HOW GEOLOGICAL HAZARDS AFFECT THE ALHAMBRA

Neotectonics and slope stabilization at the Alhambra, Granada, Spain

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Geologic Hazards in literature

Shortly after completing a biography of Christopher Columbus in 1828, Washington Irving was preparing a book called "*A Chronicle of the Conquest of Granadd*", a history of the years 1478–1492, and was continuing his research on the topic. Aided by a 35-year-old guide named Mateo Ximenes, Irving was inspired by his experience to write "*Tales of the Alhambra*". The book combines description, myth and narrations of real historical events, even up through the destruction of some of the palace's towers by the French under Count Sebastiani in 1812, and the further damage caused by an **earthquake** in 1821.

A. The effect of Earthquakes

Alhambra Damaged by Earthquakes

Scientists have found evidence that structural damage to the Alhambra is due to seismic activity.
A world heritage site, the Alhambra is one of the most visited monuments in Europe. Overlooking the city of Granada, the breathtaking Alhambra Palace is perhaps the most famous example of Moorish architecture, and one of the world's best-known Muslim constructions. However, the Granada ***Basin***, in which the Alhambra lies, is in one of the most seismically active zones in the Iberian Peninsula.

The Alhambra is located in the central sector of the Betic Cordillera, and is one of the most seismically active zones in the Iberian Peninsula. Historical evidence shows that the last major earthquake occurred there in 1431 and was responsible for the partial collapse of the Arab barrier. The Christian wall, built in 1526, has also been partially destroyed by ***rockfalls*** related to tectonic activity, but new evidence indicates that the area surrounding the Alhambra has been undergoing recent and recurrent, though moderate, seismic activity.
The research carried out by scientists in Granada, and published in the *Journal of Quaternary Science*, reports that although the structural damage displayed by the Alhambra is far from significant, it seems that the ***cracks*** can be related with underlying ***faults*** that are possibly seismically active.
Some of the cracks show a geometrical continuity with ***fault planes*** in the underlying rocks, the conglomerates of the "*Alhambra formation*", while collapsed segments of a wall surrounding the Alhambra coincide with underlying faults that cut ***Quaternary*** soil levels.
Based on their observations of the *Alhambra Formation* and the surrounding geomorphological evidence, the researchers have described the seismic risk associated with the faults of the Alhambra and surrounding areas as moderate.

Fig. 1. South view of San Pedro Cliff, showing to the right the fault-line scarp. Above stand the Alhambra walls and, at the foot, River Darro and Albaicín houses.

The Alhambra (Fig. 1) is one of the most important national monuments in Spain, visited annually by up to 2 million domestic and international tourists. One of the most incised rivers of the region, the Darro, which drains into the depression, is situated in the eastern part of the town. The Alhambra's walls are close to escarpments generated by incision of this river. ***Slope stability*** of the escarpments on this side of the Alhambra hill has been a critical problem since the construction of this palace. In this area, the 65.5 m high San Pedro Cliff (Fig. 1), a ***dihedral*** 65.5 meters high, is the steepest escarpment of the Alhambra hill. This eroding cliff reaches to 23.8 meters from the Alhambra palace wall. Retreat of this cliff has occurred through superficial ***slab falls*** mainly induced by the floods of the Darro River, the ***loosening*** produced by the extensional tectonic regime, erosion, ***seepage*** coming from Alhambra palace and earthquakes.

Geological setting

The Alhambra palace was constructed on the top of a hill, on a conglomeratic sequence that constitutes the *Alhambra formation*. The city of Granada is located at the base of the Alhambra hill, on a plain, surrounded by mountains. From a geological point of view, this plain is known as the Granada basin, which underwent continuous ***subsidence*** between the Upper ***Miocene*** and the ***Quaternary***, under marine conditions between 6-7 and 11 millions years ago and with continental infilling until approximately 0.5 millions years ago. The Alhambra conglomerates correspond to ***alluvial fans***, upper Pliocene–lower ***Pleistocene*** in age, known as the Alhambra formation, mostly constituted of rounded stones with an average size of 10 cm. Alluvial fans have been made from erosion of the ***basement*** of the Granada basin outcropping in the Sierra Nevada relief. This basement is formed by **metamorphic** rocks and by sediments of the ***Palaeozoic*** to ***Mesozoic*** ages.

Cracks and faults in the Alhambra hill: origin of "San Pedro escarpment"

The Alhambra hill is a local divide between two important rivers draining from the Sierra Nevada to the Granada depression: the Darro and Genil Rivers. The present configuration of these two rivers evolved over the last 0.5 million years. The drainage pattern of the Darro River was incised in the conglomerates of the Alhambra Formation.

At present, the base of the San Pedro escarpment is covered by a ***debris cone*** that protects it from possible undercutting during flooding. The retreat of the escarpment is relatively slow, occurring at an average rate of 8 cm/year by means of ***soil creep*** and slope wash, except in the western part of the escarpment where tension joints parallel to the slope cause successive superficial slab falls.

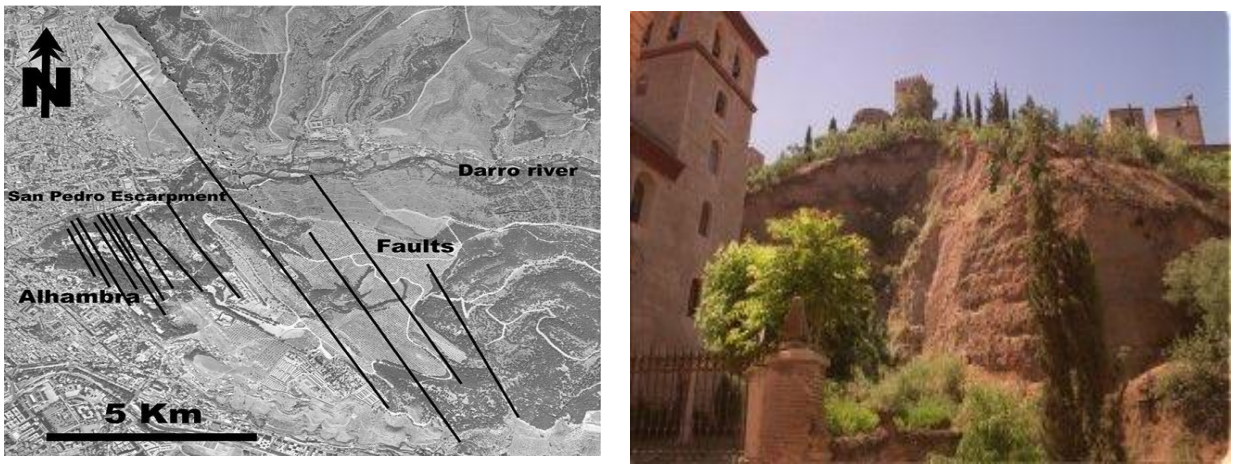
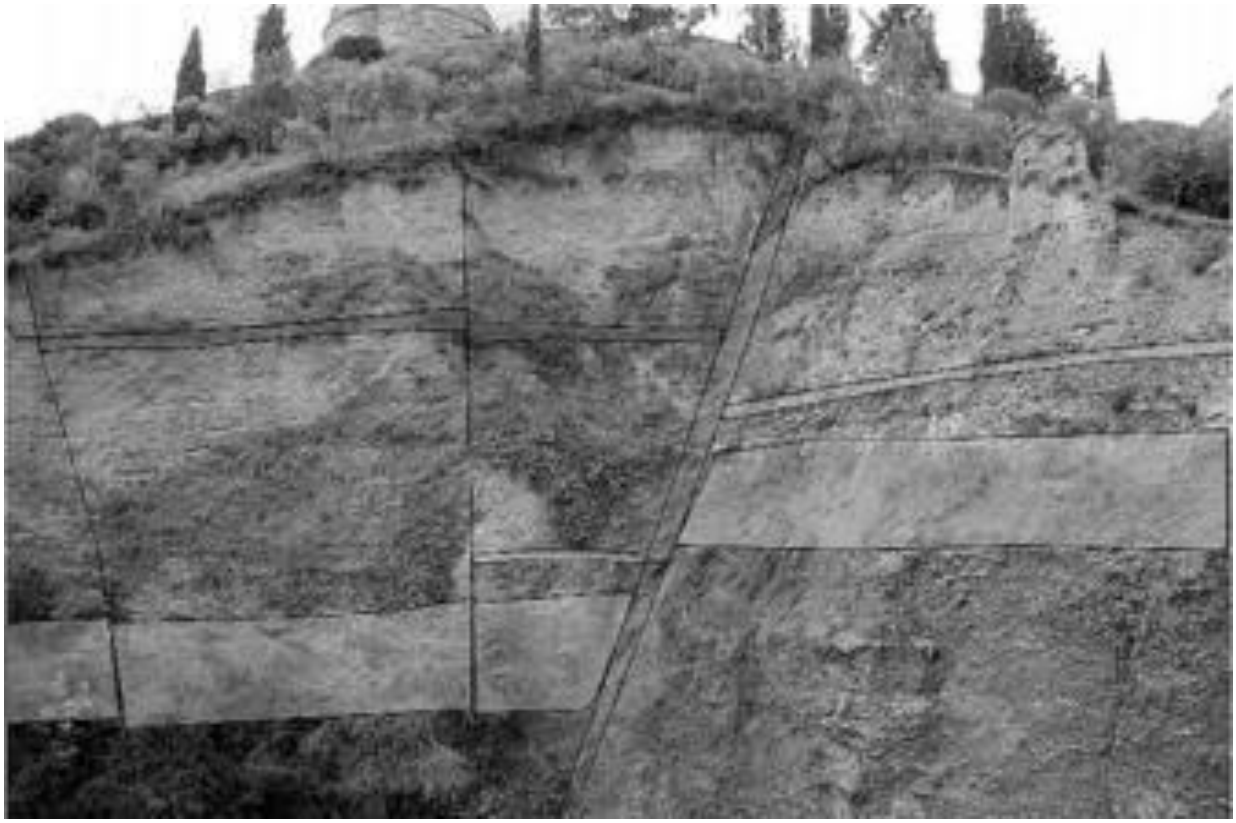


Fig. 4. NW-SE normal faults in the surroundings of San Pedro Cliff.



The western part of the San Pedro escarpment corresponds to a fault line; the fault-plane outcrops in the innermost part of the escarpment, showing a normal-fault displacement of about 7 meters. This fault is the most important one of a set that ***outcrops*** along the northern hill slope of the Alhambra. In some cases, the activity of these faults seems to be very recent and may be related to earthquakes. The seismic risk associated with these faults (and maybe some non-outcropping ones) appears to be moderate, as some historical damage to the Alhambra walls and the Arab barrier is reported.
The most important earthquake affecting the Alhambra and neighbouring areas occurred in 1431, being responsible for the partial collapse of the Arab barrier. Moreover, the Christian barrier, built in 1526, has numerous cracks geometrically related to fault-planes outcropping in the Alhambra Formation, i.e. faults and cracks are continuous and have similar ***strike*** and ***dip***. We hypothesize that these cracks are due to post-1526 small displacements along the faults, occurring during recent earthquakes in the region, as the barrier is so light that loads applied to the rock are negligible. In the same way, numerous cracks and collapses in the Alhambra walls appear mostly concentrated and aligned in a NW–SE strike with Christian wall cracks and faults.

B. The effect of Sliding:

Alhambra threat. Scientists are working to stop the palace sliding downhill
The guardian, Wednesday 26 May 1999 00.37 BST

The Alhambra, Granada's magnificent Moorish palace-fortress, has survived wars, earthquakes and developers. Now it is going downhill as the land on which it is built slowly crumbles into a river gorge.
A team from Spain's leading scientific institute have begun to study the causes of the **subsidence** which, they calculate, is eating into the ground at the rate of 2cm a year.
The hill on which the Alhambra is perched has a high clay content and the scientists suspect that **waterlogging** may be to blame. Water may be leaking from a network of irrigation channels under the palace.

They intend to plot the trajectory of water from "suspicious" fountains and waterways, using an isotope system with tiny amounts of radiation put into the water.
"There is no immediate threat," said Mateo Revilla, the Alhambra's director. "The spot worst affected is 25 metres away from the Alhambra itself. But, of course, we're working to get to the root of the problem and solve it as quickly as possible."

The possible remedies include covering the hillside with a protective net or building new water channels. "We must keep an open mind until we've established precisely what is happening," Mr Reyes said. Subsidence has been a problem in the past. In 1520, soon after Spain's "Catholic Monarchs" Ferdinand and Isabella conquered Al-Andalus, the southern

kingdom ruled by the Moors for 700 years, the base of the Alhambra hill was propped up with stones. In 1601 a landslide destroyed part of the wall around the forest below the fortress. Another landslide in 1985 ate away more of the hillside.

The search for a solution could be hampered by the bitter infighting surrounding the Alhambra. Municipal, regional and central authorities of various political hues regularly fight for control of the monument - with millions of visitors each year, one of the most popular in Spain.