THE LANDSLIDE OF CALAIZA IN THE COAST OF GRANADA (ANDALUSIA, SPAIN).

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ABSTRACT

The Tropical coast of Granada Province, in Southern Spain, was intensively developed during the 80s and 90s., A residential complex of several urbanizations, was built up on the Eastern slope of the coastal Cerro Gordo hill (Almuñecar), on the pre-existing landslide of Calaiza, unidentified in the preliminary technical studies, thus giving rise to a set of incidents associated with this unforeseen unstable slope. To insure sea views from all houses, excavations and fillings were practiced giving place to a stepped slope on which new foundations of structures and roads were located and subsequently progressively damaged by increasing cracks and deformations, leading 42 houses into ruins in the period 2003-2016. Since 1990 annual and monthly rainfalls were variable in the area, and some peaks of rainfall eventually were associated to damages proliferation, although more frequently damages were recorded during dry or low rainfall seasons, when water infiltrated from pipelines breaks. This expressed the damaging effects of a combination of permanent sliding at low annual rate and bad constructions practices during eventual heavy rains or dry periods. An overall perspective of the geotechnical and geomorphological features of the study area, the landslide reactivation, and its correlation to the evolution of damages, as well as its legal consequences, is presented.

Keywords: Mediterranean coastal landslide, Betic Cordillera landslide, landslide dendrochronology, DINsAR landsliding assessment

INTRODUCTION.

The Calaiza landslide is one of the coastal landslides in the rocky Mediterranean Andalusian coast in Southern Spain, consisting mainly of marble and schist Alpujarrides units, Mesozoic formations of clays, silts and chalks, and eventually very recent Quaternary deposits on the Eastern margin of Cerro Gordo, a coastal cliff at the West of La Herradura (Almuñécar, Granada). Other landsliding examples are either also in the coast of Almuñécar at the Eastern border of Cerro Gordo hill and in the nearest Punta de la Mona cape, also affecting an urban complex, or elsewhere at the West of Salobreña (Granada) (Chacon et al., 1992, 2014, 2016; Fernández et al. 1994; Notti et al, 2015; Mateos et al, 2016b).

Fig.1. *Perspectives of Cerro Gordo hill, at the bottom of the landscape, and the coast of La Herradura, a very small fishing village, a) in 1970 (left); b) the same area in15/06/2001 (right) with an advanced urban complex.*

Land-use changes widespread in the Spanish Mediterranean coasts during the intensive and quick process of housing constructions starting in the late fifties and maintained until the current century; throughout the study area these building projects frequently were accomplished with inadequate or insufficient previous geotechnical surveys; in the study area the construction of new housing developments progressed quickly as shown in the next two images. La Herradura became a coastal touristic village of more than four thousand inhabitants while the cliffs leading to Cerro Gordo hill were heavily occupied by new villas and urbanizations (Figures 1, 2).

Fig. 2. *Left: section of the shaded topographical map of the Mediterranean coast of the Granada Province (Spain); the East-West distance between borders of the map is 3.5 km. To the West are settled Cerro Gordo and Cármenes del Mar complex above the beach of Calaiza (Playa de Calaiza). Right: Western Mediterranean Sea and position of the study area (Topographical maps of Spain 1:50.000; sheet*

1055; and section of 1.250.000 © Instituto Geográfico Nacional (ING), Spanish Ministry of Development).

Fig. 3. *Geology and geomorphology of Cerro Gordo (Almuñécar, Granada, Spain). Lithological units: 1 (blue with vertical lines) Lower Palaeozoic, layers of schistose marble embedded in unit 2 (dark blue with black horizontal dots) of Triassic marble which is over thrusting unit 3 (yellow with oblique incline trace lines) Lower Triassic to Palaeozoic schist, unit 4 (dark brownish green), Lower Palaeozoic schist and unit 5 (quartzite and sillimanite-K feldspar bearing dark schists; unit 6 are Quaternary pink coloured silt and conglomerate (yellow with vertical lines), unit 7 (grey with black v), Holocene debris deposit. Source: Geological Map of Spain 1:50.000, sheet 1055, Motril (Granada), Avidad et al. (1973). Below b) geomorphological sketch of the site of Cármenes del Mar in 1970 at the Eastern slope of Cerro Gordo*

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING.

The coast of Granada province (South of Spain) was excavated in the emerging meridional border of the Internal Zones of the Betic Cordillera, in the Alpujarride Domain composed by schistose rocks of variable degree of metamorphism, interlayered with marble units in a complex folded and thrusted alpine structure. In particular the geology of Cerro Gordo, as described by the Geological Map of Spain (Figure 3; Avidad et al. 1973), is featured by a tectonic superposition of Triassic marble on dark grey schist with migmatite layers and light coloured layers of feldspar bearing gneisses (Alberquillas nappe, Sanz de Galdeano 1997; Sanz de Galdeano and López-Garrido 2003) while no attention was paid to the terrain geomorphology and its modelling.

Nevertheless in the General Geotechnical Map of Spain, scale 1:200.000, sheet 5-11/83 Granada-Malaga (ENADIMSA 1973), Cerro Gordo hill, limited to the sea by a cliff coast, is classified into geotechnical class I2, meaning a favourable condition for construction (marble units highly resistant to erosion, good drainage and sufficient bearing capacity), although "*with eventual presence of geomorphological problems such as rock falls and related phenomena in sites with very highly deformed or tectonically crushed rocks*".

The water table in the slope is disseminated in this fissured and fractured marble unit above the impervious black to dark brownish schist unit which is cropping at the base of the slope. This fisural aquifer maintains a low flow rate, and it is found at varying depths along the sector. It is interesting to mention that the clean water supply in the municipality comes from a network of pipelines around the urban areas of Almuñécar, which includes the village of La Herradura and numerous neighbouring urbanizations. A geo-radar profiling with a British 24 geophones UTSI (GV2) model and 50 MHz of antenna frequency was performed in 2007 along different ways and tracks of the Complex indicating a widespread presence of vertical fractures filled with water up to more than 20 m of depth. These vertical fractures delimitate large blocks of marble rocks in Cerro Gordo.

Recent researches suggest the influence of sea level fluctuations since Neogene times on the coastal Mediterranean morphology, expressing the long-term global climatic change, and a complex process of "eustasy", more active in Eastern than in Western Mediterranean (Mörner 2005), driven with a predominantly tectonic component. In the Western Mediterranean the tectonic evolution is mainly related to regional uplifting of the Betic Cordillera, as a collisional effect in the boundary of the Eurasian-African plates, so determining the geomorphological evolution of the coastal border at both sides of the Mediterranean Sea.

Fig. 4. *Detailed view of the Cerro Gordo hill in Almuñécar (Granada, Spain). Above: a) vertical view of Cerro Gordo in July 1986 before any construction was made in which the landslide scarp is apparent; a narrow way to Calaiza beach appears. A yellow circle delimitates the area later occupied by the urban complex; b) oblique view of a relict exhausted block slide at the western slope of Cerro Gordo in July 2010; also some other scarps and fractures are visible; c) Cerro Gordo in July 2010 after the construction of the complex of Cármenes del Mar complex is settled in the upper right area of the view. A yellow point indicates the position of the small sewage plant.*

LANDSLIDE DESCRIPTION

The Calaiza landslide was primarily identified by the authors in the period 2005-2012 and described unpublished technical reports addressed to the affected urbanizations, and only partially published later (Chacón et al. 2014, 2016); its name was selected from the small beach at the foot of the landsliding mass (Figure 2a). It is installed in the landscape and affects to the middle to lower sections of a residential complex of 415 houses built up since 1997 when the basic infrastructure works started, to 2006, when the last sets of homes were effectively finished and occupied. The area affected by the instability process comprises an irregular section of a wider slope with 80-140 m of height interval, a horizontal traverse length of 120-350 m and 100-320 m of horizontal parallel length, in which are settled a considerable number of houses and the main accessing ways.

The urban complex development (Figure 4) comprises single-family detached houses and apartments, distributed in seven singular sub-urbanizations. Only the three ones settled in the upper sections of the slope are outside the landsliding area, while the other four have been damaged, often heavily, by landsliding effects accumulated throughout several years, and furthermore by pathologies derived from bad construction practices, particularly concerning local inadequate infilling and insufficient drainage treatments in the preparation and execution of building foundations. The complex is supplied with clean water by pipelines connected to the municipal network of Almuñécar, while the sewage is accumulated in small underground septic tanks, located in different points in each sub-urbanization, and connected each other to an outlet pipe and finally to a coastal conduit expelling the residuals to the sea (Figure 4c).

Fig.5. Projection into the current urban area of the preliminary zonation proposed by private geotechnical firm to the builders for the further development of the Eastern margin of Cerro Gordo (La Herradura, Granada, Spain). The zonation indicates: A) area suitable for building; B) area suitable with restrictions; C) area not recommendable for building. Only areas in the upper parts were considered suitable for building, and the rest either needs some restrictions or is not recommendable.

The main steps in the progressive construction and failure of the slope in the lower section of the urban complex, beside the main communal decisions taken by the affected owners, are summarized below, with reference to the different urbanizations composing the complex and starting with the first decisions on the study area. Some data on the rainfalls recorded in each period are added to illustrate possible relationships with observed geotechnical problems:

1988: A preliminary geotechnical assessment on the area, made by a regional Andalusian geotechnical private firm, identified some evidences of slope instability and recommended a deeper geotechnical study supported by borehole sampling and laboratory data; nevertheless that was not accomplished by the builders. Also in this assessment, low density isolated housing only in a limited area of the slope was recommended (Figure 5).

Figure 6. Rainfalls in the whole Almuñécar municipality which includes La Herradura: series 1, 1991-2010. Ordinate: amount of precipitation in mm/m^2, abscise: annual hydrological cycles. The historical average, shown by a blue dotted line, is 429 mm/m^2

1997-1998: Evidences of ground deformations were observed before the construction in the lower and middle sections of the slope, although in this period rainfalls were below the local annual average, after a previous historical record in 1996-1997 (Figure 6). Several geotechnical reports by another private geotechnical company were based on 14 drills not deeper than 30 m, with inclinometer control in 5 of them and revealed the presence of a layer of weathered schist showing critical stress at the base of the terrain. This was interpreted as leading: "*to a situation of dire consequences, such as the destabilization of an important area of the slope with its additional effects, practically irreparable by its excessive cost and by the accessory consequence of rejecting, at least in an immediate approach, any possibility of building on the mobilized area*". Also several landsliding scarps were identified in areas not assessed by any drilling and associated to local rupture planes at depths up to 40 m. In any case, these reports did not mention any single large landslide affecting the middle and lower sections of the slope.

1999-2000: New geotechnical reports by the same geotechnical firm identified small variations in some of the inclinometers data which were related to blasting of terrains, compaction settlement or vibrations induced by the movement of trucks and excavators, although again an overall landsliding of the whole area was not recognised. Some of the inclinometric drilling identified sliding planes at 12 m of depth in two small areas. Also some vertical fractures in the medium and lower sections of the urban complex were found and it was recommended to increase the control of local sliding in lower parcels immediately above Calaiza beach. Nevertheless, later in December of 2000, another geotechnical report for a project to build up 97 new houses in the middle section of the slope, does not identified evidences of general slope landsliding, focused the origin of some slope deformations just on consequences of infiltration of water accumulated on the impervious basal schist unit and therefore proposed an intensive drainage treatment and the need of maintaining the natural drainage network of the slope. It is interesting to remark that in 1999 the annual rainfall was in the historic average while the year 2000 was only slightly more humid (Figure 6).

2001-2003: The first houses in the middle section were finished and started to be occupied by the owners until 2006, including buildings in the highest section of the urban complex. This period was dry along 2001; average in 2002 and slightly humid in 2003 when two daily heavy peaks with 40.5 mm/m^2 (22nd May) and 44.0 mm/m^2 (8th October) were recorded (Figure 6). Since 2002 new cracks damaged at least 11 houses in the middle section of the urban complex, and the displacement of a wall, anchored later in 2004, was observed at one of the lower gates (Figure 7).

2004-2006: The widespread extension of cracks and deformations in the lower section of the urban complex was followed by a program of reinforcing treatments by new walls, piling and anchoring of some foundations. The origin of these damages was mainly attributed again to water leakage and infiltration on site or from the upper sections. The rainfall profile along these years (Figure 6) shows dry or extra-dry annual values in 2004 and 2005, followed by average rainfall in 2006, although also some daily storms were recorded with 40 mm/m^2 on 28th March 2004 and 12th December 2006 and 32 mm/m^2 on 27th January, 11st September and 8th November 2006.

Figure 7. Overall perspective SE-NW of the slope above the Calaiza beach: a) in 2001 during the urban complex construction and b) in 2010 when it was finished. The outcrop of the dark grey schist unit near the Sea level is clearly visible as also the landslide main scarp.

2007-2010: After a fairly dry average annual rainfall in 2007, an increase of precipitation was recorded in 2008 and 2009, being both humid although specially in 2009 with monthly peaks in February (119,8 mm/m^2) and December (326,6 mm/m^2) with historic monthly records only overpassed in 2010 (Figure 6). New intense damages affected the middle and lower housing lineations, again attributed to water infiltration although incidental leakage from breaks of the general municipal network took place at the middle section. Those new damages were extensively repaired and some more retaining walls were built up and afterward anchored. A new project of slope reinforcing and stabilization was submitted to the Almuñécar City Council and from October 2008 until February 2009 a new partial reinforcing of slopes and foundations was accomplished in some houses of the lower section. Nevertheless again new cracks and damages appear in the same area by September 2009. In the period September 2009-October 2010 very heavy rains were recorded in the region with 536,4 mm/m^2 in 2009 and 875,4 in 2010 when a new historical annual record was established (Figure 5). Increasing of damages was observed again in the middle and lower sections of the urban complex, affecting also houses and slopes previously reinforced.

In 5th March 2010, an “on site” inspection of the urban complex was spent by the Municipal Architect, and afterward by 27th March 2010 a resolution from the Almuñécar City Council urged the builders company to accomplish a full stabilization project, giving 10 days to the affected Communities to provide a written report from their technical advisors. In December 2010 a new accidental breaking of the water supply pipelines network flooded several houses in the northern side of the lower section.

All these cases affected buildings and ways which had in common some construction practices, particularly the widespread excavation and/or infilling of the irregular original slope in order to arrange a stepping urban complex with the aim of offering views to the sea from every house (Figure 7).

It may be remind that although some of the technical reports indicate different evidences of landsliding in the eastern Cerro Gordo slope, and also local stabilization treatments were recommended and partially applied, the presence of the Calaiza landslide, as a general morphological feature of the zone, was not identified.

2010-2014: A judicial law-suit of the affected urbanizations against the builders and real estate companies took place. By 16th May 2014, the magistrate-judge resolved a providence on a plan of precautionary measures, comprising immediate corrective geotechnical works to prevent imminent damage in houses and vials whose judicial appraisal is about 4.5 million euros.

Figure 8. View of construction in the upper section, with retaining walls and infills in 2001. (b) and (c) details of later reinforcing treatment at the foot of the main scarp near Calaiza, with almost vertical piling trending toward the slope, covered by a later concrete slab reinforced by wire mesh.

A long judicial process was initiated in October 2013 by the affected owners against property developers and construction companies. The 3rd November 2014 was published a sentence favourable to the claiming urbanizations later confirmed on 30th December 2016 in the convicted appeal before the High Court of Andalusia (sentences 165/2014 and 310/2016).

In 25th November 2015 the regional Parliament of Andalusia (southern Spain) with its official agreement (code 10-15/PNLC-000195) declared the need to manage the critical situation under a state of emergence legal consideration, thus supporting a similar prior declaration of the Almuñécar City Council. 24 houses had reached such a level of damage that the competent municipal authority of the City of Almuñécar considered them officially in ruins; unsuitable for residential use, and therefore withdrawing the permission of habitability. Given the progressive advance of building pathologies, by October 2016 another 42 houses were declared in ruins.

From the mentioned geotechnical assessments, the main overall conclusion is that the constructions were initiated without a previous geotechnical study of the whole area and only with some later insufficient and partial studies for groups of houses when early evidences of ground instability appear, further geotechnical researches were developed.

Concerning previously published preliminary papers, the overall assessments of regional stability conditions and susceptibility mapping of the Southern Granada province, indicates the abundance of planar slides and rock falls in the coastal areas (Chacón et al. 1992; Fernández et al. 1994). A characterization of spatial distribution of rock discontinuities analysed the slope stability conditions near several new urbanizations affected by landsliding in the coastal municipalities of Salobreña and Almuñécar (Granada province, Southern Spain) (Chacón et al. 2014, 2016).

Nearby coastal areas such as Punta de la Mona (Almuñécar) and Castell de Ferro (Granada) with similar marble rock massifs were studied by Irigaray et al. (2003; 2012) focusing 40 slope cuts along the main road where the stability conditions were identified using the SMR index (Romana, 1985) and a kinematic analysis of the different types of failure (planar, wedge, and toppling) in a GIS environment, followed by a probabilistic analysis of the limit equilibrium in the slopes where the conditions of kinematic failure were satisfied; their results show several slope cut sections with limited stability plotted on a linear susceptibility map.

A remote sensing analysis of the study area was made using DInSAR technique with ESA images for the period 1993-2000 was made by Fernandez et al (2009) and later assessments with this technique were published by Notti et al et al. (2015) and Mateos et al. (2016b); their results are summarised and discussed later.

Other central and western Mediterranean coastal areas have been also affected by landslides of different types, in various geological and geomorphological conditions. So, rock falls in the coast of Majorca (Baleares Islands, Spain) were recently described (Mateos et al. 2012, 2013; 2016a, b; Sarro et al. 2014); also different landslides were reported in Malta Island (Mantovani et al. 2013) and the coasts of Amalfi and Maratea in Campania and Basilicata Regions of Southern Italy (Ciervo et al. 2016; Pellicani et al. 2016) and debris flows affecting the coast of Ischia Island (Italy) were described by Nocentini et al. (2015) who applied dendrochronology techniques to assess potential landsliding areas on that Tyrrhenian Sea island.

LANDSLIDE CLASSIFICATION.

As described before, in the study area there are several evidences of landsliding; in the Western slope of Cerro Gordo a large exhausted rock block slide scar appears shown by vertical relict scarps in both margins with visible open cracks in its Western border (Figure 4b). The scar is a quadrangular depression resulting from the sliding of a mass of marble on its schistose basement, to be buried under the sea. In the Eastern slope of Cerro Gordo, the map and cross section (Figures 9, 10) show the distribution of landsliding areas related either to Calaiza landslide, including more recent local flowing of infills in different sites of the urban complex, where new scarps and rupture breaks appear since the construction of the urban complex. Also may be distinguished the upper or lateral sections of the urban complex outside the landsliding area in which little or no pathologies are found.

Figure 9 Map of distribution of damaged areas in the urban complex according to data recorded in 2016

Figure 10. Vertical cross section of the study area. 1. Upper Paleozoic black to grey schists, deeply weathered; 2. Lower Triassic Marbre; 3. Recent slope debris cover; 4. Anthropic infills.

From an interpretation of surficial displacements, distribution of outcrops of soil and Alpujarride units, combined with data from GPR and drilling made in the early stages of the constructions, permitted to propose a cross section of the whole slope, showing some of the vertical fractures, infilling of the slope and average position of water table and the distribution of landsliding areas.

Considering the available data and the size parameters defined by WP/WLI (1993), the landslide shows a *width of displaced mass* $W_d \approx 220$ m, an *average length of displaced mass* $L_d \approx 120$ m and an *average depth of displaced mass* $D_d \approx$– 30 m, from which results an averaged *volume* in the order of $8x10^5\ m^3$. In the *magnitude classification* proposed by Fell (1994) it should be considered in volume as a *medium-large sized landslide* (Chacon et al, 2016). The main scarp was clearly visible before the construction of the urban complex as shown in Figures 1a, 3b, 7b and 11.

Activity and velocity

A geotechnical study made in 2006-2007, when the urban area was completely finished, based on boreholes with inclinometers identified a failure plane dipping gently (25-28º) toward the Southeast (N 105º E) at depths between 10 and 45 m; according to these data the mass was moving at an average annual velocity of 38 mm (with a maximum of 88.7 mm) during that biannual measurement period (GG, 2007) (Figure 11).

According to the inclinometric measures taken in different drillings (Figure 13) the slide plane appears at variable depth (8-50 m) apparently unrelated to the slope elevation in which the drilling was made although the two shallowest (8 m depth) slide planes appear at the highest slope elevation (90-120 m). Nevertheless, the distribution of recorded depths to slide plane in the upper elevations (90-120 m) varied from shallow (8-12 m) to more elevated (50 m) depths showing some asymmetry of the plane, or the presence of several planes. Concerning trends of slips there is a preferred orientation towards N110ºE, which varies between N 90 and 220 ºE. Some probes indicated extreme values towards N 5 to 50 ºE or towards N 340 ºE. Considering that the inclination of the slope is preferably toward N110 ºE the above data area consistent with sliding toward the lower section of the slope.

*Figure 11: a) Depth to slide planes in different drillings; b) measures on drillings of displacement trends of slip planes and velocities in µm/day (in = µm * 0.000039370) from inclinometer data from GG (2007, 2011). It is apparent the average trend of inclination of the slide plane toward N110, varying between N90 and N220. Some drillings indicate extreme values toward N5 – N50 or toward N340, associated to other slide planes associated to the main slide.*

A caution about the data on velocity is necessary because the annual rainfall along the measuring period 2006-2007 corresponds to rainfalls on the local average (2006) or slightly below (2007), therefore it could be expected higher velocities in annual periods with higher annual rainfall as was the case in 2009-2010, although it would depends on the sensibility of this deep old landslide to this factor. Near the landslide scarp, in the middle section of the urban complex, the depth to the sliding plane is obviously highly reduced, reaching less than 10 m below surface and the amount of ground, ways and building deformations was much higher and quicker, as after the heavy rainfall of 2009-2010.

A fairly progressive quick episode of slope deformation was observed between 2003 and 2005 when a linear NE-SW failure of the slope affected the lower section of the urban complex, appearing clearly observable along ways, walls and buildings along its path. Eventually, local damages were associated to quick flowing of undrained infills below the urbanized ground growth at highest velocities attaining decimetres per hour in few days, expressing site conditions associated usually to infill thickness and level attained by the accumulated water. This was observed in some houses built on infills in the middle section of the urban complex and also at the northern end of the lower edge of the urban complex, where the infill was exhausted by debris flow and creek progressive growth until the final destruction of the house founded on it).

RADAR images from ERS-1 and ERS-2 ESA satellites were processed to estimate vertical displacements in the study area, and other areas of Granada province, in the period 1993-2000, comprising the first steps of construction of the urban complex after 1998,by a-DInSAR technique, described in Biescas et al. (2007) and Fernandez et al. (2006, 2007, 2009), to a set of 15 images of ascending trajectory in the mentioned period to obtain "*line of sight*" (LOS) displacements in terms of millimetres per year. In the study area the obtained results along these 7 years of analysis only attained up to 2.4 mm/year although clearly centred in the Calaiza slide area (Figure 12), on a small corner in which block falls prevail below the mentioned slope escarpment in the Eastern border of Cerro Gordo and the upper part of the adjacent small extension of pine forest (Fernandez et al, 2009). It may be remind that these DInSAR data for the period 1993-2000 show much lower velocities than the obtained by inclinometric measuring on drilling in the period 2006-2007 when the urban complex was built up, probably expressing the crucial influence of landsliding activity resulting from the constructive process.

Figure 12. *DInSAR assessment of vertical displacements up to 2.4 mm/year (period 1993-2000) in Cerro Gordo and nearby areas*

On the same area Mateos et al (2016b) applied a PS-DInSAR technique which delimitate a few areas with movement in the later period 2003-2009, while no sign of movement was detected in the upper section of the slope. In this unstable area they got a few PS with -2 to -5mm/yr. A pair of PS appears in the east part of the scarp with rates between -5 and -7 mm/yr and two PS more in the central upper part of the landslide mass, one of them in the area where cracks and moderate damages appear. The highest velocity values (more than −10 mm/year) are represented by two PS located outside the urban complex.

Geomorphological reconnaissance also revealed the presence of tilted trees on the landslide near the scarp (Figure 3b) with relatively young tilted trees close to fresh open cracks observable in 2005 although formed probably two years before, and also mature trees with curved trunks (Figure 13a, b). A dendrochronological analysis was carried out in 2008 to analyse and dating these landslide reactivations. 24 trees were sampled by means an increment Pressler borer, 20 located on the landslide and the other 4 outside for dendrochronological control. The small number of trees that were sampled was because, on one hand, a large extent of the landslide ground surface was deforested during the urbanization and, on the other hand, ground deformation and tree tilting in translational slides occur basically near to the landslide scarps and foot, therefore in a small part of the landsliding area.

Figure 13. *Dendrochronological analysis of the activity of the Calaiza landslide: a) Tilted pines located near the head scarp of the active part of the landslide in the northern limit of the lower section; both presence of fresh open cracks and leaning tough right tree trunks indicate very recent activity (photo taken in February, 2008) ; b) Mature tilted pine with a curved trunk; recovery of the vertical position of the upper part of the trunk suggests that some years or a few decades have elapsed since tilting event occurred; c) Core sample of a young tilted pine; change in wood colour by the presence of reaction wood (due to tilting) is apparent in the ring formed in year 1996; d) Chronology of tilting events of trees living on the landslide; e) Monthly rainfall from 1960 to 2010 in the coast of Granada.*

The dendrochronological record covered the span 1934 - 2008, along which 10 tree tilting events occurred, the oldest one in the dendrochronological year (equivalent to the hydrological cycle and running from October to September) 1939-40 (Figure 13c). One of the three trees sampled that were still alive was tilted that year suggesting that the landslide has been reactivating along the whole time interval recorded by the growing tree rings.

The main landslide reactivation events occurred in 1965-66, 1978-79 and 1995-96, periods in which tilting of two or three trees each one took place. Other tree tilting events involved a single tree; they could be caused by small movements of the landslide or by local instabilities of the slope. It is worth noting that other minor reactivations events could have been not recorded by tree rings if they produced small displacement (i.e. not significant ground surface deformation) or if affected only trees tilted in previous events.

Origin and diachroneity.

There are no data about the origin of this landslide although its coastal setting suggests that its appearance could be conditioned by sea erosion and slope profile adjustments during long term variations of sea level (Leone et al., 1996; Cardinali et al., 2002); there are no historical evidences of its eventual triggering by some of the rare large earthquakes affecting the regions, like those of 1755 and 1884.

Considering the available historical information, it is concluded that the Calaiza landslide is clearly visible in aerial photographs from 1956. In the other hand, according to dendrochronological data exposed before it was moving at least by 1934. Also, it has been corroborated that the creek, probably associated to an exhausted planar slide, on the Western slope of Cerro Gordo (Figure 3c), is roughly reproduced in old topographical maps of the XVII and XVIII centuries. An example is the *«Tabularum Geographicum Contractarum»*, a small atlas published in Ámsterdam in 1616 by Jodocus Hondius and Petrus Bertius archived in the Library of the Spanish Geographical Institute in Madrid. It appears even more clearly in the "*First portolan book of the coast of the Granada Kingdom*" written by Juan de Medrano (1730) and archived in the Hispanic Digital Library of the Spanish National Library (manuscript Mss/10165, page 25).

Nevertheless, given the unprecise resolution of these maps, in which only the broad geomorphic shape of Cerro Gordo may be recognized, it is not possible to confirm the highest likelihood of being initiated previously to the 1755 Lisbon earthquake, which also damaged severely the Andalusian lands (Martínez Solares and López Arroyo 2004).

Summary classification of Calaiza landslide.

Taking in account the available data the Calaiza landslide may be describe by the following features. Its volume is around 1.2x10 ^{6} m^{3} and therefore may be considered "*very large*". From the combination of its "*very large volume*" and "*dormant to very slow movement*" it may be considered as "class 4, *very high intensity*", according to Cardinali et al (2002) and Chacon (2012) and in a stage of "*development*" in term of its overall evolution (Chacon et al., 1996).

Concerning its type it is a "*compound* " (Fell,1994) *planar slide* with partial flowing of some shallow infills over the mass. It has been moving at speeds below 0.3 mm/y, therefore in a "*dormant*" or "*extremely slow*" regime (Hansen, 1999; WP/WLI, 1995) and it is "*active*", "*in advance*" and "*composed*" according to the "*state*", "*distribution*" and "*style*" criteria of definition of the landslide "*activity*" (WP/WLI, 1993a,b). Nevertheless higher velocities attaining 38 mm/yeas were recorded after the construction of the urban complex, although those register were taken only in 2006 and 2007. Finally, it shows a *degree IX* of "*diachroneity*", as it has been "*active"* along the last 100 to 1000 years, in a scale of XII degrees (Chacon, 2012; Chacon et al. 2010, 2014).

TRIGGERING FACTORS

The main climatic influences determining the precipitations in the study zone, at the Western North Mediterranean border, derive from a combination of European NAO (North Atlantic Oscillation) trends, which although very relevant in the Northern areas of the Iberian Peninsula, only influences on the Mediterranean coast in the period December-February while decreased significantly the rest of the year, when the external influences are determined by ENSO (El Niño Southern Pacific Oscillation), and North African influences of the Saharan thermal and winds distribution.

During these periods under NAO influence, storms and high precipitation are introduced in the Mediterranean linked to changes in the atmospheric winter flow (exceptional towards the NE during 4 months from December to March in extreme cases). Among other negative NAO maxima affecting the Iberian Peninsula were those recorded in 1996 and 2010, with differences in the 4 months of winter.

From this complex network of influences and the trends of global climatic evolution in the central coast of Portugal, the frequency or interval of prolonged and intense rainfall episodes resulting from NAO influence has been established in the range of 5 to 24 years; given the magnitude and global extension of processes of atmospheric circulation it may be acceptable that are also significant in Southern Spain. It also determines that annual rainfall is diminishing in Western Mediterranean while the number and intensity of heavy rainfall of very short duration increases (Mariotti et al. 2002; Machado Trigo et al. 2005; Alpert et al. 2006; Brönniman 2007).

Some examples of landslides in the Betic Cordillera show that its activation was triggered by intense precipitation in two historical annual rainfall records in the study area (1996-1997 and 2009-2010), when the rainfall reached more than double the average cumulative precipitation for a typical hydrological year in Spain (Palenzuela et al. 2015; 2016). In this sector, uncommon rainfall events were highlighted and their rainfall variables and return period were obtained, by applying a frequency analysis based on the generation of multiple partial duration series (Palenzuela et al. 2016a, b).

Month	Mean	Max.	Min.	σ	CV (%)	Years
Jan.	61.9	306.0	0	60.9	98.3	1970
Feb.	43.3	**178.8**	0	48.2	111.1	**2010**
Mar.	41.2	160.7	0	37.3	90.6	1960
Apr.	42.0	236.0	0	45.3	107.9	1971
May	22.5	**125.0**	0	27.3	121.2	**1996**
June	7.5	61.0	0	14.0	187.2	1980
July	0.6	13.0	0	2.5	422.4	1979
Aug.	1.6	36.5	0	5.8	369.6	1952
Sept.	22.5	**124.0**	0	29.0	129.0	**2009**
Oct.	44.0	**139.0**	0	42.0	95.4	**1999**
Nov.	53.6	214.0	0	47.5	88.6	1951
Dec.	78.5	**326.6**	0	81.5	103.9	**2009**
Year	429.3	**886.0**	**215.0**	141.0	32.8	**2010/1993**
H. Year	436.3	**875.4**	**81.5**	148.4	34.0	**2010/1953**

Table 1. *Monthly rainfall records in Almuñécar, period 1947-2010 showing mean, maximum, minimum. (σ) standard deviation, (CV) coefficient of variation, (H) hydrological year. The most recent maximum values are pointed out in bold.*

The recorded rainfall in the study area (source: Spanish National Meteorological Agency) support the previously ideas, particularly the trend of increasing abundance of short heavy rainfall events, which at the same time seems more and more intense when monthly and annual data are compared. Thus, the data on distribution of rainfall in the municipal term of Almuñécar (which includes Cerro Gordo) indicates that higher maximum records occurred in different months, while annual rainfalls ranged from a minimum of 81.5 mm in 1952-53 to a maximum of 875.4 mm in 2009-2010 and it is quite clear that maximum accumulated monthly rainfall concentrated in the winter period of December to February, along the whole record since 1947, with the only exception of 1973 when the maximum was recorded in spring, period March to May (Figure 5, Table 1).

In bold the most recent maximum values and corresponding year are shown in Table 1, with significant data in 1995-1996 and 2009-2010. All the average monthly values were overpassed since 1951 except in November. Maximum monthly values are maintained since 1951 in November; 1952 in August; 1960 in March; 1970 in January; 1971 in April; 1979 in July; 1980 in June; 1996 in May and December; 1999 in October; 2009 in September and 2010 in February. The current historical record of annual rainfall was established along the hydrological year 2009-2010, and also in monthly values of February and September and in the winter quarter of December, January and February.

Seismic activity is another potential landslide triggering factor to be considered, although the seismicity of the region is moderate and the probability associated to earthquakes with MSK magnitudes above 5.0 or 6.0 is low and much lower than in the Eastern Mediterranean regions (Grünthal et al. 2012). For a t475 year return period the official Spanish Seismic Hazard regulation (NSCE-02/2002) recognizes PGA values ranging from 24 to 370 cm/s^2 for the whole Andalusian territory, with the highest expected values (PGA > 300 cm/s^2) in some parts of the Granada Province and in the town of Vélez Málaga, while a basic ground acceleration close to 0.20g is considered for the study area (Benito et al. 2010).

The information on consequences on the Andalusian terrains of the two only large earthquakes recorded in historical times (1755, Lisbon earthquake, 9.0 M, with epicentre near the Azores islands, Martinez

Solares and López Arroyo, 2004 and 1884 Andalusian earthquake, Intensity X, MSK, Lopez Casado et al, 1992 with epicentre in Arenas del Rey a small village at 53 km away to the SSE of Granada town) is very general and the seismic triggering of large landslides has been only demonstrated in connection with these large landslides in the inner part of the Cordillera, near Granada city, but not in the coastal areas.

DERIVED DAMAGES AND OVERALL PROPOSED STABILIZATION TREATMENTS

Regarding buildings structures, apart from their typologies, their common trend is a rigid structure with superficial foundations through tied-up superficial concrete footings, reinforced concrete pillars, and slabs. The construction of the thermal envelope commonly involves a rigid shell that uses cavity walls – exterior layer: cement-rendered one-half foot of perforated brick; insulated air cavity; interior layer: gypsum rendered 7 cm light brick. According to the Promoter's specifications document, all interior partitions are two-sided gypsum-rendered 7 cm light brick and bathrooms and kitchens are ceramic tiled. Hence, the houses built consist generally of medium-quality average construction (Figures 5, 7, 9, 10, 14), previous to the implementation of the Spanish National Construction Regulations Act (CTE, 2006).

Figure 14. *Some examples of damages: a) structural damages in a house in the upper affected section; b) failure of way along its front; c and d)) lateral displacement of two houses in the upper affected sections; e) deformation and wall cracks of a passage house in the lower side of the middle section; f) Deformations and partial rupture of a wall of stone attached to another one of reinforced concrete also inclined; Deformations of one of the main access road to lower part of the middle section; g) Overall view of slope failure affecting a wall and the way accessing to the lower side of this section; h) Detail of the deformation and overturning of the sidewalk under the leaning wall forward by the thrust of the ground composed of fillings; i) Closer view of upward displacement by a local rotational slide of the way accessing to the lower side of the section; j) Open cracks and circular breaking of the way in between houses of the lower section affecting some parking rooms; k) Open cracks in footings and foundation walls of a house in the upper affected section ;l) slope failure by a local slide flow affecting a section of the lower way accessing to Calaiza beach; the former retaining wall is also broken.*

Concerning the operative building method in those pronounced slopes, the constructions settled through embanks and terraces, traced out of the ground levels defined by the new urbanisation roads – which significantly modify the existing topography (Figures 1, 3, 5, 7, 9). This forces the construction of large retaining walls and important infills to level the terraces and allow for clearly stepped foundation levels, both in private lots and in common areas –sets of stairs, open pathways, landscaped areas, and pools.

The need to align the homes in levels that guaranteed sea views, frequently led to foundations on the infills that had been previously deposited on the excavated parcels. Pilling deep down on the terrain would have afforded safer conditions for the buildings. Likewise, finishing in pathways and pavements, as well as in pools and gardened areas, were built on poorly compacted and drained fillings.

A common practice directly observed by the authors is that when swimming pools in the upper residential sectors were emptied for cleaning, the water flushed through the drainage system and, given the frequent breaks and loses of water, accumulated in the infills of the lower sectors of the urban complex. These were built on the deep landslide mass and were ultimately affected by changes in the humidity and consistency of the infills when saturated after some rainy periods or the frequent accidental water infiltration events..

In practice, a sensitive instability situation was created by slope sliding, forced by constructive activity and related results, which combined with water filtrations lead to amplify the soil movements. This creates a harsh panorama for buildings due to pressure and cave-ins, as the foundation levels are subject to cracks, rotations, tractions, and highly demanding stresses that exceed the technical regulations limits.

The whole is worsened by filtrations into terraces and through the undrained backside of the large retaining walls, producing a wide range of damages more or less increased depending of the susceptibility to landsliding and variable bearing capacity of foundation terrains.

The rigid ceramic walls show stress lines through fissures and cracks. In some areas of the different urbanisations, pressure on the soil has affected whole houses, damaging structural concrete walls and even tie-bars that link the superficial footings, producing complete structural affection that has led to collapse, and in some cases forced the complete demolition of the affected buildings. The same detriment has happened to landscaped areas throughout the different urbanisations, causing damages in fences, brick walls, slabs and staircases unable to withstand beyond the slightest land movements. As a consequence, the land deformations have altered retaining and garden walls –both masonry-made and plastered, as well as slabs, pavements, and pools, in both private and common areas. Given the magnitude of the issues, local reparation of damages does not seem suitable unless a large-scale intervention is put in place. This would limit and contain the general deep landslides shown on the geotechnical studies already conducted, and would need to be further studied on those still pending, taking into account the technical advice of qualified experts. In 2015, due to the fear of immediate collapse, 24 houses were sealed by the City of Almuñécar while by September of 2016 they were 42; furthermore, many other were progressively increasing its damages (Figure 14).

Applied and proposed stabilization measures and treatments.

For an overall slope stabilization the technical assessments (CG 2007, 2011) suggested remedial works along the Calaiza beach slope front and the foot of eastern slope of the lower side of the middle section, with a large basal stabilizing wall at the foot and widespread treatment of local containing walls and foundation reinforcement in different sections of the urban complex, with treatment of rock slopes against block falls and to avoid further effect of up warding erosive down cutting in the lower section and finally the repair of the widespread damages in houses, ways and communal areas of the middle and lower sections of the urban complex. In the meantime, before the availability of financial support for this really expensive geotechnical overall program which may attain a large amount of money (>10^9 €), some preliminary urgent treatments has been resolved by the Tribunal proposing an urgent treatment of the most damaged houses and ways and a widespread repair of drainage network with extension to infilled sections, local soil compaction and reinforcing of infilled sections, and implementation of a monitoring and surveying program until the evidence of a new slope equilibrium in the urban complex. The increase of damages during recent rainfall periods (2002-2016) expressed a very urgent need of this geotechnical treatment in order to avoid major slope failures in the near future.

CONCLUSIONS

The construction of the urban complex of the urban complex on the eastern margin of Cerro Gordo in La Herradura (Almuñécar, Granada) in South Spain began in 1998, ignoring a 1988 preliminary geotechnical report that suggested the presence of landsliding and slope instability limitations, and advised further geotechnical studies which were not accomplished. The urban complex population raised above 2000 inhabitants within several sub-urbanizations. The presence of the old planar slide of Calaiza under the building area was not considered despite the geomorphological evidences. The landslide crown is established in the upper boundary of the middle section of the urban complex at elevations of 90 to 140 meters while the sliding plane appears in drillings at 45 to 60 meters of depth in the middle part of the slope, before leaving the slope at the slide foot nearby under the Mediterranean Sea.

Despite the subsequent reinforcing of slopes and houses by several retaining walls the damages have affected a wide irregular section of the urban complex covering 80-140 m in height interval, 120-350 m in horizontal traverse length, and 100-320 m horizontal parallel length. Currently, 42 houses were declared in ruins and many others suffer different levels of damage.

A DInSAR assessment of vertical displacement in the period 1993-2000 determined downward rates up to 2.4 mm/y in the whole landsliding area, while in 2014-2016 similar vertical velocities has been assessed in some parts of the urban area, although reaching up to 5-7mm/y at specific sites in its middle and lower sections, as shown by scattered permanent DInSAR (Mateos et al., 2016b); Azañon et al.,2016). Along with these landslide displacements, since 2003 were observed local vertical displacement in the middle and lower parts of the urban complex. It attained higher downward rates in short periods with local flowing and widespread damages derived from deformations of the foundation terrain, frequently a thick badly compacted infilling with fine and granular soils lacking of appropriated drainage treatments. These damages occur after heavy rain periods and severe infiltration of water by accidental breaks in the pipeline network of the urban complex, being frequently difficult to differentiate damages and terrain deformations of geotechnical origin from those resulting from accumulated effects of the very slow displacement of the Calaiza landslide. By 2010 damages affecting houses, swimming pools, ways and roads were widespread, and since 2014 after a complicated law-suit resulting in a favourable sentence, the owners are waiting for the financial solution for the immediate execution of an extensive program of drainage, repair and stabilization in the whole urban complex.

The "*active"* Calaiza landslides has a mass of about $1.2\text{x}10^{6}$ m^3, therefore a "*very large*" magnitude, moving at a "*extremely slow*" velocity below 0, 3 mm/y, it is "*in advance*" and "*composed*" of several parallel planes, and is damaging the urban complex with a "*very large intensity*" in a stage of "*development*" allowing a centennial future evolution until its final exhaustion, given its *degree IX* of "*diachroneity*" or alternatively immediate geotechnical stabilization and contention program, according tho the criteria and classification of landslide activity, magnitudes and consequences published by WP/WLI (1993a, b, 1995); Cardinali et al. (2002) and Chacon et al. (2010, 2014).

The main triggering factor is water infiltration from rainfall and frequent severe events of breaks in the pipelines network, although eventually sudden more active triggering effects could be also possible in a region considered of moderate seismicity, with an accepted probability of some large quakes every five centuries. Nevertheless, considering the overall amount of damages recorded in the urban complex since it construction, beside to the Calaiza landslide effects, there are much more significant damages derived from bad construction practices, especially by the inadequate preparation of terrains for foundations by mean of thick infills not always sufficiently compacted and drained.

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Figure 1

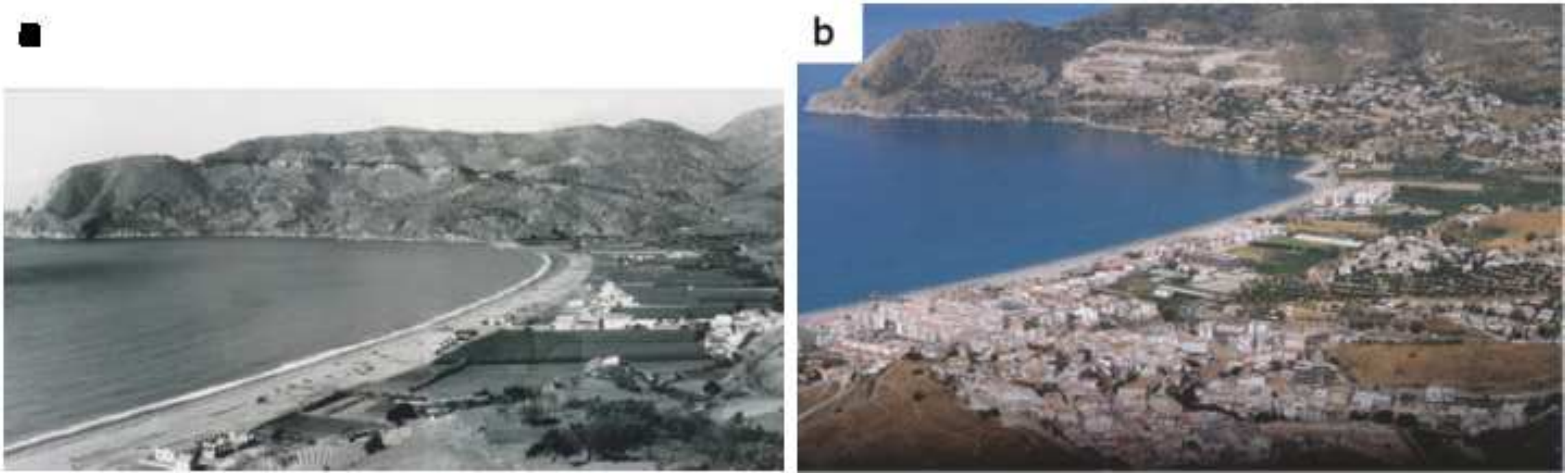


Figure 2


Cerro Gordo o El Nogal
Las Palomas
San Nicolás
San Carlos
Playa de Calaiza
Playa de la Herradura
La Herradura
Punta de la Mona
Cueva de las Palomas
Las Terrazas
Cala del Perro
Cueva de los Gigantes
Cueva de los Genoveses

Figure 3

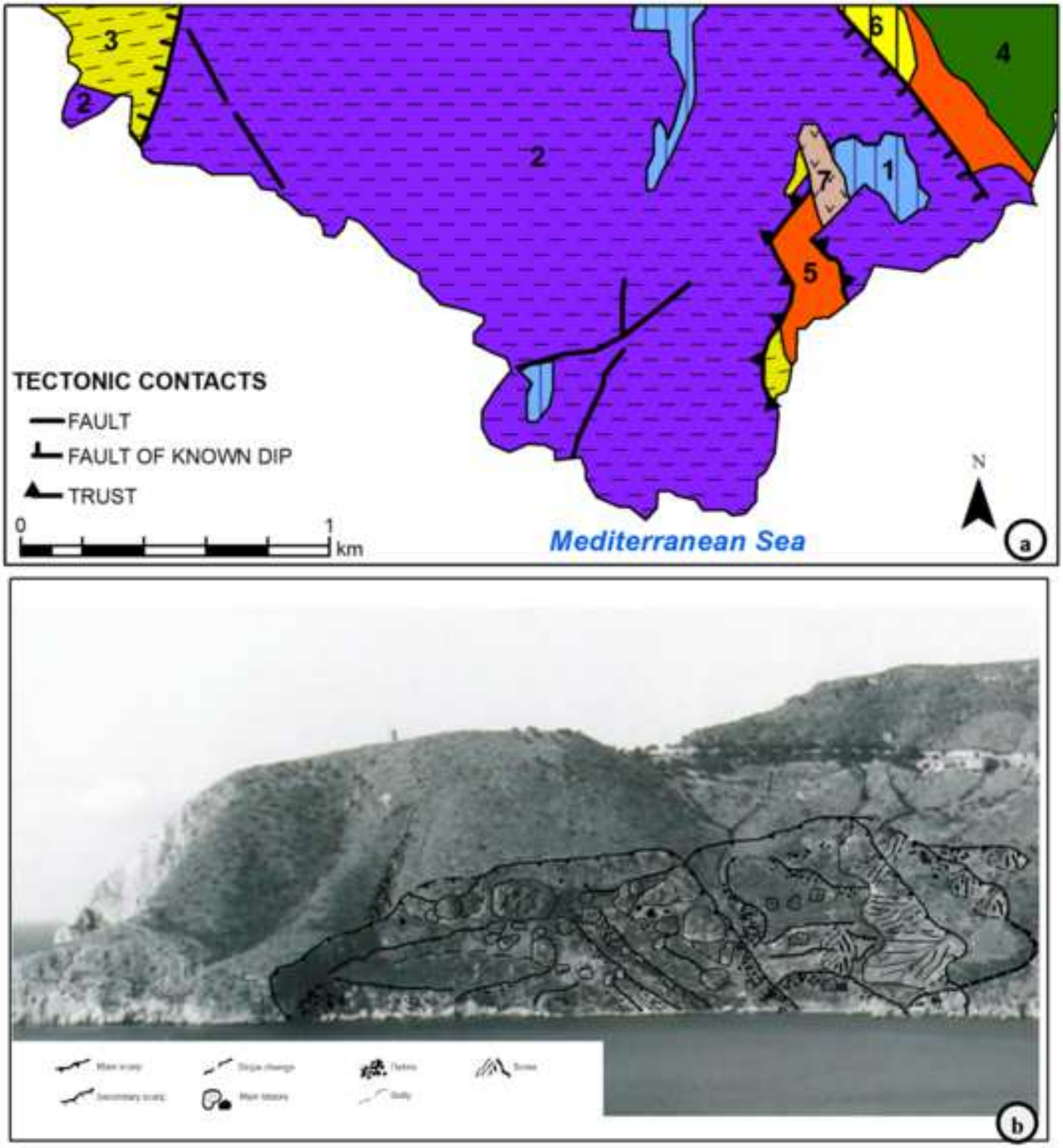
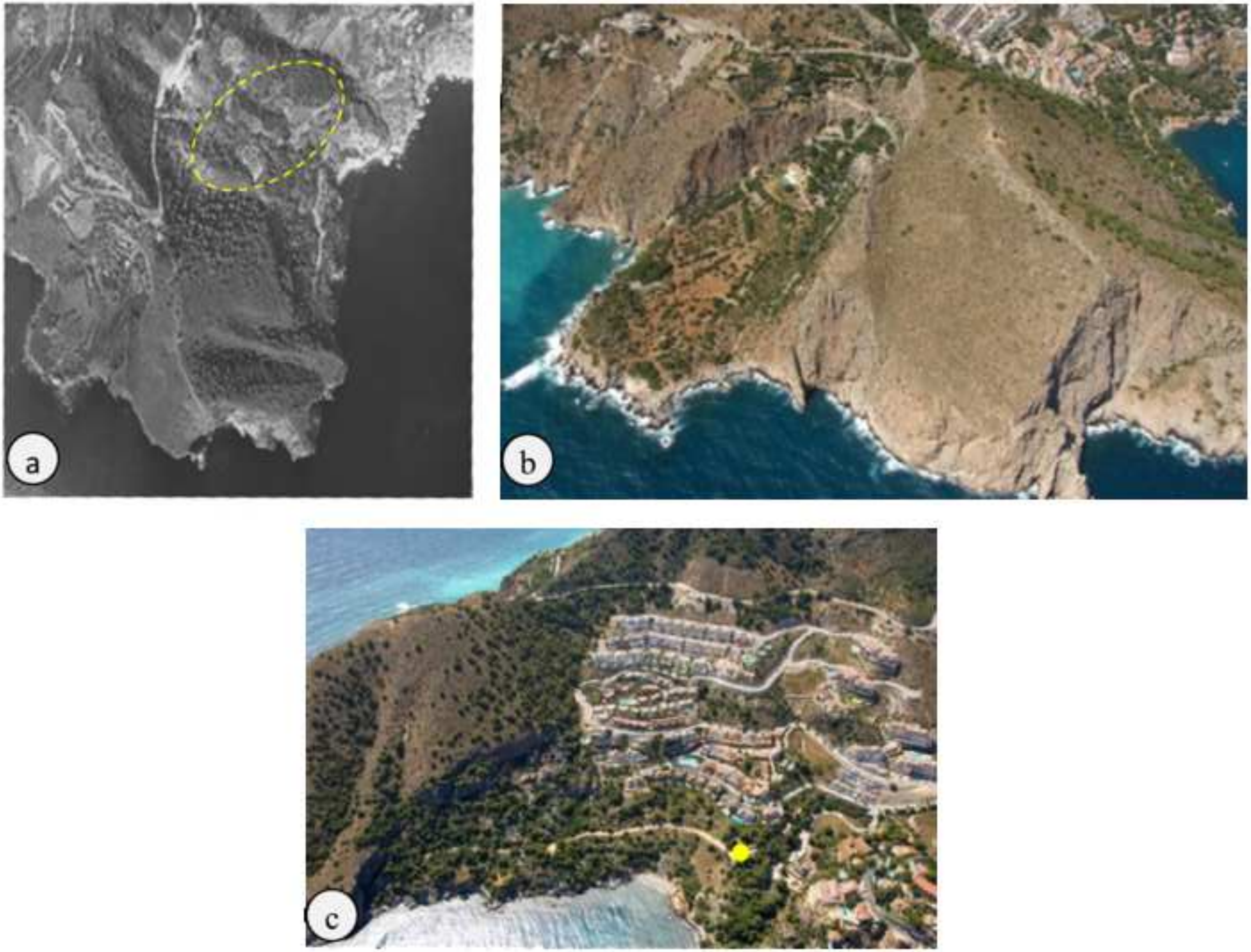
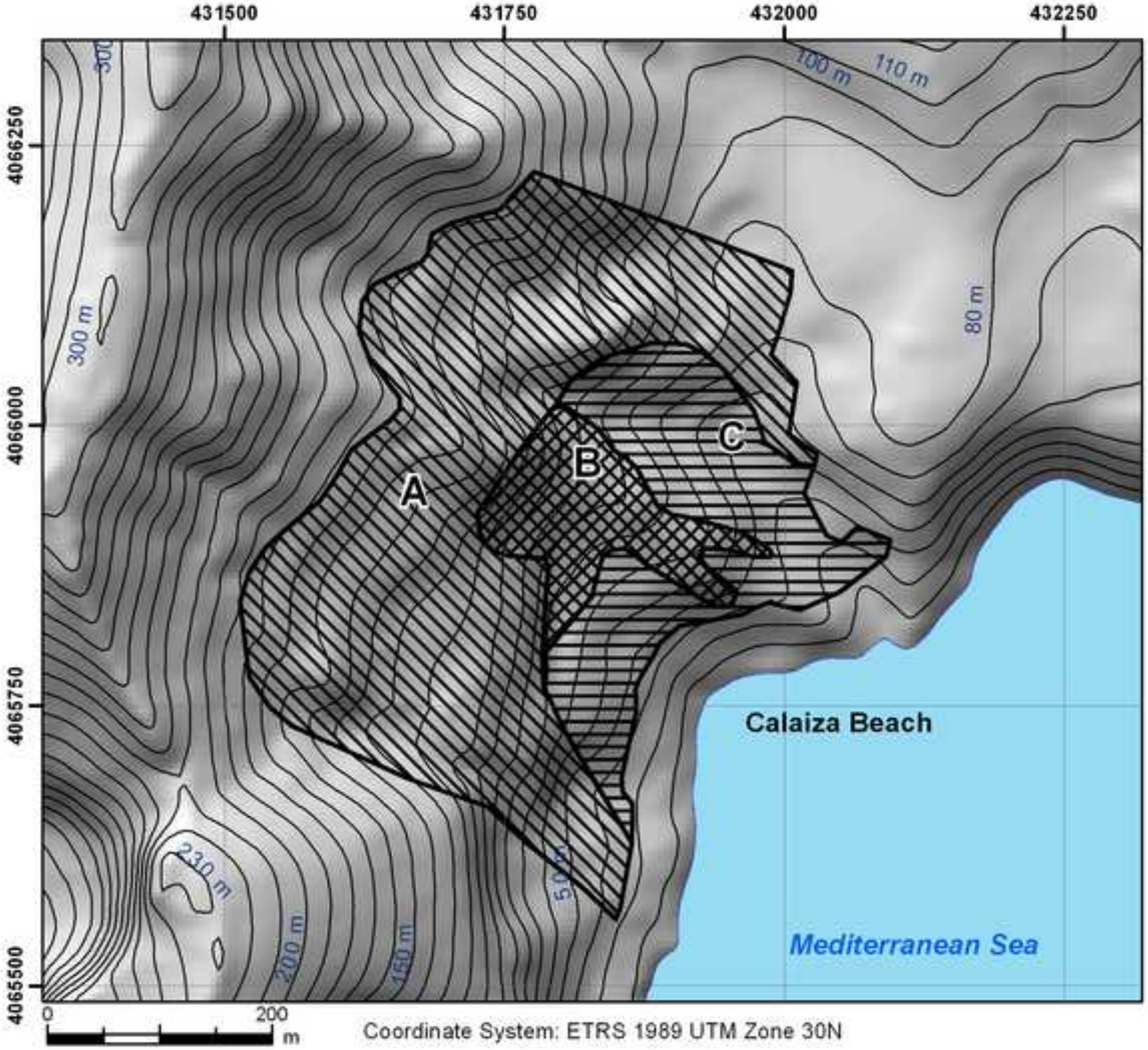

3
2
2
6
4
7
1
5
TECTONIC CONTACTS
FAULT
FAULT OF KNOWN DIP
TRUST
0
1
km
Mediterranean Sea
N
a
Main scarp
Slope change
Talus
Scree
Secondary scarp
Main blocks
Gully
b

Figure 4




431500
431750
432000
432250
4066250
4066000
4065750
4065500
300
300 m
100 m
110 m
80 m
230 m
200 m
150 m
50 m
A
B
C
Calaiza Beach
Mediterranean Sea
0
200
m
Coordinate System: ETRS 1989 UTM Zone 30N

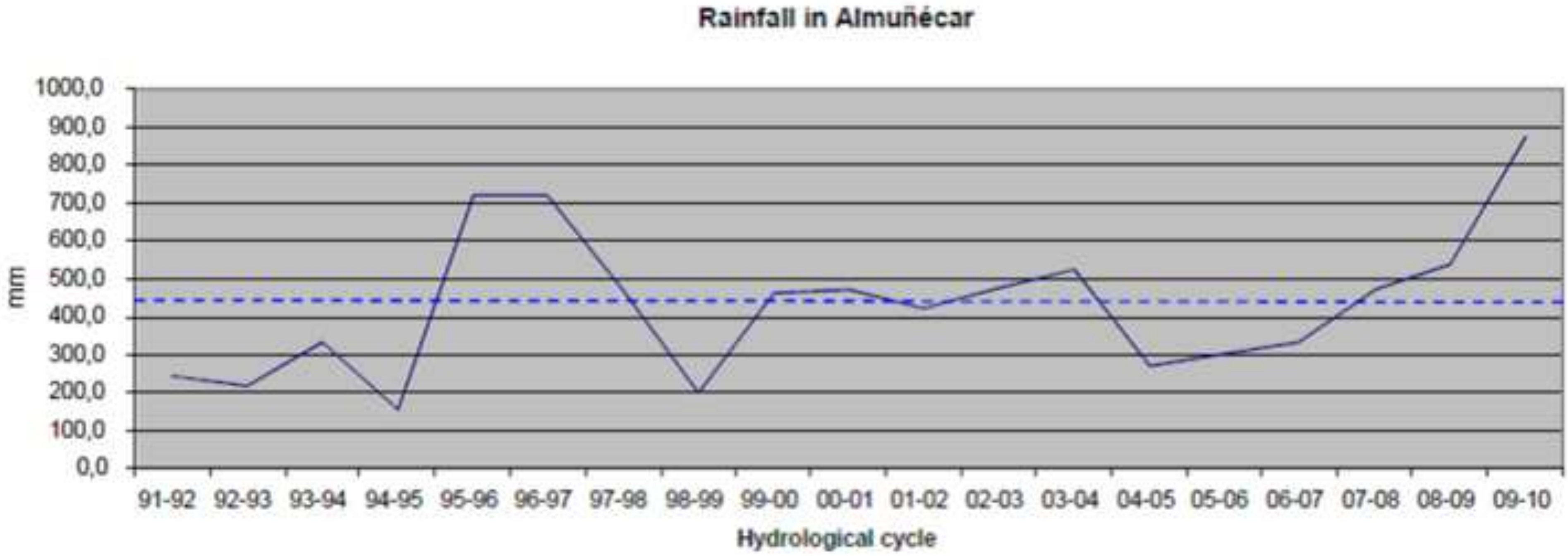
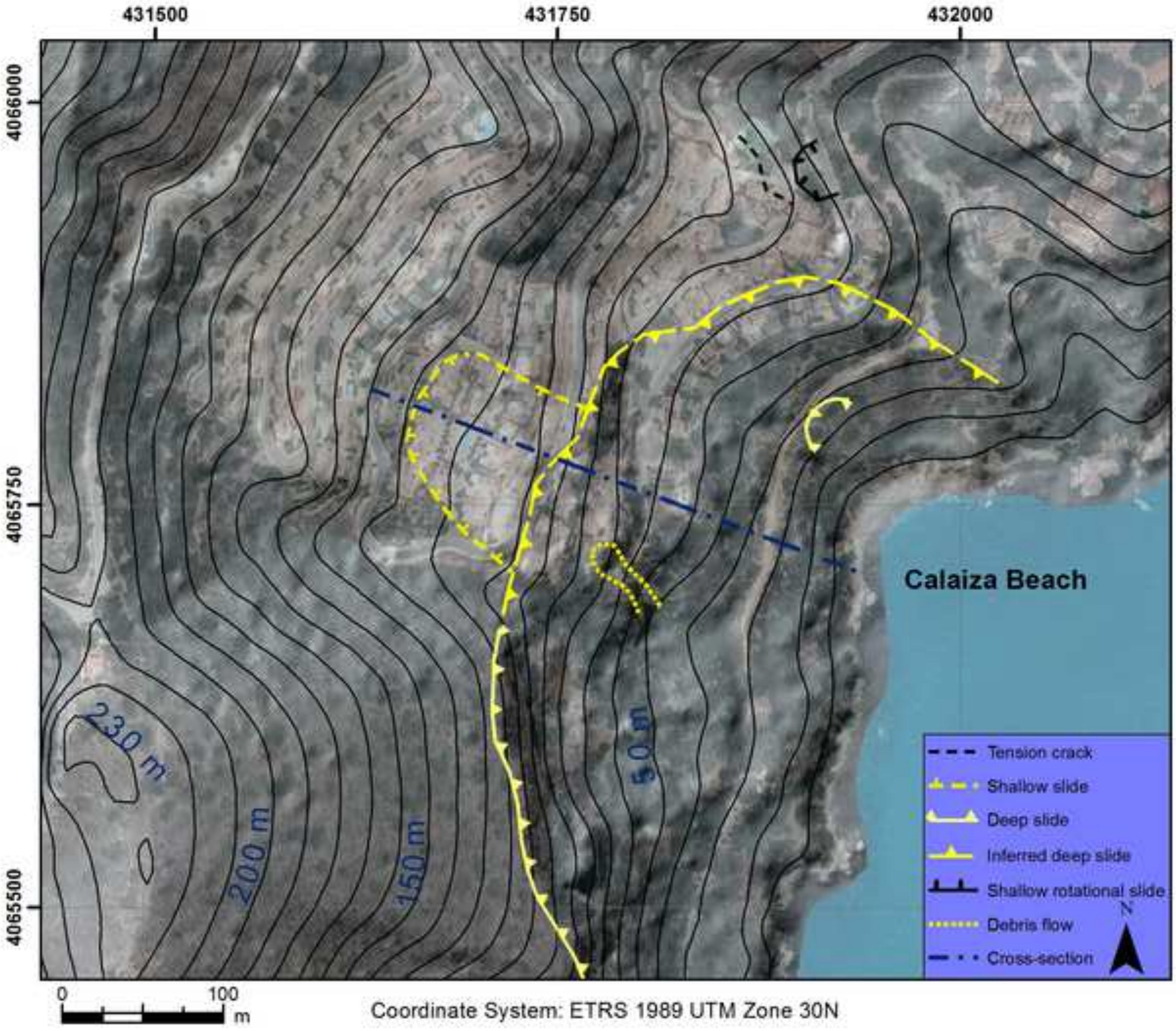

Rainfall in Almuñécar
mm
1000,0
900,0
800,0
700,0
600,0
500,0
400,0
300,0
200,0
100,0
0,0
91-92
92-93
93-94
94-95
95-96
96-97
97-98
98-99
99-00
00-01
01-02
02-03
03-04
04-05
05-06
06-07
07-08
08-09
09-10
Hydrological cycle

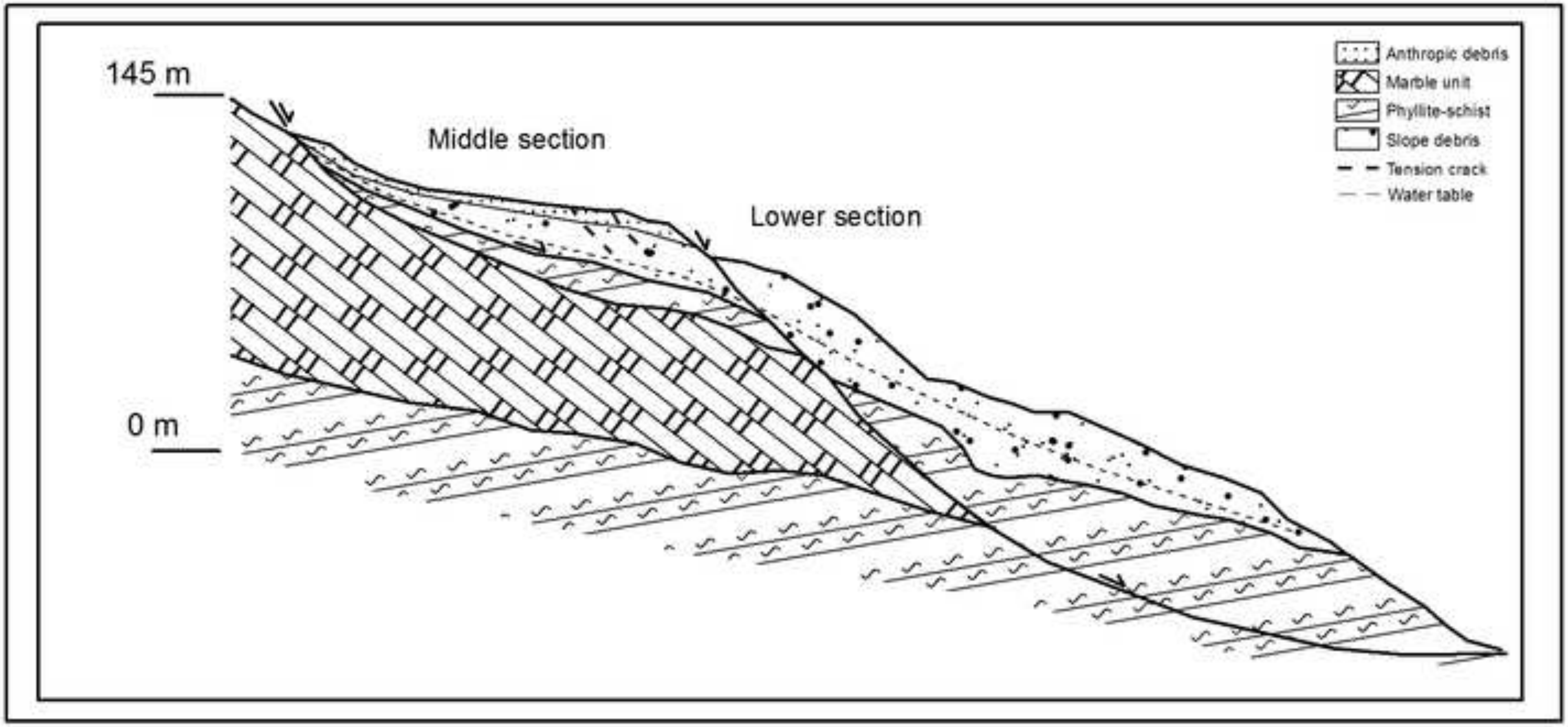
Figure 7

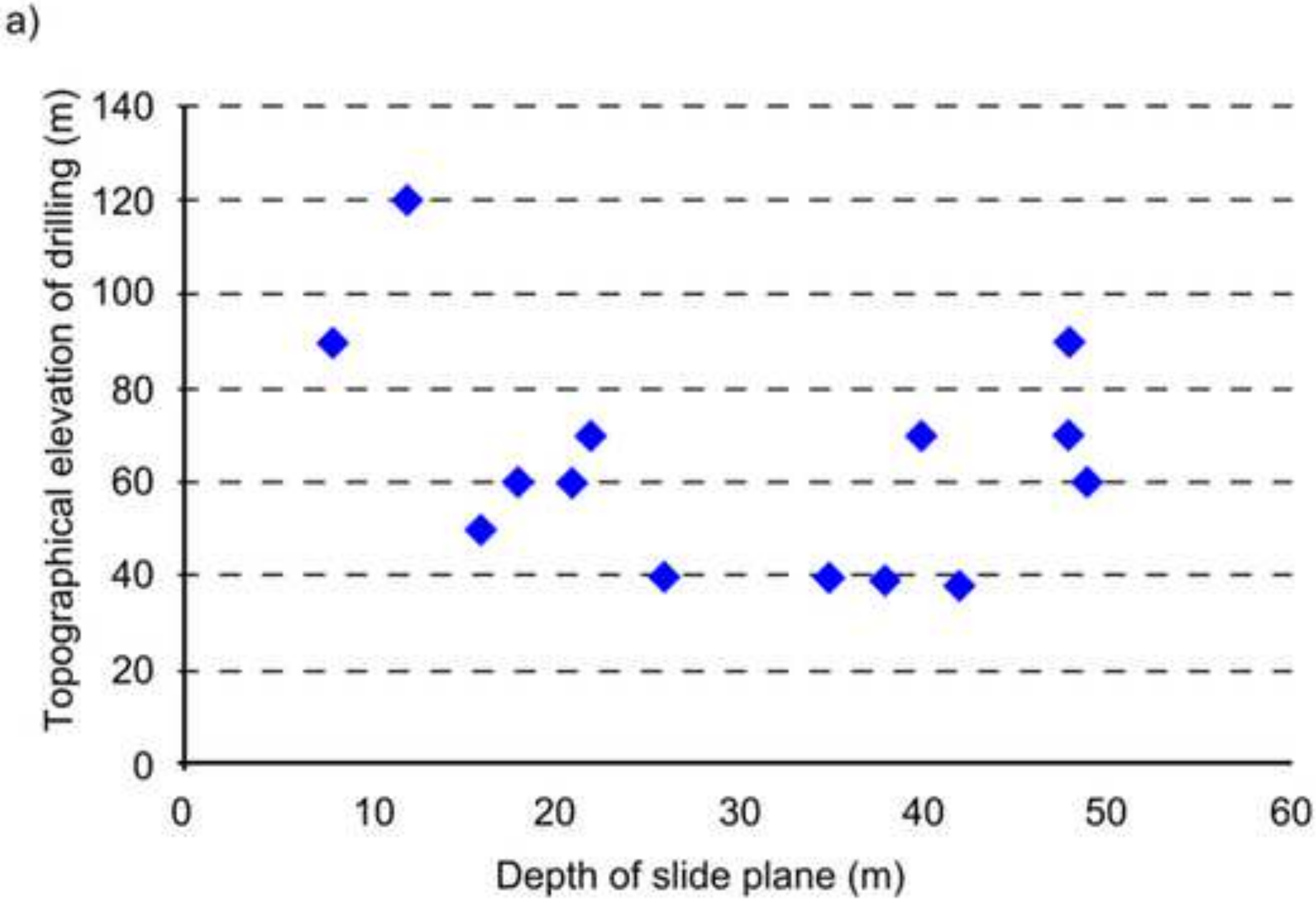
Figure 8

Click here to download Figure Figure 8.tif

Figure 9


431500
431750
432000
4066000
4065750
4065500
230 m
200 m
150 m
50 m
Calaiza Beach
Tension crack
Shallow slide
Deep slide
Inferred deep slide
Shallow rotational slide
Debris flow
Cross-section
N
0
100
m
Coordinate System: ETRS 1989 UTM Zone 30N


145 m
0 m
Middle section
Lower section
Anthropic debris
Marble unit
Phyllite-schist
Slope debris
Tension crack
Water table


a)
Topographical elevation of drilling (m)
0
20
40
60
80
100
120
140
Depth of slide plane (m)
0
10
20
30
40
50
60

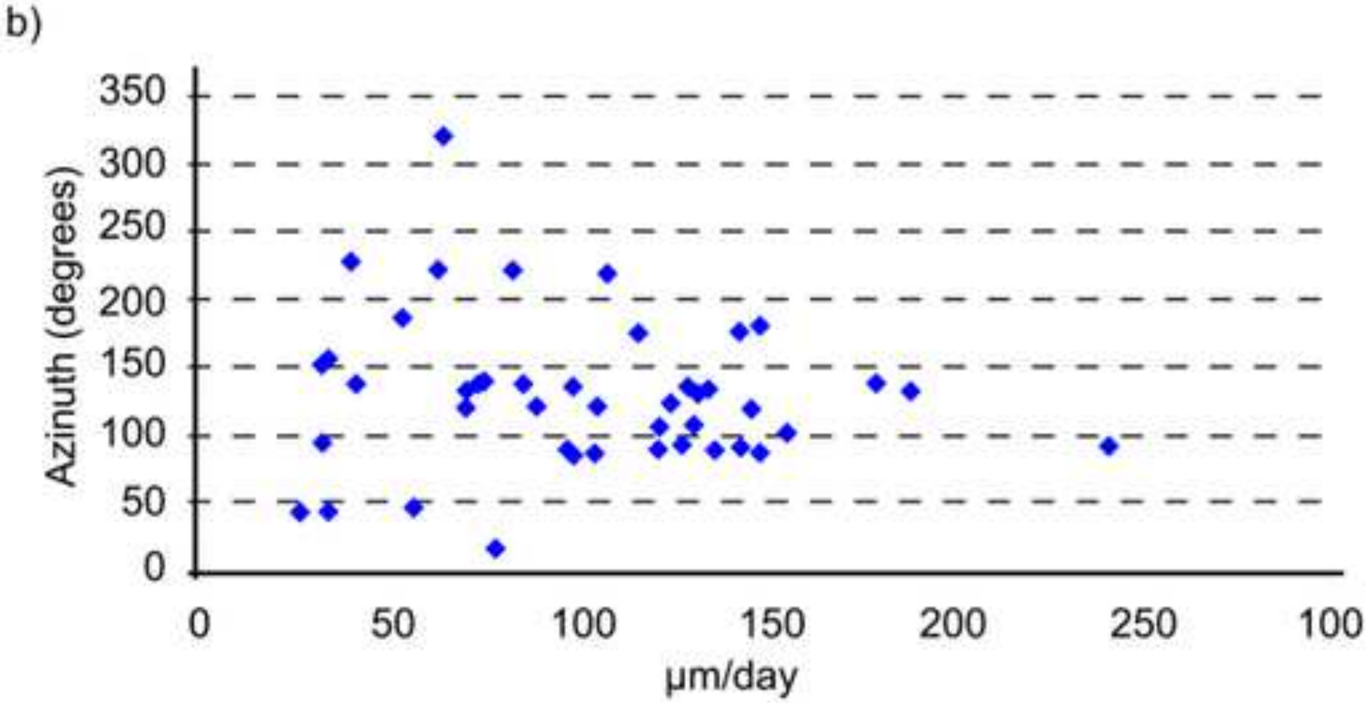
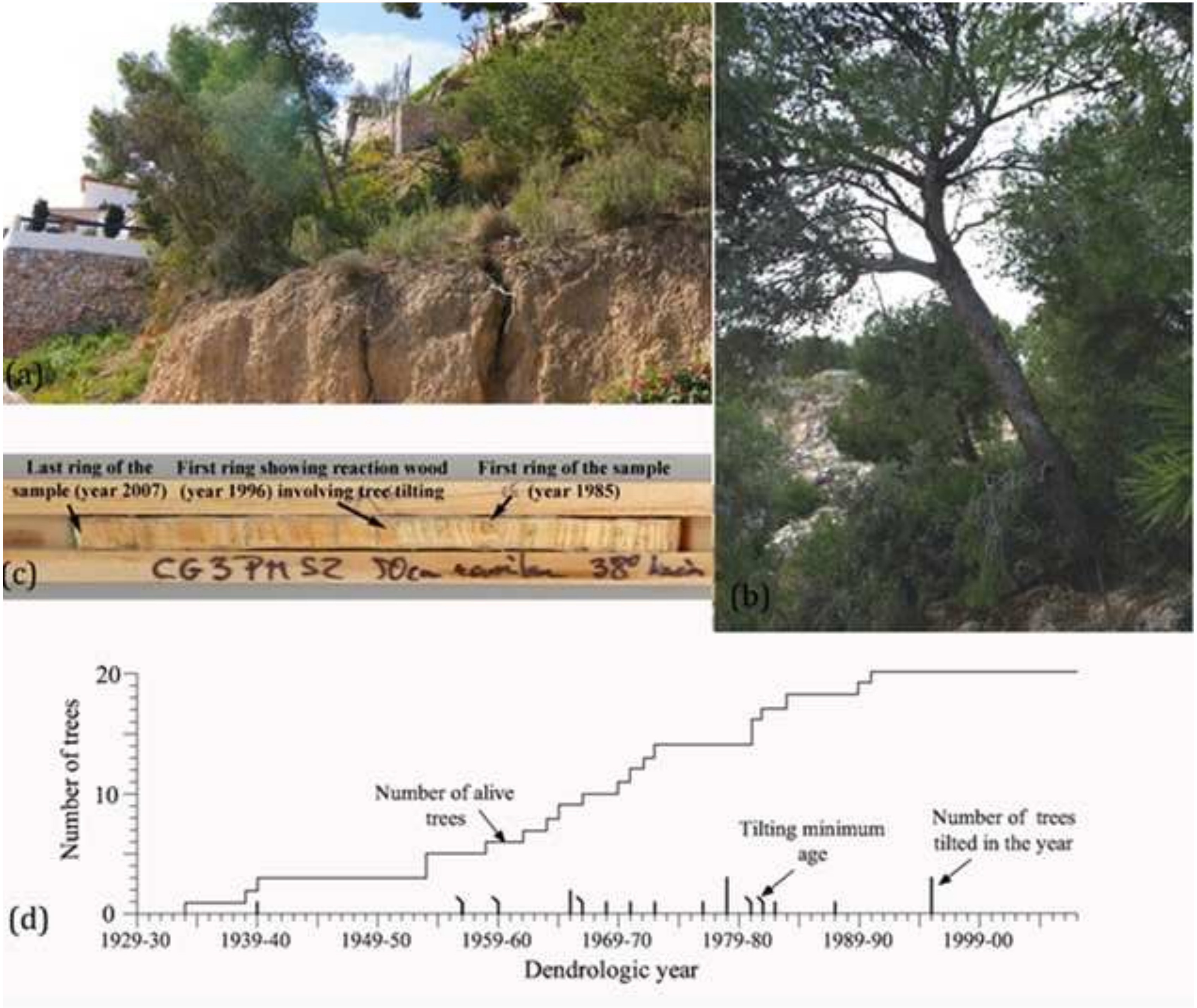

b)
Azinuth (degrees)
0
50
100
150
200
250
300
350
μm/day
0
50
100
150
200
250
100

Figure 12

Figure 13


(a)
Last ring of the sample (year 2007)
First ring showing reaction wood (year 1996) involving tree tilting
First ring of the sample (year 1985)
CG3PM S2 50cm
38°
(c)
(b)
(d)
Number of trees
20
10
0
Number of alive trees
Tilting minimum age
Number of trees tilted in the year
1929-30
1939-40
1949-50
1959-60
1969-70
1979-80
1989-90
1999-00
Dendrologic year

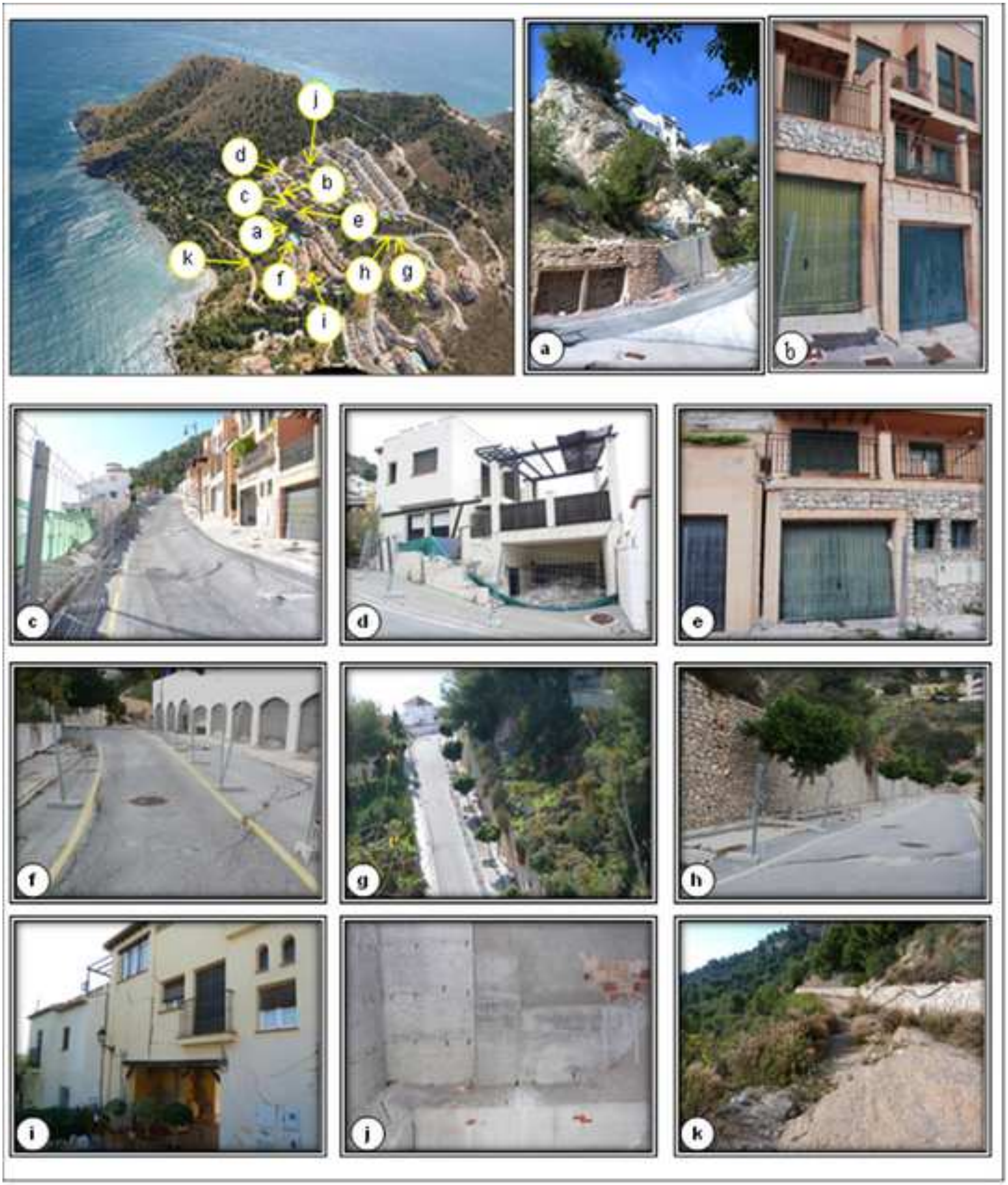

j
d
b
c
e
a
k
f
h
g
i
a
b
c
d
e
f
g
h
i
j
k

Table 1. Monthly rainfall records in Almuñécar, period 1947-2010. The most recent maximum values are pointed out in bold; σ: standard deviation; CV: coefficient of variation; H. Year: hydrological year

Month	**Mean**	**Maximum**	**Minimum**	**σ**	**CV (%)**	**Years**
Jan.	61.9	306.0	0	60.9	98.3	1970
Feb.	43.3	**178.8**	0	48.2	111.1	**2010**
Mar.	41.2	160.7	0	37.3	90.6	1960
Apr.	42.0	236.0	0	45.3	107.9	1971
May	22.5	**125.0**	0	27.3	121.2	**1996**
June	7.5	61.0	0	14.0	187.2	1980
July	0.6	13.0	0	2.5	422.4	1979
Aug.	1.6	36.5	0	5.8	369.6	1952
Sept.	22.5	**124.0**	0	29.0	129.0	**2009**
Oct.	44.0	**139.0**	0	42.0	95.4	**1999**
Nov.	53.6	214.0	0	47.5	88.6	1951
Dec.	78.5	**326.6**	0	81.5	103.9	**2009**
Year	429.3	**886.0**	**215.0**	141.0	32.8	**2010/1993**
H. Year	436.3	**875.4**	**81.5**	148.4	34.0	**2010/1953**