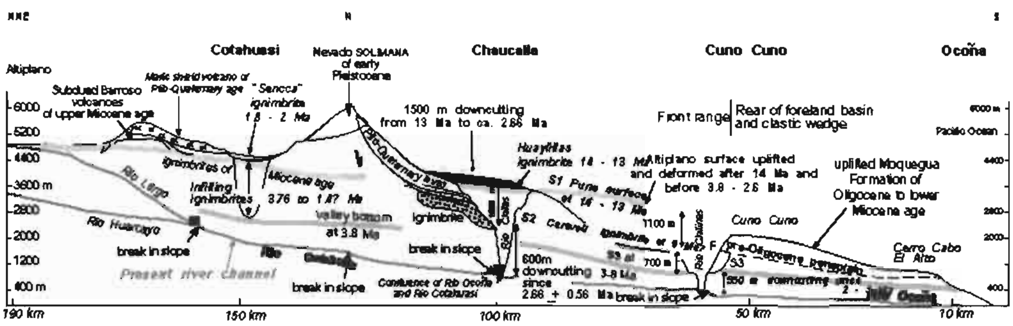


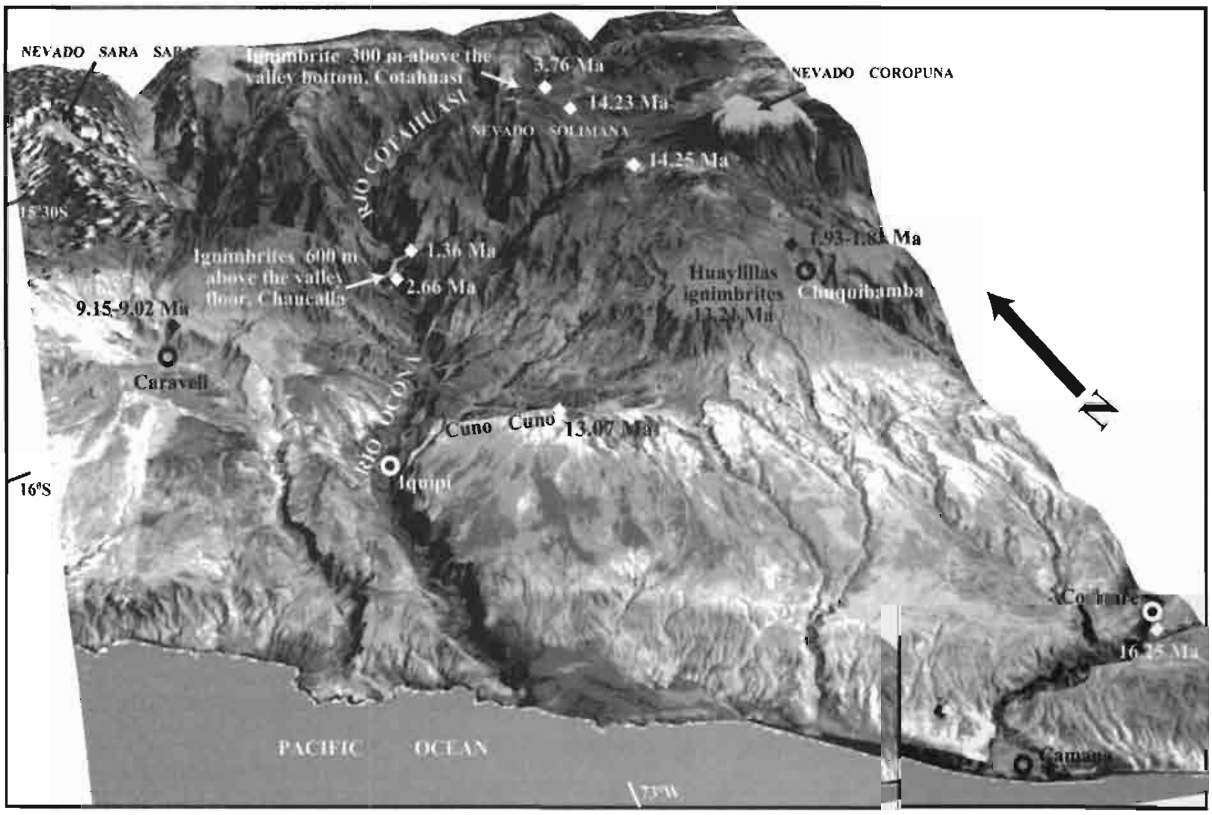
Figure showing the canyons of the Rio Ocona and Cotahuasi through the Western Cordillera, and four groups of ignimbrites (14 - 13 Ma, 9 Ma, ca. 3.76, and ca. 2.66 - 1.36 Ma). The amount of uplift and downcutting is estimated using the S1 (pink), S2 (orange), and S3 (green) palaeosurface and the ignimbrite tops. Green and blue indicate valley bottom and channel gradients at ca. 3.8 - 2.6 Ma and at Present, respectively.

Dating of the valley fills reveals the history of downcutting.

Ignimbrites crop out 1000-1300 m above the Rio Ocoña canyon on the SW flank of Nevado Solimana. These ignimbrites are inset in the valley at 2400 m asl, 1600 m below the plateau of the Huaylillas and Sencca ignimbrites of Rio Arma. They crop out 600 m above the present valley bottom and have been dated at 2.66 ± 0.56 Ma. Thus they do not correspond to the ca. 3.8-Ma-old valley bottom at 2700 masl in the Cotahuasi canyon. This indicates an increase in the present channel gradient compared to the one at 3.8 Ma (Fig. 1), which may be due to a new or faster incision between 3.8 and ca. 2.66 Ma. Alternatively, the break in slope upstream of the confluence may reflect differential uplift between the northern Cotahuasi canyon and the southern Ocoña canyon since 3.8 Ma.

The 3.8 – 1.4 Ma-old Sencca ignimbrites erupted well after uplift and valley cutting because they were channelled in valleys of late Miocene age. Upon reaching the western slope of the Andes, they expanded and mantled the S2 palaeosurface (covered by the Caraveli ignimbrites ca. 9 Ma), which is cut down in the S1 palaeosurface by 300 to 600 m. The Caraveli ignimbrites, deposited in shallow valleys cut in middle Tertiary sediments, eventually covered the Tertiary sediments of the piedmont and the older basement. The piedmont itself, Eogene in age, has been formed by the deposition of a clastic wedge of conglomerates and distal sand and siltstones as a result of uplift and erosion since about 25 Ma (Kennan, 1999). The 3.8 – 1.4 Ma-old Sencca ignimbrites then covered straths cut on the edges of the Ocoña canyon and tributaries at 300-400 m above the valley bottom.

A volume in excess of 90 km^3 has been removed in each canyon along the 140 km-long course of the valleys. At least ¾ of the volume was removed by 3.8 – 2.7 Ma. The average incision rate (190 m Myr^{-1} at. Cotahuasi) is inferred from the depth of the channel. The incision rate was relatively low (210 m. Myr^{-1}) between 13 and 9 Ma, but this rate probably accelerated twice between 9 and 3.8 - 2.7 Ma, as exemplified by a 1200 m-high break in slope over a valley reach of 30 km near the confluence. The incision rate was so fast after ca. 1.4 Ma that the Rio Cotahuasi cut down the valley fill at 1200 m Myr^{-1} above the town of Cotahuasi, meanwhile the Rio Ocoña and its tributary Rio Arma cut down as much as 1400 m in the volcanic fill since 1.4 Ma. Fast rates suggest increasing runoff and/or easy erosion of a poorly indurated pyroclastic valley fill.



WHAT CAUSED VALLEY INCISION SINCE 4 MA?

Two processes can initiate valley cutting and accelerate erosion: (1) changing base level of the rivers either by increased uplift or a fall in sea level, or (2) increased runoff due to climatic or meteoric changes.

Huaylillas ignimbrites 13 - 14 Ma old at the flanks of the western Andes in S Peru are only mildly folded and only within a few areas, indicating limited crustal shortening at least in the region between the High Plateau and Coastal Cordillera since that time. If the palaeosurface has been tilted by only 2 degrees, this would result in uplift from about 2500 m to 4000 m asl. in the area of Chuquibamba (Fig. 2). Thus, more than half of the entire observed uplift (=about 2000 m) of the Western Cordillera may post-date the emplacement of the Huaylillas ignimbrites and thus is younger than 13 Ma.

Given the evidence for an earlier phase of uplift from the thick conglomerate sections below the Huaylillas ignimbrites, this suggests a second or continued phase of uplift between 13 - 14 Ma and 3.8 Ma prior to valley cutting. We favour a fairly continuous phase of uplift mostly through tilting in that area of the Western Cordillera instead of the series of compressive phases suggested by other workers on independent lines of evidence (e.g. Sébrier et al., 1988). We argue that uplift was more or less continuous, and that downcutting may have taken place before 9 Ma but most likely before 3.8 Ma, and again before 2.7 Ma, based on dated valley infillings. Therefore, valley cutting was probably initiated by climatic changes, resulting in glaciation of the high Andean peaks and increased discharge onto the western Andean slope. Clapperton (1993) argued that glaciation started after 3.27 Ma in Bolivia, somewhat later than the first deep valley cutting as observed by us in southern Peru.