Landslide activity in Upper Palaeozoic shale sea cliffs: a case study along the western coast of the Algarve (Portugal)

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Abstract A stretch of 48 km of sea cliffs up to 120 m high in the Algarve area of Portugal exposed heavily folded Palaeozoic shales. A study has been undertaken to assess the retreat of these sea cliffs. Nine sets of aerial photographs taken between 1947 and 1991 have been assessed, particularly to determine the retreat at the top of the cliffs. The time distribution of landslides shows some relationship with the average annual rainfall, and the space distribution provides a perspective of rates and patterns of cliff retreat in the different geographic locations. The landslides were predominantly planar, the larger ones having failure surfaces with a low dip consistent with long-term displacements at near residual strength. Examples are described. Back analysis indicates an average friction angle at the time of failure of between 23 and 25°, assuming negligible cohesion.

Activité des mouvements de versant en falaises côtières en schistes du Paléozoïque Supérieur: une étude sur la côte occidentale de l'Algarve (Portugal)

Résumé Des schistes argileux paléozoïques, intensément plissés, affleurent sur 48 km de falaises côtières, de 120 m de hauteur au plus, dans la région de l'Algarve au Portugal. Une étude a été engagée pour évaluer le recul de ces falaises. Neuf séries de photographies aériennes, prises entre 1947 et 1991, ont été analysées pour déterminer en particulier le recul des sommets de falaise. La répartition dans le temps des glissements de terrain montre une corrélation avec le module pluviométrique. La répartition dans l'espace permet d'envisager des vitesses et des schémas de recul des falaises dans les différents secteurs concernés. Les glissements sont principalement des glissements plans, les plus grands présentant des surfaces de rupture de faible pendage en accord avec des processus de rupture à long terme ne mobilisant pratiquement que la résistance résiduelle au cisaillement. Des exemples sont décrits. Une rétro-analyse donne un angle moyen de frottement entre 23 et 25° en supposant une cohésion négligeable.

Keywords Cliff retreat · Palaeozoic shales · Planar landslides · Residual strength · Portugal

Mots clés Recul de falaise · Schistes argileux · Glissements plans · Résistance résiduelle · Portugal

Introduction

To assess the frequency and types of the retreat phenomena that occurred along the sea cliffs eroded in the Upper Palaeozoic of the western Algarve, a systematic inventory was made by comparing the aerial photographs of 1947, 1958, 1974, 1980 and 1991. This would allow the identification of retreat events in the cliff crest larger than 2 to 3 m (Marques 1994, 1997). The coastal sections studied are included in a Natural Park (Parque Natural do Sudoeste Alentejano e Costa Vicentina) where the population is sparse, although there has been a large increase in the last decades.

The comparative studies of the aerial photographs along 48 km of cliffs eroded in the mainly Carboniferous shales and greywackes allowed the identification of 54 cliff crest retreat events, each corresponding to a single landslide or a group of landslides that occurred at the same site in the period between consecutive aerial photograph surveys. The study included:

1. The measurement of the relevant dimensions of the landslides.
2. The maximum local retreat.
3. The horizontal area lost at the top of the cliffs.

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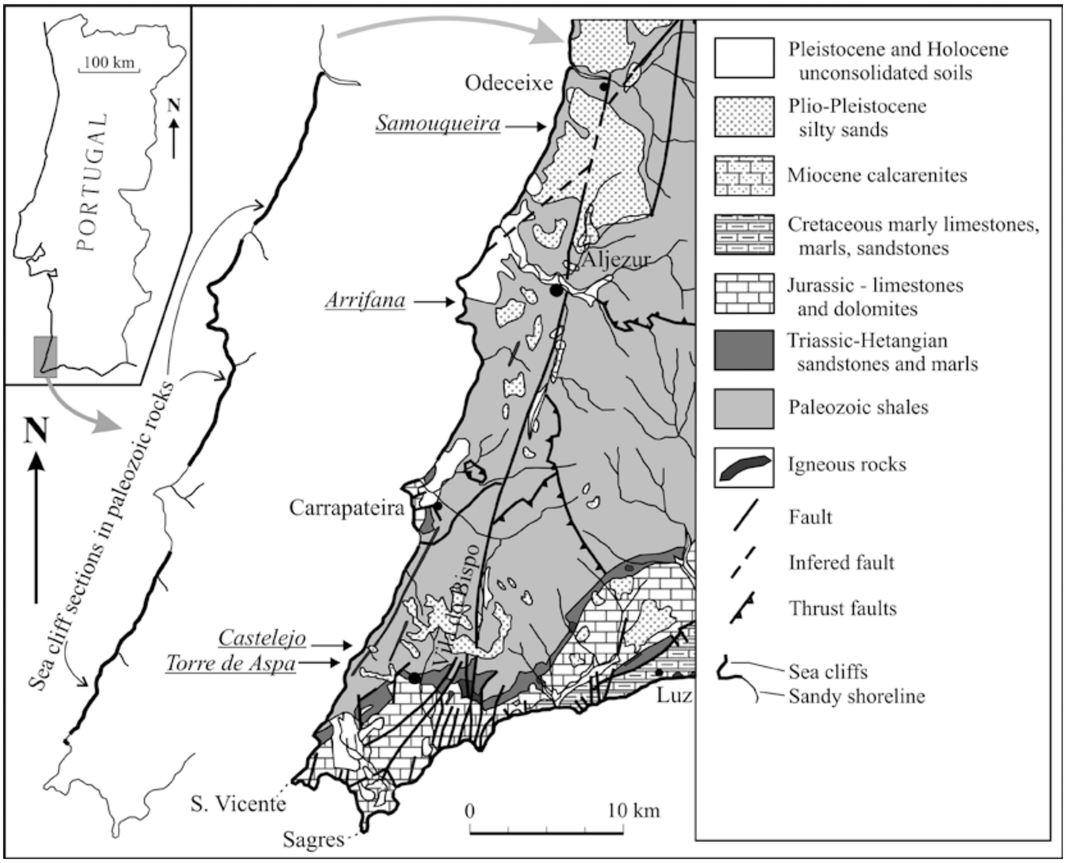

Fig. 1
Location of landslides along the Algarve coast and relevant geology. [Adapted from Manuppella (1992)]

4. Provisional identification of landslide types.
5. Indications of the geomorphological context in which the slips took place.

Many of these landslides were then examined in the field to confirm the significant morphological features, characterise the geometry of the displaced rock masses and locate the failure surface.

This paper describes the landslide activity of the cliffs of the western Algarve. The types, sizes, spatial distribution and timing of the landslides were analysed and compared with the geomorphology and available information regarding the external factors of slope instability. Selected examples of planar landslides that occurred where the shear resistance is at or near residual strength are described and the back analysis undertaken reported. The examples selected (Fig. 1) are from Praia da Samouqueira, 1 km NW of Arrifana, near Torre de Aspa and at Praia do Castelejo.

Geological setting

The western coast of the Algarve (Portugal) is dominated by sea cliffs, mainly composed of an Upper Palaeozoic (Upper Devonian–Carboniferous) sequence with minor sections of mainly Mesozoic carbonate rocks. As seen in Fig. 1, the Jurassic rocks outcrop mainly in the headlands of Carrapateira and the S. Vicente–Sagres region. Along the cliffs there are also small outcrops of Triassic sandstones and Hetangian Keuper marls. Holocene cemented dune sandstones are present in some areas.

The Palaeozoic rocks are included in the western border of the South Portuguese Zone, a part of the SW branch of the Iberian Variscan Arc. They include an Upper Devonian basement and the condensed facies of the Bordeira anticline, overlain by a Carboniferous flysh sequence—the Brejeira Formation (Ribeiro et al. 1987).

The general sequence includes the Bordeira–Carrapateira Formations (Ribeiro et al. 1987) which are exposed only in small sections of the sea cliffs and were not affected by the planar landslides described in this paper: the Tercenas Formation (Famenian–Lower Carboniferous) is overlain by the Carrapateira Group which includes the Bordalete (Carboniferous: Middle and Upper Tournaisian), Muração (Carboniferous: Visean–Lower Namurian) and Quebradas (Carboniferous: Namurian) Formations. These geological units, deposited on a shallow continental platform, are mainly composed of dark grey shales alternating with sandstones and dolomitic limestones. Overlying these shales is the Brejeira Formation (Baixo Alentejo Flysh group; Carboniferous: Middle Namurian–Lower Westphalian). These deposits are an Hercynian flysh unit which forms a large part of the cliffs in the study area. This flysch deposit is mainly composed of dark grey shales alternating with generally thin sandstone beds, arranged as typical fining-upwards turbidite sequences. The relative bed thickness of the two lithological types is quite variable along the coast, with a greater proportion of shale rather than sandstone, except at the prominent coastal cliff sections to the south of Arrifana (SW of Aljezur) and at Torre de Aspa region (west of Vila do Bispo); see Fig. 1.

The Palaeozoic rocks were folded and faulted by the Hercynian Orogeny which included three main deformation phases (Ribeiro 1983; Ribeiro et al. 1987; Silva et al. 1990). The first is the most important and was responsible for the SW vergent folding, associated with the main thrusts and the creation of a slaty cleavage dipping to the NE. The second deformation phase caused local refolding of the previous structures to produce near-vertical, NE–SW-trending hinge surfaces and, locally, a crenulation cleavage. A third deformation phase produced the NNE–SSW-trending Bordeira anticline and locally an intersecting slaty cleavage with the same general trend. The rocks exposed in the cliffs are mainly composed of alternating layers of shale and greywacke, mostly affected by NW–SE-trending folds with an axial planar cleavage dipping NE. The highly folded structure and the irregular contour of the cliffs makes the relations between the dip of the strata and the cliff faces extremely variable from site to site.

Geomorphology, climate and seismicity

The sea cliffs are mainly 40 to 100 m high, with a maximum height of 120 m near the geodetic station at Torre de Aspa. The profile of the cliffs is very irregular and varies from place to place, mainly as a consequence of the heavily folded and faulted geological structure and the varying erosion resistance of the Palaeozoic rocks.

The toe of the cliff toe usually abuts intertidal abrasion platforms, which are locally covered by small gravel beaches and rare sand beaches. Near-vertical cliff faces which extend significantly below sea level (plunging cliffs), indicating very limited cliff retreat during the Holocene, occur only in a small section southwards of Arrifana.

The SW coast of Portugal is attacked by a high-energy wave regime generated in the North Atlantic Ocean, with a predominant fetch (long swell) from the NW and storms from the west (Pires 1989). The effect of the waves on present-day cliff erosion is slightly reduced by the extensive intertidal abrasion platforms, while the very frequent islets and reefs that exist near the coast also reduce the erosive impact of the waves.

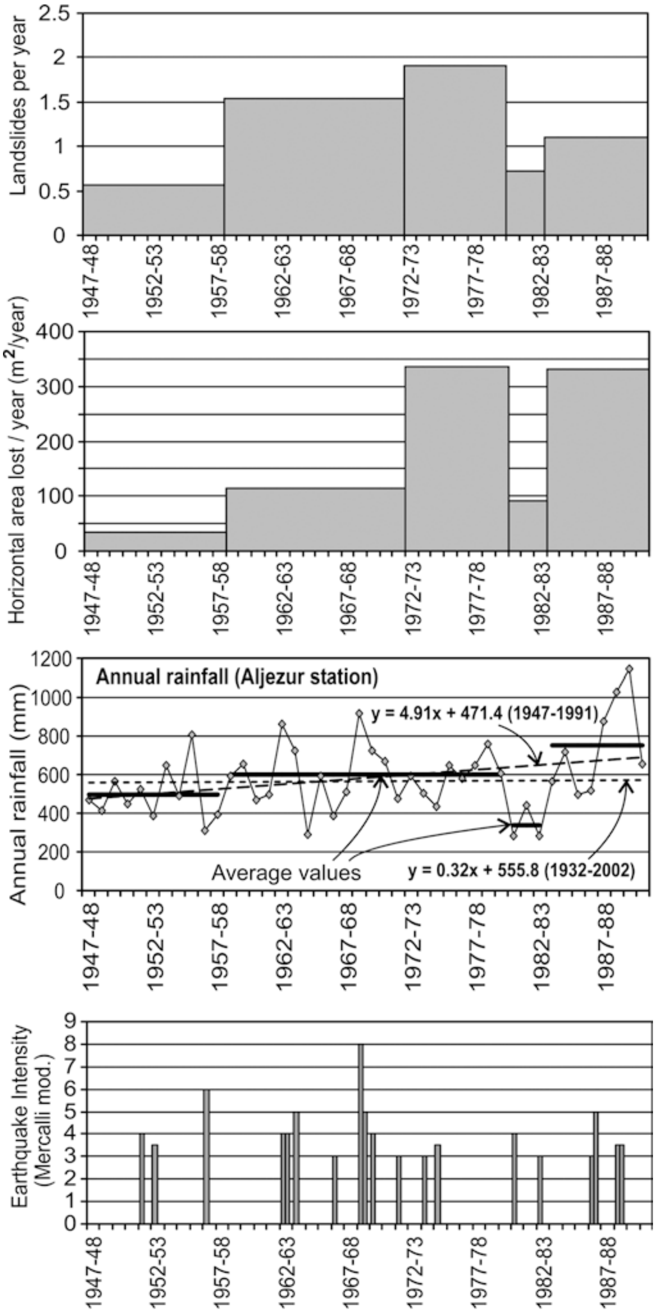

Fig. 2
Time distribution of number of retreat events and horizontal area lost at top of cliffs. Annual rainfall at Aljezur station, with linear regression of data and mean values for periods of retreat events dating 1947–1991 and linear regression of the 1932–2002 data. Summary of earthquake intensity at the study area

The mean annual rainfall at the Aljezur station was about 570 mm for the 1947–1991 period. However, the actual rainfall is quite variable, from lower values of approximately 300 mm/year to maximum values in excess of 800 mm/year (Fig. 2). Linear regression and moving average analysis figures are currently indicating that there may be as much as an additional 5 mm rainfall per year for the 1947–1991 period. However, considering a longer series from the same station (1932–2002), the linear regression slope is substantially lower, indicating a 0.3-mm/year increase (Fig. 2). The 30 years moving average curve shows a clear waviness, but also indicates a small overall increase in annual rainfall. The lower slope of the 1932–2002 series trend is probably caused by the particularly dry years of the 1999–2002 period. In fact, an increasing annual rainfall of 1 to 2 mm/year is a common trend with the other meteorological stations located along the western and southern coast of the Algarve. This is well documented by the long rainfall data series from the stations at Faro (1894–1993; 1.8 mm/year increase) and Lagos (1902–2001; 1.1 mm/year increase). Besides the mean annual rainfall increase, Marques (1997) has concluded that the rainfall occurs in shorter periods, with a significant increase in torrential showers in more recent years.

The region is one of the most earthquake-sensitive areas in Portugal. In the landslide survey period it was affected by the 28 February 1969 earthquake which had a maximum local intensity of 8 on the Mercalli modified scale. Other smaller earthquakes with a maximum local intensity lower than 6 have also been recorded, as shown in Fig. 2 (Anonymous 1947–1992).

Engineering geological properties

The available geotechnical information on the rocks outcropping along the coastline in the study area is limited. Point load tests on fresh to slightly weathered greywacke sandstones and muddy quartzites with average dry unit weights of 26.3 kN/m^3 yielded Is_{50} values between 1 and 10 MPa. The unweathered shales have an average dry unit weight of 26.5 kN/m^3 and point load strengths generally of only 0.5 to 1.5 MPa parallel to bedding, while at right angles to the bedding they are between 1 and 3 MPa. Small-scale field tilt tests produced friction angles between 27 and 34°—greater than the residual friction angle for these rocks, mainly because of the roughness of the specimen tested and the low confining stresses (Barton and Choubey 1977; Xian-Qin and Cruden 1992).

Landslide distribution

The systematic comparative studies of the aerial photographs were performed according to procedures conceived to assess the evolution of the cliffs. This used a combination of qualitative systematic comparison for retreat detection and precise measurements for the assessment of quantitative data, namely the local maximum and mean horizontal retreat at the cliff top and the length of cliff affected by the retreat. The accuracy of the methods used is dependent on the quality and scale of the available aerial photographs and on the skill of the observer (Marques 1994, 1997). Practical experience suggests that a skilled researcher using 1:30,000 scale aerial photographs can identify and measure local retreats of more than 2 to 3 m.

The space distribution of the landslides that occurred in the study area in the period 1947–1991 can be effectively analysed by means of a plot of the accumulated number of retreat events, accumulated horizontal area lost and accumulated volume of materials displaced against the length of cliff section. As a distinct property of cumulative plots, the different slope sections of the curve reflect the cliff retreat intensity variations along the coast. Due to the inherent limitations of the source data, the horizontal area lost at the cliff top is considered to be the most accurate measure of the cliff retreat. The number of retreat events does not in fact reflect the landslide's relative size and a retreat event can correspond to a group of landslides that occurred at the same site between consecutive aerial photographs. The volume displaced was computed on the basis of crude estimations of the thickness of the failed rock masses.

Figure 3 gives a cumulative plot of horizontal area lost at the cliff top against the length of cliffs, arbitrarily set at the southern end of the studied coastal section. The slope of the linear regression lines of selected parts of the data (different sections of cliffs) gives an estimate of the cliff retreat in metres for the corresponding sections during the 44 years of the study period. The mean annual retreat rate for each section is obtained by dividing those values by the number of years of the study.

The data indicate that the cliff retreat rates are highly dependent on the choice of the physical extent of the cliff sections, with variations between 0.004 m/year for the whole coastal section (0.16 m/44 years) to a maximum of 0.017 m/year at the cliff section located west of Vila do Bispo (Fig. 3). On the other hand, due to the magnitude of some of the cliff retreat events and the short length of the study period in comparison with the time required for a cliff evolution cycle to be completed, the mean retreat rates have a limited local representativeness. Nevertheless, they provide a standardized variable which allows comparison of cliff sections with different retreat behaviours.

The retreat events could only be dated to the periods between consecutive aerial photographs. Clearly, therefore, the time distribution of events is artificially smoothed and it is not possible to relate the landslides directly with the activity of the external triggering factors. These relations can thus only be discussed in a qualitative manner.

The time distribution of the landslides (Fig. 2) indicates that these were more frequent during the 1960s and the 1970s. However, the horizontal areas lost had a different pattern, caused mainly by the occurrence of two large failures—the Castelejo landslide (1972–1980) and the Torre de Aspa landslide (1984–1991). As seen in Fig. 2, the number of landslides and the area lost had some relationship with the mean annual rainfall, but the correlations obtained are not satisfactory. Several attempts were made to relate the time distributions of the landslides with the different rainfall threshold values with various forms of the annual and monthly maxima, but again the results were not significant. This may be due to the influence of other potential triggering factors, such as the occurrence of storms, for which there are no systematic data available. In addition, it may reflect the inherent limitations of the landslide data, especially the small number of photographic surveys and time between them.

From the data provided in Fig. 2, however, it would appear that the earthquake that occurred on 28 February 1969 did not cause a significant increase in landslide activity. It is noted also that this occurred during a particularly wet period.

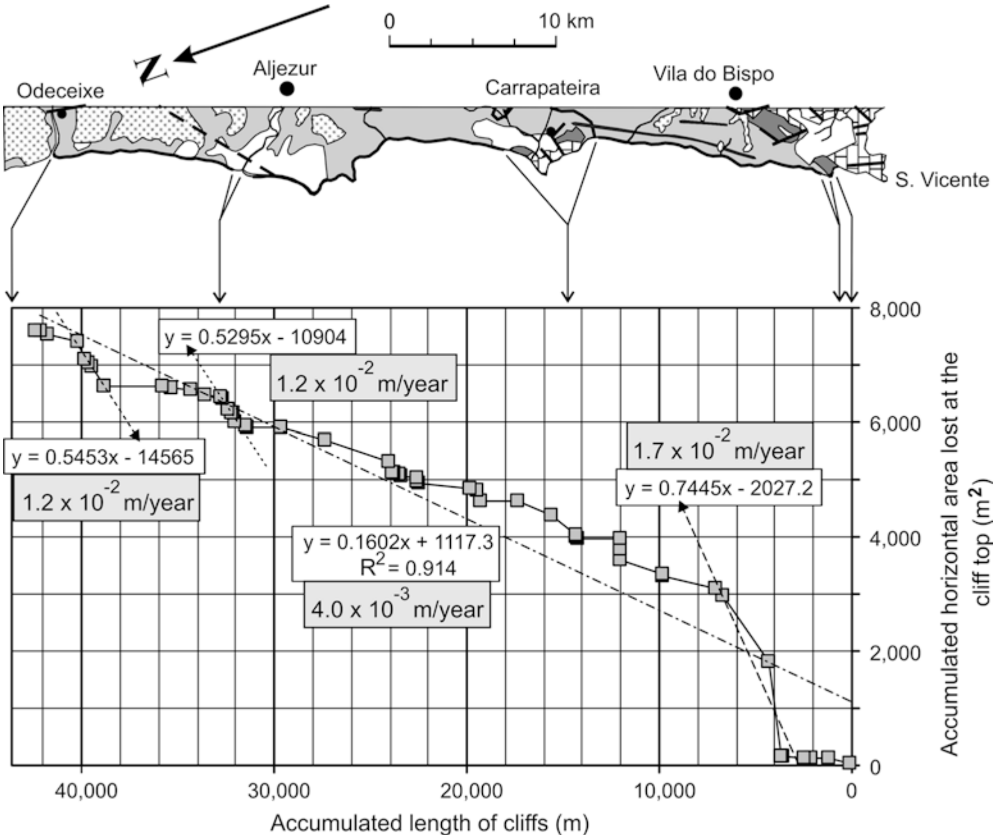

Fig. 3
Spatial distribution of areas lost at top of cliffs, linear regression equations of different parts of the data and corresponding cliff retreat rates

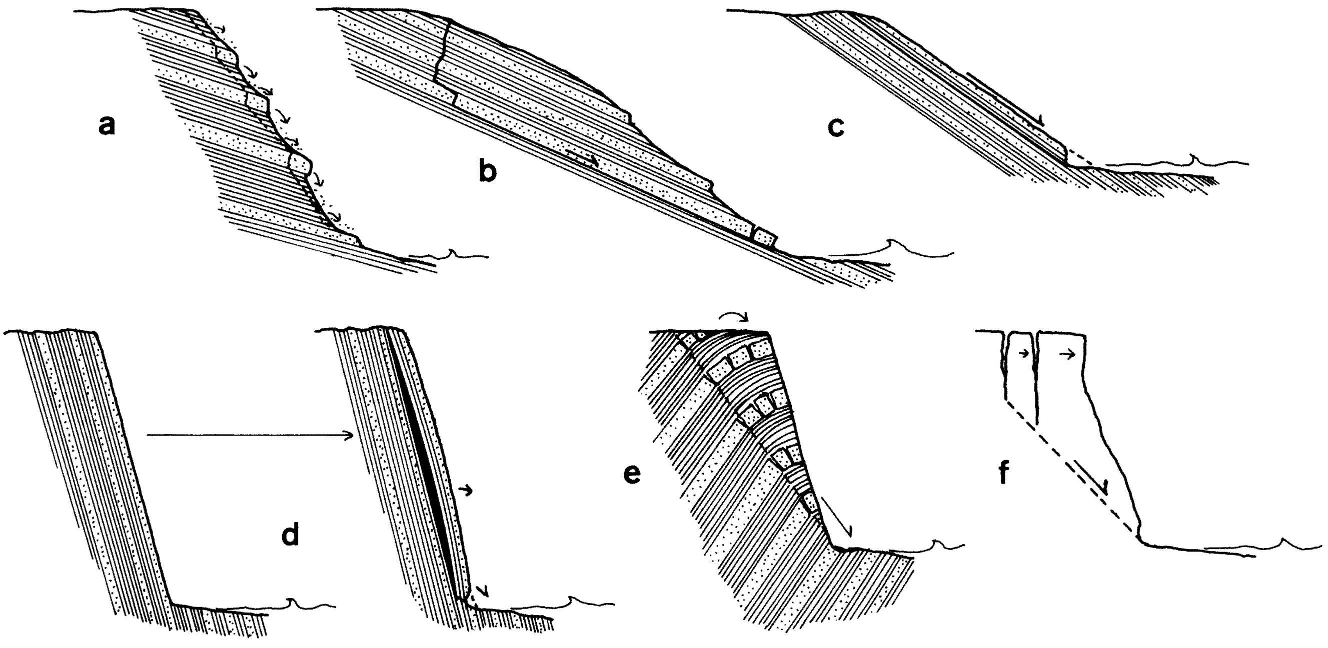

Fig. 4
Slope movement types in the Palaeozoic shale and greywacke cliffs. For explanation of parts **a**–**f** see the text

Landslide types and sizes

As seen in Fig. 4, the slope instability types detected during field surveys along the Palaeozoic shale cliffs are generally related to the geological structure. In some cases, small instabilities are related to granular disintegration of the shales with consequent toppling followed by planar sliding of the greywacke sandstone beds (Fig. 4a). This occurs mainly where low dips are directed towards the free face. This type of process, which involves individual blocks being disturbed within a single cliff face, is difficult to detect on aerial photographs and hence its influence was not considered in this study. Intermediate dips (Fig. 4b and c) favour the occurrence of planar slides where support is removed by toe erosion. Steeper bedding (Fig. 4d) favours the progressive deformation of the outer slabs by buckling of the rocks at the base of the cliff, resulting in the opening of tension cracks along the bedding in the low and intermediate part of the cliff. Ultimately notch widening by marine erosion tends to cause collapse by planar failure. The penultimate example (Fig. 4e) is the result of the failure of a section of the cliff preceded by the flexural toppling/draping of the strata near the free face (Goodman and Bray 1976). In the case of Fig. 4f, the bed orientation is variable and not related to the cliff face. In this example, the main failure is planar, but also typically preceded by some amount of toppling (de Freitas and Watters 1973; Goodman and Kieffer 2000).

In terms of the relative frequency of the different types of failure in the present inventory (*n*=54), 85% of the mass movements identified were of the planar type, possibly preceded by varying amounts of toppling and corresponding to the types in Fig. 4e and f. The amount of initial toppling could not be evaluated by an aerial photograph-based study. The remainder of the movements (15%) include toppling failures, completely developed toppling followed by planar slides and a buckling failure.

With only three exceptions, the landslides caused the cliff to retreat less than 15 m, with most resulting in a retreat of less than 10 m (Fig. 5). These usually had steeply sloping failure surfaces, typically higher than 45°, and were mainly caused by spalling of the outer layers of the rock mass. In contrast, the larger and least frequent movements slipped along failure surfaces with much lower angles of between 22 and 25°. This suggests they were long-term failures with the movement at an angle similar to the residual strength of the material.

The size distribution of the landslides included in the inventory, expressed in terms of horizontal area lost at the cliff top, indicates that the three larger ones were the main contributors to the global cliff retreat and hence the computed cliff retreat rates (Fig. 6). This cumulative plot indicates that the movements with a horizontal surface area of more than 100 m^2 account for almost 90% of the total area lost at the cliff top, the contribution of the smaller ones being almost negligible when computing the retreat rate. This suggests that whilst the analysis of the aerial photographs could not identify all the numerous movements which had (or may have) occurred, this method is suitable as it is the larger landslides—most likely to be identified during the photo interpretation—that are most significant in terms of land loss.

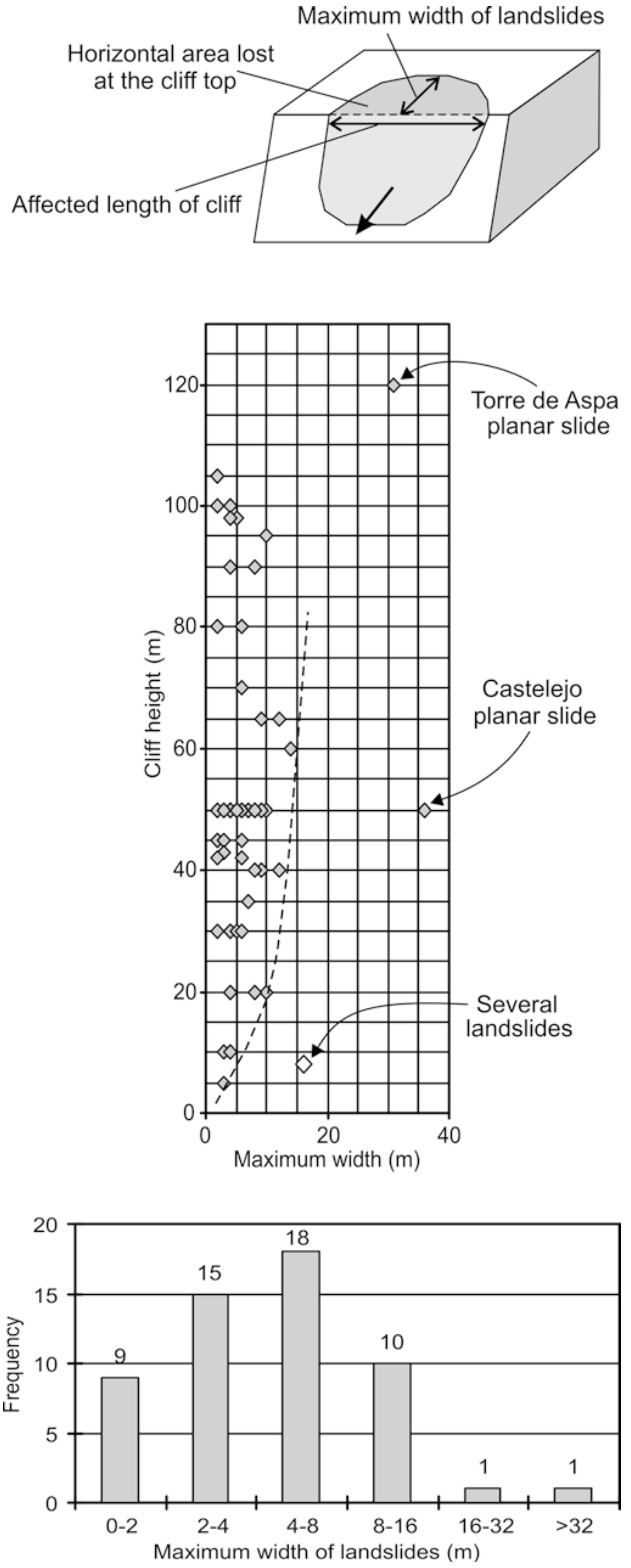

Fig. 5
Relationship between cliff height, maximum width and frequency distribution of landslides between 1947 and 1991

Examples of some landslides

Slope instabilities at Praia da Samouqueira

This site (Fig. 1) is located in a small bay, 0.5 km NNW of the geodetic station at Esteveira, and 5 km NNW from the village of Rogil. The cliffs are composed of alternating thin

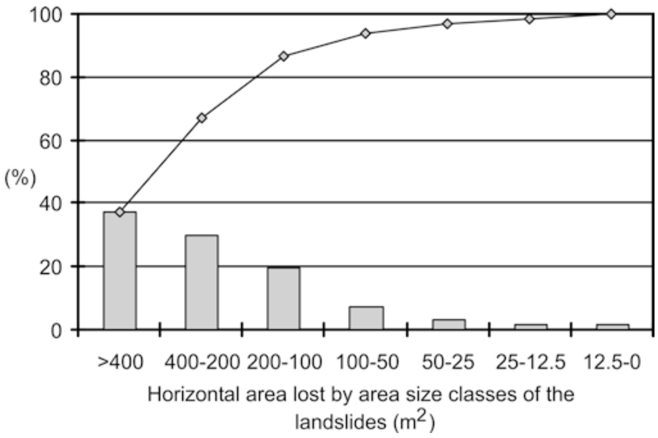

Fig. 6
Histogram and cumulative plot of horizontal area lost at top of cliffs with size class of landslides

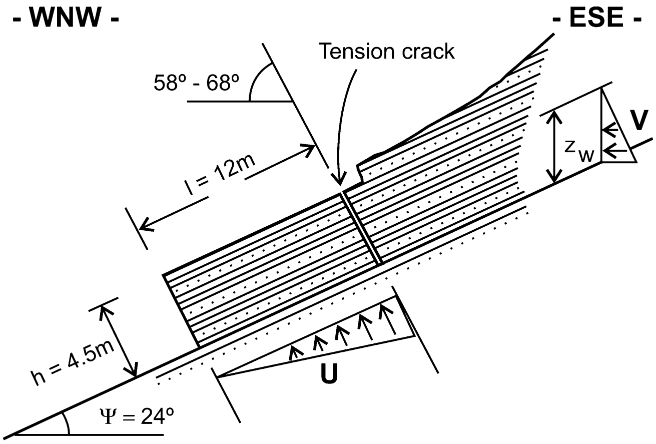

Fig. 8
Section of the slipped block at Z2 (Fig. 7) with the elements considered for back analysis

to medium layers of black shales and greywacke sandstones of the Brejeira Formation. As seen in Fig. 7a, the unstable zones are situated where the cliff has a NNE–SSW

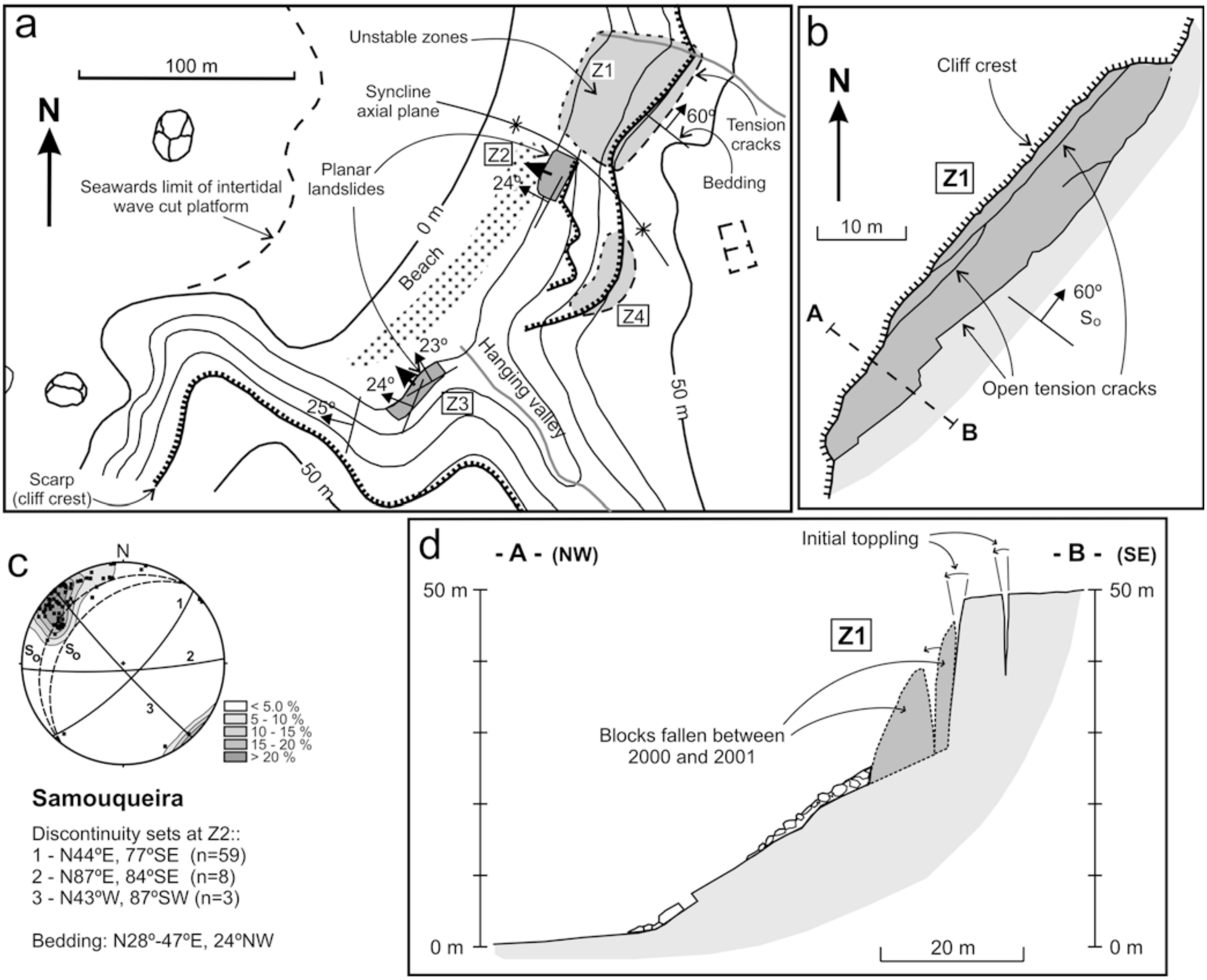

Fig. 7
a Location of Samouqueira landslide site, **b** detail of cliff crest, **c** stereograph of discontinuities measured and **d** geometry of cliff section

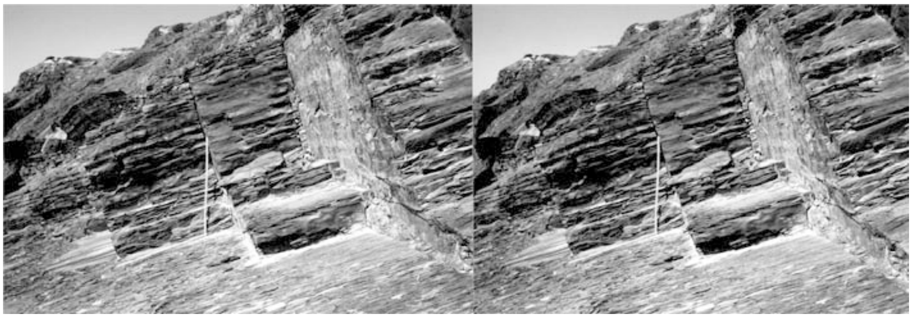

Fig. 9
Stereoscopic view (from SSW to NNE) of unstable blocks located southwards of Z2 (Fig. 7)

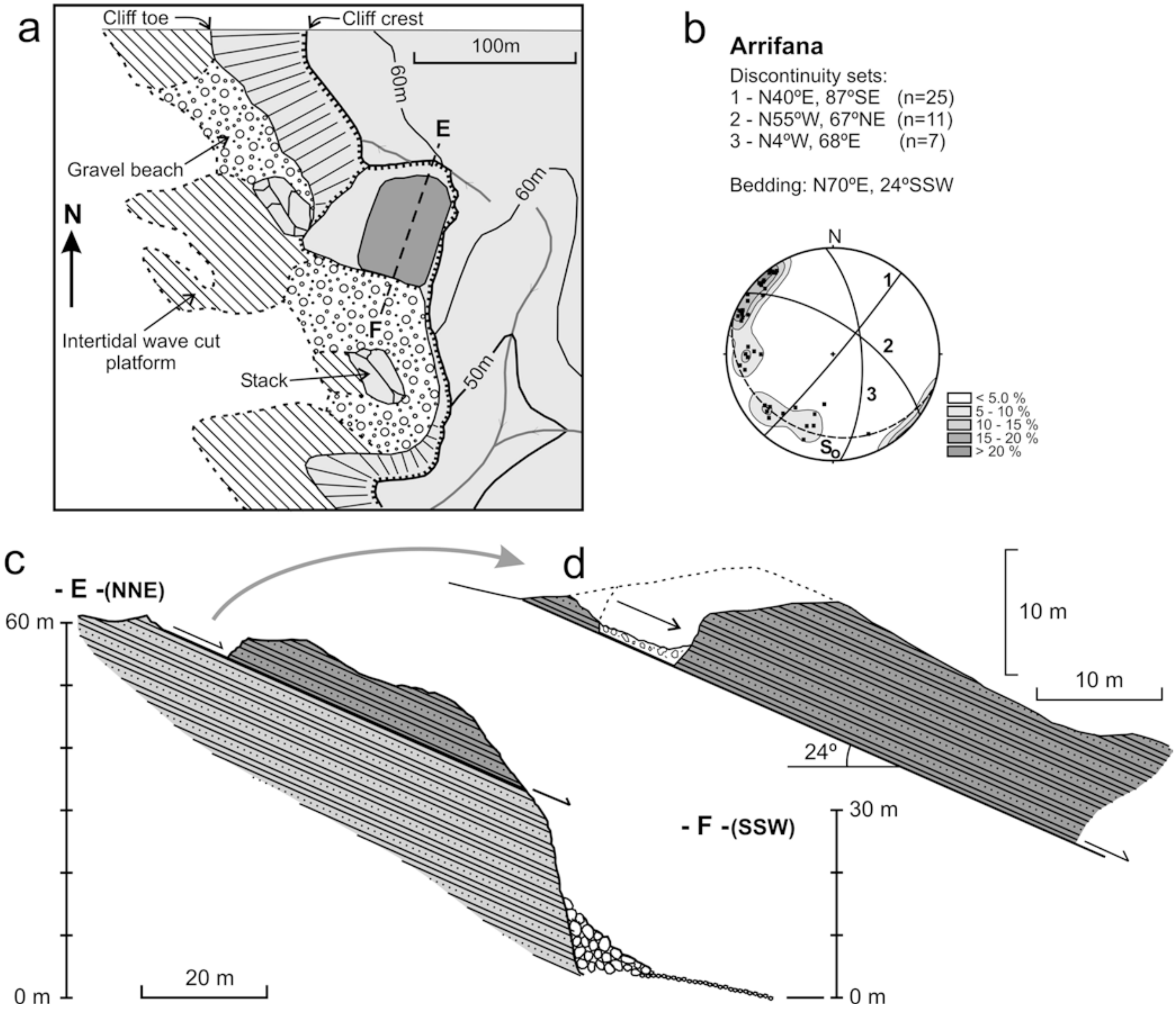

Fig. 10
a Location of the Arrifana landslide site; **b** stereograph of discontinuities; **c** and **d** landslide profiles

trend. The beds dip at approximately 24°WNW along most of the cliff face and in the northern part form a closed straight limb fold, with the northern limb overturned, dipping 60° to the NE with a cleavage parallel to the fold hinge.

The principal fracture sets are N030 to N070°, dipping between 60° to the SE and near vertical. There is a large variation in the orientation, with some approximately parallel to the cliff face. The E–W fractures dip at between 70°S to near vertical, while those trending NW–SE are near vertical along the slope dip direction (Fig. 7c). The rocks

Fig. 11
Stereoscopic view (SSE to NNW) of upper part of the slipped block at Arrifana site

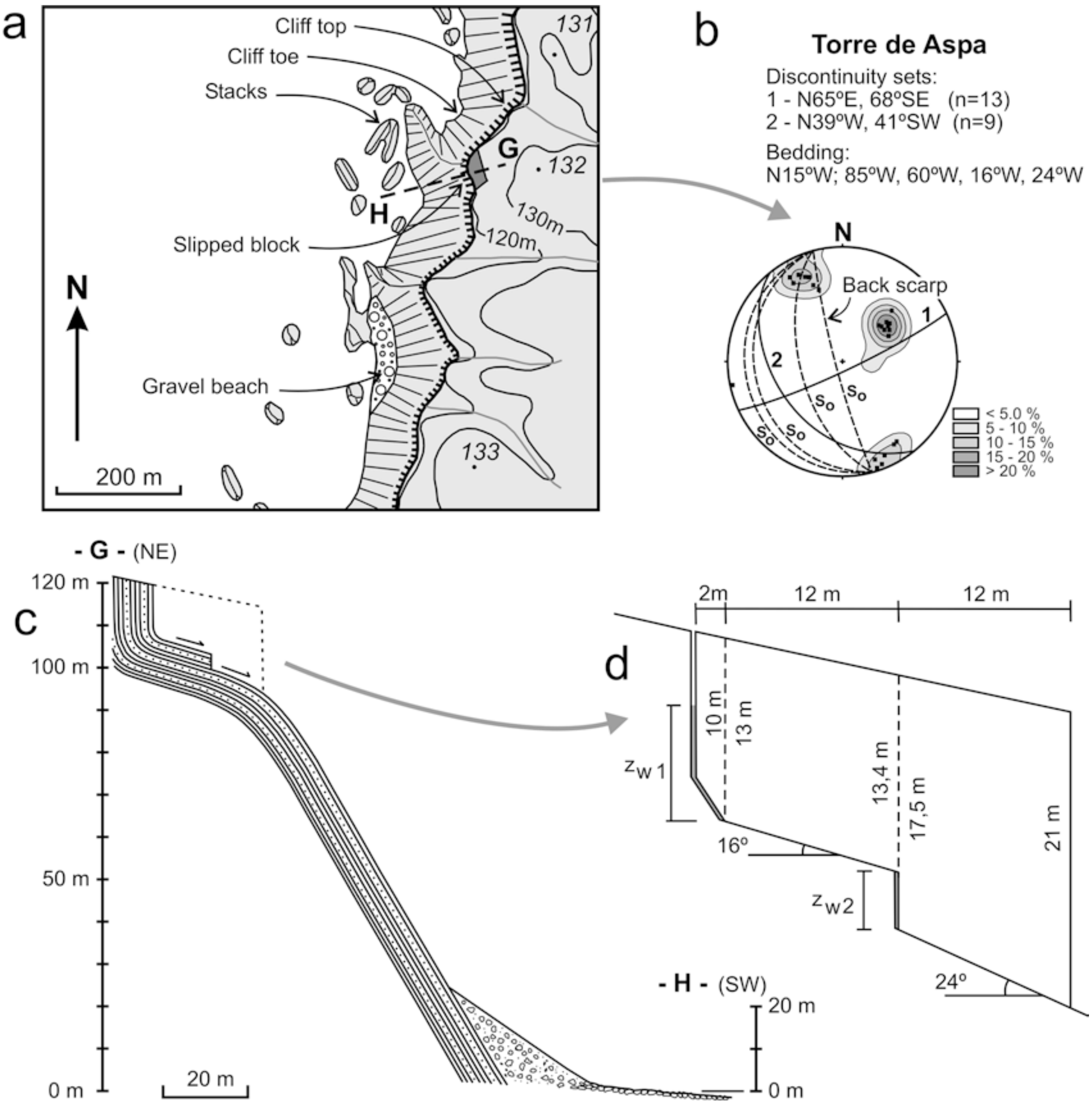

Fig. 12
a Location of the Torre de Aspa landslide site; **b** stereograph of discontinuities; **c** and **d** landslide profiles

in the upper part of the cliff are weathered and have a yellowish-brown colour. In the lower part, the weathering is mainly restricted to the major discontinuities and the rock mass has a dark grey to black colour.

At the upper part of the slope (Z1) there are large tension cracks which began opening before 1991 and widened almost continuously to a maximum of 1 m in the summer of 2001. In spite of the long evolution of this failure, only the outer slabs of rock collapsed between 2000 and 2001. Where the beds are dipping at some 60°NE, the cliff face is almost at right angles to the geological structure and it is possible for the stronger greywacke sandstones to form a steeper face (Fig. 7d). The field evidence suggests that while the cracks may open due to lateral movement of large rock masses, the main failure is a planar slide.

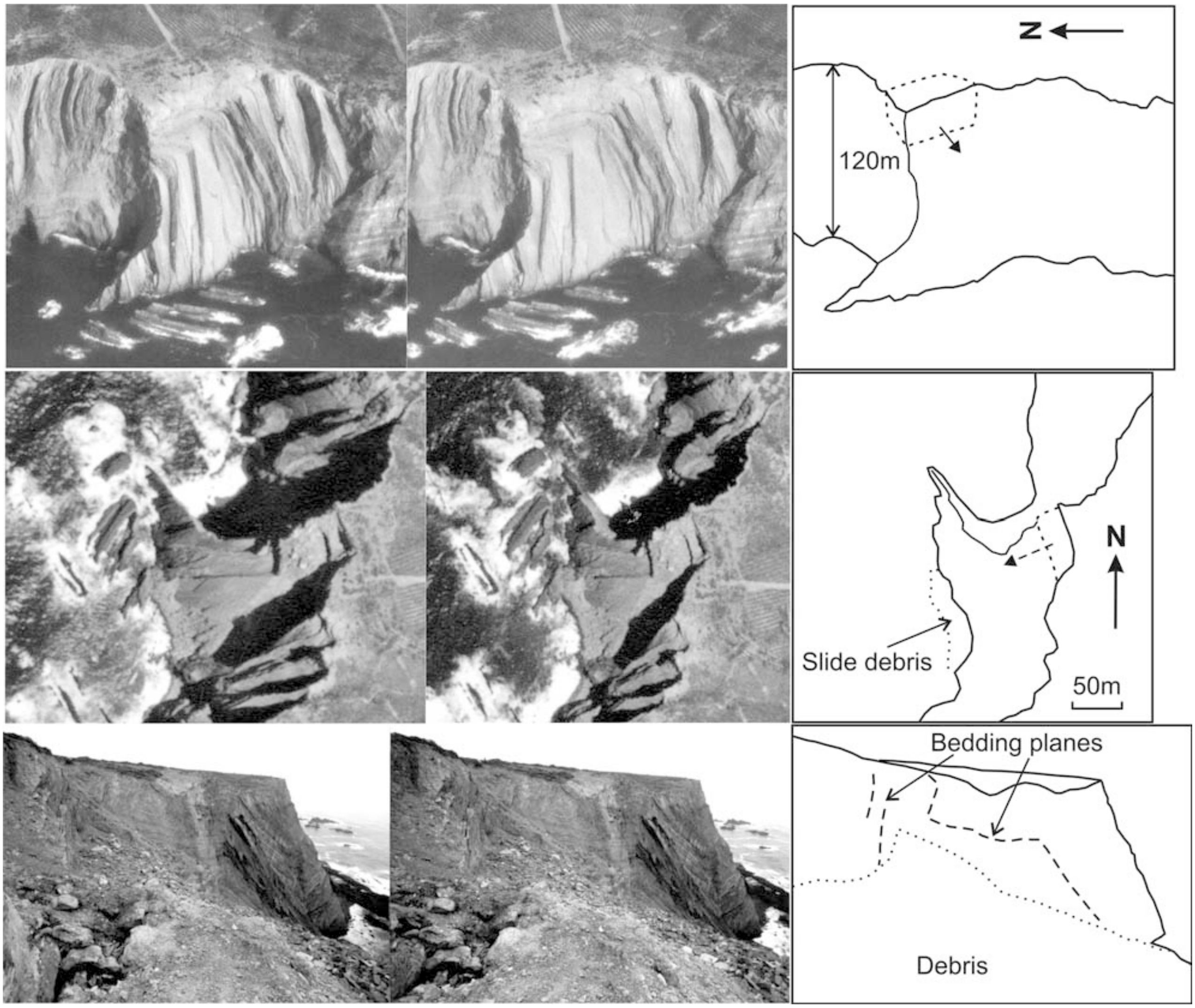

Fig. 13
Stereoscopic views of the Torre de Aspa site before (*top photos*, 1984) and after (*middle photos*, 1991) the failure. The *lower photographs* looking from the north show the missing slipped block

At the lower part of the cliff there are two planar landslides (Z2 and Z3, Fig. 7a), where the dip of the beds is only some 24°. The landslide located to the north (Z2) is limited by discontinuities trending NE to SW; a cross section is given in Fig. 8.

Along the lower part of the cliff there are large slipped blocks on bedding planes dipping seawards at 24° and also blocks likely to be moving, indicated by the open tension cracks (Fig. 9). The sliding planes are smooth, planar features such that the joint roughness coefficient (JRC) is near zero. As a consequence, friction mobilized during failure is likely to be close to the basic friction angle of the shales (Barton 1976). The only interruption to the smooth surface is an intersection of the beds by the slaty cleavage. Although this provides some slight undulation, the axes of the undulations are parallel to the bedding dip and to the block movements and hence do not have a significant influence on the sliding of the blocks.

The planar slide NNW of Arrifana

About 1 km NNW of Arrifana village, a planar landslide started between 1947 and 1958, with some further movement between 1958 and 1980. Since then the aerial photographs indicate it has remained stable. The slide affected rocks of the Brejeira Formation (Pedra da Carraça member). Here the local sequence includes at the base grey shale in 0.1 to 0.4 m thick beds alternating with thinner sandstones which are overlain by thicker beds of greywacke with interbedded shales. The shear plane is in the lower unit, which is moderately to highly weathered and dips to the SSW at 24°. Figure 10 shows a sketch of the area (Fig. 10a), the orientation of the discontinuity sets (Fig. 10b) and two cross sections of the slide (Fig. 10c and d). The structure of the slide is similar to the one described at Samouqueira, although the displaced block is higher. As seen in Fig. 11, the block mass has broken up along discontinuities, effectively at right angles to the cliff face. At the top of the slide there is a small creek which was intersected by the opening of the tension crack during the failure. Undoubtedly water from this creek flowed into the tension crack and contributed to the initiation of the slide.

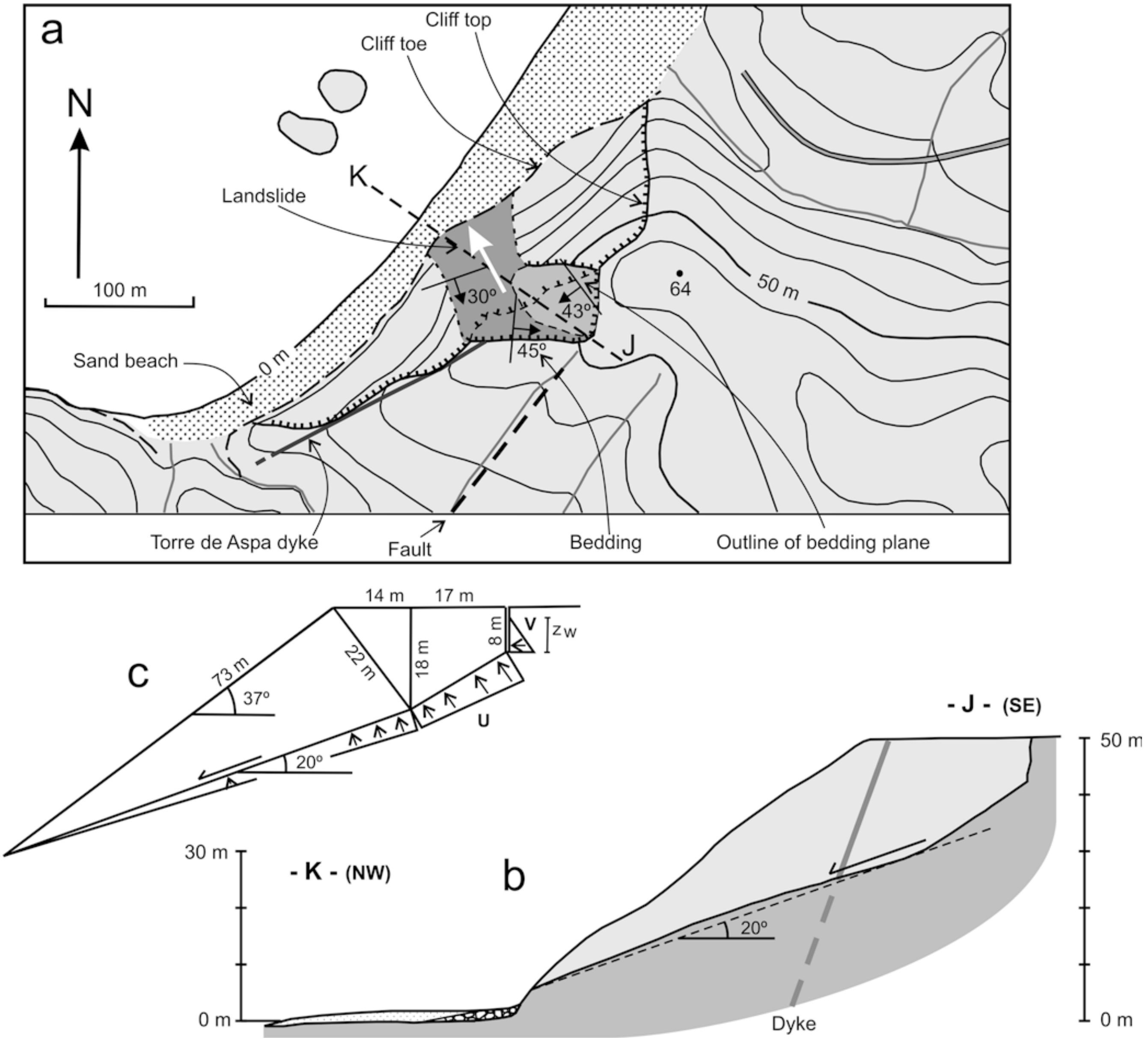

Fig. 14
Location of the Praia do Castelejo landslide site; **b** landslide profile; **c** dimensions used in the back analysis

The planar slide of Torre de Aspa

The aerial photographs indicate that between 1984 and 1991 a large planar landslide occurred approximately 0.5 km WNW from the geodetic monument of Torre de Aspa (Fig. 1). At the top of the cliff, some 120 m high, a large block 26 m wide x 64 m long (an area of 1,664 m^2) failed on a low-angled plane and displaced a volume of some 25,000 m^3 (Figs. 12 and 13).

The rocks affected by the movement belong to the Brejeira Formation and include alternating layers of moderately weathered shale and greywacke sandstone, light brown to light grey in colour. The folds have hinge surfaces dipping eastwards, with the upper fold of the open type with near straight limbs (Fig. 12 and 13). The failure surface developed at two levels along bedding planes. The rear portion of the failure surface again follows the bedding plane curvature (Fig. 12) and undoubtedly a tension crack would have developed prior to the main mass movement. Seawards, the dip steepens such that in most of the cliff it is approximately 60°. As a consequence, when the mass failure took place, the material was able to slip quickly from a height of approximately 90 m. The middle photograph in Fig. 13 shows some of the debris at the base of the cliff which has still not been removed despite the vigorous wave action at the cliff toe.

The planar landslide of Praia do Castelejo

A large planar landslide occurred between 1976 and 1980 in the cliff that forms the SE limit of the Castelejo beach (Fig. 14). The landslide affected the Brejeira Formation which consists of dark grey laminated shales arranged in beds up to 1 m thick. The shales are interbedded with greywacke sandstones between 0.1 and 0.2 m thick. The

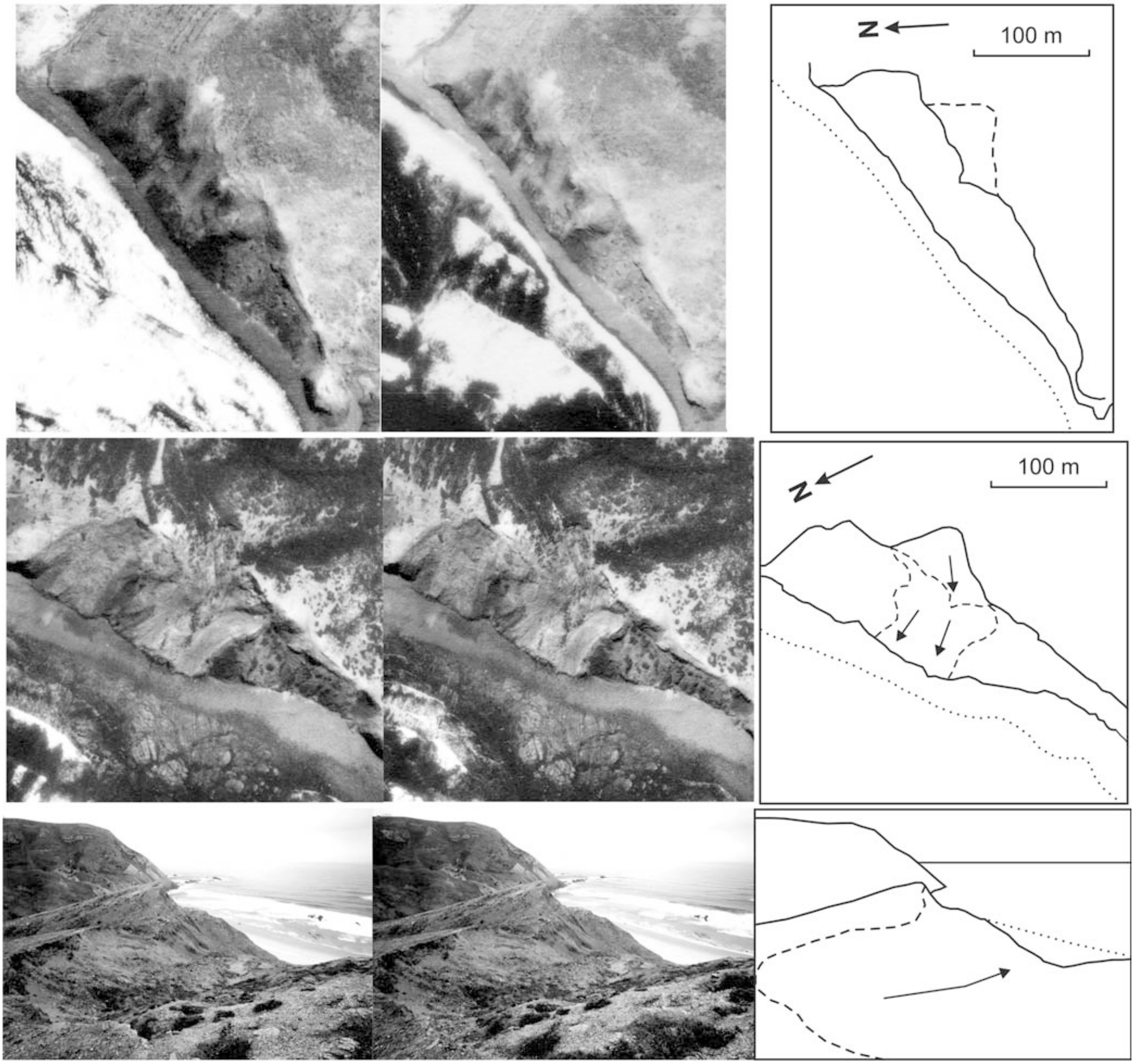

Fig. 15
Stereoscopic views of the Praia do Castelejo site before (*upper photos*, 1972) and after (*middle photos*, 1980) the failure. The *lower photographs* looking from the east show the southern edge of the landslide upper scarp

whole rock mass is moderately to highly weathered and cut by closely to very closely spaced discontinuities. The whole of the cliff face in this area has suffered dilation due to superficial decompression such that it is now partially covered by rock fragments.

The Palaeozoic rocks are highly folded and cut by two main faults, one striking NNE–SSW and the other ENE–WSW. The latter is filled by the Torre de Aspa Dyke, well exposed in the upper part of the cliff face (Fig. 14). Due to the complex geological structure it was not possible to separate clear discontinuity sets. The eastern part of the slide developed along a highly weathered shale layer which had a strike N126° and dipped to the SW at 43°. The western part of the failure surface cut across beds with a variable, generally SE–E dip. Thus, approximately half of the failure surface cut across the bedding planes, different from the conditions found in the previous examples of landslides described.

Figure 15 presents enlarged portions of the aerial photographs illustrating the cliff morphology before and after the failure and indicates the amount of information that can be obtained by comparing the photographs. In the 1972 photos, a ground deformation suggests a previous opening of tension cracks and a small amount of movement of the subsequently displaced rock mass. The 1980 photos show slope failure debris which appears to have formed a ridge at the lower part of the cliff, terminated towards the sea by a small scarp. The distal portion of the ridge was eroded by the sea before the summer of 1980 and

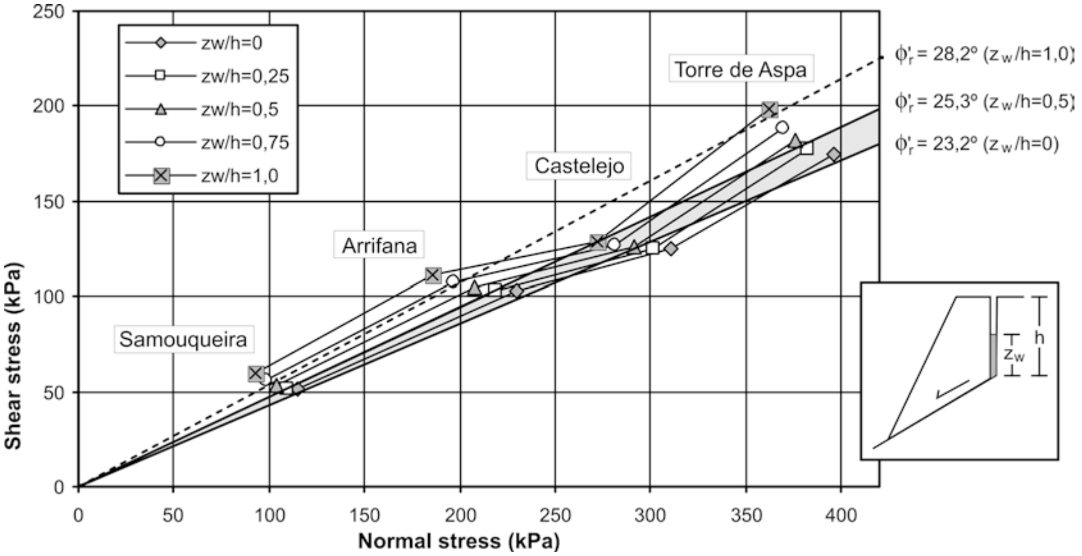

Fig. 16
Summary of back analysis results

the upper part has been progressively washed away; the present-day situation is shown in the lower photographs of Fig. 15.

Back analysis and discussion

It is clear from the above that the former three mass movements have taken place on natural sedimentary planes, in directions at right angles to the fold hinge (Arrifana and Torre de Aspa) and parallel to the fold hinge (Samouqueira). In the case of Castelejo, the failure surface developed partially along a bedding plane but also across bedding planes. Assuming that a negligible cohesion existed on the plane of movement, a back analysis was undertaken to establish the angle of friction at the time of failure.

In order to establish the geometry of the mass movements, crucial for a back analysis, measurements were taken from the aerial photographs (corrected following photogrammetry principles) and available maps. A number of field surveys were also undertaken using tape and compass and, in inaccessible areas, using an optical rangefinder distance meter with coupled clinometer, which provided an accuracy of ±5% of the measured distances.

In this rock sequence, the analyses were undertaken using the simple limit equilibrium method proposed by Hoek and Bray (1981):

$$\mathrm{W}\sin\Psi + \mathrm{V} = \mathrm{c}\cdot\mathrm{A} + (\mathrm{W}\cdot\cos\Psi - \mathrm{U})\cdot\tan\varphi \qquad (1)$$

where

$$\mathrm{V} = {}^{1}\!/_{2}\gamma_{\mathrm{w}}\cdot \mathrm{z}_{\mathrm{w}}^{2} \qquad (2)$$

$$\mathrm{U} = {}^{1}\!/_{2}\gamma_{\mathrm{w}}\cdot \mathrm{z}_{\mathrm{w}}\cdot\mathrm{A} \qquad (3)$$

$$\mathrm{W} = \gamma\cdot\mathrm{A}\cdot\mathrm{H} \qquad (4)$$

and

W is the weight of the block;
Ψ is the slope of the sliding plane;
c is cohesion;
γ is the unit weight of the rock;
γ_w is the unit weight of water;
z_w is the water height at the tension crack;
A is the area of the base of the sliding block;
ϕ is the friction angle;
H is its average thickness measured at right angle to the base.

A number of calculations were made for each individual slide, assuming that cohesion at failure was negligible and that the failures occurred at a factor of safety equal to 1. Clearly the water pressure in the rock mass would depend on the height of water in the individual tension cracks, which would provide not only a disturbing force but also, by passing beneath the block, an uplift force. The friction angle ϕ was obtained by the following formula:

$$\phi = Arc\tan\left(\frac{W\cdot\sin\Psi + V - c\cdot A}{W\cdot\cos\Psi - U}\right) \qquad (5)$$

As it was not possible to know how much water could have existed in a tension crack, it was decided to undertake analyses assuming the tension crack was empty, quarter full, half full, three-quarters full and completely full. The result analyses of the four slides, with the five water level conditions are given in Fig. 16. In the case of Samouqueira, Arrifana and Torre de Aspa, it is likely that the water pressures did not exceed half the height of the tension crack as pre-failure movement would have removed some of the confinement. In the case of the Praia do Castelejo landslide, it is likely there was better lateral confinement (Fig. 15) and hence the water could have risen further up the tension crack.

The narrow range of friction angles computed by the back analysis (23–25°) are consistent with the failure conditions and the field estimates of the friction angles. This aspect is particularly well illustrated at the Samouqueira site, where the failure planes that developed along the bedding are very smooth and hence likely to be at or near the residual/

ultimate state. On the other hand, with the Castelejo slide, approximately half of the failure surface cut across the shale beds and the back analysis provided similar data, suggesting that the low friction angles reported may be due to the particular weathering conditions present along the coast. Indeed, these values are somewhat lower than those usually reported in the literature for rocks of similar composition and stratigraphic position. It is of note, for instance, that Kennard et al. (1967) reported triaxial tests on the Coal Measure shales at the Balderhead dam site in the UK which gave ϕ' values of 33° for the slightly weathered rock and 26° for weathered rock. Values of $\phi'=30°$ are reported by Rocha (1976) for shales from Portugal, while Barton (1976) and Hoek and Bray (1981) suggest a general value of $\phi'=27°$. During the field surveys, no coal seams were found which might explain the lower friction values computed.

It should be noted that Anderson and Cripps (1993) found that the shear strength of Carboniferous mudrocks was lowered significantly related to the chemical changes that occur on exposure, particularly the release of sulphuric acid which affects the integrity of the permeable horizons through which it moves. The shales of Brejeira Formation present along the Algarve coast are also dark mudrocks and hence likely to contain pyrite. In such rocks the possibility of aeration, bacterial activity and decomposition related to the movement of acid waters could account for lower values than might otherwise be anticipated in a normal desk study. The action of this weathering process may also be favoured by the dry climate of the region, that causing quick and frequent wetting and drying cycles conducive to rapid shale degradation.

Conclusions

The Algarve coastline, which contains cliffs up to 120 m high, consists mainly of Palaeozoic strata in which shales frequently form a weaker lithology. This has resulted in the formation of smooth/weaker horizons on which extensive mass movement has taken place, particularly where the rocks are dipping seawards at various angles as low as 22–25°. The research has used a series of aerial photographs from which it was possible to locate landslide activity in space and time. Unfortunately it is not possible to identify exactly when the slips took place and hence relate the period of mass movement to cumulative and/or specific rain events.

The paper discusses four specific landslides and notes that in three of these it is unlikely that water pressures accumulated in rear tension cracks reached more than half their height. At Praia do Castelejo, however, the lateral confining conditions meant that more water was retained in the developing rear tension crack.

Back analyses were undertaken which showed that for three of the slides (Samouqueira, Arrifana and Torre de Aspa) the friction angles were similar. A likely failure envelope through the calculated points indicates that where no water was present in the tension crack a ϕ'_r value of approximately 23° must have been present for the failure to take place, assuming no cohesion. As the Castelejo slide partially cuts across bedding, it is likely there was a higher water level in the tension crack. The low friction angle may be accounted for by the smoothness of the failure planes due to decomposition/weathering of the lithology at this zone. In addition, weathering resulting from water containing weak sulphuric acid as a consequence of bacterial action on the iron pyrite present in the mudrock strata along this coastline could also have played a part.

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References

Anderson WF, Cripps JC (1993) The effects of acid leaching on the shear strength of Namurian shale. In: Cripps JC, Coulthard JM, Culshaw MG, Forster A, Hencher SR, Moon CF (eds) The engineering geology of weak rock. AA Balkema, Rotterdam, pp 159–168

Anonymous (1947–1992) Anuário Sismológico de Portugal (in Portuguese). Instituto Nacional de Meteorologia e Geofísica, Lisbon

Barton NR (1976) The shear strength of rock and rock joints. Int J Rock Mech Min Sci Geomech Abstr 13:255–279

Barton NR, Choubey V (1977) The shear strength of rock joints in theory and practice. Rock Mech 10:1–54

de Freitas MH, Watters RJ (1973) Some field examples of toppling failure. Geotechnique 23:495–514

Goodman RE, Bray JW (1976) Toppling of rock slopes. In: Proc Specialty Conf on Rock Engineering Foundations and Slopes, ASCE, Boulder, Colorado, vol 2, pp 201–234

Goodman RE, Kieffer DS (2000) Behavior of rock in slopes. J Geotech Geoenviron Eng ASCE 126:675–684

Hoek E, Bray JW (1981) Rock slope engineering, 3rd edn. Institution of Mining and Metallurgy, London

Kennard MF, Knill JL, Vaughan PR (1967) The geotechnical properties and behaviour of Carboniferous shale at the Balderhead Dam. Q J Eng Geol 1:3–24

Manuppella G (1992) Carta Geológica da Região do Algarve, na escala 1:100 000 (in Portuguese). Serviços Geológicos de Portugal, Lisbon

Marques FMSF (1994) Sea cliff evolution and related hazards in Miocene terranes of Algarve (Portugal). In: Proc 7th Int Congr IAEG, 5–9 Sept, Lisbon, vol 4. AA Balkema, Rotterdam, pp 3109–3118

Marques FMSF (1997) The sea cliffs of the coast of Algarve. Dynamics, processes and mechanisms (in Portuguese). PhD Thesis, University of Lisbon

Pires HO (1989) O Clima de Portugal. Alguns aspectos do clima de agitação marítima de interesse para a navegação na costa de Portugal (in Portuguese). Instituto Nacional de Meteorologia e Geofísica (INMG), Lisbon, 34 pp

Ribeiro A (1983) Structure of the Carrapateira Nappe in the Bordeira area, SW Portugal. In: Sousa MJL, Oliveira JT (eds) The Carboniferous of Portugal. Mem 29. Serviços Geológicos de Portugal, Lisbon, pp 91–97

Ribeiro A, Oliveira JT, Ramalho M, Ribeiro ML, Silva L (1987) Carta Geológica de Portugal, na escala 1:50 000. Notícia Explicativa da folha 48-D, Bordeira (in Portuguese). Serviços Geológicos de Portugal, Lisbon

Rocha M (1976) Mecânica das Rochas (in Portuguese). Laboratório Nacional de Engenharia Civil, Lisbon

Silva JB, Oliveira JT, Ribeiro A (1990) Structural outline. In: Dallmeyer RD, Martinez Garcia E (eds) Pre-Mesozoic geology of Iberia. Springer, Berlin Heidelberg New York, pp 348–362

Xian-Qin H, Cruden DM (1992) A portable tilting table for on-site tests of the friction angles of discontinuities in rock masses. Bull Int Assoc Eng Geol 46:59–62