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Reconstruction of Equilibrium Line Altitudes of Nevado Coropuna Glaciers (Southern Peru) from the Late Pleistocene to the present

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The Nevado Coropuna (15º31'S-72º39'W) is a volcanic complex located 200 km NE of the city of Arequipa, in the Southern Peruvian Andes. The summit area in the complex is covered with a glacier system formed by dozens of branches descending in all directions totaling many km^2 in surface area. The study of the volcanic complex and its glaciers is of great interest because it is the main water reserve for tens of thousands of people, because of the risk scenario created by the presence of ice masses on a volcano with relatively recent activity, and because it constitutes an excellent geoindicator of the effects of climate change on ice masses in the western mountain chain of the Central Andes.

This research aims to analyze glacier evolution using as geoindicators variations in glacier surface and equilibrium line altitudes (ELAs), defining deglaciation rates based on those variations and preparing forecasts with them on when the ice masses might disappear if the same rates were to occur in the future. In addition, a first estimation is attempted of the chronologies of the last phase of volcanic activity and the last phase of maximum glacier advance that can be attributed to the Late Glacial or Last Glacial Maximum periods.

To achieve these aims, digital topography with 50m contour interval, two orthophotos of the central section of the Coropuna complex (15-6-1955 and 21-10-1986), an ASTER satellite image (12-11-2007) and geomorphological mapping of the volcanic complex created in a previous phase of the research (Ubeda, 2007) were integrated into a Geographical Information System (GIS). The GIS was used to determine the global extent of the glacier system, and in more detail, that of two groups (NE and SE) in 1955, 1986 and 2007. Using the geomorphological cartography as a basis, the extent of the glaciers during their last advance in the Little Ice Age (LIA) and their last maximum advance were calculated. Next, surface areas for all phases were calculated using automatic functions within the GIS operating environment. To reconstruct the ELAs of the glaciers, the Area x Altitude Balance Ratio (AABR) method was used. This method is extensively described in Osmaston (2005). To determine the rates of deglaciation, variations observed for 2007 in surface areas and ELAs against their values in 1986, 1955 and the Little Ice Age (LIA) were used as geoindicators. Establishing deglaciation rates has allowed forecasts to be made as to when the complete disappearance of ice mass could occur for three future scenarios, considering the hypothetical reproduction in each scenario of the rates of deglaciation observed since 1986 (Scenario 1), 1955 (Scenario 2) and the LIA (Scenario 3). To determine the chronology of the last maximum advance of the glaciers and the last volcanic manifestations, samples were taken from moraine blocks and glaciated rocky thresholds, and also from lava ejected during the last eruption, in the eastern sector of the complex. Due to their recent external appearance, since they have been channeled by glacial valleys and have been affected by ice masses only at the head, these lavas had been dated as Holocene. Absolute dating was performed using cosmogenic methods (Cl_{36}).

As a result of applying the proposed method, glacial system surface areas have been estimated for 2007 (47 km^2), 1986 (54 km^2) and 1955 (56 km^2), implying a reduction of ~18% in 52 years. The process appears to have speeded up in the last decades (~13% in only 21 years). Surfaces were also estimated and ELAs reconstructed for the NE and SE groups in 2007, 1986, 1955, the Little Ice Age and during the last maximum advance. Glaciers from the NE group show an area during all periods (2.3, 2.7, 2.9, 3.3 and 30 km^2) smaller than SE group glaciers (8.1, 9.9, 10.3, 11.9 and 66.5 km^2). An individual analysis of glaciers in the NE and SE groups in 2007 shows a reduction in surface area two to four times greater than that observed between 1955 and 1986. ELAs are also

higher for all periods in the Northern section (5968, 5930, 5923, 5886 and 5186 m) than in the Southern section (5862, 5806, 5787 and 4951 m). The depression in ELAs during the LIA was similar in the NE (~82 m) and in the SE (~86 m). However, the 2007 ELA shows a depression of 106 m in the Southern direction. The magnitude of this depression has shown a marked tendency towards reduction in recent decades (136 m in 1955 and 124 m in 1986). Furthermore, the decrease in ELA depression seems to occur faster, with $\downarrow$Z ~12 m between 1955 and 1986 and $\downarrow$Z ~18 m between 1986 and 2007. However, during the Little Ice Age (~110 m) that value was closer to the current value (106 m).

Depression in ELAs during the last maximum glacier advance has been estimated at ~782 m (NE) and ~847 m (SE). During that period, the N-S depression reached a maximum value of 235 m. These results agree with those obtained for the eastern range of the Central Andes (Smith et al. 2005 a and b) and are also within the depression intervals and trends proposed in regional-scale studies (Kelin et al. 1999). Analyses performed on a sample from a block situated on a lateral moraine in the Queñua Ranra Quebrada (NE group of the complex) suggest a chronology of ~17 Cl_{36} ky. for the last maximum ice mass advance. This date is in agreement with the depression in SST temperature during the same period, deduced from analyzing Mg/Ca ratios in marine foraminifera shells from the Galapagos Islands (Lea, 2006). Using surfaces and ELAs as geoindicators, deglaciation rates and the Horizon without glaciers (H_0) have been calculated globally, for the complete glacier system in scenarios 1 and 2, and for glaciers in the pilot group in scenarios 1, 2 and 3. Results show that the deglaciation process is occurring differentially. Whereas several masses could disappear in a few decades, others could be preserved for centuries. Regarding the last phase of volcanic activity, a lava sample has been dated at only ~2 Cl_{36} ky. Testing the proposed method has allowed the modeling of glacier evolution using variations observed in surfaces and ELAs as geoindicators.

Results from the global-scale analysis are only a preliminary approximation to the problem. Detailed analysis of the glaciers in the NE and SE groups has yielded more precise results. Forecasts about future glacier retreat, interest in finding out about their past evolution and the absolute chronology of the last phase of volcanic activity, which confirms their recent character, suggest the need to extend our understanding of the evolution of the Nevado Coropuna's volcanic complex and glacier system.

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