Landslides
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Coastal lateral spreading in the world heritage site of the Tramuntana Range (Majorca, Spain). The use of PSInSAR monitoring to identify vulnerability

Abstract The Bàlitx area is located on the steep coastal side of the Tramuntana Range (Majorca), a mountainous region which was declared a World Heritage Site by UNESCO in 2011 in the cultural landscape category. The Bàlitx site was occupied by farming areas with dry stone constructions and water storing systems of both Roman and Islamic origin. The coastal landscape is characterised by a large fault escarpment of up to 260 m in height. Lateral spreading processes are favoured by local stratigraphy and tectonics in an energetic coastal dynamics scenario. Block spreading morphologies are identified along the escarpment, with large, rocky blocks of volumes up to 60×10^3 m^3 moving very slowly until their collapse. Consequently, a thick and highly karstified breccia deposit is accumulated at the base of the scarp. The lowest, oldest breccia outcrop has been dated (Th/U), and an age of 82.5 ± 5.6 kyr was obtained, reflecting the time span this process has been active. Additionally, numerous geomorphological slope features are identified in the area: landslides, rockfalls, and, more specifically, long and deep cracks in the hanging wall block of the fault, which also reveal active lateral spreading processes. Coastal dynamics have been investigated by interpreting offshore geophysical studies, bathymetry data and borehole information to determine the role of wave energy in the stability of the slope. Additionally, 14 SAR images from the ALOS PALSAR satellite have been exploited for the present work, covering a period spanning from 2007 to 2010, an anomalous rainy period in the region. Images were processed using the Persistent Scattered Interferometry (PSI) technique. PSInSAR results reveal that the rate of movement for the Bàlitx lateral spreading is extremely low (− 5.2 mm/year on average), but major activity has been detected in the NE sector, where velocity rates can reach values of up to − 16 mm/year Coastal dynamics in the area can explain this, as a small island generates wave refraction and reflection determining more intense erosive processes in the NE part, which lead to a greater destabilising effect on the slopes. A simple vulnerability approach has been developed to take the elements of cultural heritage into account. Vulnerability increases from SW to NE, in accordance with landslide activity. The Bàlitx case study could provide a testimony to the effects of mass movements and coastal dynamics in an exceptional example of Mediterranean agricultural landscape.

Keywords Lateral spreading · PSI · Coastal dynamics · World Heritage Site · UNESCO · Vulnerability · Majorca

Introduction

The island of Majorca (Spain), located in the western Mediterranean, has a variety of different geomorphological domains, most prominently the Tramuntana Range (1.100 km^2) in the northwestern part of the island. The Tramuntana range was declared a World Heritage Site by UNESCO in 2011 in the Cultural Landscape category. This landscape is the fruit of the exchange of knowledge between cultures (the Muslim and the Christian) and it is a good example of "the combined works of nature and man", with small-scale works performed for a productive end, and conditioned by the limitations imposed by the physical medium (very steep topography). The cultural heritage is made up of paths, terraces, walls and traditional constructions in dry stone to extend farmland, improve harvests and prevent damage from soil erosion and very frequent slope movements. The region also contains an exceptional hydraulic heritage to exploit water on an island with long, dry summers. One of the consequences of mass tourism in Majorca since 1960 has been a progressive abandoning of the ancient cultivation system and therefore, increasing landscape degradation (Mateu i Lladó 2014). The inscription of the Tramuntana area on the World Heritage List offers a new scenario for its management and protection that encompasses a better knowledge of the natural processes involved, including landslide activity.

Lateral spreading typically develops on slopes consisting of brittle rocks underlain by soft formations and there tend to be extremely slow movements with velocity rates below 16 mm/year (Cruden and Varnes 1996; Pasuto and Soldati 1996; Conti and Tosatti 1996; Gutiérrez et al. 2012). Lateral spreading processes are reported throughout the Mediterranean region in geologically active and unstable coastal environments. This is the case of the NW coast of Malta, where Magri et al. (2008) and Galea et al. (2014) have identified lateral spreading rates and vertical motions of several millimetres per year by applying GPS monitoring. Carobene and Cevasco (2011) also refer to a large-scale lateral spreading on the Ligurian coast (Italy) in favourable geological conditions. The stratigraphy and tectonics of the Tramuntana coastal fringe, with prominent Jurassic limestone escarpments overlying ductile Triassic clays, determine block spreading phenomena in many sectors of the range (García-Moreno et al. 2015). Sea level fluctuations, as well as important climate changes, occurring during the Quaternary seem to have contributed to the intense slope dynamics in this region (Gelabert et al. 2003; Mateos 2006; Mateos et al. 2007). The case reported in the present work aims to provide a new insight into lateral spreading processes in the western Mediterranean region.

In coastal areas, shoreline erosion frequently results in landslides and complex slope activity. Wind-induced waves can play a vital role in the stability of slopes; in fact, wave refraction has a direct influence by focusing wave energy on promontories and on some parts of the coastline. In this sense, small-scale morphology of the shoreline may determine the distribution of the most landslide-active areas. A detailed analysis of the coastal dynamics

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along the Tramuntana Range was carried out by Mateos (2006), taking into account offshore data from the Spanish Ministry of Public Works and Transports (MOPT 1992). The author established a clear correlation between the presence of large coastal landslides and a greater thickness of unconsolidated deposits on the marine platform. The original information will be reinterpreted in the present work for the Bàlitx case study.

Persistent Scatterer Interferometry (PSI) techniques have proved useful in mapping and monitoring different types of landslides, especially slow moving landslides (Herrera et al. 2013; García-Davalillo et al. 2014; Scaioni et al. 2014; Delgado et al. 2011; Notti et al. 2015; Frodella et al. 2016). In the Tramuntana Range, the state of landslide activity was analysed by Bianchini et al. (2013), exploiting ALOS PALSAR satellite images acquired during the period 2007–2010. In that work, over 300,000 measurement points (PS) were detected throughout the Tramuntana Range, permitting the evaluation of the state of activity of many previously inventoried landslides (77 cases). Of this number, 42 were classified as active as they present an average velocity greater than 5 mm/year. Some of the active PS are located in areas where lateral spreading processes were identified; however, as yet they have not been analysed in detail. In the present work, a thorough analysis of the PS results in the test site will be carried out.

This paper reports a block and slab-type lateral spreading identified in the central sector of the Tramuntana Range (Majorca), on the steep coastal landscape of Bàlitx (Fig. 1), where many elements of cultural heritage have been identified. The purpose of this research is to carry out an integrated survey of the Bàlitx area which includes the following: (1) a thorough geological and geomorphological investigation; (2) a search for evidence to determine the temporal span the lateral spreading has been active; (3) a detailed study of offshore sedimentation and coastal dynamics; (4) the identification and mapping of the cultural heritage elements within the site; (5) a monitoring of the slope activity by applying PSInSAR techniques; (6) an evaluation of factors which determine current slope activity regarding the spatial distribution of ground motion; (7) an evaluation of the vulnerability of the cultural heritage elements.

This work aims to measure lateral spreading displacements in the Mediterranean region by applying PSInSAR techniques and supports recent initiatives which exploit PSI data to assess geohazards affecting cultural heritage. The results have a wider relevance regarding issues of hazard and risk related to the protection and safeguarding of cultural heritage.

Methods

To achieve the objectives posed in the previous section, the following methodological approaches were carried out:

- Geology and geomorphology were investigated by means of a digital elevation model (5 × 5 m), aerial photography, field mapping and previous research studies. Field mapping was connected with structural measurements of joints, fractures as well as cracks affecting the area. To be able to conduct a thorough study, a section was mapped out from a boat as the steep relief left some parts practically inaccessible. Geological and geomorphological maps were drawn at a scale of 1:10,000, taking into account all the features related to previous and current slope activity.
- A sample was collected to be able to date the lowest and oldest deposit formed as a consequence of the lateral spreading process. Pure calcite was found for dating using the Th/U method.
- Coastal dynamics in the Bàlitx site were investigated by interpreting geophysical studies, bathymetry data and borehole information obtained by the Spanish Ministry of Public Works and Transports (MOPT 1992) along the Tramuntana coast while searching for offshore sand deposits (to replenish beaches). A geological map of the offshore platform to a water depth of − 50 m has been drawn at a scale of 1:10,000 for the present research.
- A field study of the cultural heritage elements was carried out, identifying terraced areas with dry stone construction, small hydraulic constructions as well as other specific components. A map with the cultural heritage elements was created at a scale of 1:10,000.

Fig. 1 View of the Bàlitx area from the air. It is located on the steep coastal side of the Tramuntana Range (Majorca) where a high fault escarpment (of up to 260 m in height) characterises the landscape. S'Illeta is a small island located at the foot of the cliff

- The slope activity of the Bàlitx area has been evaluated by exploiting ground surface displacement data available from previous works (Bianchini et al. 2013). These measurements were retrieved from the Persistent Scattered Interferometry (PSI) processing of 14 SAR images (with a pixel resolution of 37 × 37 m) acquired by ALOS PALSAR in L-band (24 cm wavelength) in ascending orbit over the whole Tramuntana Range during the period spanning from 1/1/2007 to 28/6/2010, an anomalous wet period in the region. Data were processed using the Stable Point Network (SPN) technique (Crosetto et al. 2011), an advanced differential interferometric processing technique that includes both the Small Baseline (SB) and the Persistent Scatterers (PS). Ground displacement measurements were later projected along the steepest slopes.
- A correlation (by GIS overlapping) has been made between the PSI measured displacements and the mapped geomorphological features to determine the sectors with greater slope activity.
- A correlation (by GIS overlapping) between the PSI measured displacements and the cultural heritage elements has been developed to determine which components of the site are located in the most active areas.
- All the information has been integrated to assess the vulnerability of cultural heritage elements to landslide hazards in Bàlitx.

Geological context

Regional setting

The Tramuntana Range is the main mountainous alignment of Mallorca, with a maximum length of 90 km and an average width of 15 km (Fig. 2). The geological structure of this Alpine chain, with geological units dipping SE, leads to a southern slope that is gentler than that on the coast, which is much more rugged and abrupt, with a prevalence of very high cliffs overlooking the sea. The peak line is more than 600 m a.s.l., and the central sector is the highest. There are numerous peaks with altitudes higher than 1000 m, the Puig Major (1445 m) being the highest peak on the island. The NE-SW mountain alignments of the range correspond to the reliefs caused by the Miocene compression (Burdigalian to Langhian) linked to the Alpine Orogeny. Basically, its geological structure consists of a series of NW directed thrusts sheets, the regional detachment level being the Late Triassic (Keuper) sediments, marls and gypsum with volcanic rocks (Álvaro 1987; Gelabert et al. 1992; Gelabert 1998). The stratigraphy of the Tramuntana Range begins with the deposits of black shales (Palaeozoic in age) until the more recent colluvial sediments from the Quaternary. Carbonated lithologies clearly predominate and especially Jurassic limestone which constitutes the framework of the mountains (Mateos et al. 2002).

During the Upper Miocene, extension transformed the large-scale Alpine geological structure into a system of horsts

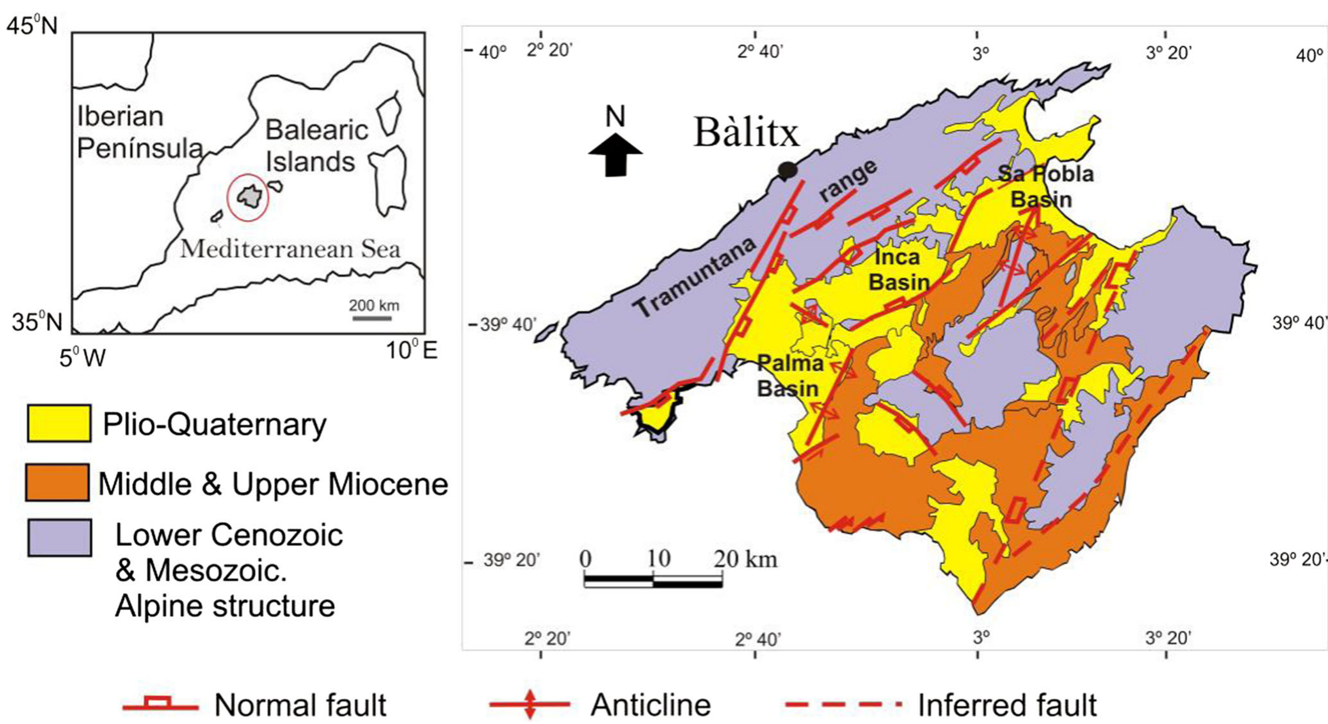

Fig. 2 Location of the island of Majorca in the western Mediterranean and the Tramuntana Range in the northwestern part of the island where the Bàlitx site is located. The geological map of Mallorca (based on Sàbat et al. 2011) shows the main geomorphological domains. The Tramuntana range is a Neogene Alpine structure and consists of a series of NW directed thrust sheets. The post-orogenic basins (Palma, Inca and Sa Pobla) are semi-grabens developed along normal faults at the foot of the mountains. The coastal fringe of the Tramuntana Range has a NE-SW trend, parallel to the main tectonic structures

and semi-grabens that became independent basins at the beginning of Quaternary (Sàbat et al. 2011) to form the present basins of Palma, Inca and Sa Pobla along a NE-SW-trending trough (Fig. 2). Currently, a relative quiescent and mainly extensional stage continues (Sánchez-Alzola et al. 2014). The instrumental record shows that the present-day seismicity is shallow (< 10 km deep) and of low magnitude ($m_{bLg} < 3.5$), mainly focused on the island's central sector and in the Palma Basin (Silva et al. 2001). No historical seismicity is reported in the Tramuntana Range region.

The Bàlitx area is located on the coastal fringe of the Tramuntana Range, in its central sector and immediately north of the Port de Sóller (Figs. 2, 3). The main geological features which determine the morphology of the range are presented in Bàlitx: NW directed thrusts sheets as well as post-Alpine (post middle Miocene) normal faults.

The Bàlitx area

A geological map (scale, 1:10.000) of the Bàlitx area has been drawn up (Fig. 3). This map shows the superposition of two thrust sheets in the area. The upper unit is composed of limestones from Lower Jurassic (Lias), with a thickness that is progressively thinning towards west. The Liasic limestones are overlying the materials from the Upper Triassic (Keuper facies), which are widely exposed along the coastal fringe and constitutes a softer and unconsolidated material. The thrust surface can be identified above the cliff at a height of 16 m (Figs. 3, 4) and has exploited the soft Keuper layer. The thrust contact is located where older

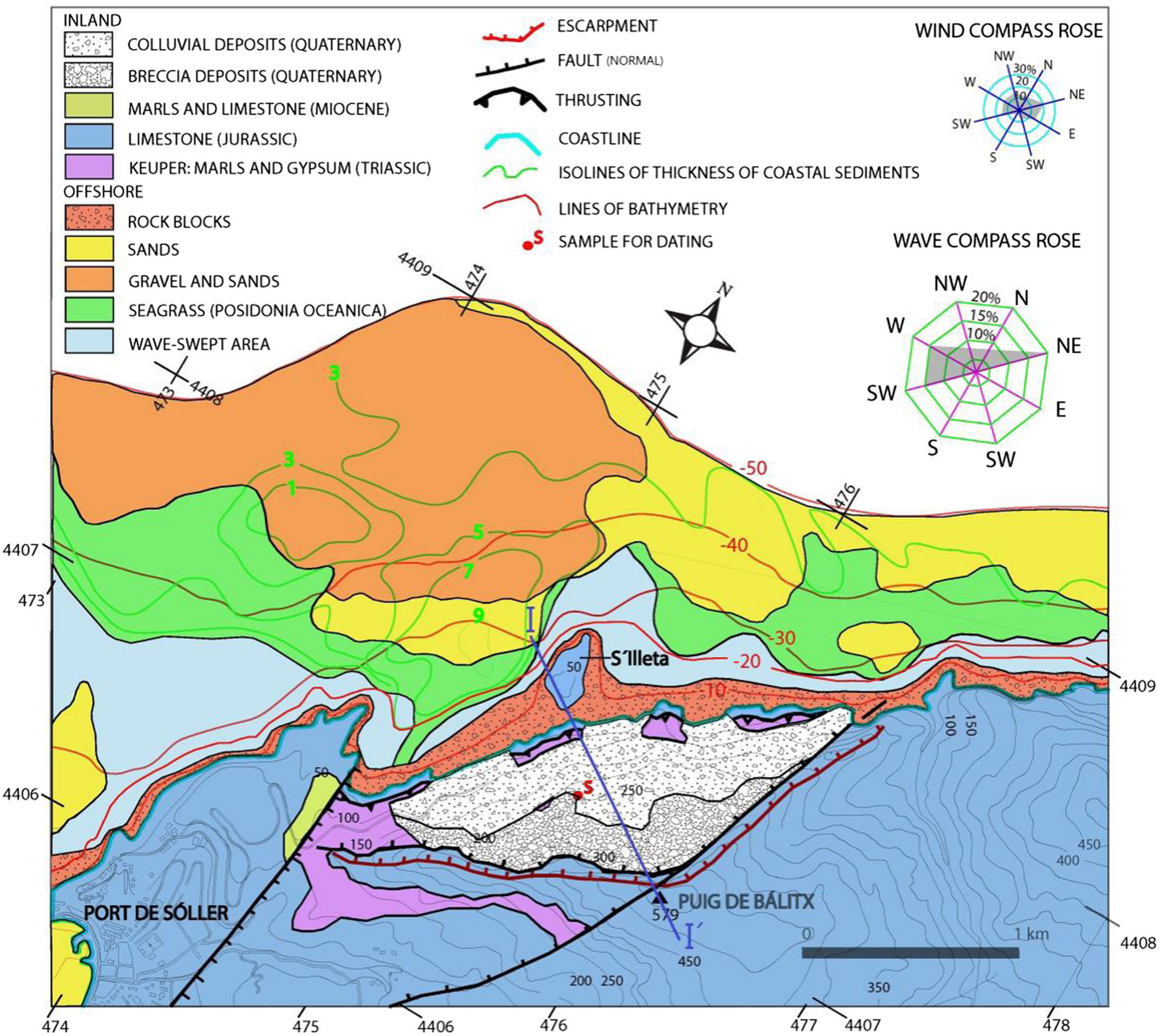

Fig. 3 Geological map of the Bàlitx area (inland and offshore). The coast is characterised by a brittle limestone formation (Jurassic) overlying the softer Triassic formation: marls with gypsum and volcanic rocks. This configuration favours lateral spreading processes. Bathymetry and the sedimentation on the offshore platform (including thickness-isolines of the coastal sediments) are represented based on the interpretation of MOPT (1992) data

materials (Triassic-Keuper) overlie younger materials (Jurassic-Lias). Because of its ductile behaviour, the Keuper materials (as a whole) are strongly deformed. Immediately above the thrust surface, some gypsum levels from the Keuper are well identified and they constitute the detachment level for thrust development. Colom (1970) identified and dated (with paleontological evidence) the presence of the Lias rocks (limestone) dipping about 12° southwards at the base of the Bàlitx coastal cliff (below the thrusting) and on the small island of S'Illeta. Most of the Bàlitx slope is widely covered by Quaternary colluvium material reflecting the intense slope dynamics in the area.

Integrating all the data, a simplified geological cross-section of the Bàlitx area was constructed (Fig. 4). The normal fault breaks the previous compressive structure along a surface trending NE-SW with an inclination of 60° towards NW. Gelabert (1998) refers to post-compressive normal faults being common in the western limbs of antiformal structures in the Tramuntana Range, as happens in Bàlitx. The thickness of the limestone formation in the fault escarpment can reach values of up to 260 m, but it decreases progressively towards the SW end of the escarpment, where the Triassic formation widely outcrops (Fig. 3). In the hanging wall block, Quaternary sediments cover most of the slope, but the same favourable lateral spreading geological disposition for lateral spreading takes place, as both the limestone and the Quaternary deposits overlie the soft Triassic materials.

Coastal dynamics

Regarding coastal dynamics in the Tramuntana Range, the main storms are driven by strong NE, N winds (up to 40 m/s) with a large associated fetch (900 km NE and 300 km N). For most of the year (56.4% of days), the Tramuntana coast is affected by northerly winds, and heavy storms are very frequent during winter with significant wave heights over 3 m (Mateos 2006). The absence of significant tides (< 0.25 m tidal range) restricts coastal morphology changes to waves and coastal currents (longshore) and especially to those severe windy and rainy episodes when wave erosion processes are enhanced. Small islands, such as S'Illeta, may disturb coastal processes, generating wave refraction and reflection and determining the spatial distribution of erosion and deposits along the coastline.

Geophysical studies, bathymetry data and borehole information from the MOPT (1992) referring to the Tramuntana coast have been analysed. Figure 3 shows the map drawn up for the Bàlitx coastline. The average value of the slope of the adjacent marine platform is around 8°, and the wave swept area (where the rock basement crops out) does not exceed the bathymetric of − 35 m. The distribution, thickness and nature of the coastal sediments can be summarised as follows:

- There is an accumulation of large blocks of rock along the Bàlitx coast up to water depths of − 15 m, which reflects intense slope dynamics.
- A meadow of seagrass (*Posidonia oceanica*) can be found at depths of between − 10 and − 45 m in the shallows located to the SW part of S'Illeta and with an extension of around 1.2 km^2. To the NE, the meadow is less extensive (± 0.7 km^2), and is located at greater depths, between − 20 and −45 m. *Posidonia* only grows in clean and calm waters. This distribution indicates that the SW part is less energetic.
- Sand deposits with the greatest thickness (9 m) are identified only in the SW sector of S'Illeta, which also reflects a less energetic environment.
- Additionally, there is an accumulation of coarser shoreline sediments (gravel and sands) up to depths of − 50 m off the western part of S'Illeta, which are not identified in the eastern part.

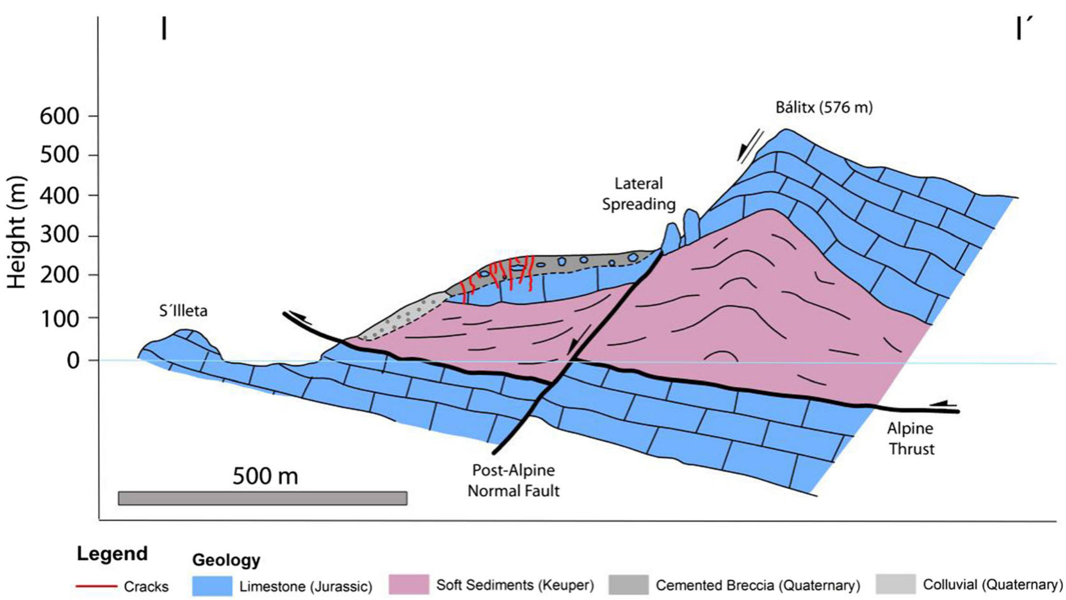

Fig. 4 Simple cross-section of the Bàlitx geology (I-I' trace is indicated in Fig. 3). The normal fault is located in the western limb of an antiformal structure and breaks the previous compressive structure. Below the thrust surface, Jurassic limestone outcrops at the toe of the cliff and on the small island of S'Illeta. Not only in the footwall block but also in the hanging one, lateral spreading is favoured because brittle rocks overlie the soft Triassic rocks

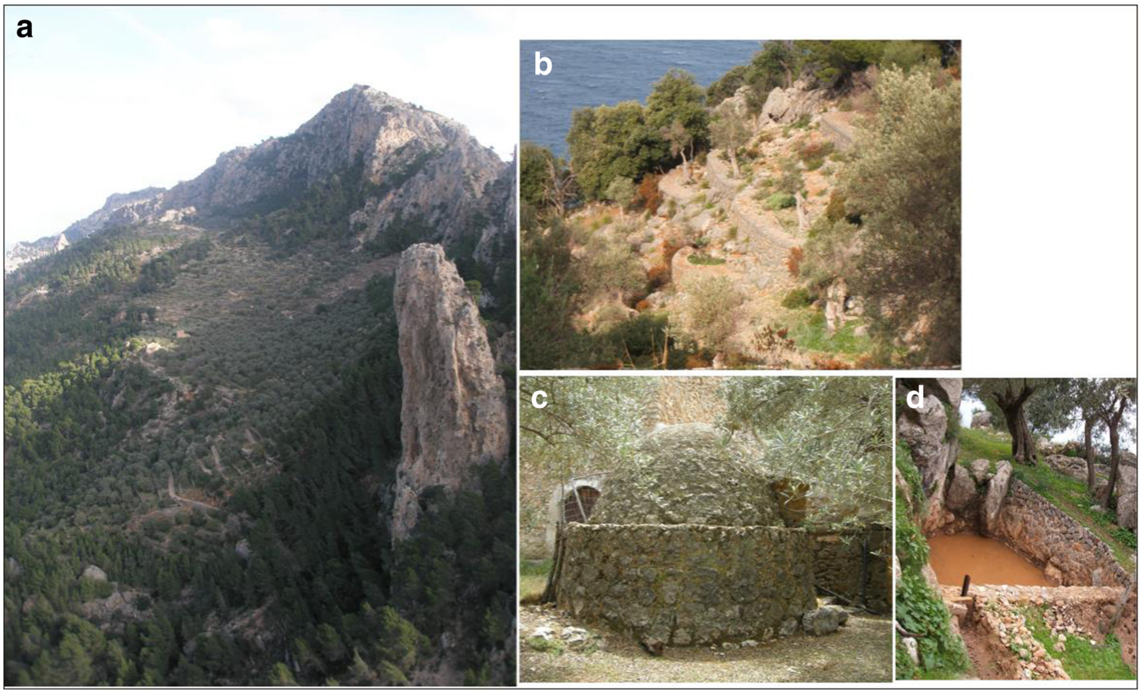

Fig. 5 Elements of cultural heritage in Bàlitx: **a** terraces with dry stone constructions and centenary olive trees are found extensively on the upper part of the slope; **b** deterioration of abandoned terraces with a progressive invasion of scrub; **c** the Roman cistern in "Cases de Ca les Bales" which is still in use and **d** small hydraulic constructions to make use of the scarce water resources in Bàlitx

S'Illeta clearly divides the coastal strip into two sections: a stretch to the NE of the island, where the wave energy is more intense, and a stretch to the SW which is more sheltered from wave energy and where coastal sedimentation is favoured. As regards slope dynamics, the NE sector of Bàlitx is affected by greater coastal energy.

Identification of cultural heritage

Terracing is the greatest exponent of cultural heritage in Bàlitx, with dry stone constructions of Islamic origin (which have been extended and adapted since the thirteenth century). Terracing is a procedure for making steps in the land to obtain spaces for the planting of olive trees. Terraces in Bàlitx are narrow and with a vertical step of several metres, reflecting the steep gradient of the slope, and they support centenary olive trees. They are mainly located in the upper part of the hanging wall block and are, more specifically, over the Quaternary breccia deposit (Figs. 4, 5a). Terrace walls were built using no mortar or cement of any kind and they are perfectly integrated into their natural scenic context. Most of these agricultural terraces have been abandoned since the middle of the twentieth century and they are tending to disappear in many areas of Bàlitx (Fig. 5b). When cultivation stops, new environmental dynamics occur: vegetation re-colonisation (scrub mainly) and soil erosion with subsequent landscape homogeneity (Lasanta et al. 2013). Additionally, the water scarcity context of Bàlitx, without natural springs, led to the construction of traditional systems for collecting, conducting and storing rainwater. Bàlitx preserves one of the oldest cisterns on the island, Roman in origin (Mateos and González 2009), which is still in use (Fig. 5c). Additionally, small dams, channels, pools, ponds and tanks (Fig. 5d) can be identified. A map with the cultural heritage elements has been drawn up (Fig. 6), at a scale of 1:10,000.

Geomorphological investigation of lateral spreading and dating

Along the fault escarpment

The geological setting of Bàlitx favours the existence of lateral spreading. The thick layer of the limestone formation, which constitutes the scarp, overlies soft and plastic materials (clays and marls with gypsum from the Keuper), and both are laterally unconfined on the coastal face. The distension determines the strong upper layer fracture and their separation into strips moving along the slope. Additional factors favour lateral spreading:

- Dramis and Sorriso-Valvo (1994) consider that folding, even with a slight curvature, can break rocks, favouring the formation and opening of joints. In Bàlitx, the upper limestone massif is folded in a NE-SW open anticline and the strata are highly tilted (Fig. 4).
- Chemical weathering, especially solution processes, has produced a Karst terrain which aids in further widening the joints and allows deeper infiltration of rainwater.

Congruently, a set of vertical fractures parallel to the limestone escarpment has been identified and which results in large blocks of rock moving very slowly over the Keuper sediments. Nevertheless, lateral spreading is much more evident in the SW part of the escarpment (Fig. 7), as the thickness of the limestone layer is not as great and the soft Triassic sediments widely outcrop. In this

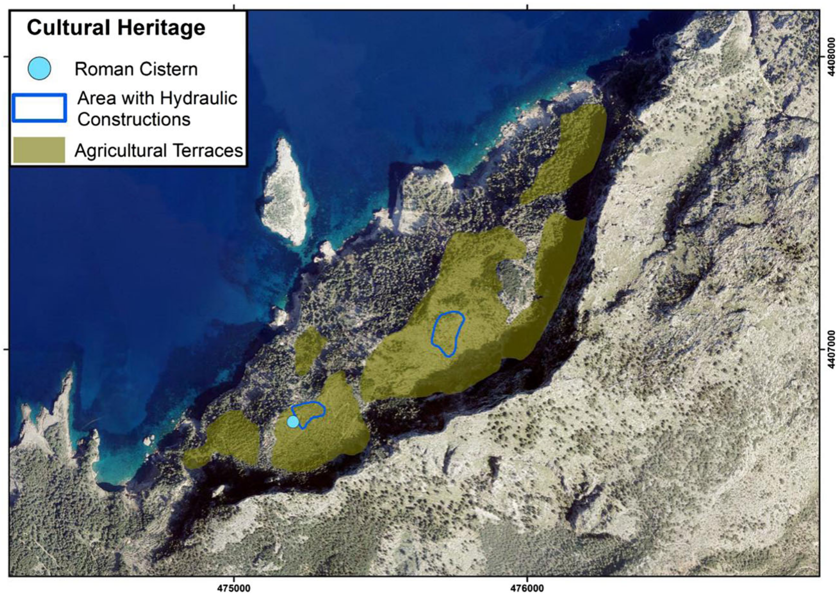

Fig. 6 Map of Bàlitx with the cultural heritage elements identified: dry stone walls for agricultural terraces, the Roman cistern and small hydraulic constructions

sector, blocks with a volume over 60,000 m^3, heights of 95 m, and lateral displacements up to 70 m are identified (Figs. 5a and 7). The movement ends with the collapse of the block, which is fragmented and accumulated at the foot of the scarp giving rise to a chaotic deposit constituted by karstified breccias cemented by calcite, with a thickness up to 65 m (Fig. 4). Along the escarpment, different stages of block spreading can be observed: initial detachment, displacement phase, block collapse and deposit. A detailed analysis of the breccia deposit reveals large inserted dolostone blocks, some of them with flowstones in different positions, proving that the blocks have moved. Additionally, many blocks are also the result of a significant rockfall activity along the escarpment.

Dating

To be able to date the beginning of lateral spreading at the escarpment, a thorough survey of the resulting deposits was carried out. An outcropping located at the base of the deposit was selected (sample S in Fig. 3) as it was considered to be the oldest outcrop. It is a breccia deposit with large blocks inserted (some of them > 3000 m^3 in volume) and with flowstones. The calcite cement in the breccia deposit has been dated with Th/U (Noller et al. 2000), and a date of 82.5 ± 5.6 kyr was obtained. This dating reveals that lateral spreading has been active since (at least) the Late Pleistocene.

In the hanging wall block of the fault

Again, there are conditions favourable to lateral spreading in the hanging wall block of the fault, as the limestone and the colluvial breccias overlie the soft materials from the Keuper (Fig. 4). In this case, both formations are not only laterally unconfined, but they are also subjected to the continuous processes of coastal erosion at the base of the cliff, which induces a great loss of lateral strength.

At the top of the hanging block, numerous cracks have been identified (Fig. 8). They are mainly located in the central and NE sector and affect, not only the karstified breccias (Fig. 8a, d), but also the soil and the traditional stone walls in the area (Fig. 8b, c). They are decametric cracks with openings up to 50 m in width and depths over 30 m, and they constitute a high risk in the area, which is very popular with hikers. Chemical weathering, especially solution processes, has produced a karst terrain which contributes to a further widening and deepening of the cracks, allowing a deeper infiltration of rainwater. A rose diagram of the orientations of the cracks is represented in Fig. 9. The preferential orientation is N45° E, parallel to the coastline. Field observations determine that cracks located in the northeastern sector show signs of major activity as they continuously distort the traditional terraced walls (Fig. 8c) which regularly have to be rebuilt.

Additionally, numerous recent and shallow landslides have been mapped as well as rockfall deposits. A geomorphological map has been drawn up (Fig. 9) representing all those features related to current slope activity. Large collapsed blocks at the base of the escarpment, which correspond to the lateral spreading process, have also been represented.

PSInSAR analysis exploiting ALOS PALSAR radar images

The methodology presented by Bianchini et al. (2013) to create landslide activity maps by means of Persistent Scatterer Interferometry (PSI) was of use in evaluating the state of activity of the existing landslides throughout the Tramuntana Range. The exploitation of ALOS PALSAR satellite images acquired during the period 2007–2010 allowed the detection of over 300,000 measurement points (PS) of ground surface displacement and the identification of 42 active landslides with an average velocity greater than 5 mm/year. The main criterion in selecting the ALOS PALSAR imagery was the temporal spanning, as it covered a very rainy period on the island. During the period 2008 and 2010, the island of Mallorca experienced the coldest and wettest winters of the last 48 years with accumulated rainfall twice the average and values of daily rainfall up to 300 mm (Mateos et al. 2012). Additionally, high rainfall values coincided with low temperatures and freezing processes in the highest zones of the Tramuntana Range. The coast of the range was also struck by numerous marine storms with waves over 8 m. The severe

Fig. 7 Block spreading in Bàlitx. Large blocks of limestone are separated and displaced from the main escarpment. This process is more evident in the SW extreme (yellow circle), where the thickness of the limestone layer is not as great and the Triassic soft sediments widely outcrop at the base

climate conditions triggered 66 mass movements in the range, including landslides and rockfalls (Mateos et al. 2015). Subsequently it was considered that the ALOS PALSAR monitoring time period represented a good opportunity to detect ground deformations throughout the range, and specifically on coastal slopes affected by very slow movements, such as lateral spreading.

Fig. 8 Large cracks in the hanging block, with decametric lengths and openings of several metres. The cracks have been identified, not only in the cemented breccias (**a**, **d**), but also in the soil and in the traditional terrace walls (**b**, **c**) showing that it is an active, current process

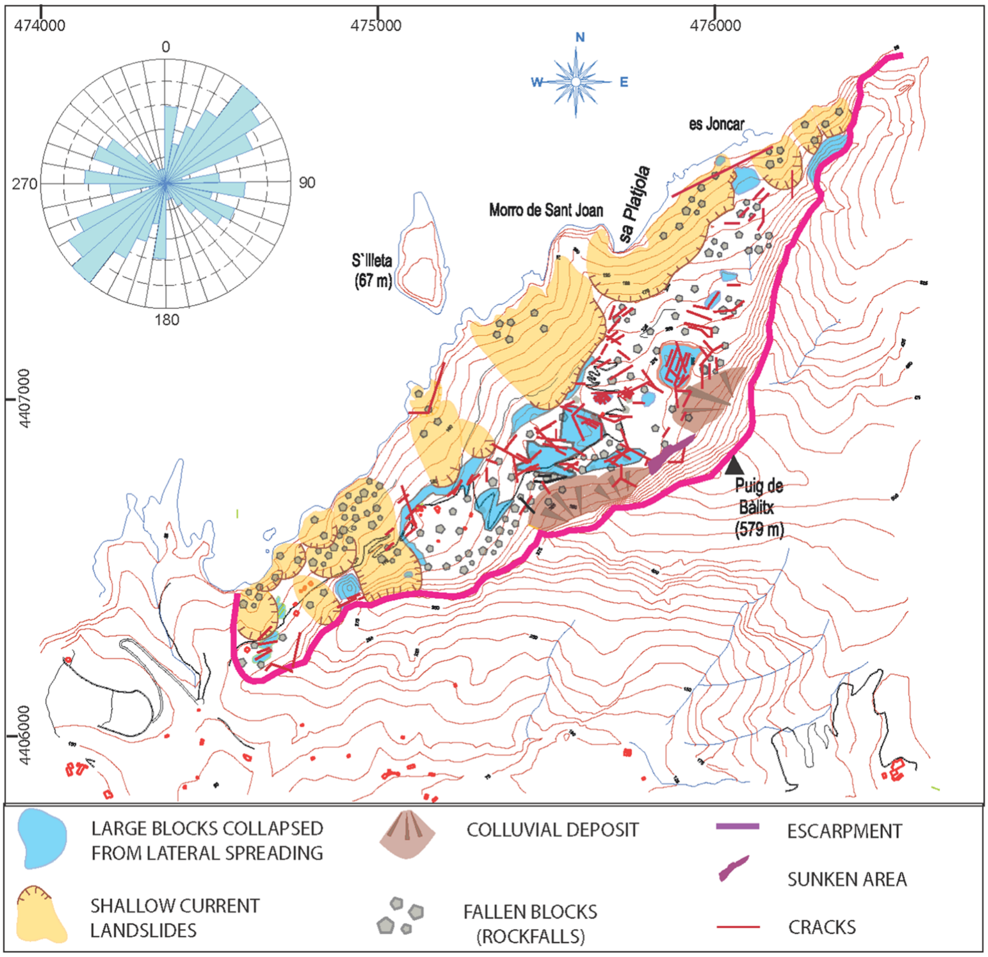

Fig. 9 Geomorphological map. All features relating to present-day active processes are represented: cracks, shallow slides, lateral spreading collapsed blocks, rockfall blocks, etc. A rose diagram of the orientations of the cracks is represented, showing preferential N45°E, parallel to the coastline

Based on these regional results, a detailed interpretation of the PSI displacement estimates retrieved over the Bàlitx area has been performed. The 291 detected measurement points (PS) within Bàlitx account for an average velocity projected on the steepest slope (VSLOPE) of − 5.2 mm/year (Fig. 10a). This velocity is slightly greater than the stability threshold set by Bianchini et al. (2013) and for the average VSLOPE (− 3.4 mm/year) of the 2427 PS located 1 km away from the Bàlitx area. In the present work, the same threshold (− 5 mm/year for VSLOPE) has been applied as it was selected taking into account the statistical velocity distribution and the standard deviation of the ALOS dataset in the Tramuntana Range.

Landslide activity evaluation

In order to distinguish the most active sectors, the geomorphological features mapped in the field (Fig. 9) have been combined with PS measurements. Four landslides of the 15 mapped show a sufficient number of PS (17 on average) allowing the state of activity to be evaluated. Figure 10 shows the correlation between data. The average velocity value for each geomorphological feature (landslides and cracks) has been calculated. Major activity is concentrated in the northeastern sector where two landslides (the largest) show velocities of over 5.5 mm/year (most of the PS with VSLOPE between − 5 and − 16 mm/year); whereas the southwestern area is more stable, as the largest landslide within this sector represents just 4.0 mm/year VSLOPE.

Similarly, the combination of measured displacements with the crack inventory (Fig. 10b) reveals that 69 of the total of mapped cracks (136) coincide with detected PS. From this number, 40% can be considered active, since the VSLOPE of the PS surpass the − 5.0 mm/year activity threshold. Again, active cracks are concentrated in the northeastern sector, which coincides with the observations made in the field.

PSI on the elements of cultural heritage

Applying the same procedure as in the previous section, the VSLOPE velocity map has been combined with the cultural heritage inventory map (Fig. 6) to evaluate the state of activity for the different elements. The result is the maps shown in Fig. 11a, where major activity is detected on the agricultural terraces and in areas with hydraulic constructions located in the NE sector (most of the PS with VSLOPE between − 5 and − 16 mm/year). The Roman cistern is located in a stable zone. The map in Fig. 11b shows a simple approach, indicating the cultural heritage polygons in areas with VSLOPE over − 5 mm/year and below this threshold.

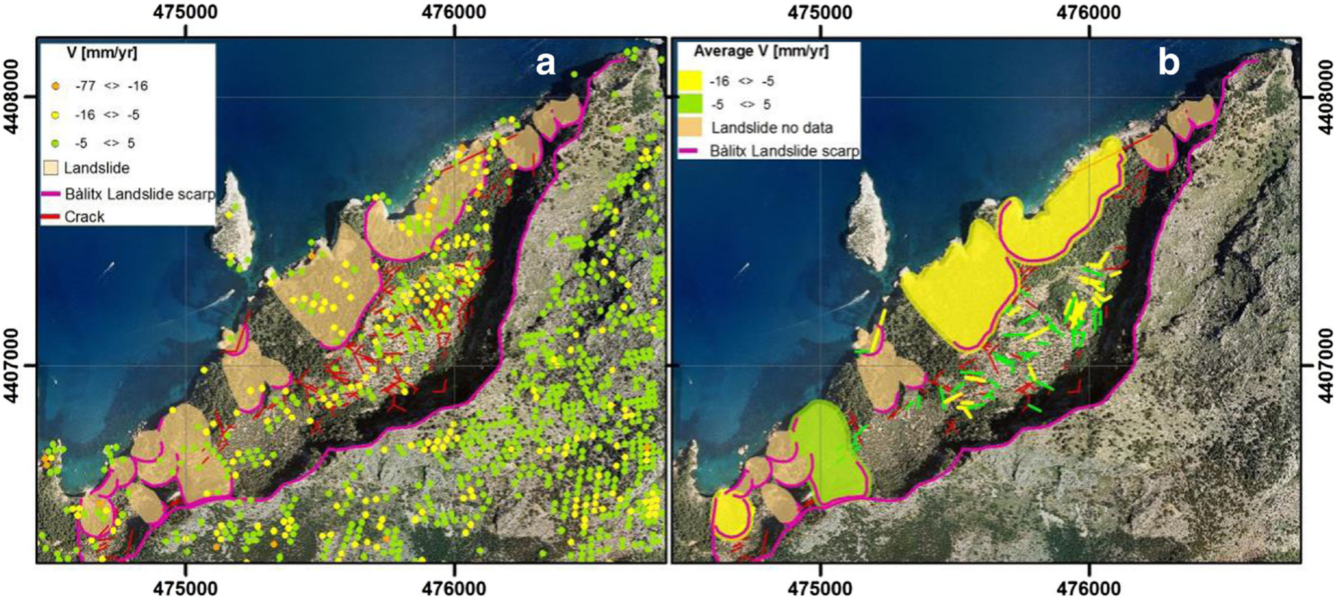

Fig. 10 ALOS PALSAR PSI results. **a** VSLOPE velocity map (mm/year) superimposed onto the geomorphological map. **b** Average velocity value for each geomorphological feature (landslides and cracks). The northeastern part of the Bàlitx landslide is currently the most active area

Discussion and conclusions

The northern and coastal slope of the Tramuntana Range in Majorca is characterised by a steep and clipped topography where several gravitational processes are recognisable. A block and slab-type lateral spreading is described in the present work in the coastal area of Bàlitx. The multifaceted nature of the work performed prompts the following discussion and conclusions:

Geology and lateral spreading

The area is characterised by a large normal fault escarpment with a steep inclination (60°) and a height of up to 260 m. Stratigraphy and tectonics determine lateral spreading processes. The thick slab of massive limestone from Lias, which constitutes the escarpment, overlies soft and plastic materials from the Keuper facies. A penetrative set of tensional and vertical fractures parallel to the escarpment determines the individualisation of rock blocks, some of which have volumes over 60,000 m^3, which very slowly move away from the rock wall, over the Keuper sediments until their collapse. Different stages of block-evolution can be observed: detachment, displacement, collapse, and deposit. This process generates a chaotic deposit constituted by highly karstified breccias, cemented by calcite and with flowstones in different positions, proving that the blocks have moved. The fault repeats the same stratigraphical configuration in the hanging block. Large and deep cracks are identified in the Quaternary breccias at the top of the hanging

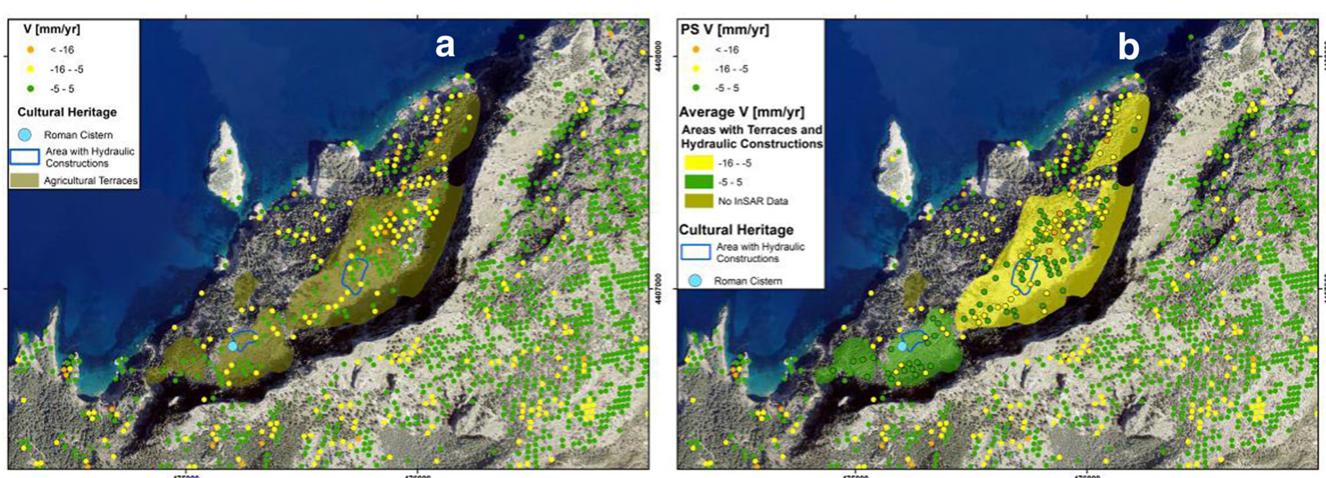

Fig. 11 **a** PSI results superimposed onto the cultural heritage inventory map. **b** The cultural heritage polygons have been differentiated based on an average velocity value of < − 5 mm/year (in green) and > − 5 mm/year (in yellow)

wall, and they reveal active lateral spreading processes. Field observations determine that the northeastern sector shows major signs of activity, as the cracks are deeper-penetrating and they distort the old dry stone terraces and the soil.

The origin of the lateral spreading process

Dating the calcite cement of the lowest breccia outcrop, which can be considered the oldest deposit of the lateral spreading dynamics, an age of 82.5 ± 5.6 kyr was obtained. This date corresponds to the Late Pleistocene, and specifically to the oxygen isotopic stage OIS 5a, the Riss-Würm interglacial, a high stand period when the sea level in Majorca was located at 1.9 m apsl (Ginés 2000; Fornós et al. 2002; Tuccimei et al. 2006; Bardají et al. 2009). Additionally, previous palaeoclimate studies (Zazo et al. 1997; Zazo et al. 2003; Zazo 2006; Leroy and Roisson 1996; Vesica et al. 2000; Macklin et al. 2002) refer to the climate in the western Mediterranean region becoming more humid by the end of the oxygen isotopic stage OIS 5e (110,000 years ago), and that the Riss-Würm interglacial is not only characterised by warmer temperatures than present in the area (around 4–6 °C higher) but also by an increase in rainfall/runout. This information suggests that the initiation of the lateral spreading process could be related to a wetter, warmer period than the present, which could greatly contribute to the following: (a) the acceleration and accentuation of the phenomenon of karstic dissolution, (b) the greater opening of the tensional fractures which induced a higher water percolation and (c) a greater lubrication of the sliding surface; the stratigraphic contact between the Keuper sediments and the Liassic limestone.

Slope activity and coastal dynamics

PSInSAR results support major activity in the northeastern coastal sector of Bàlitx, with velocity rates of over 5 mm/year, whereas the southwestern area is more stable, with velocity rates below 5 mm/year. On the NE coastal slope, the largest landslides have been identified, showing VSLOPE velocity values of up to − 16 mm/year. Additionally, the greatest concentration of cracks is in this sector, most of them surpassing the − 5.0 mm/year activity threshold. Coastal dynamics can explain this, since in the coastal strip located to the NE of S'Illeta island, erosive processes are more intense, as the offshore sedimentation denotes, leading to a greater destabilising effect on the slopes. It can be concluded that the small-scale morphology of the coastline clearly controls the current slope activity and its heterogeneous distribution throughout the Bàlitx face.

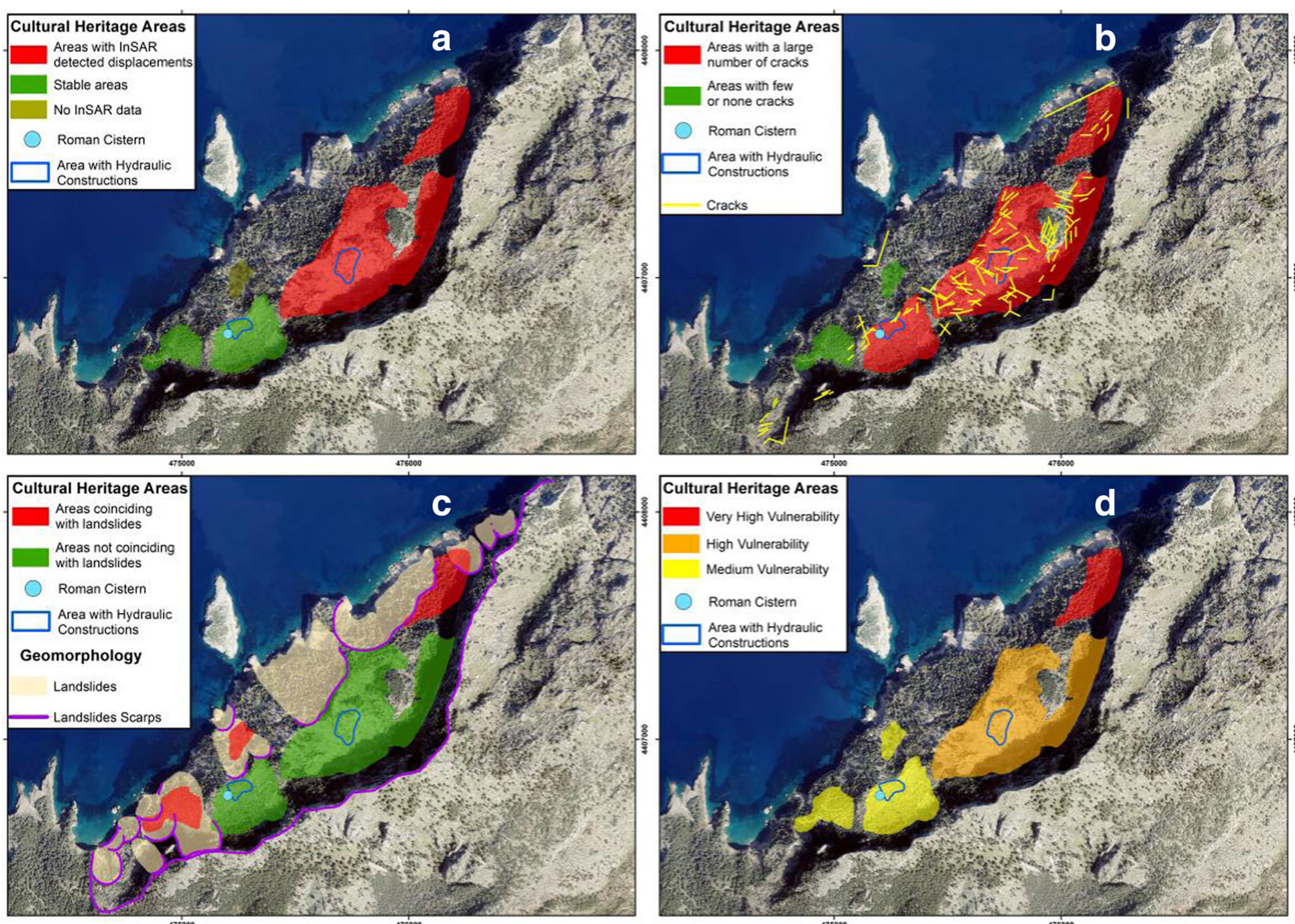

Fig. 12 Vulnerability approach for the cultural heritage elements. **a** PSI results: cultural heritage polygons located in areas with VSLOPE > − 5 mm/year (red) and VSLOPE < − 5 mm/year (green); **b** crack location: polygons with N. cracks < 6 (in green) and those with N. cracks > 6 (in red); **c** landslides: polygons which coincide (partially or totally) with landslide bodies (in red), and those which do not (in green); **d** vulnerability classification of the cultural heritage areas

Vulnerability of the cultural heritage

A simple approach has been developed to estimate the vulnerability degree of the cultural heritage elements. In practical terms, vulnerability is expressed by the link between the intensity of the landslide and its possible consequences and it should consider the potential damage severity (Delmonaco et al. 2009). With this perspective in mind, the following maps have been combined:

- The PSI results interpreted in Fig. 11b. A semaphore map (red/green) is created (Fig. 12a) with the cultural heritage polygons located in areas with VSLOPE > − 5 mm/year (red) and VSLOPE < − 5 mm/year (green).
- The crack location. Red has been attributed to the polygons with more than six cracks and green to those with a number of cracks below six. The map in Fig. 12b was created. The threshold of six cracks has been selected as it is twice the average number of cracks per hectare taking into account the total polygon surface (45 ha).
- Cultural heritage elements on landslide bodies. Cultural heritage polygons which coincide (partially or totally) with landslide bodies have been differentiated in red, and those which do not in green. Map in Fig. 12c is created taking this criterion into account.

An estimation of the vulnerability of the cultural heritage elements to landslide has been obtained by overlapping the three maps. The same weighting has been given to each factor and the following criteria applied to evaluate the degree of vulnerability:

- Cultural heritage polygons with only one negative factor will be considered as having a medium degree of vulnerability. They are represented in Fig. 12d in yellow and are located in the SW extreme of Bàlitx. Two of the polygons are located on landslide bodies; and the polygon with the Roman cistern is affected by a number of cracks over six.
- Cultural heritage polygons with two negative factors will be considered as having a high degree of vulnerability. This polygon is represented in orange (Fig. 12d) and contains the largest number of cracks. Additionally, the polygon is identified with an average VSLOPE velocity of over −5 mm/year. One of the hydraulic construction areas is located in this polygon.
- Cultural heritage polygons with three negative factors will be considered as having a very high degree of vulnerability. It is the red polygon and is located in the NE extreme of Bàlitx (Fig. 12d). The polygon is partially located on a landslide, with a number of inventoried cracks above 6, and the attributed average VSLOPE velocity is over −5 mm/year.

An overall analysis indicates that vulnerability increases from SW to NE, in accordance with the landslide activity controlled by the coastal dynamics.

All the collected information, and the data interpretation carried out in the present work, should be of use in the design of mitigation measures for the conservation of cultural heritage in this exceptional example of Mediterranean agricultural landscape. Additionally, the methodology presented could be applied to any other cultural heritage site affected by geomorphological hazards.

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