


Cosmogenic exposure dating constraints for coastal landslide evolution on the Island of Malta (Mediterranean Sea)

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Abstract Landslides affecting the north-western coast of the Island of Malta have been investigated and monitored for 10 years. As a result of a bathymetric survey, it was discovered the deposits continued out onto the seafloor, thus raising questions as to the timing of their development. Furthermore it was uncertain as to which environment they developed in and which factors controlled their movements. The aim of this paper is to investigate representative detachments to chronologically constrain these mass movement events and outline their spatial and temporal evolution. Samples for exposure dating using the cosmogenic nuclide ³⁶Cl were collected from head scarps and blocks located within two long-term monitored landslides characterised by extensive block slides. The results indicate the oldest dated block detachment occurring in a subaerial environment at ca. 21 ka, when the sea level was about 130 m lower than at present. Mass movement possibly accelerated when sea level reached the landslide toe during the post-glacial marine transgression. Considering the timing of block movement, the landslide deposits observed today appear to be related to a first-time failure involving a large part of the slope, though an alternative hypothesis is also

taken here into account. This main event is likely to have been followed by secondary movements influenced by toe undercutting and clay saturation due to rising sea level. However, further research on mass movement kinematics is required in order to model their evolution and explore whether this interpretation is widely applicable along the Maltese coast.

Keywords Landslides · Exposure dating · Cosmogenic nuclides · Malta · Mediterranean Sea

Introduction

Mass wasting constitutes one of major geomorphological processes in landscape evolution of mountain, coastal and submarine environments. Mass movements are highly sensitive to any change in spatial and/or temporal factors, such as climate conditions (Borgatti and Soldati 2013). Hence, dating landslides is important for determining rates of meso-scale erosion in the landscape (Lang et al. 1999; Gutiérrez et al. 2010; Walker and McGraw 2010) and the recurrence interval of successive instability phases. Indeed, it is known that large landslides (more than 10⁶ m³) have often experienced long and complex histories, where creeping movements alternated with episodic accelerated events, over a timescale of more than 10⁴ years (Sewell et al. 2006; Pánek 2015). Through the reconstruction of landslide geomorphological evolution, it is possible to understand the conditions favouring slope instability and to analyse the predisposing and triggering factors. The analysis of controlling factors together with the determination of the landslide frequency gives meaningful information for the assessment of possible landslide future evolution and related hazards (Lang et al. 1999; Borgatti and Soldati 2010b).

It is known that some landslides could have been induced by climate change. For example, more humid conditions related to

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higher precipitation amounts in the early Holocene are likely to have triggered large landslides in the Dolomites (Soldati et al. 2006; Borgatti and Soldati 2010a). Elsewhere, mass movement activity within the Maritime Alps followed the main Holocene short-term climatic fluctuations centred on 4.2 ka BP, suggesting this was an important phase for triggering rock slope failures in the Alps (Zerathe et al. 2014). Additionally, several landslides developed in formerly glaciated areas were triggered by deglaciation processes such as glacial unloading, fluctuations in pore pressure, and increased water supply (Prager et al. 2008; Darnault et al. 2012; Ballantyne et al. 2014; Hartvich et al. 2017).

The Maltese coasts are an ideal location for the investigation of coastal slope instability. Among the different types of landslides recognised and mapped, attention has been focused on block slides, which are the most widespread type of mass movements along the northern coasts of the Island of Malta (Devoto et al. 2012, 2013a; Prampolini et al. 2017). The aim of our research was to determine timing of landslides and rates of movement of the block slides, providing the first direct ages on coastal instability in the Maltese archipelago. We used exposure dating with the cosmogenic nuclide ^{36}Cl to determine when blocks were detached from the coastal cliff complex. The block slides of the north-western coast of Malta were chosen for dating because they have a simple exposure history and have already been investigated in detail for 10 years (Magri et al. 2008; Devoto et al. 2013b, 2015; Mantovani et al. 2013). Previous studies have shown that the terrestrial part of the landslide runout extends below sea level. It was previously hypothesised that these landslides developed during a sea level low-stand in the course of the last glacial cycle and that they were subsequently submerged by post-glacial sea level rise (Foglini et al. 2016). However, absolute dating of these landslide scarps and blocks is essential for defining a chronological framework and to determine the palaeo-environmental conditions during their onset and successive development.

Geological and geomorphological setting

The Maltese archipelago is located in the Sicily Channel (central Mediterranean Sea) and comprises the islands of Malta, Gozo and Comino. It is characterised by a typical Mediterranean climate with hot and dry summers (mean temperature of 27 °C), relatively humid autumns and short and mild winters (mean temperature of 12 °C) and average annual rainfall precipitation of 500 mm (Malta International Airport weather station).

The Maltese Islands are composed of an Oligo-Miocene geological succession deposited in a shallow marine environment which lies sub-horizontally, slightly tilted 4° towards the NE. The geological formations are listed from the oldest to the

youngest Lower Coralline Limestone Formation, made up of shallow water carbonates; Globigerina Limestone Formation, made up of marly-carbonate; Blue Clay Formation, constituted by marly-clayey units; and the shallow water carbonates of the Upper Coralline Limestone Formation (Fig. 1; Pedley et al. 2002; Baldassini and Di Stefano 2016).

The stratigraphic succession is displaced by two fault systems. The oldest one is WSW-ENE-oriented and its major lineament is the Great Fault that divides the Island of Malta into the North Malta Graben and the South Malta Horst. It is also responsible for a *horst-and-graben* structure characterising the northern area of Malta. The most recent system has a NW-SE orientation, parallel to the Pantelleria Rift system, and controls the trend of the northern and southern coasts of the archipelago (Jongsma et al. 1985; Alexander 1988; Dart et al. 1993) (Fig. 1).

The north-western coast of Malta is characterised by outcropping of the harder Upper Coralline Limestone overlying the softer and more erodible Blue Clay. The superposition of these two lithological units, characterised by different mechanical behaviour (limestones over clays), favours the development of lateral spreads evolving into block slides (the most widespread type of slope failure in the archipelago). Deformation within the clays cause tensile stresses within the limestone plateau that enable the development of trenches and persistent cracks (cf. Pasuto and Soldati 2013). Thus, large blocks and pillars are isolated and detached from the limestone cap. Successively, they tilt forward or backward and slide downhill (block slide) creating large accumulations of rock masses along the coast (*rdum* in Maltese; Fig. 2). Rock falls and earth flows are also common and often can be considered as collateral phenomena of lateral spreads and block slides.

An ongoing long-term monitoring programme has been carried out at two coastal sites of the north-western sector of the Island of Malta, Anchor Bay and Il-Qarraba. It includes GPS (Global Positioning System) (Fig. 3a), tape extensometer and fissurimeter measurements. Satellite Persistent Scatterer Interferometry (PSI) analyses (Fig. 3b) were carried out for the entire north-western coast of Malta to analyse present-day deformation trends and perform a landslide susceptibility assessment of the area (Piacentini et al. 2015; Mantovani et al. 2016). In 2012, a bathymetric survey carried out offshore the north-western coast of Malta highlighted the presence of large block accumulations on the seafloor. These are located in the same stretches of coast that are affected by rock spreads and block slides and extend up to 500 m from the shoreline, reaching a maximum depth of ca. 30–40 m. A large accumulation is also observed offshore Ras in-Niexfa, the northern promontory of Anchor Bay, with general orientation W-E and spreading to about 40 m of depth (Fig 2). Il-Qarraba peninsula is also

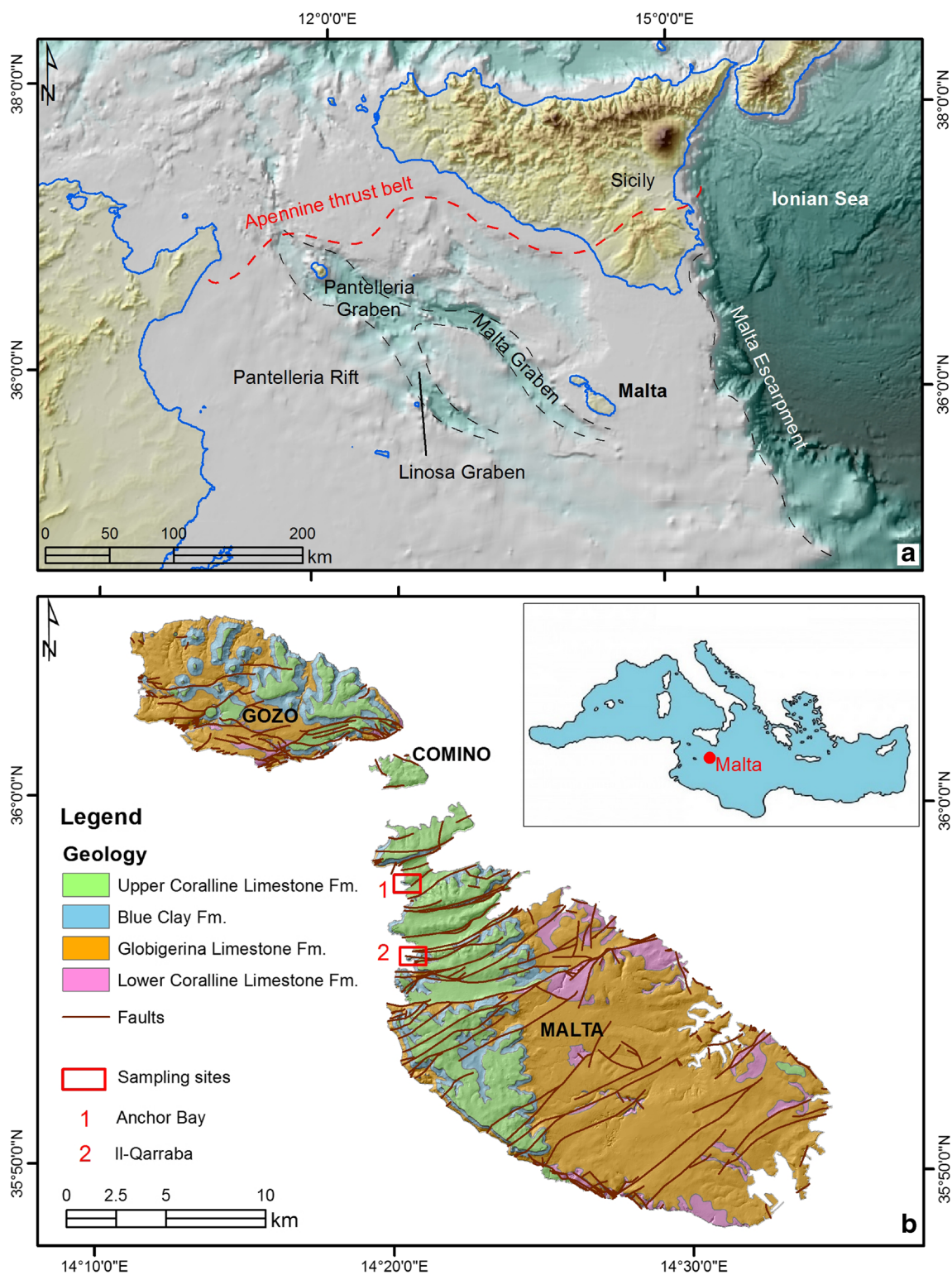


Fig. 1 Geographic, geodynamic (a) and geological setting (b) of the Maltese archipelago

surrounded by a semi-circular accumulation of blocks located on the seafloor down to ca. 25 m. Soldati et al. (2015) and Foglini et al. (2016) interpreted these as block slides extending below the present sea level; thus the emerged and submerged deposits are part of a single landslide

complex, of which only one third is above sea level at present (Fig. 2). Anchor Bay and Il-Qarraba were considered as ideal sites for further studies because of the availability of existing descriptive data and for the representative geological and geomorphological conditions.

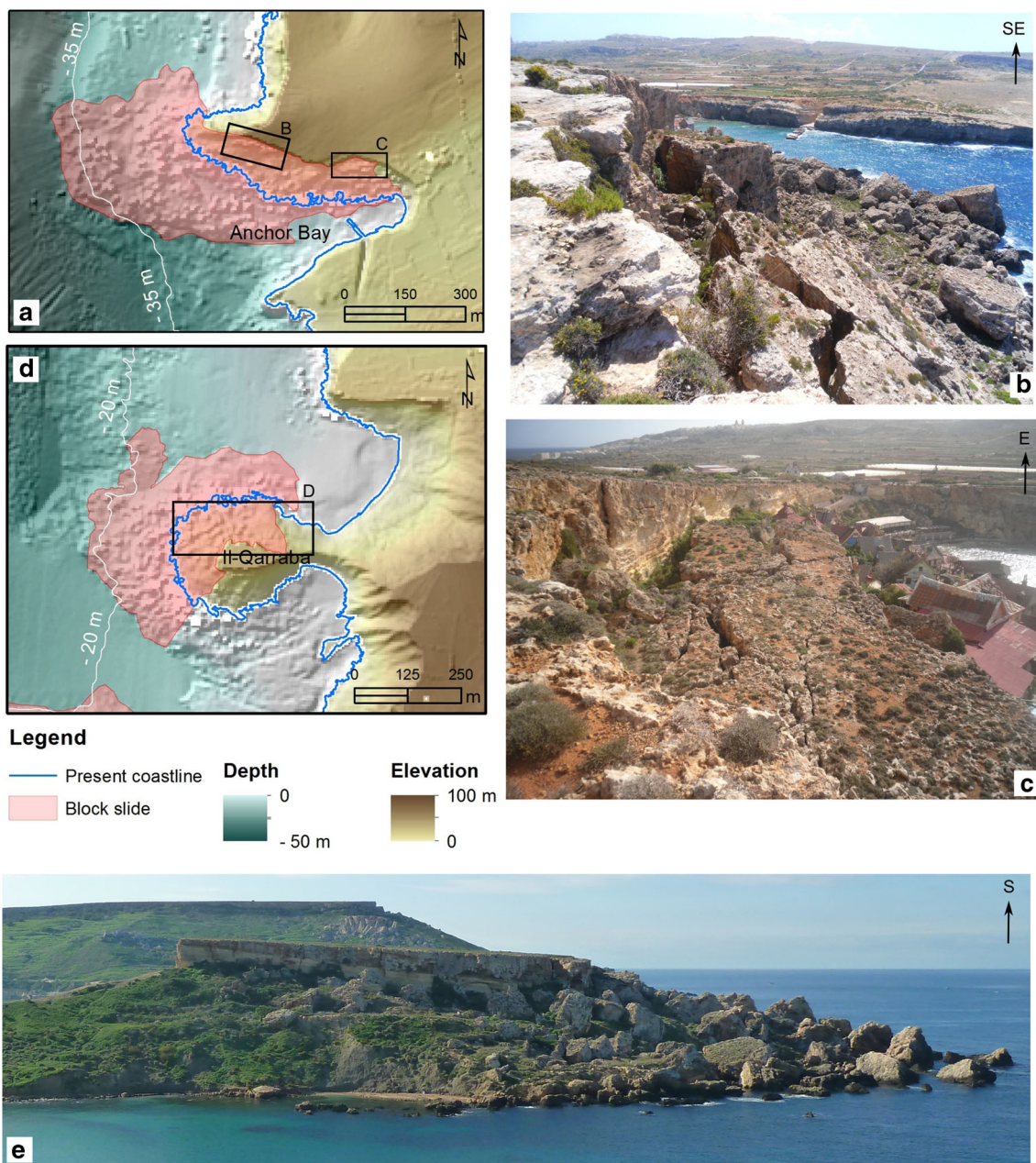


Fig. 2 Extension of the block slides affecting Anchor Bay (a) and Il-Qarraba (d); a and c pictures of the emerged portion of Anchor Bay landslide; d picture of the emerged portion of Il-Qarraba landslide

Materials and methods

Site selection and sampling strategy

Exposure dating using cosmogenic nuclides (especially ^{10}Be and ^{36}Cl) is now one of the most commonly employed techniques for dating landslides (Sewell et al. 2006; McIntosh and Barrows 2011; Pánek 2015; Ivy Ochs et al. 2017). Exposure dating has the advantage over radiocarbon where no organic matter is available for dating and requires only the presence of a freshly exposed, unweathered rock

surface. This technique provides reliable dating for several types of mass movement that were not previously datable, such as deep-seated gravitational slope deformations, including lateral spreads (e.g. deep-seated landslides in Hong Kong; Sewell et al. 2006). By collecting multiple samples along a vertical profile on a deep-seated landslide scarp, it is possible to calculate the slip rates of individual detachment event (e.g. Séchilienne landslide in French Alps analysed by Le Roux et al. 2009 and Alpine landslides studied by Zerathe et al. 2014). Either the scarp face or blocks on a landslide can be exposure dated. Since this

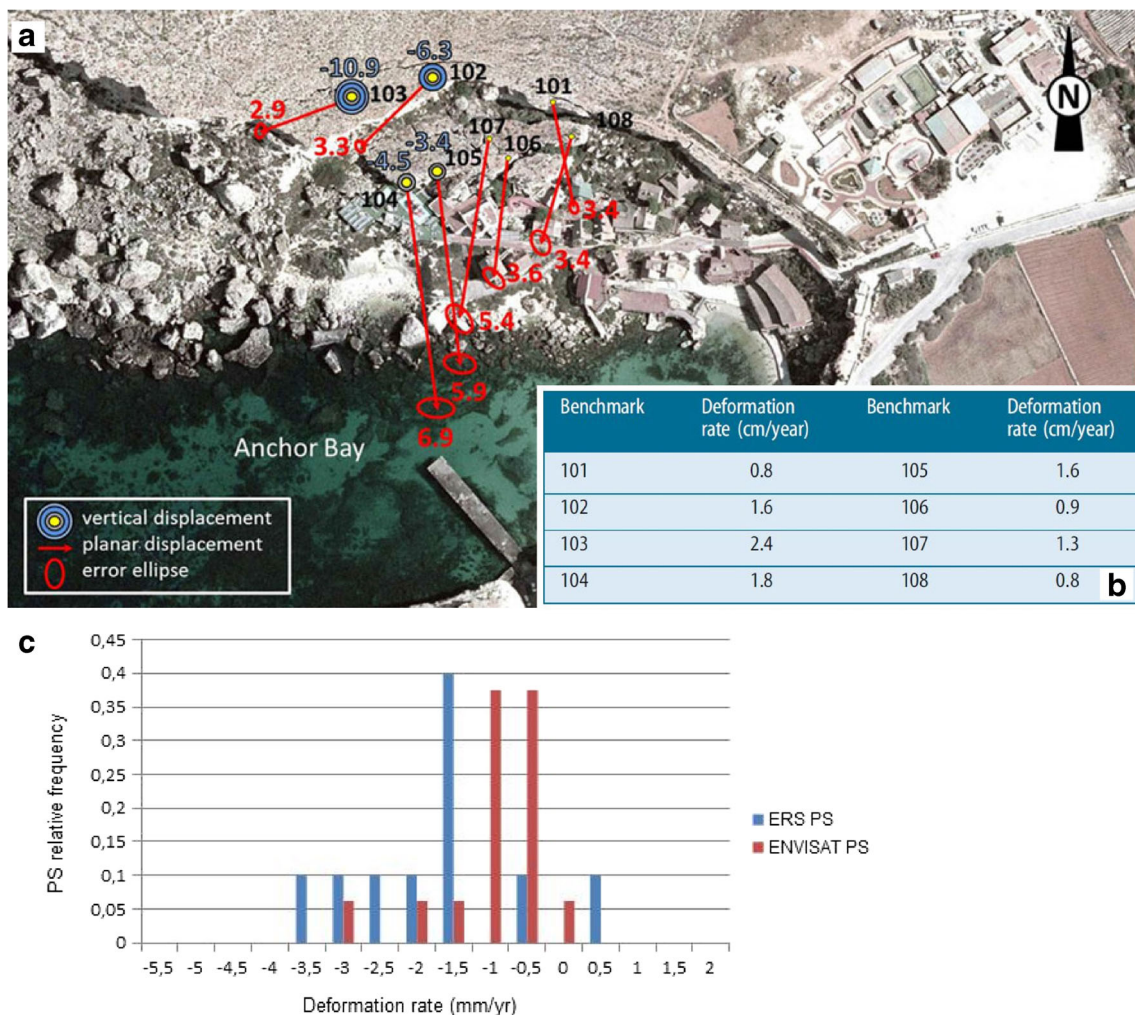


Fig. 3 **a** and **b** Results of GPS measurements at Anchor Bay (modified after Mantovani et al. 2013); **c** Persistent Scatterer Interferometry results at Il-Qarraba (modified after Mantovani et al. 2016)

technique requires predictable exposure to cosmic rays, it is necessary to sample using the following criteria, according to Sewell et al. (2006), Ivy-Ochs and Kober (2008) and Zerathe et al. (2014). The surfaces of the sampling site must:

- have undergone single-stage exposure or have a known exposure history
- have been continuously exposed in the same position;
- have never been covered by sediments;
- have undergone only minimal surface weathering because loss of surface material results in younger apparent exposure ages (in the case of significant surface weathering, it is necessary to estimate an erosion rate).

From satellite photographs, it is clear that the entire north-western coast of Malta is affected by active landslides. Anchor Bay and Il-Qarraba are monitored through a network of different instruments (Fig. 3) which show that the landslides are moving “extremely

slowly”, according to the velocity classification by Cruden and Varnes (1996). The mean displacement rate measured is 7 mm/yr (Devoto et al. 2013b; Mantovani et al. 2013; Devoto et al. 2015). At Anchor Bay, GPS measurements show lowering in the area affected by rock spreading comprised between 5.8 and 10.2 cm in 10 years, whereas the sector affected by block sliding is mainly characterised by horizontal movements (about 5.2–5.8 cm of total planar displacement). Over a 10 year period at Il-Qarraba, vertical movements were generally lower than 1 cm, except for one block which lowered of 3.6 cm, while planar displacements ranged between a few mm to 2.7 cm. Finally, interferometric analyses confirm the displacements and the velocities measured by the GPS monitoring (Mantovani et al. 2013).

At Anchor Bay, three samples were collected for exposure dating from the main block slide scarp (Fig. 4) forming the promontory of Ras in-Niexfa, which is about 20 m high, oriented W-E and facing

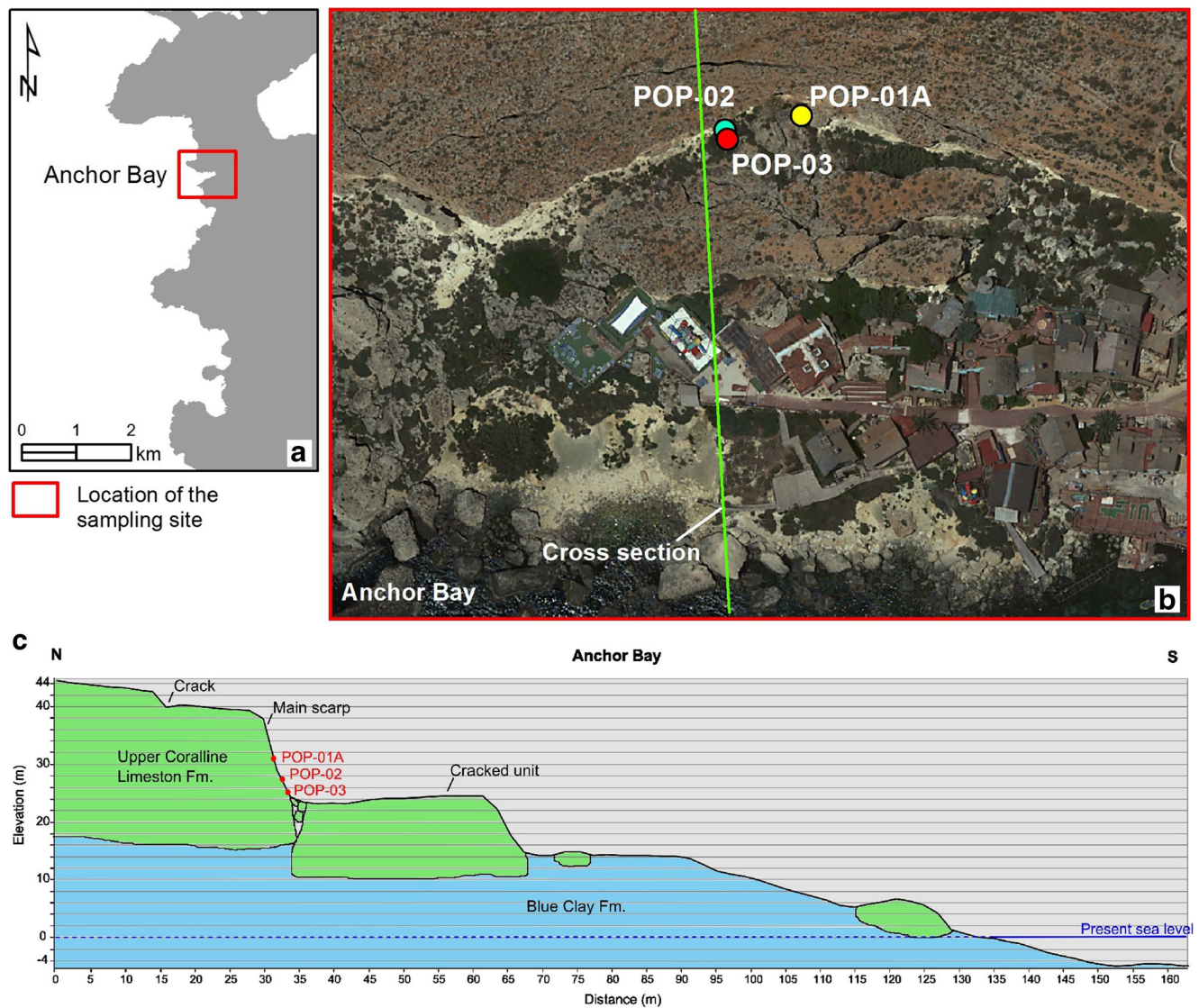


Fig. 4 Location of the samples collected at Anchor Bay: **a** location of the site along the NW coast of Malta; **b** plan view site, samples location and line along which the cross section in **c**) is drawn; **c** cross section of the block slide and sampling location

the inner part of the bay. From that, a large block (overall dimensions of 94×31 m) detached and lowered through time until it reached the present setting. Three samples were collected in a vertical profile to estimate the vertical slip rate of the block. POP-01A was taken ~ 3 m down from the top of the landslide scarp and samples POP-02 and POP-03 were collected from a lower subvertical surface with well-preserved slickensides (Fig. 4).

At Il-Qarraba, two further samples were collected from a limestone cap which makes up an E-W oriented peninsula (Fig. 5). Sample QAR-02 was taken from the limestone cap scarp facing the sea to the west. From this scarp, a large limestone pillar was isolated, detached and slid downhill tilting slightly forward. Sample QAR-01 was collected from the west-facing surface of this detached

block (Fig. 5). The exposure ages of these two samples represent the time elapsed since this block was detached and isolated. Site data for both locations are listed in Table 1 and pictures of samples location are in Fig. 6.

Exposure dating methods

Given the limestone composition of the Maltese landslide sites, we chose ^{36}Cl for exposure dating. In this rock type cosmogenic ^{36}Cl is dominated by spallation and muon-induced reactions from ^{40}Ca . ^{36}Cl and chloride content were measured on the acid soluble fraction of the rock. In all cases the limestone was dominated by the carbonate fraction ($>98.5\%$). The proportion of magnesium carbonate was determined by ICP and the calcium carbonate content was reconstructed stoichiometrically (Table 2).

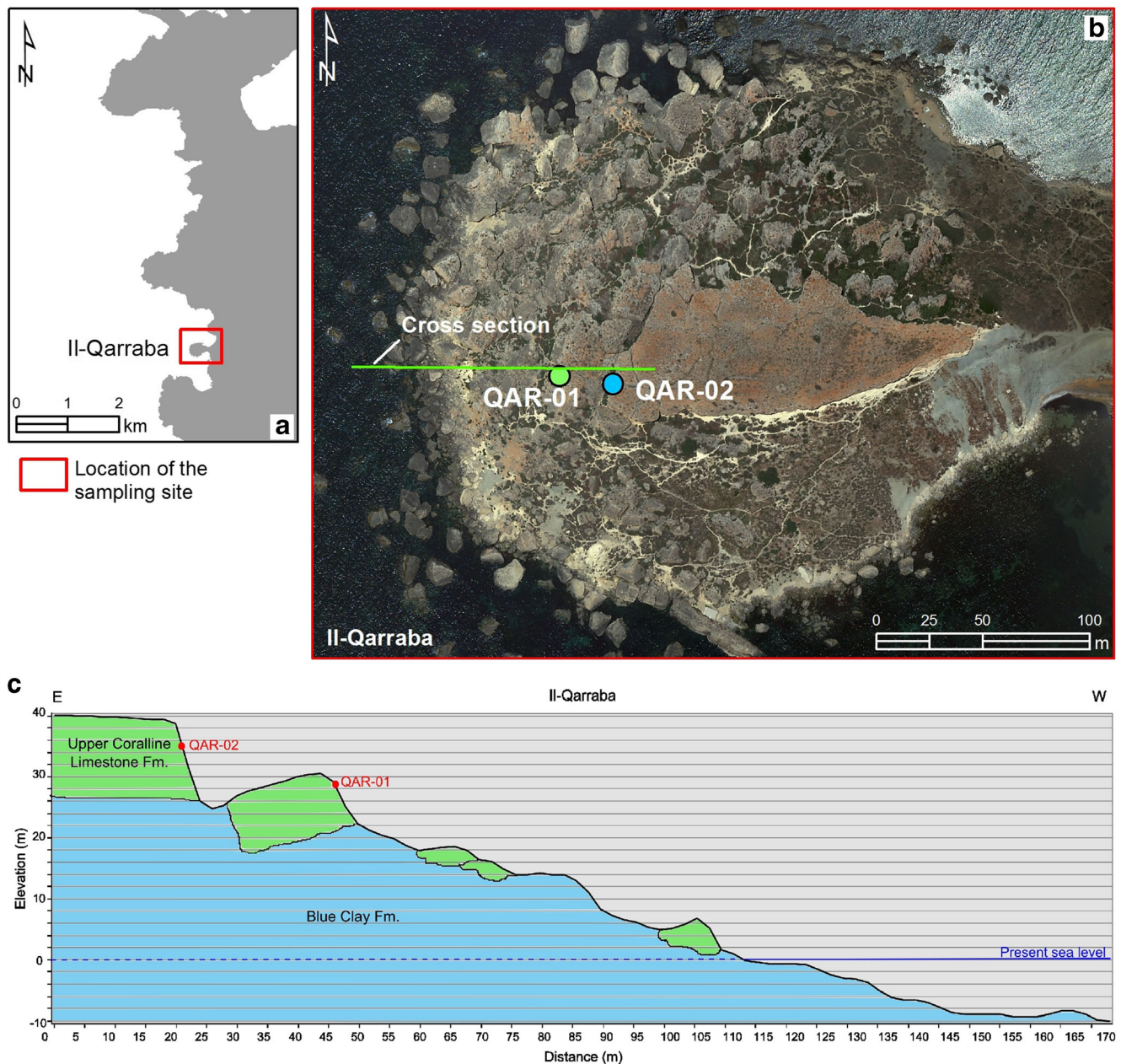


Fig. 5 Location of the samples collected at Il-Qarraba: **a** location of the site along the NW coast of Malta; **b** plan view site, samples location and line along which the cross section in **c**) is drawn; **c** cross section of the block slide and sampling location

Chloride content was determined by isotope dilution. We calculated production from spallation and muon capture on Ca and on minor elements, using the production rates of Stone et al. (1996a, b, 1998), Evans (2001) and Masarik and Reedy (1995) following Barrows et al. (2013). For ^{36}Cl production by neutron capture on K and Cl we followed the procedures of Liu et al. (1994), Phillips et al. (2001) and Stone et al. (1998) and calculated the nucleogenic contribution following Fabryka-Martin (1988). The production rates were scaled for altitude and latitude using the scheme of Stone (2000). AMS measurements were made at the Nuclear Physics Department at the Australian

National University. In coastal settings a significant source of reduction of the cosmic ray flux is topographic shielding due to cliffs. Shielding was measured using an inclinometer and a compass and calculated following standard techniques. All measurement errors, including production rate errors, are fully propagated on individual ages.

Results

The surface exposure ages from Anchor Bay and Il-Qarraba are reported in Table 2.

Table 1 Samples characteristics for both the sites

Sample	Latitude (N)	Longitude (E)	Altitude	Lithology ^a	Horizon correction	Thickness ^b
Anchor Bay						
POP-01A	35°57'41.425"	14°20'24.97"	31.09 m	limestone	0.7469	5 cm
POP-02	35°57'41.32"	14°20'24.30"	26.69 m	limestone	0.6943	4.5 cm
POP-03	35°57'41.25"	14°20'24.33"	23.57 m	limestone	0.7266	3.5 cm
Il-Qarraba						
QAR-01	35°55'38.18"	14°20'23.69"	28.91 m	limestone	0.7595	3 cm
QAR-02	35°55'38.07"	14°20'24.72"	39.59 m	limestone	0.6453	4 cm

^a $\rho = 2.5 \text{ g/cm}^3$

^b $\Lambda = 160 \text{ g/cm}^2$

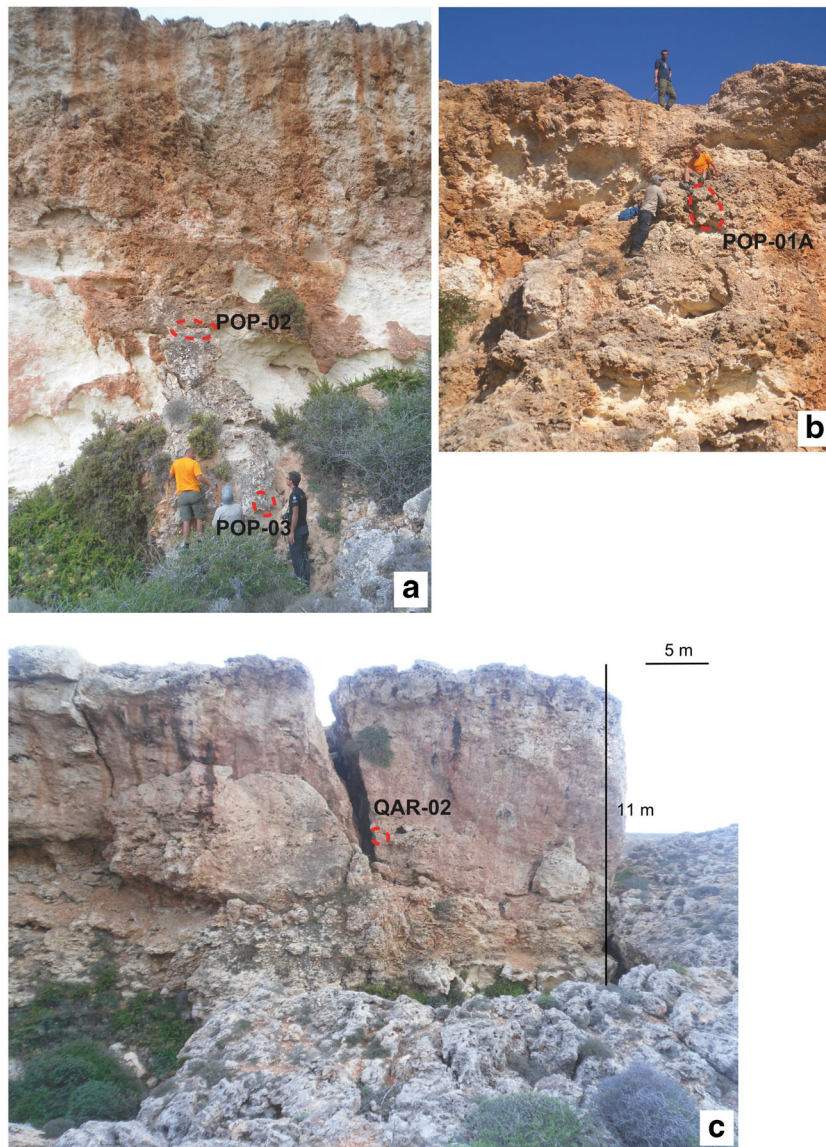


Fig. 6 Detail of the sampled scarps at Anchor Bay (a and b) and Il-Qarraba (c)

Table 2 Cosmogenic ray exposure age results

Sample	MgCO ₃ (%)	CaCO ₃ (%)	[Cl] ppm	[³⁶ Cl] _c (×10 ⁵ g ⁻¹) ^a	[³⁶ Cl] _r (×10 ² g ⁻¹) ^b	Exposure age (ka)
Anchor Bay						
POP-01A	0.91 ± 0.02	98.2 ± 0.02	4.59 ± 1.1	3.00 ± 0.15	1.6 ± 0.5	21.7 ± 1.4
POP-02	0.70 ± 0.02	97.6 ± 0.02	14.36 ± 0.68	1.23 ± 0.06	4.9 ± 1.2	9.2 ± 0.5
POP-03	0.61 ± 0.02	98.0 ± 0.02	21.31 ± 0.31	1.08 ± 0.05	7.3 ± 1.7	7.4 ± 0.4
Il-Qarraba						
QAR-01	0.91 ± 0.02	97.6 ± 0.02	12.22 ± 0.24	1.48 ± 0.06	4.2 ± 1.0	10.2 ± 0.6
QAR-02	0.84 ± 0.02	97.8 ± 0.02	10.87 ± 1.19	1.87 ± 0.09	6.81 ± 2.4	15.3 ± 1.0

Data are normalised to the GEC standard (³⁶Cl/Cl = 444 × 10⁻¹⁵)

Carrier ³⁶Cl/Cl = 1 × 10⁻¹⁵

³⁶Cl decay constant 2.3 × 10⁻⁶ yr.⁻¹

a. c = cosmogenic component

b. r = background nucleogenic component

Anchor Bay

The uppermost sample (POP-01) on the detachment face has an apparent age of 21.7 ± 1.4 ka. Since this sample was 4.15 m from the surface of the limestone plateau and therefore almost completely shielded from cosmic rays, it provides an age estimate for the initiation of displacement if displacement was rapid (< 1000 years). If the initial movement of the block was slow (> 1000 years), then the sample would have been only partially shielded during its early exposure history and therefore the age is a maximum only. Further down the face (8.4 m lower) the next sample has an apparent age of 9.2 ± 0.5 ka (POP-02) and POP-03 4.25 m lower has an apparent age of 7.4 ± 0.4 ka. Excluding exposure from partial shielding, these exposure ages give maximum movement rates of displacement between the top of the face and POP-01 of 0.2 mm/yr, between POP-01 and POP-02 of 0.7 mm/yr and between POP-02 and POP-03 of 2.4 mm/yr. Hence, the vertical slip rate increased by an order of magnitude through time.

Il-Qarraba

The west-facing scarp of the plateau where the block detached has an age of 15.3 ± 1.0 ka (QAR-02) and the outer face of the block has an age of 10.2 ± 0.6 ka (QAR-01). The results indicate that the block detached from the plateau first (~15 ka) and then subsequently broke and detached another block from the front (~10 ka).

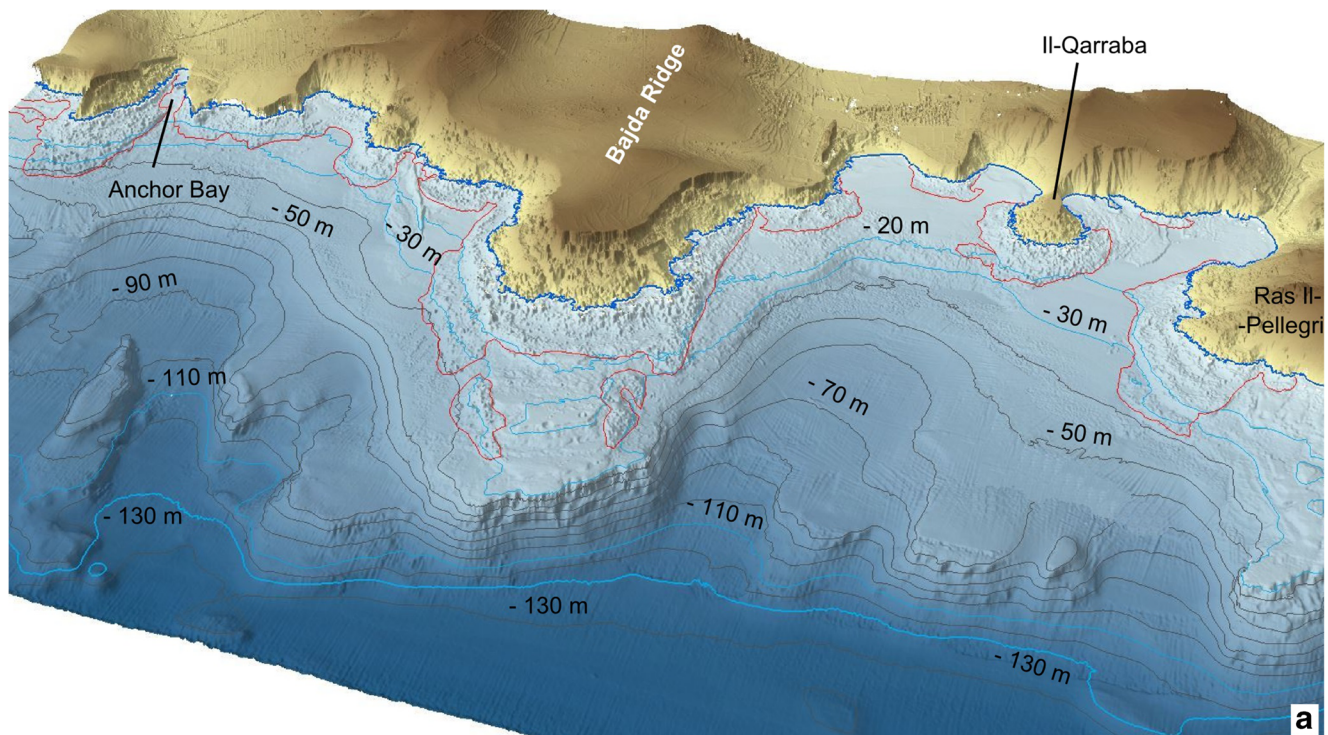
Discussion

During the last glacial cycle and up to the last glacial maximum (LGM), sea level fall was characterised by minor oscillations with a magnitude of tens of metres in time intervals of

1000 years or less and reached a minimum during the LGM (130 m below sea level) (Siddall et al. 2003; Lambeck and Chappell 2001, Lambeck et al. 2002, 2011; Clark et al. 2009). According to Clark et al. (2009) and Lambeck et al. (2011), the LGM is considered to have occurred between 26.5 to 19.0 ka BP. This period is followed by a time interval (19–12.5 ka BP) of sea level rise that increased in rate from 3.3 mm/yr to 16.7 mm/yr (14 ka BP – meltwater pulse 1A) to be constant from 12.5 to 11.5 ka BP (Younger Dryas) (Fig. 7b; Lambeck and Chappell 2001, Lambeck et al. 2002).

The initiation of displacement (or at least the oldest movement dated) at Anchor Bay occurred 21.7 ± 1.4 ka during the LGM lowstand (ca. 130 m b.s.l.), whilst the oldest displacement at Il-Qarraba dates back to 15.3 ± 1.0 ka when sea was about 115 m b.s.l (Fig. 7a, c). At both times the sea level was much lower than the depth of the present outer extent of landslides at the two sites (ca. 40 and 25 m b.s.l. at Anchor Bay and Il-Qarraba, respectively). Consequently, both landslide events occurred when sea level was not high enough to influence cliff instability. However, landslide evolution could have been influenced by sea erosion and clay saturation due to the successive sea level rise during the post-glacial period. On the other hand, the climate characterising the LGM period (around 21 ka) could have been more humid and temperate (Hunt 1997; Hunt and Schembri 1999), favouring a higher saturation of the Blue Clay. This is likely to have favoured ductile deformation of the Blue Clay and displacement of the overlying limestone blocks, promoting sliding downhill.

According to the reconstructions of Lambeck et al. (2011) and Furlani et al. (2013), sea level was high enough to start interacting with the landslides at ca. 9.5 ka for Anchor Bay site (40 m b.s.l.) and 8 ka for Il-Qarraba site (20 m b.s.l.). Thus, just the latter movements at Anchor Bay (9.2 ± 0.5 and 7.4 ± 0.4 ka ago)



- Total extension of landslide runout
 — Isobath related to a specific dated event
- | | | |
|-----------------------------|----------------------------|---------------------------|
| - 130 m → 21.4 ± 1.3 kyr BP | - 30 m → 10.0 ± 0.5 kyr BP | - 15 m → 7.4 ± 0.4 kyr BP |
| - 110 m → 15.1 ± 0.9 kyr BP | - 20 m → 9.1 ± 0.5 kyr BP | (not represented) |

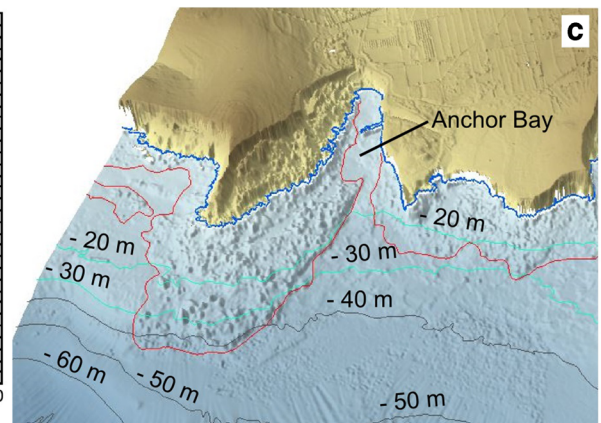
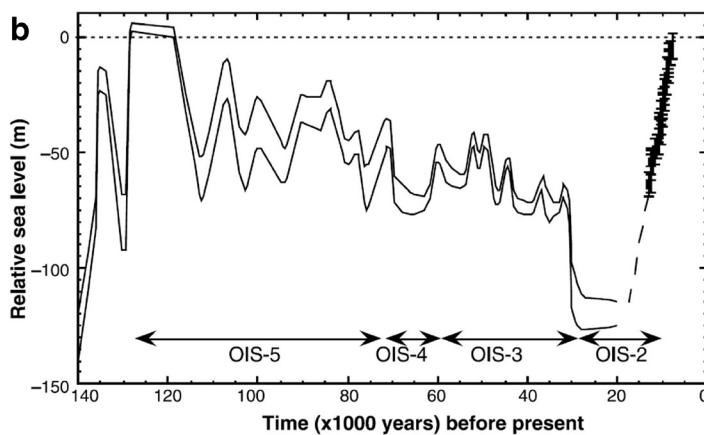


Fig. 7 **a** 3D view of the NW coast of Malta with the submerged extension of landslide runout shown with the red line. Isobaths are shown with an interval of 10 m. Isobaths in light blue are related to the

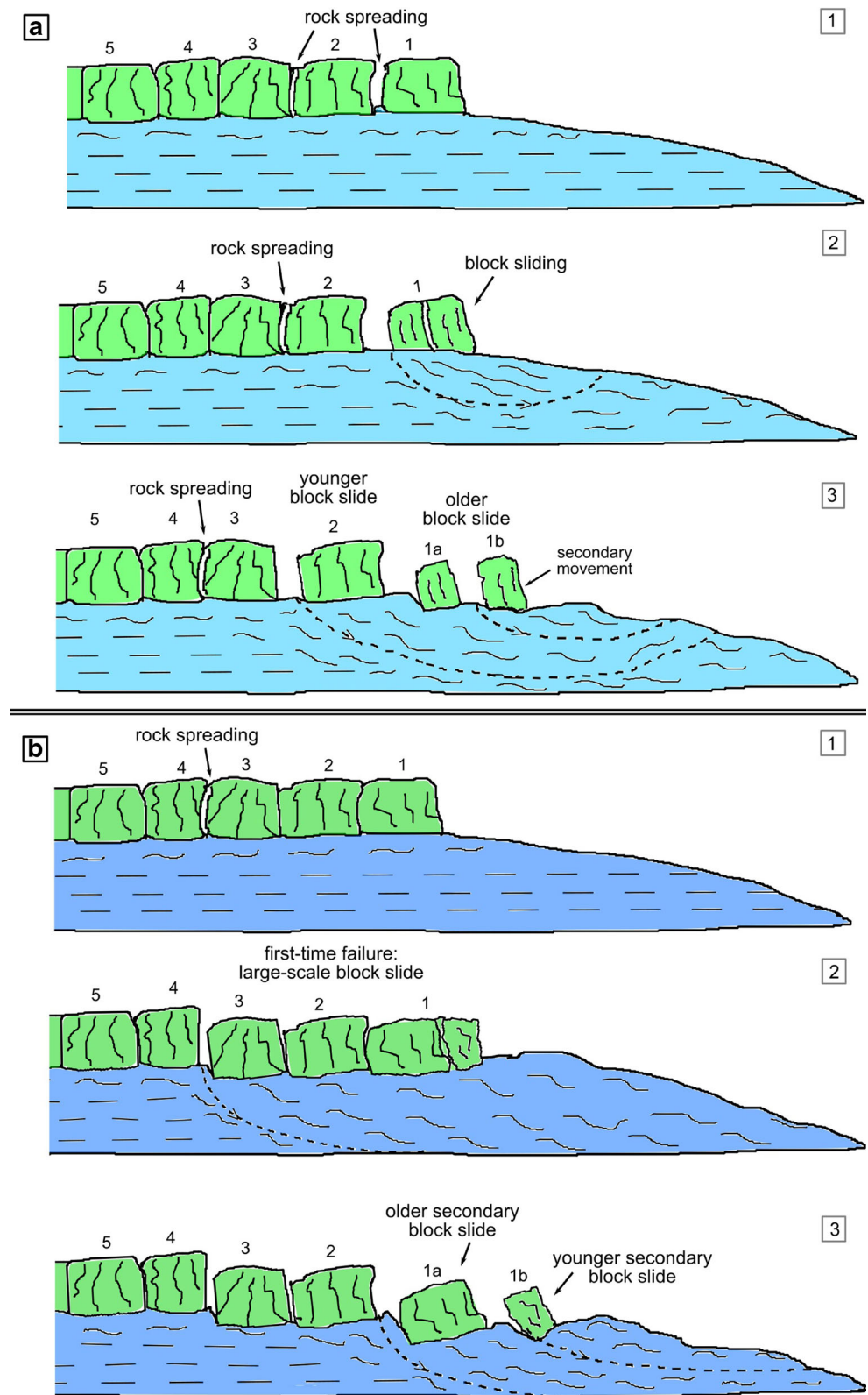
coastline at the moment of the dated events. **b** Relative sea level changes during the last glacial cycle (modified from Lambeck and Chappel, 2001). **c** Detail on Anchor Bay

were possibly influenced by toe-undercutting and clay saturation, when the relative sea level approached its present-day level and was about 15 m below the present level (ca. 7 ka ago). Considering that the Anchor Bay site shows an increase in displacement rate through time, it is possible that sliding accelerated when the sea reached the Blue Clay and started the submergence of a large part of the surrounding landslide complex.

Considering the outputs of previous studies on these landslides and the results of long-term monitoring (Mantovani et al. 2016), two modes for block slide geomorphological evolution emerge (Fig. 8):

1) progressive cliff retreat due to block detachments accompanied by slow sliding of blocks on the clayey material (according to Conti and Tosatti 1996, and Pasuto and Soldati 2013) (Fig. 8a);

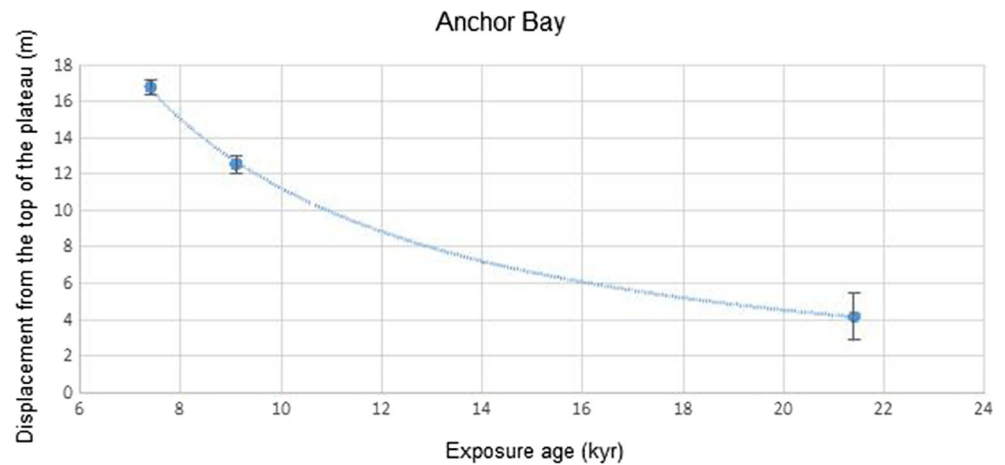
Fig. 8 Sketch showing the two hypothesised modes of cliff geomorphological evolution. **a** Regressive cliff retreat due to block detachments accompanied by block sliding on clayey material (Conti and Tosatti, 1996; Pasuto and Soldati 2013). **b** First-time failure corresponding to a large-scale sliding event involving the entire slope and successive secondary block slides further fragmenting the rock blocks displaced in the initial movement



2) first-time failure corresponding to a large-scale sliding event and successive secondary block slides further fragmenting the blocks displaced in the initial movement (Fig. 8b).

The spatial distribution of the dating results indicate that the first mode does not explain all movement. Indeed, the finding of older detachments more inland at both sites could suggest

Fig. 9 Graph of the age of the events vs the displacement of the block from the top of the plateau in case the block slide evolution followed the hypothesis n. 1, according to Conti and Tosatti (1996) and Pasuto and Soldati (2013)



that a large failure took place as initial movement followed by secondary block slides affecting the whole landslide deposit. This could be proved by the more recent ages shown by samples POP-02, POP-03 and QAR-01. This mode explains the Anchor Bay site, where a displaced limestone slab is located just at the bottom of the sampled scarp providing evidence of a possible single collapse. Nevertheless, especially for Il-Qarraba site, the limited number of ages collected makes it difficult to attribute movement to a single mode.

If the second mode (ie. first-time failure plus secondary movements) dominates, the secondary movements – meant as minor slides within the main landslide deposit – are likely to have been influenced by the actions related to rising sea level and by the presence of higher water tables which saturated the clay layer and favoured minor slides adjacent to the coast. Also toe erosion could have influenced these movements and increased the displacement rate through time. Consequently, apart from the secondary minor slides as a result of the post-glacial sea level rise, the submarine landslide complexes at both sites remain little modified by wave action. Hence, it is likely that the weight of the column of water above the submerged landslide deposits plays a role in stabilising them, while their emerged portions are still active mainly due to meteoric factors and move extremely slowly (i.e. an average of 7 mm/yr at Anchor Bay: Devoto et al. 2013b, 2015; Mantovani et al. 2013) (Fig. 9).

Conclusions

The results from exposure dating performed on block slides located along the north-western coast of the Island of Malta provide the first long-term chronological constraints on their geomorphological evolution. The analyses highlighted that the oldest detachment event occurred during the LGM (ca. 21 ka), in a subaerial environment and in a more humid climate, that favoured

the saturation of the Blue Clay inducing ductile deformation and acceleration of block sliding. Moreover, the exposure dating allows us to speculate on block slide evolution. Two modes are possible: 1) progressive cliff retreat due to block detachments accompanied by successive slow sliding of blocks on the clayey material; 2) first-time failure corresponding to a large-scale sliding event involving the entire slope and successive secondary block slides further fragmenting the rock blocks displaced in the initial movement. The second mode is suggested by the fact that older detachments were found more inland than younger detachments. However, our initial dating results cannot completely exclude the hypothesis of an evolution through a progressive dismantling of the limestone plateau as a result of successive sliding events and collateral secondary block detachments.

In order to support and better outline Maltese block slide evolution, more exposure dating is necessary, both in other sites on the western coast and along the north-eastern coast. Moreover, further investigations could focus on models that would provide a quantitative evaluation of the role of water (seawater, rain, groundwater and moisture) on landslides kinematics. This would also help with predicting future activity, considering that the environment is changing due to global warming inducing sea level rise.

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