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2D modelling of large-scale platform margin collapses along an ancient carbonate platform edge (Maiella Mt., Central Apennines, Italy): geological model and conceptual framework

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Abstract

Results of numerical simulations of large-scale platform margin collapses along the edge of the Cretaceous platform of the Maiella (Central Apennines) are presented, adding a new contribution to the understanding of the role and quantification of the various factors that control triggering of these phenomena and the production of breccias and megabreccias. For this purpose, a sophisticated numerical code, widely used in recent contexts to simulate overall mass movements and deep gravity-driven deformation, is applied for the first time to an ancient system on a scale of several kilometres. The modelling carried out is a simplified attempt to understand a very complex phenomenon produced over a very long time-span. It tests whether the perturbing causes in the model, acting together or separately, are able to activate such large-scale collapse, and helps to understand the effects of perturbing causes and their variations. In particular, modelling was carried out considering both static (variations in sea level) and dynamic (seismic events without and with fault formation) conditions and combinations of them. Variations in sea level alone do not produce all the effects observed but may certainly be a predisposing element. Seismic shock simulations show that fracturing and shear stresses are concentrated on the platform margin, representing the most sensitive and vulnerable area. Earthquake swarms associated with an active fault are the most likely means of triggering large-scale platform margin collapses, such as those occurring during the Early Cretaceous in the Maiella.

Keywords: large-scale platform margin collapses; mechanical modelling; Maiella Mountain; mid-Cretaceous platform

1. Introduction

The statement by Anderson and Crerar (1993) ...'models do not represent reality, but our idea of reality'... expresses perfectly one of the main limits in the attempt to reproduce faithfully a geological phenomenon through modelling. The quantitative approach, however, has contributed and still contributes considerably to the progress of our knowledge about the complex relationships that govern the development of depositional systems.

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The application of numerical simulation models in stratigraphy and sedimentology has, for example, enabled the evaluation and better understanding of geometric stratal patterns (e.g. Kooi and Cloetingh, 1989), the architecture of carbonate platforms (e.g. Bosence and Waltham, 1990), their production and growth rates and the architecture of depositional sequences (e.g. Pitman and Golovchenko, 1991). It also gives insights on the role of changes in sea level in the organisation of successions and the relations between the various factors that modify the accommodation space, such as tectonic subsidence, eustasy, sediment load and compaction (e.g. Bowman and Vail, 1999), etc. Nevertheless, little attention has been paid, in terms of numerical simulation, to large-scale margin collapses occurring on the edges of carbonate platforms, both recent and ancient, to their sedimentary products (e.g. breccias and megabreccias) and inherited morphologies. The understanding of these events and their triggering mechanisms have important implications for sequence stratigraphy interpretation (importance of onlap geometries near indented morphologies, the position of the breccias and megabreccias within the systems tracts) and for hydrocarbon research (spatial–temporal predictability, areas and volumes of potential reservoirs).

For the mechanisms that trigger large-scale margin collapses along the platform margin, there are largely conceptual or qualitative models in existence, based on present-day and ancient platform systems. In Recent carbonate systems, the most established cause that triggers these phenomena is the influence of seismic shocks associated with movements along fracture zones (Hine et al., 1992). Other mechanisms such as sediment load, storm waves, tsunamis, lowering of relative sea level, bioerosion, fracturing, bottom currents, etc., can cause or contribute to these events (Freeman-Lynde and Ryan, 1985; Schlager and Camber, 1986; Paull et al., 1990). In ancient carbonate systems, these phenomena and the consequent production of breccias and megabreccias are associated, directly or indirectly, with the activity of synsedimentary faults during tectonic phases (Bernoulli, 1964; Castellarin et al., 1978; Payros et al., 1999) and to variations in relative sea level (Sarg, 1988; Jacquin et al., 1991; Spence and Tucker, 1997; Bosellini, 1998; among others).

In this work, some results from the numerical simulation of large-scale margin collapses occurring along the edge of an ancient carbonate platform are presented, giving a new contribution to the understanding of the role and quantification of the various factors that control the triggering of these phenomena and the production of breccias and megabreccias. For this purpose, a sophisticated numerical code (FLAC, 2000) was used, to simulate the overall behaviour of the rock mass, in both static and dynamic conditions. This numerical code, widely used in recent contexts to simulate mass movements and deep gravity-driven deformation, in order to solve geotechnical and mechanical engineering problems (Dawson and Roth, 1999; Cala and Flisiak, 2001; Sciarra and Calista, 2001), is applied to an ancient system on a scale of several kilometres. The geological example modelled is the Maiella platform (Central Apennines), where one of the most spectacular examples of ancient carbonate platforms characterised by large-scale margin collapses on the seismic scale, is found (Morsilli and Rusciadelli, 2000; Morsilli et al., 2000, and in press). The modelling of this system was exceedingly problematic and complex, especially during the parameterisation phase. The numerical code requires the knowledge of some parameters which cannot be directly obtained from an ancient system, but must necessarily be deduced from recent, analogous systems, which are most similar to that analysed.

The main purpose of this work is to illustrate and discuss the geological situation and the adopted numerical model, the conceptual framework of the numerical code and the limits of its application, variables and about how the results of the modelling are expressed.

2. The geological model

2.1. The relict morphology of the platform margin

The geological model used for the simulation derives from a Cretaceous carbonate platform lo-

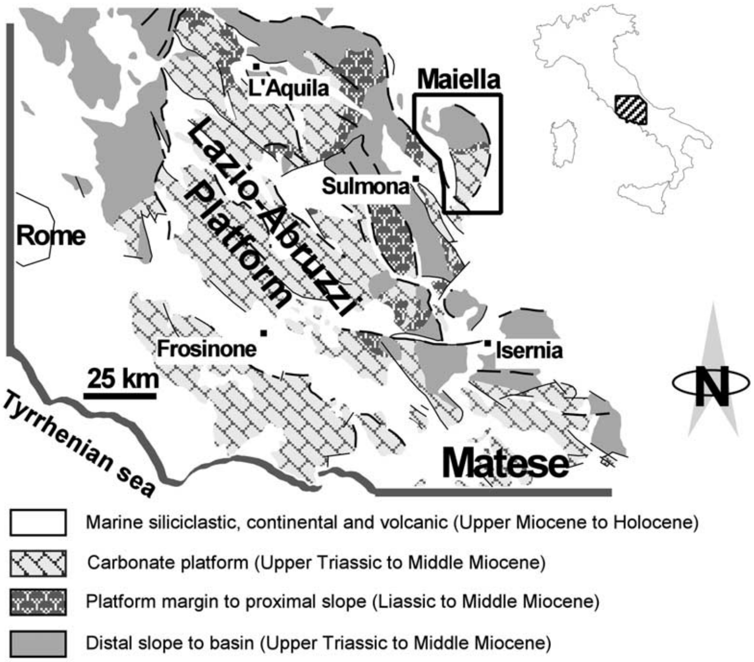

Fig. 1. Geological map of the Central Apennines showing the studied area and the broad distribution of Mesozoic depositional environments (platform, margin to proximal slope and distal slope to basin) of the Lazio-Abruzzi Platform and the main structural elements.

cated along the northern edge of the Apulian Platform and magnificently outcropping in Maiella, in the Central Apennines (Fig. 1). In this area, in spite of Mio–Pliocene tectonic activity, the original relationships between Cretaceous slope and platform deposits are perfectly preserved and observable along natural sections at the seismic scale. These are defined by a 1000-m-deep palaeoescarpment marked by the abrupt contact between Lower and Upper Cretaceous platform facies and Upper Cretaceous slope deposits (Crescenti et al., 1969; Accarie et al., 1986; Vecsei, 1991; Eberli et al., 1993; Morsilli et al., 2002). The geometric reconstruction of this contact in two and three dimensions (Morsilli and Rusciadelli, 2000) has shown that the edge of this sector of the Apulian Platform was characterised by a rather complex physiography, defined by the alternation between prominent stable tracts and indented tracts cut into the platform facies of the Lower Cretaceous (Fig. 2). This physiography seems to have originated in the wake of an imposing phase of collapses of the platform margin, which occurred between the Albian and the Early Cenomanian, as can be deduced from the age of the breccias and megabreccias intercalated in the base-of-slope to basinal successions north of the platform (Morsilli et al., 2000, 2002). The indented plan geometry and asymptotic profile of the detachment surface and the type of deposits associated with them (poorly sorted megabreccias, with sub-rounded clasts and abundant matrix) suggest that the collapses are rock-avalanche-type phenomena.

2.2. The pre-collapse depositional profile

For the simulation of the gravity-driven collapses, it was necessary to define the type and the geometry of the platform margin previous to the collapse phase. The stable, prominent portions of the margin are the most useful in the reconstruction of the pre-collapse depositional profile, since the original features are better preserved compared with the indented areas (Fig. 3). In spite of this, these sectors also show signs of erosion

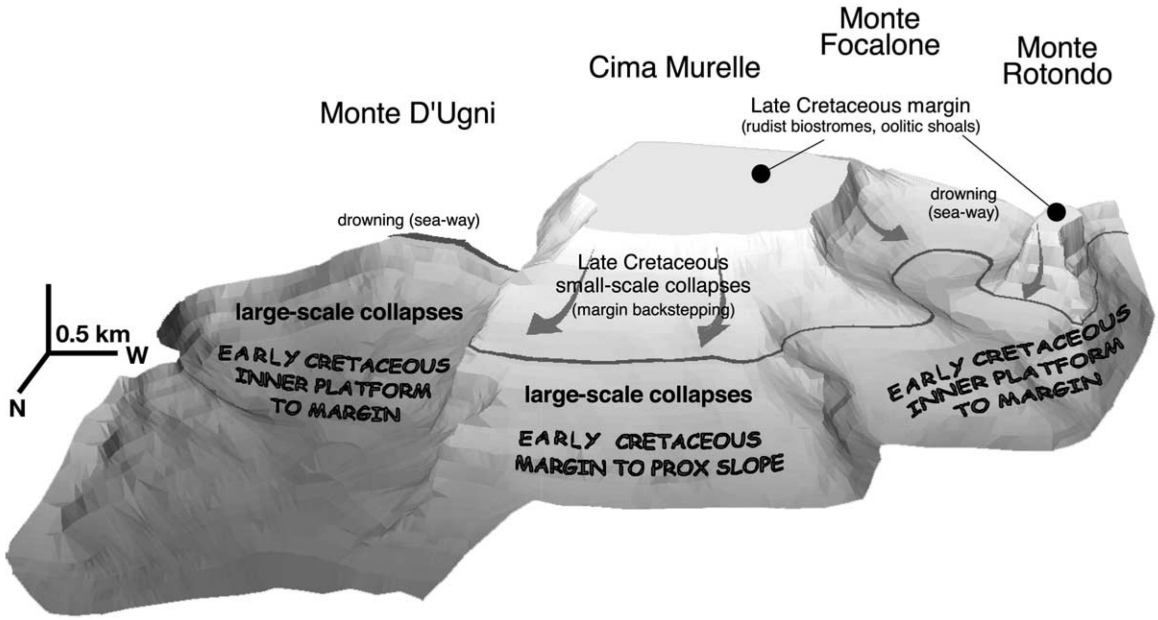

Fig. 2. Three-dimensional reconstruction of the palaeoescarpment during the Late Cretaceous. Note the complex morphology of the palaeoescarpment defined by the alternation between indented and prominent areas (modified after Morsilli and Rusciadelli, 2000).

connected with the formation of the palaeoescarpment. The abrupt interruption northwards of Lower Cretaceous margin facies suggests, in fact, that the platform margin extended beyond the present position of the palaeoescarpment. The presence of proximal slope clinostratified deposits near the base of the Selva Romana Valley outcrops (Fig. 4), provides a key element for reconstructing the geometry of the depositional profile of the platform and to hypothesise the original extent of the areas eroded during the collapses. The clinoforms observed represent the basinward continuation of the collapsed margin portion, originally located along the southern flank of the Selva Romana Valley. In the outcrops below Cima delle Murelle, a little further south of Selva Romana Valley, internal platform and margin facies are found. They represent the landward equivalents of the massive clinoforms. The material removed, which constitutes the clinoforms, must have accumulated progressively along the platform flank, corresponding to a slope that was already inclined and inherited from the development and growth of depositional systems during previous stages. The presence of a fairly inclined slope, in front of a pre-existing basin depression, would have limited the progradation of the platform and favoured its aggradation and the formation of clinoforms.

Another relevant aspect for constructing the pre-collapse geometric model is the height of the slope. This may be evaluated by considering the relationship between the platform flank and the position of the slope to basin transition with respect to the platform edge. The latter is pinpointed by the point where the morphological gradient of the platform depositional profile consistently increases (Vanney and Stanley, 1983), while the slope to basin transition is shown at the point where the inclination of the slope consistently decreases. At Maiella, this is not directly observable since it is not outcropping; nevertheless an estimate of its distance from the platform edge can be deduced from seismic surveys of the buried and non-deformed margin of the Apulian Platform offshore, in the Adriatic. Several seismic surveys recording platform to basin transition, not affected by Cretaceous faults and by erosional

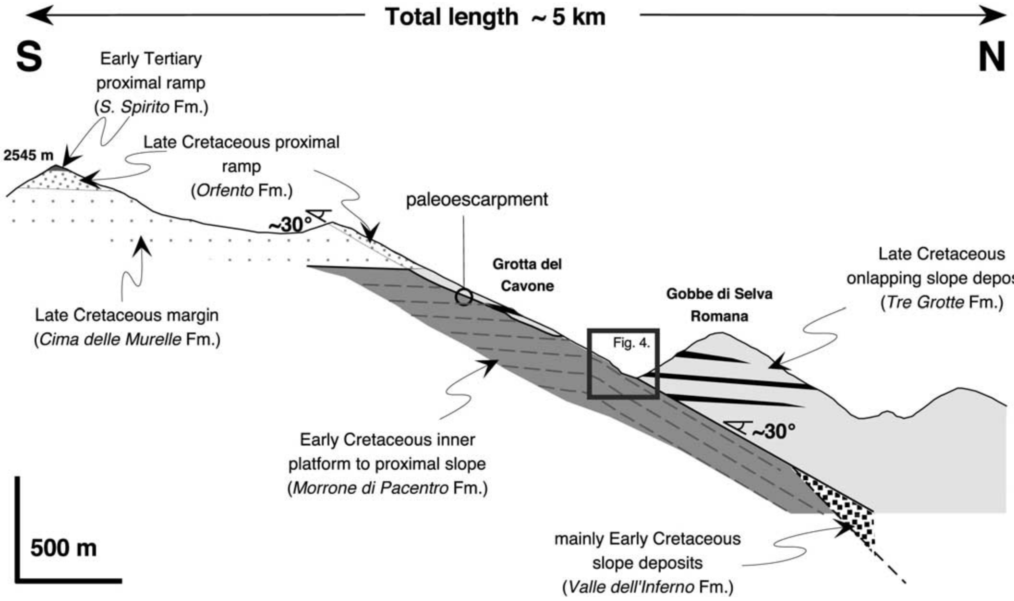

Fig. 3. Cross section along a prominent sector of the platform margin, north-west of Cima delle Murelle. The Lower Cretaceous succession, underneath the palaeoescarpment, shows facies associations dominated by rudstones and grainstones with orbitolines, rudists and corals, representative of Aptian–Albian margin environments (modified after Morsilli et al., 2002).

to by-pass slopes, have been investigated for this purpose. In this area, the slope to basin transition is marked by a break of slope and by the presence of sharper, more regular seismic reflectors, indicating the change from slope to base-of-slope deposits. This transition takes place at a distance

Fig. 4. Lower Cretaceous northward dipping (around 30°) clinoforms at the base of the Selva Romana Valley outcrops. Clinoforms are composed of alternating bio-lithoclastic grainstones and rudstones and bio-lithoclastic breccias, in medium to thick layers.

varying between 4 and 6 km from the platform edge. With an initial acclivity of around 30°, which tends to decrease rapidly as it moves away from the platform edge, the height of the slope, at the transition with basinal deposits, reaches values of about 1500 m and 2000 m, corresponding to the value of the bathymetry, without correction for compaction (Fig. 5). Geometrical and depositional features similar to those reconstructed for the Lower Cretaceous pre-collapse profile of the Maiella platform can be recognised in numerous examples of platform to basin transition, documented along the buried margin of the Friuli Platform (cf. Cati et al., 1987; Casero et al., 1990), the Dalmatian Platform (Casero et al., 1990) and the northern sectors of the Apulian Platform (Gargano area) (Morsilli and Borsellini, 1997).

Fig. 6 represents the reconstruction of the possible geometry of the pre-collapse depositional profile of the Maiella platform at the end of the Early Cretaceous, based on the interpretation of field and subsurface data. On the basis of this reconstruction it can be hypothesised that the edge of the platform extended around a further

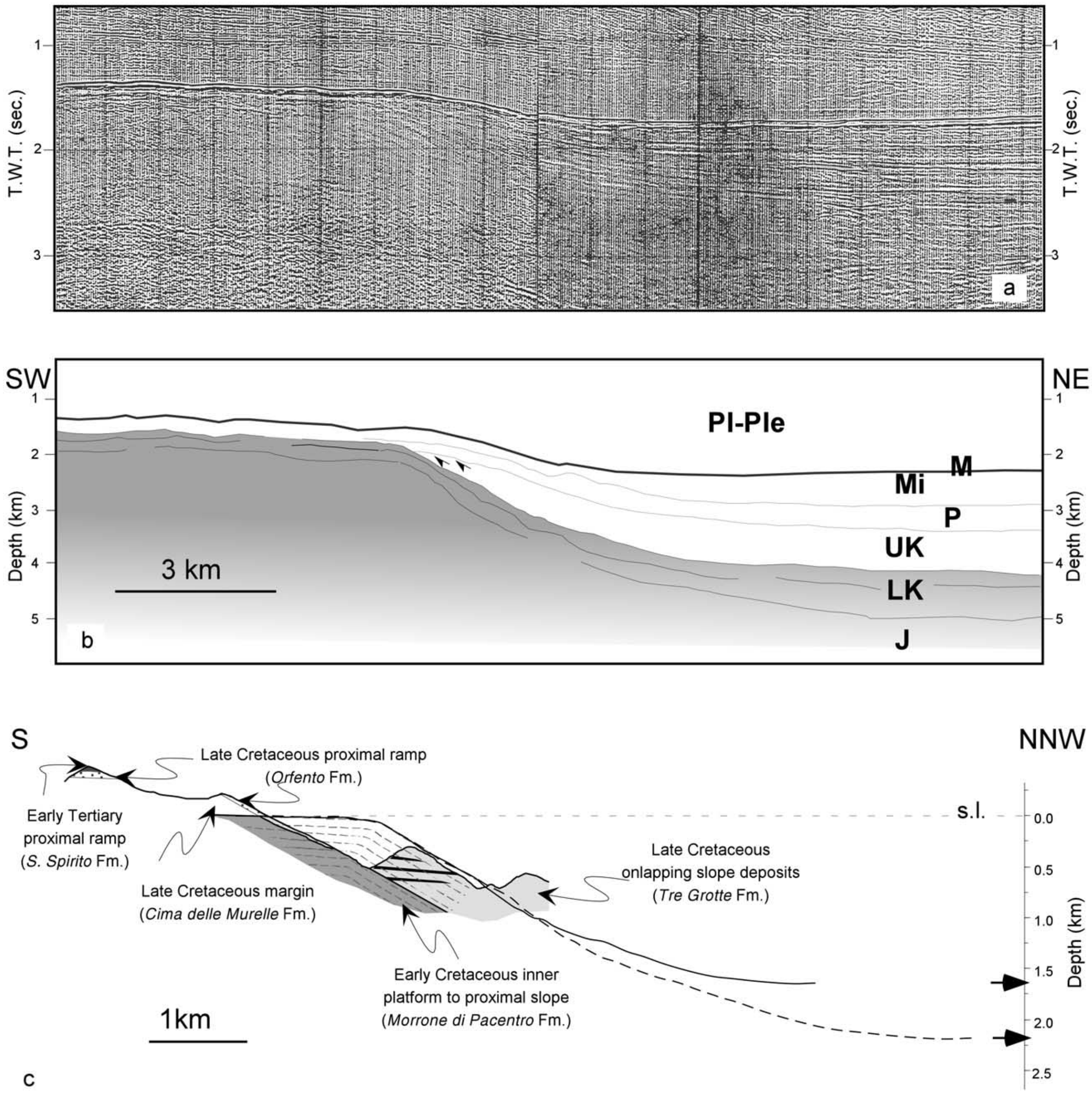

Fig. 5. Seismic survey and linedrawing (a,b) of the buried and undeformed Apulia platform margin in the Adriatic offshore. Pl-Ple: Plio–Pleistocene; M: Messinian; P: Paleogene; UK: Upper Cretaceous; LK: Lower Cretaceous; J: Jurassic. (c) Reconstruction of the depositional profile and estimation of the palaeobathimetry in the sector north of the Murelle.

1 km north compared with the present position of the palaeoescarpment, and that the maximum thickness of the sediments eroded following margin collapses was around 300 m.

3. The numerical code

The numerical code used (FLAC, 2000) is a two-dimensional (2D) finite-difference method of

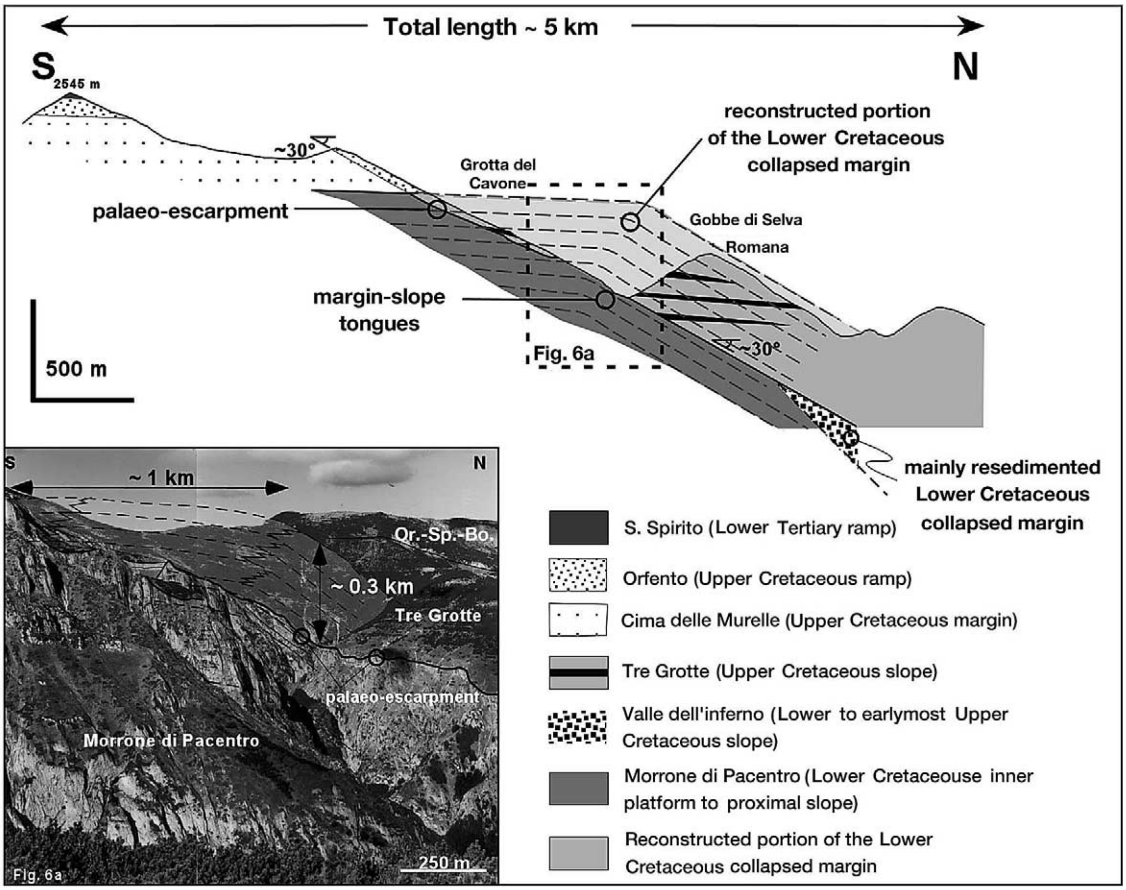

Fig. 6. Reconstructed geometry of the pre-collapse depositional profile of the Maiella platform at the end of the Early Cretaceous. Following this reconstruction, the pre-collapse depositional profile corresponds to a depositional and essentially aggrading or weakly prograding platform rimmed by an escarpment inclined about 25–30°.

numerical analysis for calculations of continuum mechanics. The system is represented by elements in a grid constructed by the user in the shape of the object to be modelled. Each element behaves in accordance with a prescribed stress-deformation law, linear or otherwise, in response to the forces applied or to the constraints imposed. FLAC is based on a '*Lagrangian*' numerical scheme that adapts well to modelling large-scale deformation and collapse (Sciarra, 2000; Sciarra and Calista, 2001).

The general analysis consists first in an overall re-equilibrium of the system and then in the study of the rupture conditions. If the system is initially unstable, the numerical code is inappropriate to carry out any types of analyses. The re-equilibrium process is thus necessary to verify the initial stress-strain conditions of the model and the congruence with the geometric profile. Hydraulic conditions, represented by fluid flow vectors, and the calculus of the pore pressures must be known during this phase. This phase proceeds independently of any mechanical effects. At the end of the analysis of the re-equilibrium process it is possible to represent the displacement and the deformation velocity vectors at each node of the meshes. In this way the behaviour of the system can be observed with reference to its geometrical, physical and mechanical peculiarities. After the re-equilibrium process, the stability analysis allows to explore limit conditions of equilibrium by varying internal (physical and mechanical parameters of

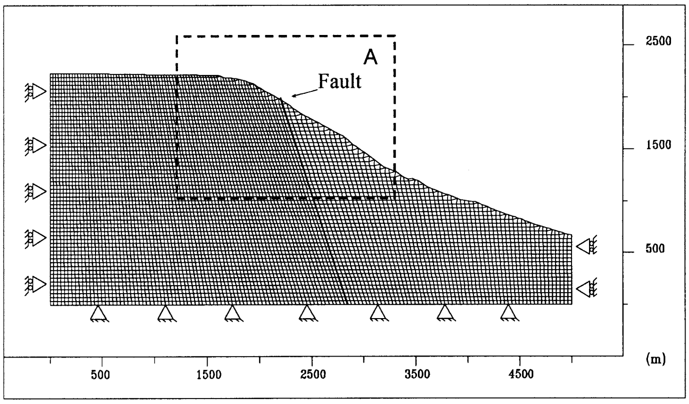

Fig. 7. Scheme of the model with the mechanical conditions of constraint imposed on the borders. Grid is made up of triangular and quadrangular meshes with an average size of 40 m.

the rock, pore pressures, etc.) and external characteristics (application of loads, seismic events, etc.). The programme is able to analyse local and general stability of the system for each variation imposed.

4. The geomechanical model

A grid with triangular and quadrangular meshes that defines homogeneous portions of material represents the mechanical situation used (Fig. 7). The average size adopted for the grid meshes (40 m) represents the optimum value to reduce both the effects of scale due to the model dimensions (2.5×4.5 km) and the calculation times which were necessarily long in this case. Adopting shorter dimensions for the single meshes produced no appreciable differences in the results.

The values for the physical and mechanical parameters relating to the two main depositional systems (inner platform and platform margin) of the model are fixed in the centre of gravity of the meshes. Different physical and mechanical parameters were assigned to the two depositional environments. For both environments Druker-Prager's yielding criterion was used (Chen and Han, 1988), which is very suitable for elasto-plastic behaviour in complex situations involving large-scale deformations.

The different choice of mechanical parameters was based on criteria concerning the different grain sizes, texture and physical distribution of the materials. In particular, materials with lower mechanical resistance were associated with slope

Table 1
Values of physical and mechanical properties used in the calculation

Parameters	Internal platform facies	Margin to slope facies
γ (unit volume weight) – (kN/m^3)	23.5	18.5
c' (cohesion) – (Pa)	$5.0{\cdot}10^4$	$4.0{\cdot}10^4$
ϕ' (friction angle) – (°)	45	35
E (elastic modulus) – (Pa) $E = E_o\left(\frac{\sigma'_h}{\sigma_a}\right)^{\alpha} \sigma'_h = K{\cdot}\sigma'_v$	$E_o = 2.2{\cdot}10^9$	$E_o = 2.0{\cdot}10^9$
Tensile strength – (Pa) $\sigma^t_{max} = \frac{c}{tg\phi}$	$5.0{\cdot}10^4$	$3.6{\cdot}10^4$
Poisson's ratio	0.33	0.30
Bulk modulus – (Pa)	$1.83{\cdot}10^9$	$1.66{\cdot}10^9$
Shear modulus – (Pa)	$4.58{\cdot}10^8$	$4.16{\cdot}10^8$
n (porosity) – (%)	20	25

environments. Table 1 shows the values used in the numerical calculation. These were taken from previous authors (Ciancetti and Sciarra, 1987), who derived them from studies of materials of local formations (Calcare Massiccio) whose physical and mechanical characteristics are similar to those of the Maiella platform during the collapse phases.

Discontinuities influence parameter values favouring conditions of instability and increasing the chances of triggering collapses. In line with the scale of the studied model, the presence of discontinuities is essentially associated with the bedding, fracturing, faults and with the effects of undercutting phenomena due to sea level changes. Long-term emersions of the platform, associated with the development of karstic forms, may have contributed to the formation of discontinuities. Excluding palaeo-karst forms related to the periodic, brief emersions of the platform top, the only karstic event of a size that would favour the formation of discontinuities able to weaken the mass of rock is the mid-Cretaceous emersion. At Maiella, as in the greater part of the peri-Adriatic Cretaceous platforms, a long-term hiatus, various types of karstic forms and the formation of bauxitic soils are associated with this emersion event.

The many studies carried out on mid-Cretaceous peri-Mediterranean platforms in plate interior settings (D'Argenio and Mindszenty, 1991) have revealed the presence of karstic forms such as karren, sinkholes, cavities and dissolution breccias, generally filled with bauxitic soils (D'Argenio and Mindszenty, 1995), and palaeo-reliefs with differences in level up to a maximum of 40 m (D'Argenio et al., 1987). These karstic forms, and especially bauxites, are found fairly distant from the edge of the platform, as is suggested by facies associations below the discontinuity. Their formation, essentially linked to dissolution phenomena through the effect of interaction between meteoric waters and emerged carbonate reliefs, is substantially different from that of karstic forms that characterise the coastal zones. In areas near the edge of the platform, the high porosity of the deposits favours water infiltration and circulation, generally inhibiting the development of karstic cavities, especially in autogenic systems (Ford and Williams, 1996) such as isolated carbonate platforms. Nevertheless, karstic phenomena in coastal areas are also linked to the presence of the so-called mixed corrosion zone. This zone corresponds to a transitional band between the freshwater layer and the more dense seawater layer. Following oscillations of the sea level, this corrosion zone moves vertically favouring the development of a considerable zone of dissolution (Ford and Williams, 1996).

To evaluate the influence of karstic phenomena on the formation of discontinuities on the edge of the platform, the possible geometric distribution of the water table in the Maiella platform was reconstructed during the mid-Cretaceous emersion. Considering the Ghyben-Herzberg law and the sea level position respectively at −40 and −80 m from the emerging top of the platform, it can be observed that the maximum depth at which karstic discontinuities associated with the fluctuation of the transition zone between fresh and salt water could develop was around 150 m. In the absence of deeper karstic phenomena linked to previous phases of emersion, the mid-Cretaceous one causes instability only in the uppermost portion of the model, through structures whose depth is completely insufficient to destabilise a portion of margin equal to that collapsed. On the basis of these elements, karstic phenomena cannot be considered a factor of deep destabilisation and do not therefore represent, in our opinion, one of the causes triggering large-scale collapses along the platform margin. Karstic phenomena, however, may have played an important role in the formation of minor structures that are at present observable along the palaeoescarpment such as notches, or may have enhanced surface decay processes of the rock mass in tension fractures. In addition, by reducing the volume of the mass and therefore the unit weight of the material (quantifiable by varying the average porosity of the materials inside the meshes), karstic phenomena act by reducing the load at the top of the slope, thus increasing stability rather than instability.

As far as fracturing is concerned we can state that this is not relevant in the initial conditions preceding the collapse phase, since the platform has not yet been subject to phenomena able to produce the relevant and several hundred metres deep fractures. For bedding, it was possible to build the model so that the mechanical discontinuities associated with them were represented by the configuration of the meshes. What has been stated above for karstic phenomena is also true for the undercutting linked to variations in sea level and to wave action, which could cause local instability in the emerged part of the platform.

Another element relating to the model definition is the knowledge of the system of constraints imposed on the model. In Fig. 7, the mechanical conditions of constraints imposed on the borders of the model are shown. They allow only vertical movement of the sides and no movement of the lower edge.

5. The conceptual framework

The modelling carried out must be understood as a simplified attempt to understand a very complex phenomenon produced over a very long timespan (from 3 Ma to 10 Ma). This simplification is necessary since it is not possible to evaluate the evolution of physico-mechanical parameters and the seasonal variations of the hydrological regimes of a system of over 100 Ma; besides, no arithmetical algorithm is able to simulate the progressive effects of an environmental degradation, which has been going on for millions of years. However, what is interesting is if the perturbing causes of the model, acting together or separately, are able to activate such a major phenomenon of collapse independently of the time required. In any case, the analysis was carried out above all to try to understand the effects induced by each perturbing cause and by variations of these. In particular, fundamental importance was given to the variations in sea level and to the presence of seismic events. A magnitude of 6° was allocated to these seismic events and they were applied several times for each variation in sea level. They are purely indicative and served to clarify only the effects on the general behaviour of the model, since the number and the real intensity of earthquakes that occurred are not known. Regarding sea level, analyses were carried out starting from a completely submerged system with subsequent lowering of the sea level up to −100 m followed by an overall rising phase.

In terms of the results expected from the model, the progress of the deformation of the meshes should first of all be analysed to verify if movements conform to the present situation of the slope. The deformation is obtained by superimposing both the static and the dynamic effects for each calculation step. Another important element is the progress of the increases in shear strain in parts of the model. The size of the model is such that, especially in seismic periods, rupture planes independent of each other may be produced. To recognise these alignments the zones of different shear strains are shown, which are also zones of possible triggering of lines of fracturing families. From each run of the programme, we are able to obtain elements that should be critically evaluated and justified. Although results often conform to the input data, they may not necessarily represent the phenomenon exhaustively. Congruence is verified through the inertial balancing of the system of stresses internal and external to the model (gravity, hydraulic forces, restraining reactions, loads) and if it is not reached it would mean either an incorrect value of input data or the rupture of the model.

6. Results of the analysis

The first results obtained refer to the hypothesis of variations in sea level for an initial homogeneous, intact model without fractures, faults or seismic events (quasi-static conditions). These variations involved the fall and progressive rise in sea level, in steps of 50 m. Fig. 8 shows the graphs relating to the horizontal displacements of the grid with bathymetric values equal to 0, −100 m and −50 m (rising phase from −100 m) of the sea level. Phenomena of localised breaking, affecting to the first few tens of metres depth, are produced along the slope because of the weakening subsequent to the fall in sea level and the action of new regimes of pore pressure. Shear strains diagram shows that maximal values are concentrated on

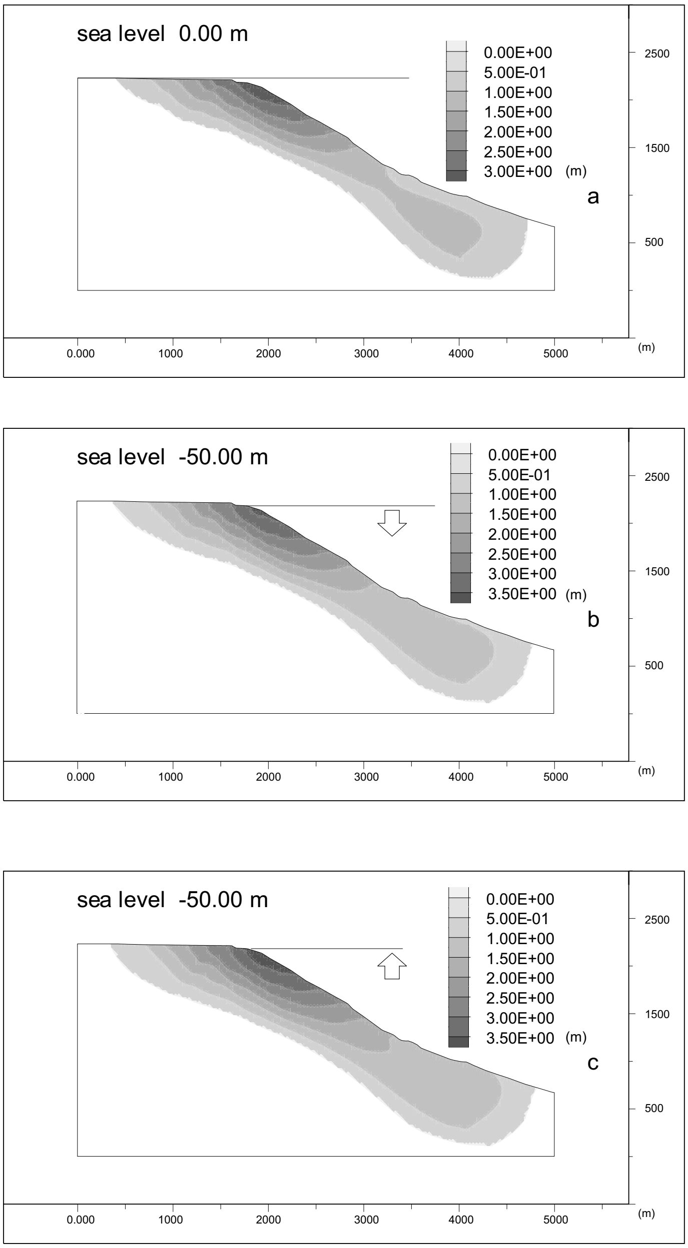

Fig. 8. Horizontal displacements of the model grid with bathymetric values equal to 0, −100 m and −50 m (rising phase) of the sea level.

the platform margin, which is therefore subject to considerable weakening (Fig. 9). During the run of the programme, areas of progressively larger shear strains are generated on the platform as well. In spite of this, sea level changes do not produce exhaustively the effects attended from field reconstruction. However, they may certainly represent a predisposing element to promote instabilities in the platform margin sector.

For dynamic analyses, an ideal accelerogram for horizontal-component earthquakes of magnitude 6 (Fig. 10) was used, applied to the base of

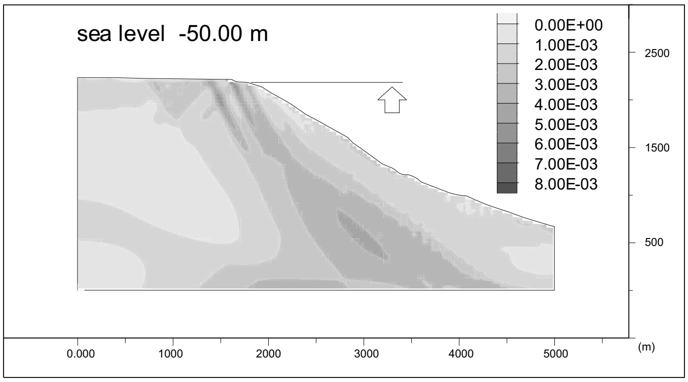

Fig. 9. Maximum shear strains in the model shown in Fig. 8, with sea level at −50 m rising from −100 m.

the model, with duration of 16 s and maximum amplitude of 9 m/s^2. The number and frequency of earthquakes remain unknown and therefore the aim is to check compatibility of the congruence of the deformations from an earthquake and the geometry of the rupture planes of the collapse phenomena observed. In this regard, diagrams showing the largest vertical and horizontal movements and the maximum shear strains recorded in the model subsequent to the application of the seismic event are illustrated in Fig. 11. The model was initially considered completely submerged and

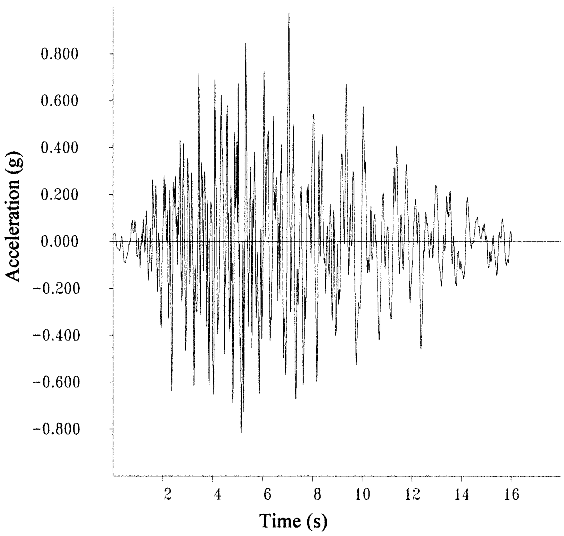

Fig. 10. Ideal accelerogram of an earthquake of magnitude 6 used in the dynamic analysis.

subsequently static effects mentioned above were combined with dynamic effects. In all cases the largest localised collapses were observed in the platform edge and in more inner positions. In addition, along the slope lineaments occur where the shear strains are largest (Fig. 11); these lineaments are perpendicular as regards the earthquake direction and dip at an angle of around 75–80° to the horizontal. It may be assumed that the areas that are most seismically vulnerable will be concentrated along these lineaments from a single earthquake, because of the concentration of shear stresses. Further seismic events will produce nothing more than a greater amplification in the deformation along these alignments. These planes can be seen also as preferential zones in which the fracturing of rock mass is concentrated. Negligible differences on the rock mass behaviour are obtained when seismic activity is coupled with sea level changes, testifying to the small influence of the position of the sea level.

Previous analyses have shown that a variety of effects (fractures and changes in the shear strain) have been produced on the modelled system by the application of changes in the sea level (static analysis), earthquake swarms (dynamic analysis) and their interactions. Moreover, it has been shown that these effects concentrate in the area of the platform margin, and they are able to produce small-scale collapses and changes in the equilibrium conditions. However, effects produced by modelling are far from those observed in the field and considered triggering factors are thus

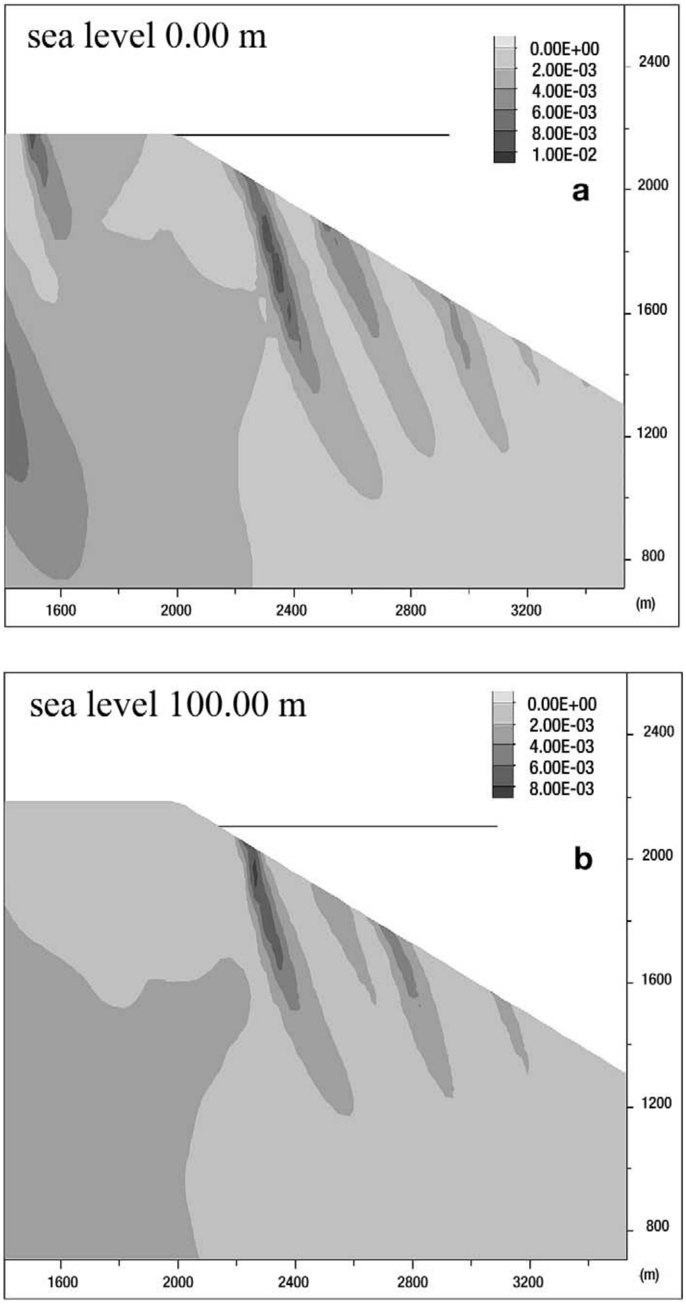

Fig. 11. Maximum shear strain increment of the numerical model during dynamic analysis at different sea levels. The zones of maximum shear strains are concentrated along planes dipping 75–80°, located on the slope and on the inner platform.

insufficient to produce large-scale collapses such as those reconstructed for outcrops from geometrical and depositional features.

A further analysis was carried out to include the effects of the progressive dislocations along a fault located along the slope. The fault downthrow is generated progressively by increments of a few metres during the fault evolution. Here

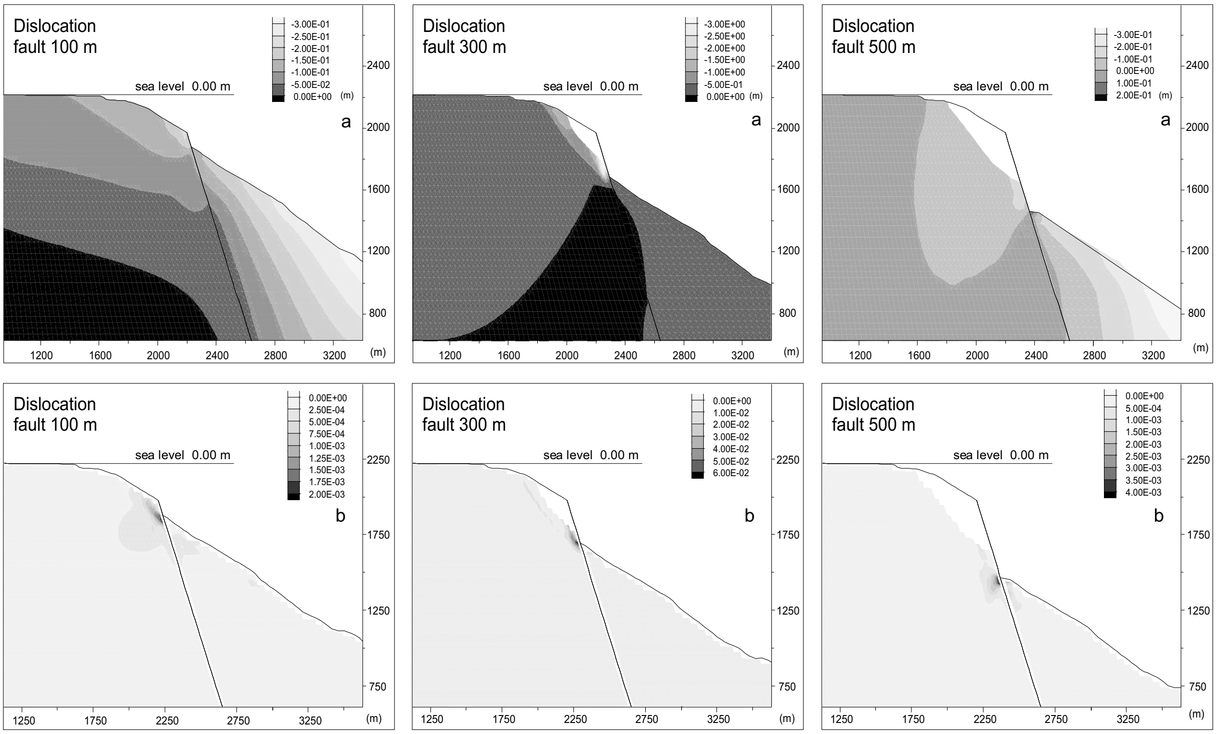

Fig. 12. Numerical modelled vertical displacements (a) and maximum shear strain increments (b) at different dislocations of the hanging wall of the fault without dynamic effects due to earthquakes.

are reported three steps corresponding to three subsequent moments during the running of the programme. The first step depicts the situation at 100 m of fault dislocation, the second step corresponds to the time at which the fault dislocation produces a cumulative downthrow of 300 m, whereas the third step (500 m) represents the situation at the end of the fault evolution, when modelling has produced geometries comparable with geological data. Both static (without earthquakes) and dynamic (earthquakes) conditions were coupled during this analysis.

Fig. 12 illustrates model results in quasi-static conditions, e.g. without earthquake swarms associated to the fault dislocation. Although an increase in the vertical displacement (Fig. 12a) and an increment of the shear strains are recorded along the slope (Fig. 12b), the rock mass rests stable and collapse phenomena are hampered during the simulation.

A different behaviour of the rock mass is observed when earthquake swarms are applied to the fault dislocation (dynamic conditions) (Fig. 13). Vertical displacements (Fig. 13a) and shear strain increments (Fig. 13b) show critical values around the platform margin, where an intense deformation is recorded as indicated by the plasticity indicators (Fig. 13c). These conditions promote the loss in the cohesion of the rock mass favouring the collapse of discrete portions of the margin (Fig. 13a).

When the modelling produces the collapse of a discrete portion of the margin, the simulation is blocked, the part corresponding to the collapsed material is removed and the slope profile is manually re-shaped according to the slide plane geometry created (compares different slope profiles of the three steps in Figs. 12 and 13). This re-shaping of the slope allows to better evaluating the rule of different geometric conditions along the slope during successive modelling phases. Successively the modelling re-starts throughout the fault displacement, simulating first static and then dynamic conditions.

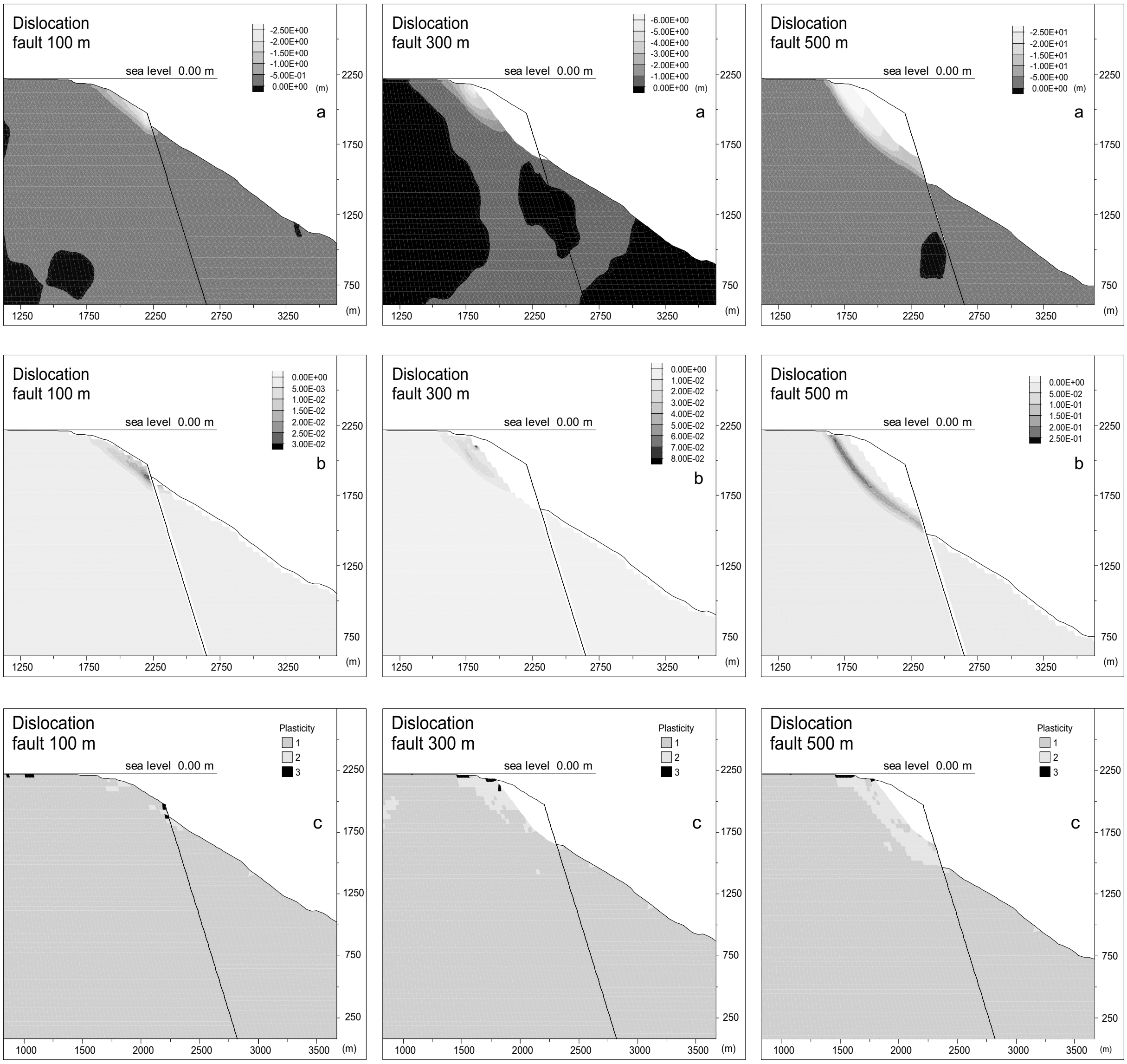

Fig. 13. Numerical modelled vertical displacements (a), maximum shear strain increments (b) and plasticity indicators (c) at different dislocations of the hanging wall of the fault during dynamic routine.

Some important results carried out from this analysis:

1 – the quasi-static simulation (without earthquakes) shows that the formation of a morphological downthrow does not represent alone a determinant condition to trigger large-scale collapses at the platform margin. This is probably due to the presence of well-cemented material on the platform margin;

2 – introduction of earthquake swarms to the fault dislocation generates the collapse of discrete platform margin portions;

3 – long time activity of the fault coupled with earthquake swarms allows reproducing geometries comparable with those observed in outcrops. Although the software does not allow simulating temporal evolution of faults activity, the total amount of displacement (500 m) suggests a pro-

tracted activity of the fault, necessary to reproduce similarity between the geometries obtained by software simulation and the outcropping ones. This activity could be referred to a time interval spanning from Albian to Early Cenomanian, corresponding to the time interval of occurrence of the megabreccia deposits;

4 – the geometry, which best approaches the palaeoescarpment reconstructed from outcrop data, is obtained after several collapse events occurring during the fault activity; this series of collapses produces the progressive backstepping of the platform edge and different megabreccia events.

7. Conclusions

This work presents some results obtained from the 2D modelling of large-scale margin collapses that characterised the edge of the Maiella platform during the mid-Cretaceous. For the modelling, a finite-difference numerical code was used, and this enabled the behaviour of the system in different static and dynamic conditions to be analysed, including both a homogeneous, intact model, and also one disturbed by a tectonic discontinuity.

The intact, homogeneous model allowed us to check the importance of the dynamic simulation in the formation of sub-vertical fracture planes along the slope; the variations in sea level seem to contribute little in the formation of fractures surfaces. Even if the application of a single earthquake to the intact model does not produce collapses equal in size to those observed, the formation of preferential fracture planes represents an important predisposing factor in the weakening of the platform margin.

The best results were obtained coupling earthquake swarms with dislocations along a fault located along the slope and more or less parallel to the direction of the pre-collapse platform margin. Families of sub-vertical fractures, asymptotic slide planes and collapses of discrete parts of the margin were produced by modelling in these conditions. A long-lasting seismic activity linked to the fault displacement is required to produce subsequent margin collapses, backstepping of the platform edge and rupture surfaces with similar geometries to those observed along the Early Cretaceous platform underlying the Murelle area.

The results obtained strengthen the hypothesis that the palaeoescarpment was caused by large-scale margin collapses linked to the tectonic dislocation of the system and associated earthquake swarms. Moreover, the principles developed and the preliminary conclusions reached may be applicable in general to carbonate platforms with features similar to those observed at the Maiella platform during the mid-Cretaceous.

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