result of both changes in the geometry of the drainage system and climate change, which resulted in some sediment being retained in the palaeodrainage basin after planation. There appears to have been little subsequent tectonic disturbance, although faults with vertical displacements generally < 10 m do cut the surface near the Argentinian border (Cladouhos et al. 1994).

Flat-lying tufts from the Yesera Formation in the Tarija Basin, dated at 6.4 ± 0.4 Ma (M. Bonhomme in Troeng et al. 1993; GEOBOL-SGAB, Villazón sheet, 1 : 250 000 series) mantle a palaeosurface at c. 2200 m. This is c. 70 km southeast of Culpina, near where we believe the eastern outlet of the southern palaeodrainage basin may have flowed into the foreland basin. There does not appear to have been young faulting between the Tarija Basin and the San Juan de Oro region (separated horizontally by only c. 15 km across strike) suggesting that the downstream end of the southern drainage systems was c. 1600 m lower than the upstream end by c. 6.5 Ma and that drainage between Culpina and Tarija may have been very sinuous if the low gradients present in the upper part of the drainage system (e.g. Ayoma–Cotagaíta region) were maintained. In this case, the palaeovalley downstream of Culpina would have to be at least 120 km long.

**Northern palaeodrainage basin**

**Morphology and field relations**

The northern palaeodrainage basin lies between 17.5° S and 19.75° S. Well-defined palaeovalleys at c. 2900–3400 m in the south and northwest of the basin converge on a broad area of low relief in the Rio Grande and Rio Mizque Valleys, where there are numerous small and scattered remnants of palaeosurfaces as low as c. 2100 m (Fig. 2). Although none of these have previously been mapped as part of the same drainage system as the higher palaeosurfaces, we believe we are justified in doing so. Their morphology and expression on satellite imagery and aerial photographs are similar to the higher surfaces and there are no topographic barriers or very steep steps between the two. The lowest surfaces are found immediately west of the Subandean fold and thrust belt, with higher regions to north and south, suggesting that this palaeodrainage basin had an outlet to the then foreland basin at c. 18.5° S. In the following sections, the morphology of surface remnants are described in detail for the regions shown on Fig. 1, starting with the higher upstream parts of the palaeodrainage...
basin before considering the scattered, lower remnants in the Rio Grande valley.

**Betanzos region (Fig. 1; region 5).** Near the Otavi watershed (Fig. 5), palaeosurfaces cut into Palaeozoic bedrock, with thin or no cover, and drop northwards from c. 3450 m to c. 3200 m over c. 15 km, before levelling out near Betanzos (Fig. 6). Nearby, there are some striking examples of the preserved palaeosurfaces which form extremely flat plains at c. 3200 m, with < 20 m relief over distances of > 10 km (Fig. 6). They define a north–south palaeovalley c. 60 km long and 30 km wide, bounded by higher regions rising to c. 4000 m, with no sign of regional tilt to the east or west. The surfaces cut across Palaeozoic and Cretaceous bedrock and are broken only locally by steep-sided protruding ridges of Cretaceous rocks. They are generally devoid of sediment cover except very locally, such as at Inchasi (Fig. 2) where c. 200 m of gravels, sands and tuffs have ponded against a protruding ridge (MacFadden et al. 1993).

**Sucre–Yamparaez–Tarabuco region (Fig. 1; region 6).** North of Betanzos, between Sucre and Tarabuco (Fig. 6), we have recognized several distinct surface types, which are described below. The highest palaeosurfaces are preserved east of Tarabuco, where gently undulose plains rise gradually from c. 3200 to 3300 m. Further east, there is a still-prominent watershed at c. 3600 m. This undulose surface merges to the west with near horizontal plains preserved near Yamparaez. Although similar to the Betanzos plains, here there are several distinct plain levels. The dominant level lies at 3160 m and shows < 10 m relief. There are also significant areas at c. 3040 m, and small, steep-sided remnants at 3200 and 3080 m. We have also noted small (< 1 km²) very flat surface remnants at c. 3000 and 3100 m cut across Palaeozoic bedrock just north of Sucre on the road to Maragua. All these plains are bounded by short, very steep steps and are generally devoid of sediment cover. Sucre city lies at c. 2850 m, in a broad, shallow bowl cut into the surrounding flat plains. In places the bowl is steep-sided, but to the east it rises through gentle undulating slopes, mantled with thin gravels and tuffs, to merge with the flat plains near Yamparaez. The Sucre bowl contains a thin (10–50 m) gravel and sand fill with tuffs. The tuffs are locally very gently folded and cut by dextral strike-slip faults with displacements of several metres. This suggests that the surfaces in this region may be locally broken by small strike-slip faults. For instance, a major norththrending fault further north, referred to as the Aiquile fault, may have been active in the Plio-Pleistocene (Dewey & Lamb 1992). However, the lack of any fault scarps crossing preserved bare bedrock surfaces, and the general concordance of surface height across older fault lines, suggests there has not been significant dip-slip motion.

**Cochabamba–Torotoro region (Fig. 1; region 8).** Between Torotoro and Cochabamba, there are numerous palaeosurfaces on either side of the present-day Rio Caine–Río Tapacari Gorge. This gorge is, in places, nearly 1000 m deep and the

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**Fig. 6.** Map of the preserved palaeosurfaces in the Betanzos and Sucre–Tarabuco regions. Note that higher, gently undulose regions (Tarabuco) grade downstream into flat plains which show distinct, steep-sided benches up to 5 km wide (altitudes of main benches shown). Altitudes and ages of dated tuffs are shown (data from Kennan et al. 1996). Near Betanzos, a 3.5 Ma tuff was deposited in a valley incised 150 m into an extensive 3200 m surface, on which deposition was occurring at the same time, clearly indicating the relatively local scale on which transport processes were operating. Over periods of 1–5 Ma, however, only a small fraction of the eroded sediment remained within the palaeodrainage systems, the bulk being carried into the foreland basin.
Fig. 7. Photograph looking down onto a large palaeosurface remnant at Arampampa and northwest towards the Cochabamba area. The gently undulose surface, at 3000–3100 m, cuts across lower Palaeozoic strata. Soils covering the surface are commonly only a few centimetres thick. Modest dissection (middle distance) has occurred in response to the deep downcutting of the Rio Caine Gorge, a few kilometres to the north. The surface cuts across the c. 19 Ma tuffs of the Parotani Basin but dissection started prior to 6.5 Ma when a tuff filled a palaeovalley cut 350 m into the surface.
surfaces are found close to the gorge, defining a northwest–southeast trending palaeovalley c. 20 km wide. The largest surface remnant, at Aramapampa, has an area of c. 200 km² and lies at an altitude of c. 3000 m with < 100 m of gentle relief (Fig. 7). Like almost all surface remnants in this part of the palaeodrainage system, the surface is cut directly into folded bedrock, with no sediment cover (Fig. 8). North of Aramapampa, palaeosurfaces rise through distinct steps towards an ancient watershed at c. 3400 m, preserved just south of Anzáido. North of the watershed the palaeosurfaces drop towards the Plio-Pleistocene Punata and Cochabamba Basins (Fig. 2). Locally, there are well-preserved horizontal surfaces at 3150, 3050 and 2950 m, with steep steps between them. From here the palaeodrainage probably ran northwest through the area now occupied by the young basins, before swinging back to join the main palaeovalley (Figs 2 and 3). High ground to the east of Punata prevents any other exit. Palaeosurfaces are also patchily preserved to the west of Cochabamba. For instance, near Llavini there are small remnants of flat benches at 3150 and 2950 m which possibly once formed part of more extensive flat plains. Nearby, Cerro Llavini and numerous other steep-sided hills in the area have gently undulose tops at altitudes between 3000 and 3200 m, which show up as bright patches on satellite images.

Rio Grande and Rio Mizque Valleys (Fig. 1; region 7). The higher surfaces in both the Cochabamba and Sucre regions gradually drop downstream towards numerous lower surfaces, exposed along the courses of the Rio Grande and Rio Mizque where these rivers cut east across the structural grain of the Cordillera. These surfaces have not previously been described nor have they been related to the higher San Juan del Oro surfaces. Distinctive bevelled ridges and areas of low relief, all with a characteristic brightness on satellite images, occur at c. 2750, 2600–2500, 2400 and 2100–2200 m, with altitudes dropping consistently to the east (Figs 2 and 3). Even as far east as Villa Redenci6n Pampa (Figs 2 and 3), there are some remnants of higher surfaces and bevelled strike-ridges at c. 2900 m. None of the height changes between adjacent palaeosurface remnants seems to be due to dip-slip faulting. No faults cut the surface remnants and remnant height remains constant across the major north–south Aiquile Fault. In general, dissection in this region has been more intense than further west.

Independencia region (Fig. 1; region 9). The most northerly palaeosurface remnants are found near Independencia, c. 70 km northwest of Cochabamba. They may be part of a third palaeodrainage system and are described in this section only for the sake of completeness. A marked watershed, rising to 3500 m, separates them from palaeodrainage in the Cochabamba region. Although there is significant Plio-Pleistocene displacement on the ESE trending Cochabamba Lineament System (Fig. 1) it is unlikely to have created a watershed of this height. The Independencia palaeosurface remnants are gently sloping valley shoulders, up to 1 km wide, at c. 3000 m, above the c. 1000 m deep gorges of the Rio Ayopaya and Rio Santa Rosa. The shoulders have the same characteristic bright reflectance on satellite images as palaeosurface remnants to the south. Substantial high late Cenozoic uplift and erosion north of the Cochabamba Lineament System, in the Cordillera Real and northern part of the Cordillera Oriental, may have obliterated most of the palaeodrainage basins in this region. Hérail et al. (1995) have recently described a c. 8 Ma valley filling sequence lying at c. 1000–2000 m on the eastern side of the Cordillera Real. The connection of these strata to the palaeosurfaces we have described remains unclear.

**Age of surface remnants and dissection**

There is little direct constraint on the timing of planation in the northern palaeodrainage basin. Clearly, the surfaces post-date 21 Ma volcanics southeast of Potosí (Grant et al. 1979). Immediately west of Potosí lies the 7–12 Ma Los Frailes ignimbrite shield (Fig. 1; dates in Kennan et al. 1995; Grant et al. 1979). Although possibly related 8–9 Ma tuffs are found far to the northeast, near Punata (Fig. 2), none are found on any of the surface remnants we have examined. This suggests that surface cutting and cleaning in this area may have continued beyond c. 7 Ma and is probably younger than in the southern palaeodrainage basin. A 6.5 Ma tuff from a valley cut 450 m into this surface near Parotani, places an upper age limit on surface planation near Cochabamba and indicates some downcutting somewhat earlier than in the Sucre region (Kennan et al. 1995).

Possible late Miocene (5–6 Ma) mammal fossils have been reported from thin deposits on a surface remnant at c. 2500 m (Muyu Huasi or Villa Redenci6n Pampa; Marshall & Sempere 1991). Post-2.5 Ma fossils of cervidae or camelidae are absent so the deposit is certainly older than middle Pliocene. The same authors report an age of 3.36 ± 0.3 Ma for a tuff at Padilla, at 2100 m. Thus, by c. 5 Ma palaeosurfaces were being cut at c. 2500 m in the easternmost part of the northern palaeodrainage basin, and by c. 3 Ma they were
Fig. 8. Photograph looking southeast (approximately downstream along the palaeovalley) from Arampampa towards Limon Pampa, a small isolated palaeosurface remnant. Note that the surface is cut directly onto gently folded Palaeozoic strata. The extreme flatness of the surface can clearly be seen to be an erosive effect and not a result of aggradation of cover gravels. Note also that throughout this part of the Eastern Cordillera (see Fig. 2) there is little relief above the general palaeosurface level.
being cut as low as 2100 m, while nearby there are remnants of c. 2900 m palaeosurfaces (flat-topped hills and bevelled strike-ridges). This suggests that between c. 10 and 3 Ma the base level at the eastern end of the northern palaeodrainage system was lowered from c. 2900 to c. 2100 m (Fig. 9). Such base-level drop may account for the pre-6.5 Ma incision observed near Cochabamba. However, the rate of any incision prior to c. 3 Ma was much lower than that subsequently, when gorges up to 1000 m deep were cut.

There are numerous dates for sediments or tuffs which mantle the palaeosurfaces in the 1.5–4 Ma age range. These provide an upper limit for planation, as well as constraining the onset of deep dissection which must largely post-date these deposits. For instance, the shallow bowl around Sucre is mantled by a 3.5 Ma tuff which is very

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Fig. 9. Schematic approximately east–west cross-sections across the palaeodrainage systems in: (a) upstream (e.g. Rio San Juan del Oro); (b) midstream (e.g. Sucre–Tarabuco); and (c) downstream (e.g. Villa Redención Pampa–Padilla) regions. The near-flat surfaces define broad palaeovalleys cut by steep-sided Plio-Pleistocene gorges. Relationships to dated deposits are shown. Note that in the downstream region there may have been a base-level drop of c. 800 m between ?10 and 3 Ma. Subsequent dissection has been much more rapid and widespread. Small, c. 50–100 m, steps between discrete surface levels in midstream and upstream regions suggest that between 10 and 3 Ma base-level drops did not significantly modify these areas.
gently folded and faulted. Near Yamparaez, southeast of Sucre, a 1.5 Ma tuff (Kennan et al. 1995) in a shallow valley cut into the 3160 m plain indicates that large parts of the plains may have remained undissected until the Pleistocene. Further east, near Tarabuco, surfaces are cut by a moderately dense dendritic network of shallow channels which contain a c. 3.5 Ma tuff (Kennan et al. 1995). At Inchasi, east of Potosí (Fig. 2), 1–200 m of sands and gravels resting on the surface have yielded 3–4 Ma old mammal fossils (MacFadden et al. 1993). However, only 8 km to the north, we have found a 3.5 Ma tuff filling a valley incised 150 m into the 3200 m surface (Kennan et al. 1995), suggesting that by 3.5 Ma parts of the surface were being moderately dissected, probably related to drainage onto the lower surfaces nearer Sucre.

**Tectonic controls on the northern palaeodrainage basin**

The major ESE trending faults of the Cochabamba Lineament System have been active since at least the early Miocene (Kennan 1994). They may have directly controlled the line of the Cochabamba–Torotoro palaeovalley, and the position of the eastern outlet of the northern palaeodrainage basin, by providing a zone of more easily eroded rock. In contrast to the southern palaeodrainage system, where surfaces and sediment cover appear to have been largely ‘fossilized’ since c. 9 Ma, base level in the eastern part of the northern drainage basin seems to have slowly dropped after 9 Ma, resulting both in the continued cleaning of palaeosurfaces into the late Miocene and a greater range of palaeosurface heights by c. 3 Ma, ranging from c. 3400 to 2100 m. In this way, higher surfaces in the east became stranded. The base-level drop was possibly a result of the normal faulting on the Cochabamba Lineament System. This faulting was probably kinematically related to a marked divergence in shortening direction around the bend in the Bolivian Subandes, resulting in tangential extension in the Cochabamba region and further east (Kennan 1994). There is also some direct evidence for post-palaeosurface deformation. For instance, sequences mantling the surface near Sucre are gently folded and faulted (see above). Also, 15 km south of Cochabamba, a c. 10 × 4 km palaeosurface remnant is warped downwards into the Parotani Basin, which has been a local, fault-controlled depocentre since c. 20 Ma (Kennan 1994).

**Discussion**

Broad, low-gradient valleys lying between strike-parallel ranges 500–1000 m higher define at least two major palaeodrainage basins in the Cordillera Oriental (Fig. 3). These appear to have reached more or less their present form by the late Miocene and have not been subjected to later tectonic tilting – large areas are remain very near horizontal. Thus, we believe that we can use present-day observed gradients to reconstruct the drainage direction and intervening watersheds. In general, the landscape at this time probably looked very much like the northernmost part of the Puna along the Bolivia–Argentina border. Topography was subdued and, although there must have been some lowering of base level in the downstream parts of the northern palaeodrainage basin, there is no evidence for steep-sided, deep gorges such as those that exist today (Fig. 9). The early stages of this palaeodrainage pattern may have been slightly different to that which subsequently became established prior to Plio–Pleistocene deep erosion. Firstly, perfectly planar palaeosurfaces are found right on watersheds between the two palaeodrainage basins suggesting one grew at the expense of the other once major high areas between the two were breached. Secondly, the Rio Pilcomayo, part of the southern drainage system, has cut back through a major high region southeast of Sucre, capturing drainage in the Betanos region that probably once drained north towards the Rio Grande as part of the northern palaeodrainage system.

We can crudely estimate the volume of sediment that must have been eroded during the cutting of the palaeovalleys. The c. 1000 m height of the intervening highlands suggests this thickness was eroded from the palaeodrainage system when it was being cut, giving a total sediment volume of c. 1–2 × 10⁴ km³ for both north and south palaeodrainage systems. We suggest that planation was the result of progressive widening of valleys as the low-gradient drainage system cut predominantly laterally, transporting weathered rock from the valley sides downstream in a low-gradient drainage system. However, a striking feature is the lack of any sediment sinks within both the northern and southern palaeodrainage basins sufficient to account for the estimated volume of material eroded during its formation. Only locally are there more than a few metres of sediment on surface remnants. Also, there is no indication of a major hiatus in deposition between c. 12 and 3 Ma (Coudert et al. 1993) in the Subandean zone, when sediment could only have been coming from the Cordillera Oriental. There has been c. 3 km of sediment deposited in the Subandean zone and foreland basin in the last 10 Ma (unpublished oil company data).

The above discussion suggests that the palaeodrainage basins could not have formed in a system
of internal drainage. This stands in contrast to much of the Puna and Altiplano, where the present-day salar and lake basins are deep, long-lived sediment sinks, often structurally controlled. We can also rule out the possibility that sediment may have been removed into the Altiplano basins to the west. The intervening watersheds are too high and there is no evidence for significant vertical displacements between the Altiplano and palaeodrainage basins since the middle to late Miocene. In this respect, we believe it is significant that the palaeosurfaces do not appear to be tectonically tilted. Thus, the generally eastward gradient of the palaeodrainage systems strongly suggests that the sediment eroded during surface formation was transported out into a foreland basin, which is now part of the Subandean fold and thrust belt (Fig. 3). Our estimates of eroded sediment volume are sufficient to provide several hundred metres of debris to the basin adjacent to the mountain belt during the late Miocene.

The extensively preserved upstream parts of both northern and southern drainage basins clearly show gradients of c. 1 in 125 in their upper parts, dropping rapidly downstream to as low as 1 in 200–250. This is comparable with gradients of erosional reaches of many modern rivers draining ancient mountain belts and is much steeper than aggradational reaches of rivers such as the Rhine (Neils Hovius, pers. comm.). Also, in the Subandean zone, marine sediments were being deposited at c. 10 Ma (Yecua formation, Marshall & Sempere 1991). Thus, if the gradients in the palaeodrainage basins were maintained downstream towards the Subandes, which were at or near sea level, the palaeosurfaces must have been at significantly lower altitude than they are now. The downstream distance from the easternmost remnants to the Subandes was probably somewhat longer than the present cross-strike distance, taking into account palaeodrainage sinuosity and shortening at the back of the Subandean fold and thrust belt. Given reasonable estimates for this distance, we suggest that at c. 10 Ma the palaeodrainage basins in the Cordillera Oriental were probably between 2 and 2.5 km lower at c. 10 Ma than they are today (Fig. 10), and that they have been gradually uplifted since then.

We believe that the deformation in the Subandean zone since 10 Ma provides a plausible mechanism for the uplift described above. Thin-skinned shortening in the Subandes accommodated c. 140 km of underthrusting of the Brazilian Shield beneath the Cordillera Oriental (Roeder 1988; Sheffels 1990; Baby et al. 1993). The precise effect of this underthrusting on uplift in the Cordillera Oriental is unclear. However, we can crudely estimate the effect if we assume that the Cordillera Oriental behaved as a rigid block which was driven up a basal décollement inclined at a similar gradient to the basal décollement in the Subandean zone itself (unpublished oil company data; Wigger et al.

![Fig. 10. Summary diagram showing proposed uplift of the palaeodrainage systems (based on real altitude data along the Rio Tumusla–Río Pilcomayo Valleys). Palaeosurface remnants clearly define a drainage system with a downstream (back of Subandes) end now at c. 2000 m. This fed sediment into the foreland basin and must have been close to sea level at c. 10 Ma. As it was uplifted, the frontal portion flowing through the Subandes must have steepened but did not cause much upstream dissection. The present gradient of the floor of the Rio Tumusla–Río Pilcomayo Valley is also shown. The prominent knickpoint may reflect upstream migration to the steep frontal portion of the palaeodrainage system.](image-url)
1993). Watts et al. (1995) have shown that the Brazilian Shield in this region has high flexural rigidity. In this case, we might expect the surface uplift as a result of underthrusting to be more than that expected for full Airy isostatic compensation, possibly by a factor of two (Lamb & Vella 1987; Lamb & Bibby 1989). Thus, assuming a basal slope between 2 and 3° and ignoring the effects of erosion, 140 km of underthrusting would result in between 4 and 7 km of crustal thickening, and c. 2 km of surface uplift. This compares well with the estimated average surface uplift, deduced above from the elevations of the palaeodrainage basins. Other calculations, assuming homogeneous crustal thickening beneath the Cordillera Oriental as a consequence of underthrusting (cf. Isacks 1988), give similar estimates of surface uplift. Erosional unloading of the Cordillera Oriental by post-Pliocene dissection may contribute a further few hundred metres to the uplift of the palaeosurfaces.

The average shortening rate in the Subandes over c. 10 Ma, of c. 10–13 mm yr⁻¹, is about the same as present day rates deduced from foreland seismicity (Dewey & Lamb 1992). If this rate has been fairly constant, then the palaeosurfaces were probably uplifted to within a few hundred metres of their present altitude by 3 Ma (Fig. 10), and the downstream gradient from the easternmost surface remnants into the foreland basin was probably much steeper than that further upstream. Late drainage modification may reflect the effects of a late Cenozoic climate change or it may be that only in the last 3 Ma was the drainage system sufficiently perturbed for the entire system to be modified.

Conclusions

Between c. 12 and 3 Ma, an extensive system of valleys with marginal pediments developed within the Cordillera Oriental in a vast region 600 km long and 100 km wide. The lack of sediment sinks within the palaeodrainage system suggests that these valleys drained directly into the then foreland basin, now deformed as the Subandean fold and thrust belt. Projecting drainage gradients downstream indicates c. 2–2.5 km of uplift relative to the foreland since c. 10 Ma, providing a direct estimate of surface uplift which avoids many of the pitfalls of interpreting palaeoaltitudes from geological data and compares favourably with uplift estimates from various structural models. We suggest that rapid dissection since c. 3 Ma most probably results from surface uplift related to Late Miocene and younger Subandean deformation and the effects of Pliocene climate change.

These palaeosurfaces also have important implications for reconstructing the tectonic evolution of the Cordillera Oriental. They can be used to bracket distinct early and late Miocene–Pliocene phases of movement on the Cochabamba Lineament System. Also, several recent discussions of Subandean structure (Roeder 1988; Coudert et al. 1993) have suggested that there may have been major out-of-sequence thrusting on faults at the back of the Subandes, and cross-sections commonly show ramps beneath these thrusts. However, the complete lack of regional palaeosurfaces tilt is inconsistent with late, ramp-related folding. The geomorphology of the Cordillera Oriental must be considered when attempting to balance cross-sections.

Palaeosurfaces like these in Bolivia may be relatively common features in many mountain belts. Unfortunately, they are likely to be short-lived. They may, however, record some features of the tectonic history of a mountain belt, such as the surface uplift history, which are not easy to deduce by other means. Examples in Bolivia, Argentina and elsewhere are clearly worthy of greater attention.

This work was supported by a grant from BP held by Professor J. F. Dewey, a Royal Society Research Fellowship (S.H.L.), Shell and British Council Studentships (L.K.) and an Austrian Academy of Sciences (APART) Research Fellowship (L.H.). We acknowledge helpful reviews by Phil Allen and Steve Flint and valuable discussion with Neils Hovius and Colin Stark.

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