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# Coastal Rock Cliff Erosion by Collapse at Puys, France: The Role of Impervious Marl Seams within Chalk of NW Europe

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**ABSTRACT**

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Analysis of a coastal chalk cliff collapse at Puys, on the NW coast of France, illustrates the combined role of lithological discontinuities within chalk (marl seams and hardground levels) and groundwater circulation on the dynamic and the triggering factors of this collapse. The Puys rockfall, witnessed on the 17th May 2000, was polyphase, with at least two clear collapse events and involved a displaced rock volume of about 85 000 $m^3$, which has induced a maximum cliff retreat of 12.5 m. Deduced from on-site examination of the deposit, completed by stratigraphical dating, the resulting collapse forms a debris-avalanche runout within which the original stratigraphy is retained. On-site structural analysis of the scar suggests an overall mechanism of sliding characterized by an outward tearing process in the upper part of the cliff and a shearing mechanism in its lower part. Heavy rainfall is suggested as the main triggering factor for this collapse. The suggested hydrogeological conceptual model consists of a multilayered aquifer, controlled horizontally by impervious marl seams and hardgrounds and vertically by pre-existing joint systems. Concentration of stresses by means of local water overpressure may thus occur on marl seams. This process is sustained by a mechanical conceptual model, which indicate rock mass displacements and local stress concentration with high water table.

**ADDITIONAL INDEX WORDS:** *Coastal rock cliff, collapse, chalk, marl seams, groundwater, conceptual models.*

## INTRODUCTION

A European scientific project, ROCC (Risk Of Cliff Collapse) has been launched in order to identify the critical parameters leading to coastal cliff collapses in chalk weak rock, and to evaluate the impact of those parameters and their interaction in such rock mass movements. Chalk is exposed along either side of the English channel. The ROCC project is focused on Upper Normandy and Picardy regions in France and on East-Sussex in the UK.

The chalk cliffs along the Channel coast are currently retreating at a mean rate of up to 0.7 m/year (MAY, 1971 ; COSTA, 2000). However, the erosion is not constant over time, but occurs by sudden collapses that may induce cliff retreats 10–20 m deep in one event. The conditions governing coastal cliff stability are controlled by both continental and marine processes. The aim of this paper is to evaluate the role of groundwater and lithology in the initiation of cliff collapse. The evolution of cliffs from stability toward failure depends on the structural, mechanical and hydraulic characteristics of the rock mass and its response to external parameters, of continental origin (meteorological conditions, changing stresses within the rock mass) and of marine origin (wave and tide action, presence of shingle, shore platform morphology). These agencies lead to the opening of fractures and deterioration of the rock material within the cliff.

We report herein (1) an account of a recent rockfall witnessed by the authors at Puys (Normandy, France), (2) a structural analysis of both the fresh scar and the associated deposit indicating the collapse dynamics, (3) an interpretation of the collapse dynamics deduced from geological data, (4) a discussion of the mechanical and hydrogeological conceptual models to illustrate the role of water and lithology in triggering collapse, (5) an overview of other collapses occurring along coastal chalk cliffs in NW Europe.

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## GEOLOGIC BACKGROUND

Puys is located near Dieppe (Normandy) on the eastern side of the English channel, where a hanging valley named "Camp de César" (oriented N 80°E) meets the coast (Figure 1). The cliff exposures occur in part of the Anglo-Paris Basin Upper Cretaceous Chalk, which ranges from the Cenomanian (98 Ma) to lower Campanian (80 Ma) in age (MEGNIEN et MEG-

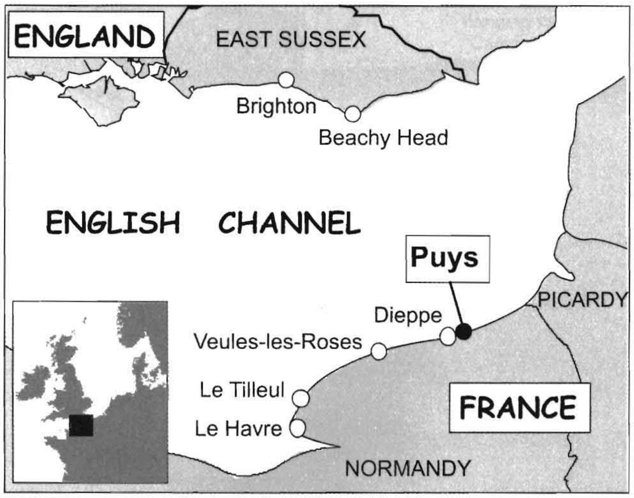



Figure 1. Location of the study area, along the coast of the English Channel.

NIEN, 1980 ; MORTIMORE and POMEROL, 1987). At Puys, horizontally bedded Turonian-Coniacian Chalk, with widely spaced fractures, extends along a vertical cliff section 60 m high, facing north-west, and exposes a lithostratigraphic succession from Lewes Nodular Chalk Formation to Seaford Chalk Formation, using the scheme devised in southern England (MORTIMORE, 1983). This classification is based on the physical properties of the chalk and is well adapted for engineering purpose and for understanding the mechanical behaviour of a rock mass during a cliff collapse.

From the base to the top of the Puys cliff, the lower 30 m are composed of Lewes Nodular Chalk Formation (Upper Turonian to Middle Coniacian) and the upper 30 m are composed of Seaford Chalk Formation (Upper Coniacian). Lewes Chalk is identified by the presence of key-lithostratigraphic markers located in the lower part of the cliff: the Breaky Bottom Flints, the Lewes Marl, and the Navigation to Light Point hardgrounds. Above, Seaford Chalk is recognized by the occurrence of numerous flint bands, including the prominent Seven Sisters flint band near the top of the cliff. The boundary between Seaford and Lewes Chalk is marked by the Shoreham Marl 2 (Figure 2). Lewes Chalk is a nodular yellowish, coarse chalk, including soft, marly bands and nodular hardgrounds, with regular flint layers, whereas the Seaford Chalk is a white chalk from very soft to medium hard, with numerous conspicuous flint bands (MORTIMORE *et al.*, 1990). The Chalk is thinly covered by brown, Plio-Quaternary sediments.

## THE PUYS ROCKFALL, 17th MAY 2000

### Collapse Timing

The collapse was observed the 17th May 2000, at 10:30 a.m., at high tide, with a north-westerly (N290°E) wave direction, and a strong wind (F9) from the SW. The authors heard the fall and witnessed a grey dusty cloud of chalk at the base of cliff as they came within view (Figure 3A). From a photograph, an initial topographic profile of the cliff and basal deposit were drawn (labelled C1 on the cliff and D1 for the deposit on figure 3A). About one hour later, a second fall occurred, changing the topographic section of the cliff and significantly increasing the size of the basal deposit.

A comparison of two successive photographs taken an hour apart provides some indications about the cliff profile evolution. Just before the first photograph, the deposit D1 formed by collapse of part of the C1 area. Then, the remainder of the C1 area collapsed to produce the D2 deposit seen on the second photograph. The back scar is arcuate, as shown on figure 3B, with the two headland areas C2 and C2' bounding a scalloped area (C3). The second deposit, labelled D2, clearly overlies the first one (D1). The rockfall was thus polyphase, with at least two clear collapse events.

### Volume Estimation

Based on on-site measurements of the collapsed area (scar and beach platform), an estimation of the global volume of rock involved is proposed. The deposit is lobate shaped, with a maximum of 120 m length and 120 m wide. At the base of the cliff, the thickness of the deposit reaches 15 m, and decreases from the cliff foot to the distal part of the deposit. The gently decreasing slope of the deposit (Figure 3A) allows us to assume an average thickness of about 7.50 m. The maximum volume of rocks involved during the two stages of failure is thus 108, 000 $m^3$ (120m × 120m × 7.50m). However, the real volume of displaced rocks is always lower than the estimated volume, due to the large amount of void space between blocks. The actual volume can be estimated using a bulking density factor. A bulking factor of 16% has been observed in Lewes Chalk earthworks where only light or no compaction is used in landfill (LORD *et al.,* 2002). In the Puys collapse, an overall bulking factor for the Lewes and Seaford chalks of 20% is assumed. This gives a displaced rock volume of about 85 000 $m^3$. Given the height of the cliff (60 m height) and the width of the back scar (100 m wide) (Figure 2), we assume that the Puys rockfall has induced a maximum cliff retreat of 12.5 m during this event, which is composed of at least two phases of failure. This value is consistent with retreat observed at the cliff top, deduced from the analysis of the successive photographs (Figure 3A).

### On-Site Scar Examination

The deposit and scar of the rockfall have been measured in detail (Figure 2). The scar consists of several subvertical planes, with slightly different azimuths, roughly parallel to the cliff orientation. These planes do not correspond to a well-developed pre-existing fracture system.

Along the base of the scar, from SW to NE, several zones have been identified (Figure 2). Zone 1: this zone is outside the scar and shows no evidence of collapse. It corresponds to the base of the C2 headland. Zone 2: this 4 m wide zone corresponds to the SW limit of the scar. It is characterized by a series of closely spaced vertical planes delineating random narrow steps. There is no clear striation but the high density of the vertical structures, giving the rock a foliated fabric,

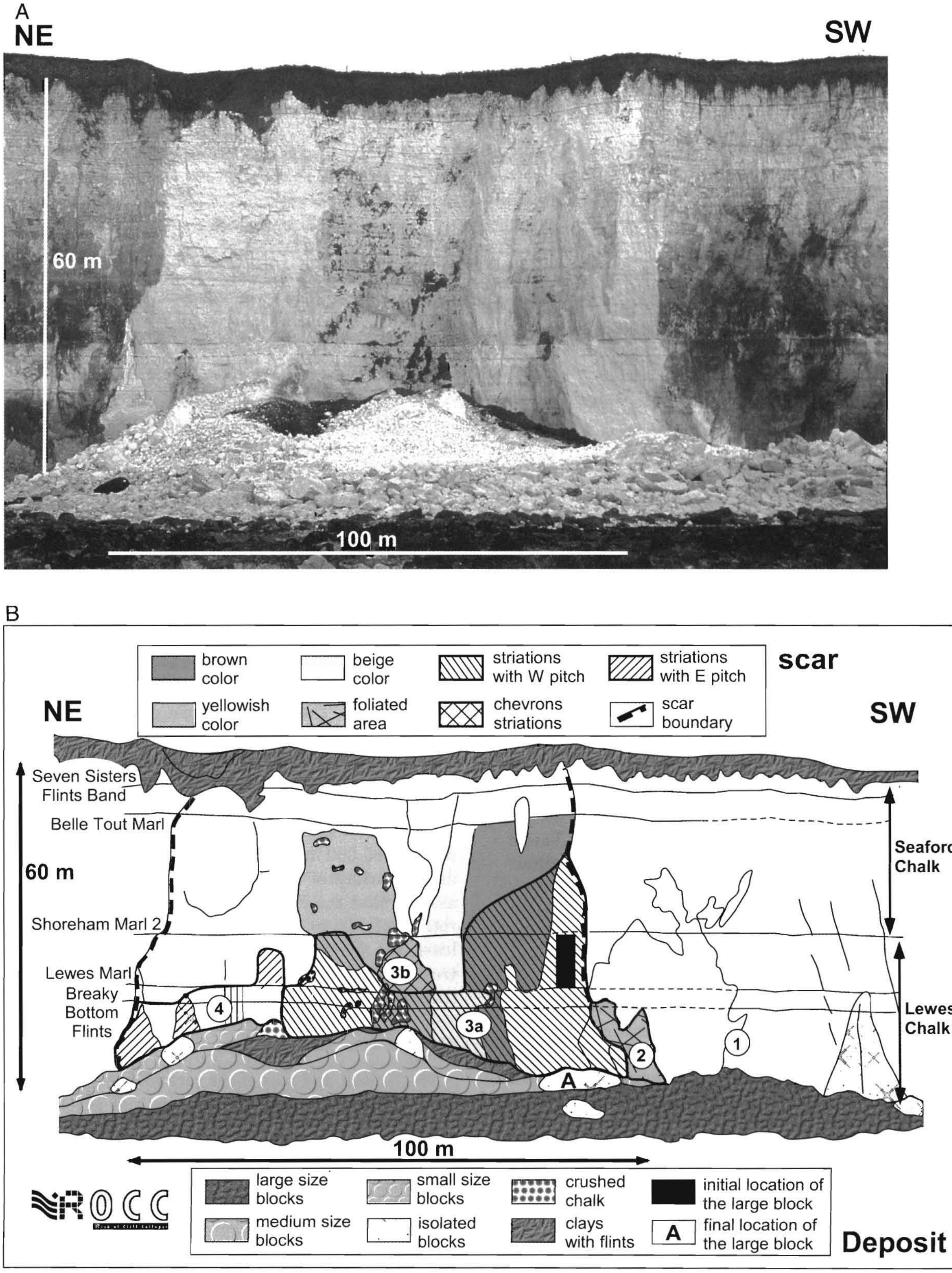



Figure 2. (A) Photograph of the Puys scar along the cliff face and deposit on the beach platform. (B) Detailed structural map of the Puys scar along the cliff face and deposit succession on the beach platform, deduced from field observation and Figure 2A. Chalk units are deduced from the reported marl seams, which are visible in the field. Numbers 1 to 4: zonation index (see explanations in the text).

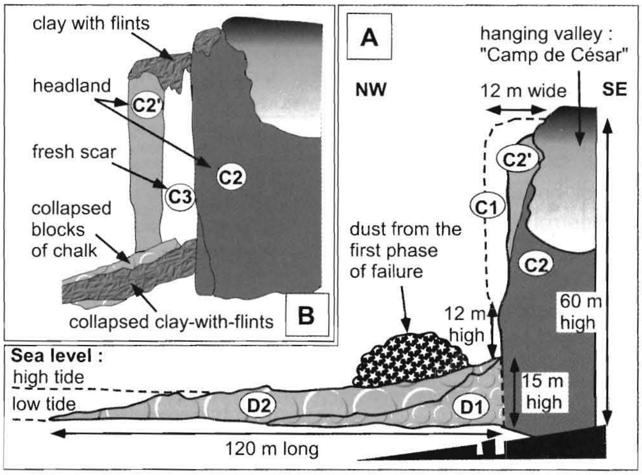


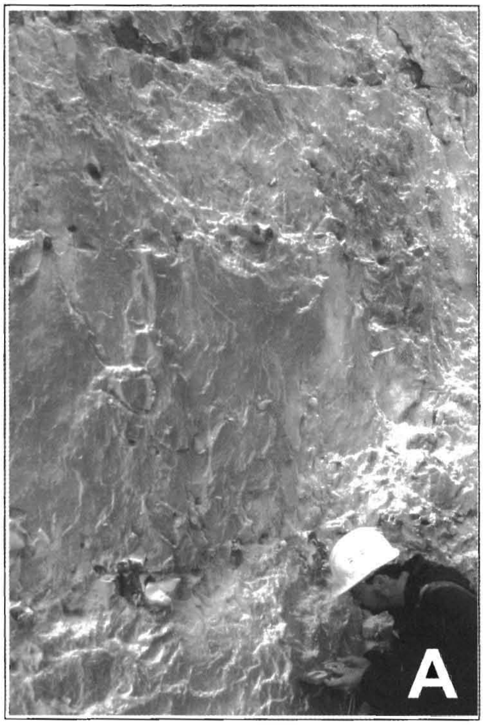

Figure 3. Topographic sections of the Puys cliff, deduced from several successive photographs. (A) Dashed line: initial position of the cliff (C1) during the first phase of collapse witnessed by a dusty cloud of chalk (stars) and D1 deposit. Grey area: final position of the cliff, after a second phase of failure, evidenced by the deposit D2. (B) A different view angle of the last cliff section, which shows the Puys scar (C3) between the two headlands C2 and C2′.

probably resulting from shearing of the chalk (Figure 4 A). Zone 3a: corresponds to the major collapsed sheared zone over a horizontal distance of 67 m. There is a series of nearly-vertical shear planes oriented dominantly N60°E, dipping 85°N and locally 100°E. The occurrence of strong slickensides and striations plunging 50°SW indicates a normal slip movement but with a significant horizontal component (Figure 4 B). Zone 3b: this area is located just above the NE termination of zone 3a, and is characterized by the superimposition of two generations of striations describing a "chevron" pattern. Zone 4: The structural features of this 29 m wide zone (plane orientation, striations, damaged zones, crushed rock) are similar to those observed in the previous zone, except that the pitch of the striations is oriented 70°E. The NE edge of the scar is defined by a partly striated plane.

A dominant sheared area dipping NW is located above Shoreham Marl 2 in the western part of the scar (Figure 2). In the upper part of the cliff as a whole, the lack of striations indicates the absence of shearing and consequently the occurrence of a tensional mode of fracture, suggesting a tearing process.

## On-Site Deposit Examination

The lobate deposit consists of chalk blocks of various sizes. The total length of the deposit (L = 120 m) corresponds to twice the cliff height (H = 60 m). The blocks form a succes-



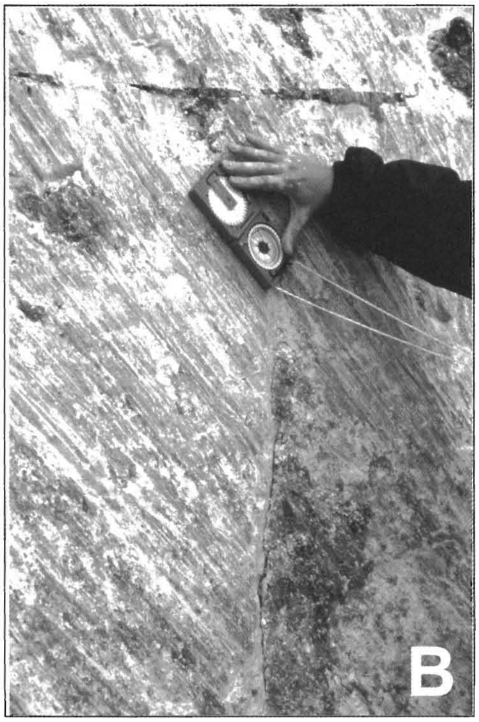




Figure 4. Photographs of typical structural features of the Puys scar. (A) Detail of the zone 2 of the scar (location on Figure 2). Foliated fabric results from shearing of the chalk. (B) Detail of the zone 3a of the scar (location on Figure 2 B). Strong slickensides and striations on the nearly-vertical shear plane. The color of these shear planes varies from white to grey and brown probably according to the percentage of crushed chalk. Within some subzones, crushed rock is visible on small surfaces indicating accumulation of stresses (Figure 2 B). Locally, there are small-scale tension fractures, which are genetically associated with the oblique-normal shear movement. Locally, some flint layers have been truncated and striated.

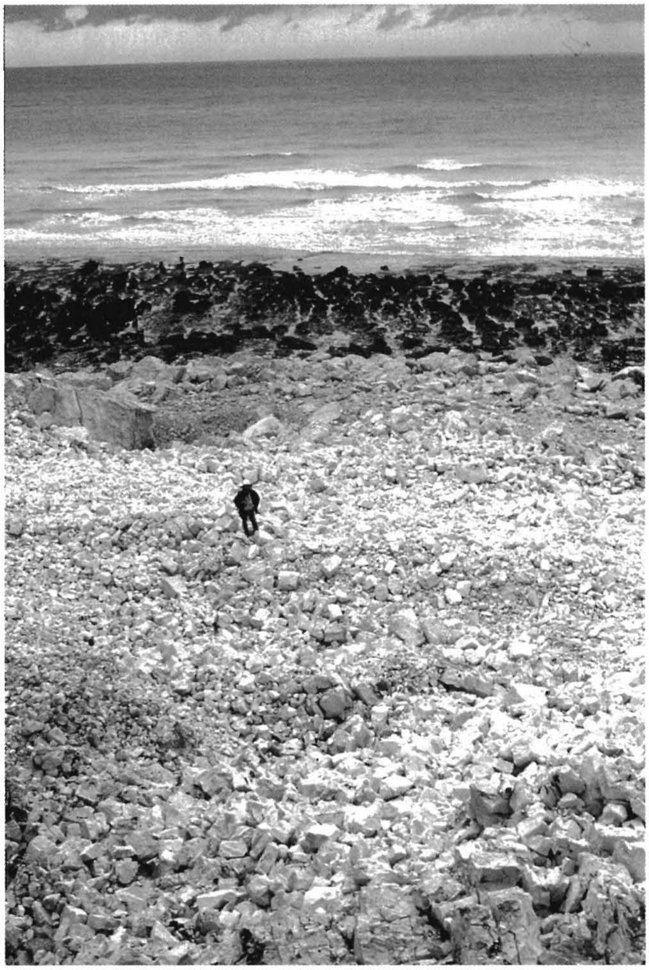


Figure 5. Photograph looking from the cliff to the sea, showing deposit of the debris-avalanche, made of chalk blocks which compose successive transverse ridges, the beach platform, and the sea. A 20 m long block is located behind the person in the left part of the photograph.

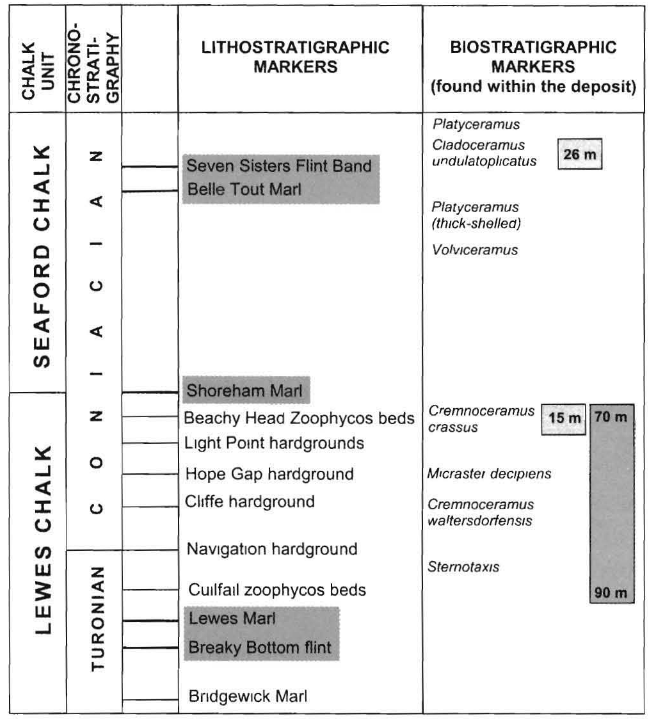



Figure 6. Stratigraphic column along the Puys scar, deduced from field observation (Figure 2) and in situ determination of key-marker macrofossils within the deposit (square with light grey), and within the 20 m long block lying on the deposit (rectangle with dark grey). Numbers indicate the distance of these fossils within the deposit from the base of the cliff (0 m) toward sea. Lithostratigraphic markers which are visible on Figure 2 B are indicated in grey color and thicker lines.

sion of 5 landward arcuate ridges, with well sorted block-size. Block size is roughly equivalent within each ridge, whereas each ridge presents a variation of block size from land (centimetre size) to sea (metre size) (Figures 3 and 5).

Moreover, a large entire block, 20 m long, locally striated, is located in the middle part of the deposit, at a distance of 70 m from the base of the cliff, and appears to be oriented with the stratigraphically upper part of the block closest to the cliff. The detailed stratigraphy of this block was determined from the occurrence of numerous fossils and characteristic lithologies, which reveals the original location of the block in the cliff. From the sea toward the land, this block contains the Cuilfail Zoophycos Beds, Navigation Hardground, marking the Turonian-Coniacian boundary, key marker macrofossils including the bivalve *Cremnoceramus waltersdorfensis,* below and within the Cliffe Hardground, and the Hope Gap Hardground with *Micraster decipiens* and large *Cremnoceramus crassus* from the top of the block in the Beachy Head Zoophycos Beds (Figure 6). This block comes from the Upper Lewes Chalk (MORTIMORE and POMEROL, 1987). It was initially located between 20 and 40 m from the base of the cliff, in the western part of the scar (Figure 2).

Other large bivalve fossils including the thick-shelled inoceramids *Platyceramus* were found in the collapse debris from the Seaford Chalk at 15 m and 26 m from the cliff base (Figure 6). These fossils were initially located towards the top of the cliff, above and below the Seven Sisters Flint Band (Figure 2).

## Dynamic of Collapse Deduced from Geological Observations

At Puys, the retreat of the cliff, estimated at up to 12.5 m, was polyphase with a minimum of two collapse events. The scar reveals a lateral zonation in terms of structural pattern, and is organised in two distinctive compartments: a dominant westward zone bearing westward plunging striations and an eastern zone bearing eastward plunging striations ; these are separated by an interference zone showing two generations of striations (chevron pattern). This suggests two episodes of divergent shearing that fit quite well with the two independent phases of collapse deduced from visual observations. From the extent of the southwest striated surface, we assume that the westward-plunging movement post-dated the eastward one. The scar also reveals a vertical zonation. Only the base of the scar is slickensided and the top shows a lack of striations that suggests outward tearing. The sliding of chalk blocks is consistent with structural features indicating a shearing process. These are: (1) a large-scale slickensided shear plane, bearing marked striations due to gouging by flints during the gravitational shearing movement. (2) small-scale fractures and minor scars that are observed locally. Their organisation is compatible with the overall kinematics of the sliding, as is their association in space and time with the major plane of the striations. (3) local damaged zones showing brecciated and crushed chalk that suggest stress concentration prior to shearing. (4) the foliated, sheared chalk that can be interpreted as stress accommodation of the slide on the basal westward border of the scar. (5) a lack of major pre-existing fractures, suggesting that the oblique gravitational shearing movement initiated on an induced plane of failure.

Chalk blocks from the top of the cliff now lie in the proximal area of the deposit at the bottom of the cliff, whereas chalk blocks from the middle part of the cliff were transported toward the distal part of the deposit. Based on the macrofossils found in the blocks, the oldest chalk units are systematically farther from the bottom of the cliff and have undergone the longest runout. This suggests an absence of toppling process, but rather a sliding dynamic. However, the lack of striations in the upper part of the scar indicates no physical shearing between blocks. The outward tearing mechanism in the upper part of the cliff and the shearing mechanism in its lower part are not incompatible with an overall sliding mechanism. The upper part of the cliff is made of Seaford Chalk which is typically more vertically jointed than the underlying Lewes chalk. Outward movement on steeply inclined surfaces in the Lewes Chalk has thus detached the overlying Seaford chalk along vertical surfaces without shearing. Shoreham Marl 2, representing the lithostratigraphic boundary between Seaford and Lewes Chalks, is also roughly the limit between the tearing off and shearing areas, visible on the scar surface (Figure 2).

The H/L ratio is an indicator of the mobility of landslides (HEIM, 1932). In massive sedimentary rocks, H/L ratios generally range between 0.08 and 0.58 and an H/L ratio of less than 0.6 indicates a long run-out landslide (HSÜ, 1975 ; UI, 1983). At Puys, the ratio is 0.5, which is not significantly lower than 0.6, and therefore the H/L ratio alone cannot be used to suggest a large debris avalanche deposit with long runout, where volume of involved rocks may reach in the millions of cubic meters. However, the lobate-shape organisation of the deposit and the occurrence of the largest blocks in the most distal landward arcuate ridge do suggest a debris-avalanche deposit type (MOORE *et al.*, 1989).

## DISCUSSION

### The Triggering Factor of Collapse

As noticed by HUTCHINSON (1969), all deep-seated coastal landslides in the chalk of Folkestone Warren (UK) recorded during the past two centuries are shown to have occurred within the period of seasonally high ground-water levels. At Puys, during both the months of April and May 2000, rainfall level was particularly high, with 143 mm in April and 134 mm in May, whereas the monthly average (over 30 years) is 55 mm and 58 mm respectively. Damaging floods occurred in the Upper Normandy region three weeks before the Puys collapse. There were two periods of intense rainfall during the third and fourth weeks of April and the second week of May, with mean rates of 21 and 28 mm/day respectively. From a study of pluviometric data and landslide events, BELL and MAUD (2000) assume that major landslides are associated with rainfall events with intensities in excess of 20% of the mean annual precipitation. At Puys, during April and May 2000, calculations indicate an excess rainfall of 260% and 230% of the mean annual precipitation respectively.

Springs of non-saline water were observed on the shore platform in front of the scar face at about 130 m from the bottom of the cliff. The largest of these springs flows upward from an open, nearly-vertical, joint trending 75°E, where the average joint spacing is 1 m. As noticed by HEADWORTH (1978) and MORTIMORE (1993), water may flow downward through subvertical joints abuting against horizontal marl seams, which act as aquicludes. At Puys, the Bridgwick Marl (within the Lewes Chalk) is located just below the shore platform and is thus able to support such a type of water circulation. This illustrates a scheme of horizontal circulation which may also occur along the Shoreham and Lewes Marls and hardground levels, within the cliff.

### Hydrogeological and Mechanical Conceptual Models

At Puys, unfortunately, no hydrogeological measurements (piezometric levels) are available. However, it is commonly accepted that chalk porosity varies with stratigraphy, due to lithological control, fracture style, and karstification (PRICE, 1987). MORTIMORE *et al.* (1990) suggest that Seaford chalk presents a high aquifer potential, whereas Lewes chalk has a low aquifer potential, except on faults.

No major faulting, pre-existing jointing or karstification, was observed in the part of the cliff face that failed. However, artesian springs were observed and heavy rainfall had occurred two weeks before the collapse. It is suggested that rain water flowed downward through the more porous Seaford Chalk (MORTIMORE *et al.,* 1990) until reaching the Shoreham Marl, which is the first significant marl seam below the ground surface (Figure 2 B).

A preliminary mechanical modelling of the instability of coastal chalk cliff was carried out with a semi-probabilistic 2D model, UDEC (Universal Distinct Element Code) (CUNDALL and HART, 1985). Data inputs are geomechanical characteristics of the chalk and its fracture content, which was collected from three representative sites selected along the chalk cliffs of NW France and composed of Seaford and Lewes Chalk, with various fracture patterns (the site of Puys was not included in this preliminary modelling procedure). The influence of a high water table was tested, with a maximum value at the cliff top level (complete saturation of fractures within chalk) and a minimum value on the beach platform, corresponding roughly to the sea level.

Even though at Puys the geological conditions differ slight-

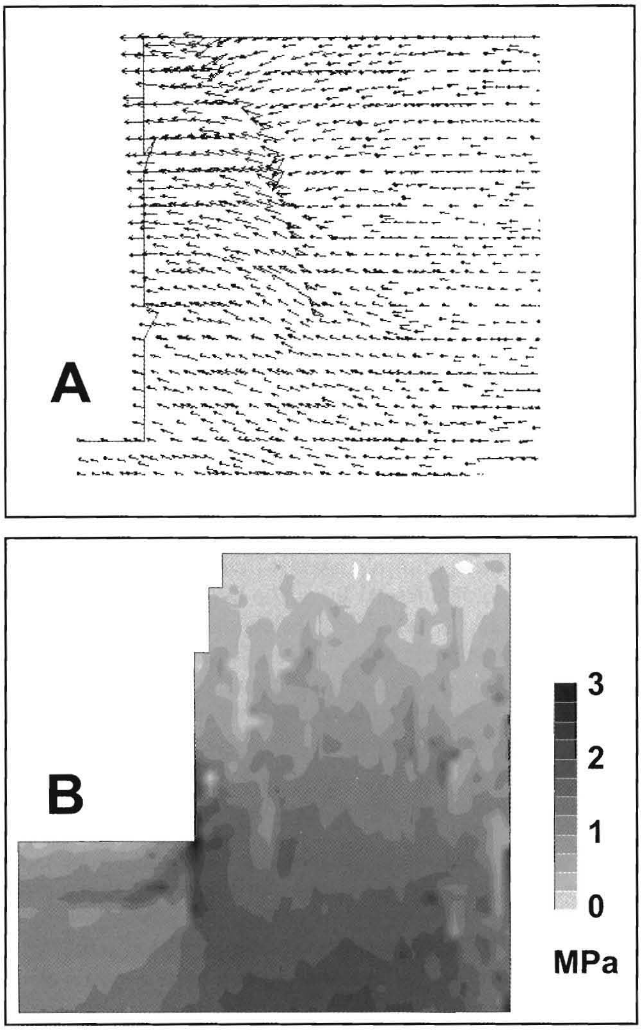



Figure 7. Results of the mechanical conceptual modelling, using UDEC (Universal Distinct Element Code). The high water table generates two phases of deformation within the rock mass. (A) First phase: visualization of a vertical 2D section of the semi-probablistic model, perpendicular to the cliff face. Dots show small displacements (less than 1 cm) within the rock mass, which inflates upward and outward, giving a displacement toward the cliff face. (B) Second phase: visualization of the same 2D section of the cliff, in terms of stresses (MPa: Mega Pascal). Blocks readjust positions due to the initial instability created during the previous stage, giving rise to a settlement at the base of the cliff.

ly from those considered during the preliminary mechanical modelling procedure, some broad similarities can be identified. The high water level generates two phases of deformation within the rock mass with first, an upward and outward inflation and, second, a settlement at the base of the cliff (Figure 7). The application at Puys of these general mechanical calculations could explain some similarities between the model and the behaviour of the chalk observed on the Puys failure. The minor horizontal displacement affecting the whole cliff could have occurred at Puys. This displacement being greater at the top of the cliff than at the bottom, this may have led to the observed detachment of the upper part of the cliff. Such small-scale displacement could correspond to the initial phase of failure. The accumulation of stresses at the base of the cliff shown in the model fits quite well with some geological observations, such as crushed, brecciated rocks and shearing zones (Figure 2 B).

The available volume of water in the chalk leads to a progressive accumulation of water on the successive marls which, in turns, causes an increased pore pressure and increased localised stresses on each marl seams. In applying these conditions to the Puys failure-scar, we note that: (1) Above Shoreham Marl 2, there is a significant change of the chalk colour, from white to yellowish and brownish (Figure 2), which may be due to an increased water saturation. At this location, the occurrence of Light Point, Hope Gap, Cliffe and Navigation hardgrounds between Shoreham and Lewes Marls reinforces the impervious role of marl seams (Figure 2 B). (2) In the upper part of the cliff, the dominant mechanism of failure is an outward tearing, which could be generated by overpressure due to water. (3) Above the Lewes Marl, the mechanism of cliff failure includes both tearing and shearing. (4) In the lower part of the cliff, shear failure is the dominant mechanism.

Finally, at Puys it is assumed that groundwater circulates through a diffuse vertical fracture network that intersects the deeper horizontal marl levels, the Lewes and Bridgewick Marls, which also act as aquicludes. The presence of a small volume of water at high pressure, trapped within the rock mass between two closely spaced impervious marl layers, could induce higher stress concentration than a large volume of water discharging from a free draining aquifer (HOEK and BRAY, 1977). Therefore, the bulk rock density combined with the water density could generate a significant stress concentration (BROMHEAD, 1986).

The occurrence of master-joints which cross cut the entire cliff closely located southward from the scar (about 100 m) (Figure 8) suggests that the cliff could have different hydrogeological behaviours: (1) some areas are well-drained thanks to a high fracture content. In that case, fracture pattern could induce the development of caves at the base of the cliff face. (2) some areas are low-drained due to the relative lack of fractures. In this case, a discontinuous horizontal notch may develop on the cliff face, probably resulting from water accumulation along marl seams. The Puys collapse illustrates the second case.

At Puys, we thus suggest a multilayered aquifer controlled horizontally by the marls and vertically by poorly developed pre-existing joint systems. The delay between heavy rain fall and the collapse, which is between one and three weeks, may be explained by the low velocity of water transmission through a poorly fractured and porous chalk (*i.e.* a dual porosity system) (BARENBLATT *et al.*, 1960 ; WARREN and ROOT, 1963). According to PRICE *et al.* (1993), the chalk matrix permeability is low due to the small size of interconnecting pore-throats, typically in the range of 0.1–10 milli-Darcy. For relatively shallow groundwater, this corresponds to a hydraulic conductivity of about $10^{-9}$–$10^{-7}$ m/s ($10^{-4}$–$10^{-2}$ m/day).

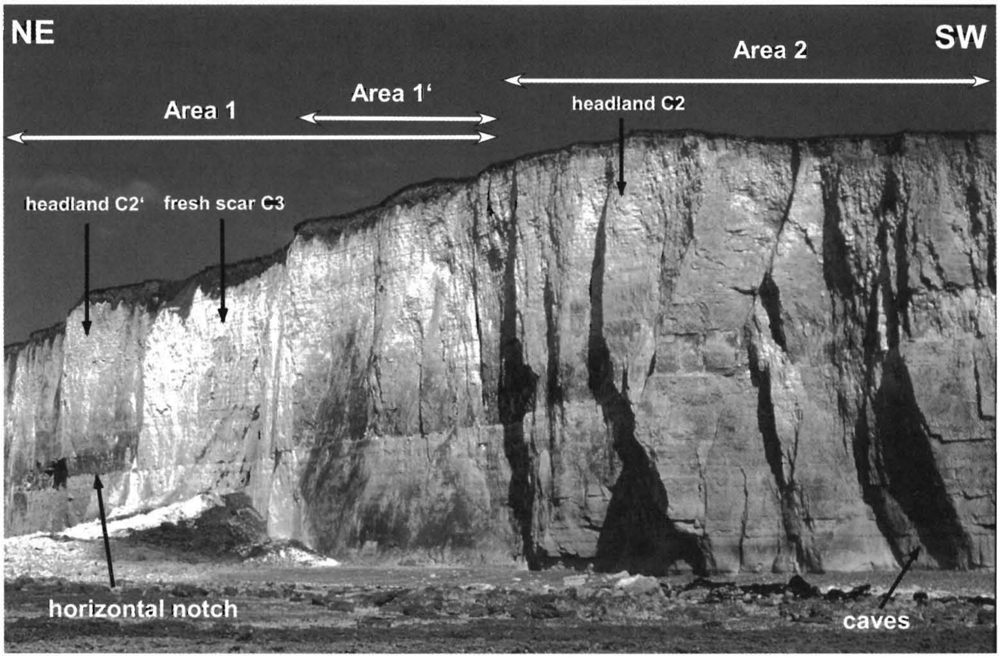



Figure 8. Large view of the cliff face at Puys. Area 1 extends northward and is characterized by a low fracture content and an horizontal notch, located in the mid-lower part of the cliff along the limit between Seaford Chalk and Lewes Chalk. The 17th May 2000 Puys collapse occurred along this area of the cliff. Area 2 extends southward and is characterized by a high fracture content all over the cliff height and small caves located at the base of the fractures at the toe of the cliff.

## Coastal Rock Cliff Collapses: Marine Erosion or Subaerial Processes?

At Beachy Head (East Sussex, UK), a collapse of about 150 000 $m^3$ occurred in January 1999 in a similar part of the Chalk succession. This failure also followed a prolonged period of heavy rainfall and slight frost. The processes described at Puys cannot be applied systematically to all the others collapses recognized in coastal chalk cliffs of NW Europe. At Le Tilleul (Normandy, France), a rock fall occurred in November 1998 again after a period of heavy rainfall and frost, but appears to be strongly influenced by a large vertical karst with partial clays-with-flints infill. This karst develops from the top of the cliff along a large scale, pre-existing, vertical fracture. In these cases, the role of groundwater appears to be of great importance in triggering the cliff collapse.

Another case of cliff failure occurred at Veules-les-Roses (Normandy, France), where a cliff collapsed in July 1999, during low tide, when the water table was assumed to be low following a prolonged dry period of high temperatures. Coastal cliff collapse appears, therefore, to be extremely variable in type and location along the NW Europe chalk coastline, due to the interaction and the respective influence of numerous triggering factors. One of these factors is related to marine erosion by waves during high tide. Major factors affecting cliff erosion due to waves are (1) the assailing force of waves acting on the base of the cliff, (2) the resisting force of material forming the cliff base, and (3) the duration of wave action. If waves are armed with shingles at the cliff foot, mechanical action characterised by abrasion and impact is added (SUNAMURA, 1977, 1982). According to many authors (*e.g.* QUIGLEY *et al.*, 1976 ; WILLIAMS *et al.,* 1993), wave attack appears to be one of the main parameters of cliff toe erosion, where repeated wave impact aids weathering to undercut the cliff toe.

Concerning the Puys collapse, there was unfortunately no observation of the cliff toe before the collapse, but the cliff portion located near the collapsed zone, without large-scale fractures (area 1') (Figure 8) does not have a basal notch. Nevertheless, at some places along chalk cliffs of the Channel, slight slaking may occur at the cliff toe where the sea reaches it. This basal notching is generally of the order of several cm. It is probably a process of weathering (repeated wetting and drying, salt weathering and water layer weathering) as described by STEPHENSON and KIRK (2000) in New Zealand. BENUMOF *et al.* (2000) suggest that the wave parameter is a secondary mechanism of sea-cliff erosion, as indicated along the Californian coastline where lithology and material strength appear to largely determine sea-cliff stability.

Coastal chalk cliffs of the Channel show a roughly vertical profile, which may be linked to active cliffs according to the sea-cliff classification proposed by EMERY and KUHN (1982), where cliffs consist of bedrock exposed by their continuous retreat under the influence of both marine and subaerial agents and processes. Field observations on chalk cliffs of the Channel illustrate a sharp angle at the sea-cliff base, which denotes generally active marine erosion (EMERY and KUHN, 1982). But the lack of evidence of continuous scarp-foot erosion may be explained by the accumulation of shingles at the toe of the cliff, which may sometimes exceed several meters in height, as at Le Tilleul. This shingle accumulation minimizes the height of the sea directly against the cliff. Nevertheless, as emphasized by NOTT (1990), BENUMOF *et al.* (2000) and STEPHENSON and KIRK (2000), waves are necessary for the removal of talus material deposited at the base of sea cliffs by subaerial erosion.

In the case of Puys, the vertical profile of the chalk cliff is not simply a function of scarp-foot erosion, but subaerial processes may be invoked as major processes controlling the cliff profile and waves as a secondary agent to maintain the cliff's vertical profile.

As underlined by KIRKGÖZ (1995), a coastal-wave impact against a wall can cause high pressures over a small area but with a typical duration of a few hundredths of a second. Nevertheless, there is an opportunity for significantly longer durations of high pressure from flows filling in a crack or a cavity with an appropriate length (PEREGRINE and KALLIADASIS, 1996). Where the cliff faces present pluri-metric caves ending with open, large-scale, fractures, as at Puys near the collapsed zone (area 2, Figure 8) can wave impact through caves filled with sea water cause slope instability at high tide?

## CONCLUSION

The Puys rockfall witnessed the 17th May 2000 was polyphase, with at least two clear collapse events. The resulting collapse forms a debris-avalanche run-out deposit within which the original stratigraphy is retained. The collapse scar exposes a vertical and horizontal zonation, indicating the type of rupture. The lack of striations in the upper part of the cliff shows an outward tearing mechanism, whereas two generations of striations in the lower part of the cliff indicate two phases of shearing, with local brecciated and crushed chalk areas, which suggest stress concentration prior to failure. The overall mechanism of collapse results from a sliding dynamic, confirmed by the organisation of chalk blocks within the deposit. Heavy rainfall is suggested as the main triggering factor for this collapse, as indicated by two periods of intense rainfall during the previous month. The delay between heavy rainfall and the collapse may be explained by the low velocity of groundwater transmission through a poorly fractured porous chalk, which favours a progressive accumulation of groundwater on marl seams within chalk and stress concentration in the lower part of the cliff.

The role of water, lithology and fracture content appears thus to be of primary importance in triggering the cliff collapse at Puys. The Puys collapse appears to be representative of poorly fractured coastal chalk cliffs that have undergone significant coastal retreat. In this case the chalk lithology becomes the dominating factor which controls the spatial distribution of water within the chalk. In similar chalk with large-scale nearly vertical fracture pattern, the role of water could be different and related to some other parameters such as frost or wave impact. The relative absence of pre-existing fractures in the cliff could be a favourable situation for generating overpressures. Within the Chalk, the water table distribution with depth is controlled by lithology, and specifically by the vertical distribution of the impervious marl seams and hardground levels which act as aquicludes. The presence of these marl seams is clearly defined by the lithostratigraphic units of Cretaceous Chalk in the Anglo-Paris Basin.

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