European and Mediterranean Workshop
'Climate Change Impact on Water-related and Marine Risks'

26-27 October 2009, MURCIA (SPAIN)

Geomorphological coastal effects of climate change along Channel shoreline

Olivier Maquaire (1)*
Stéphane Costa (1)*
Mauro Soldati (2)*
Jose Luis Zezere (3)*

(1) CNRS UMR 6554, University of Caen Basse-Normandie, Caen (France)
(2) Dipartimento di Scienze della Terra - Università degli Studi di Modena e Reggio Emilia (Italy)
(3) Faculty of Geography, Lisbon (Portugal)

**** European Center on Seismological and Geomorphological Hazards, Strasbourg (France)***

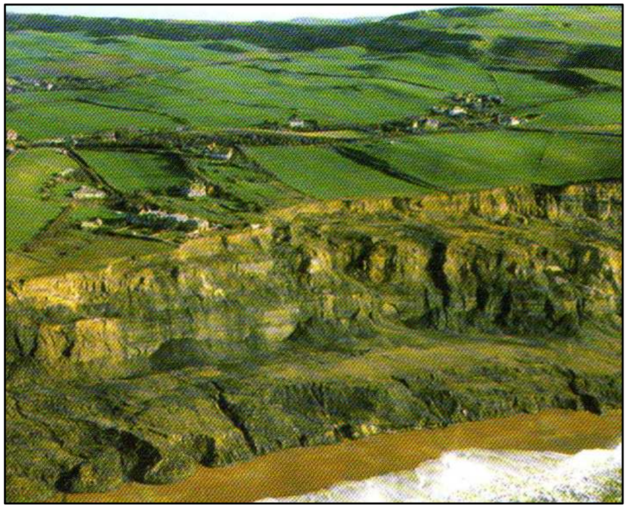
Project 'Coastal at Risk' supported by EUROPA Agreement

A great diversity of the coastal shoreline

- **Each type of coast has its own specific landform & behavior**

• Hard rocks cliffs (sandstone, chalk)

• Soft cliffs & coastal slope (clay, marl)



Photographies from R. McInnes, 2006; Costa & Maquaire

A great diversity of the coastal shoreline

- **Each type of coast has its own specific landform & behavior**

• Spits, inlets & tidal deltas

• Estuaries & tidal rivers

• Lowlands & barrier beach

• Sand beach & dunes

Photographies from R. McInnes, 2006

Coastal shoreline is affected by several hazards

- **Mass movement hazards inducing the retreat of the shoreline and of the cliffs**

• Rockfall in hard rocks

• Mudflows in marls & gully erosion

Photographies from Costa, Zezere & DIREN Normandie

Coastal shoreline is affected by several hazards

- **Mass movement hazards inducing the retreat of the shoreline and of the cliffs**

• Rotational & translationnal slides

• A hazard in conflict with land use planning and urbanisation in environmentally sound places

Photographies from Joly, Maquaire & DIREN Normandie

Coastal shoreline is affected by several hazards

- **Storm surge hazard**

- an open shoreline exposed to the General Circulation

Etretat
February 1990

Mers-les-Bains
February 1990

• large valleys orthogonal to the shoreline and cliffs,

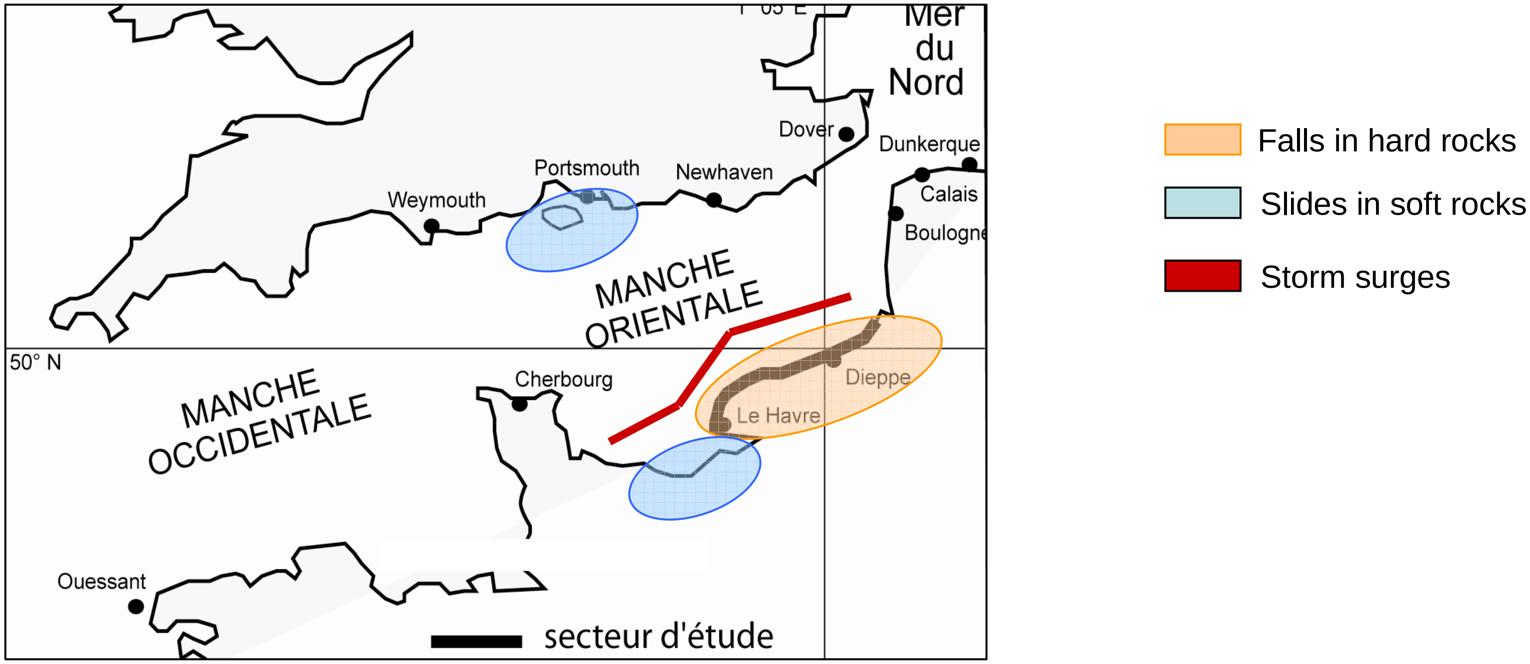
• low elevations,

• a preferential location of the inhabitants and the economic activities in the valleys,

• very often: a gravel beach leaned with a seawall not playing its part of protective plug.

Photographies from Costa

Content



Talk is focused on the dynamics of the cliffs and coastal slopes with main illustration on the Channel coast.

Main causes of evolution & instability of coastal slopes

- identification of predisposing and triggering factors (*hard rocks & soft rocks*)
- assessment of the role of each factors (safety factor)

- **Main predicted impact of climate change**
- **Quantification of the shoreline and cliff retreat**
- **Study case: slides in soft-rocks coastal slope (marls)**
  - Villerville-Cricqueboeuf slide, Normandy, France
  - St Catherine’s slide, Isle of Wight, England
- **Conclusion & forthcoming steps**

Main causes of evolution & instability of coastal slopes

- **identification of preparatory (& predisposion) and triggering factors**

Coastal slope is under the influence of **several processes**:

Marine processes: wave (direction, height, …), tide, storm surges, longshore drift, …

Sub-aerial (or continental) processes: weathering, climate (rain, thaw-freeze), water regime change (infiltration,…), hydrological (watertable fluctuations), …

Human activities: artificial excavation, landuse modification, urbanisation, drainage, …:

Preparatory (& predisposion) factors: topography, lithology, structure, landcover, …

Triggering factors: **climatic conditions** (rainfall, t°, …), **sea erosion**, anthropic actions, earthquake, ….;

- **Assessment of the role of each factor** by the calculation of the ***safety factor F***.

A slope is stable when the *resisting forces* are superior or equal to the *driving forces* (or destabilising forces). The ratio between resisting forces and driving forces is the ***safety factor F***.

➔ **Safety factor value is time-dependent** following the influence of each factors

Main causes of evolution & instability of coastal slopes

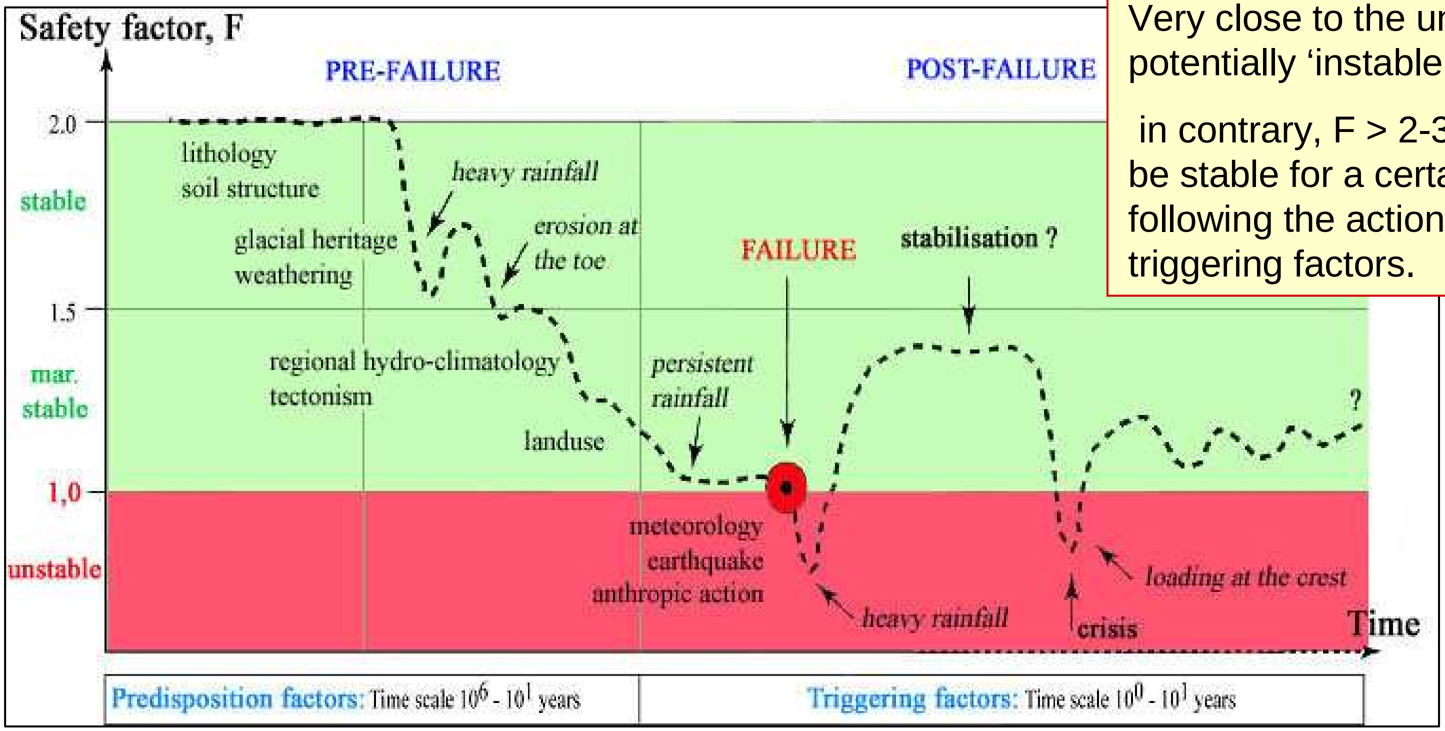
- **Assessment of the role of each factor** (***safety factor F***).

➔ Slope stability (Geomechanical modelling)

Future evolution of the coastal slope depends of the 'actual value' of its factor of safety:

Very close to the unit, slope potentially 'instable' or,

in contrary, F > 2-3, slope will be stable for a certain 'delay' following the action of the triggering factors.



Evolution of safety factor through time - time influence of predisposition and triggering factors on instability (from Van Asch *et al.*, 2007)

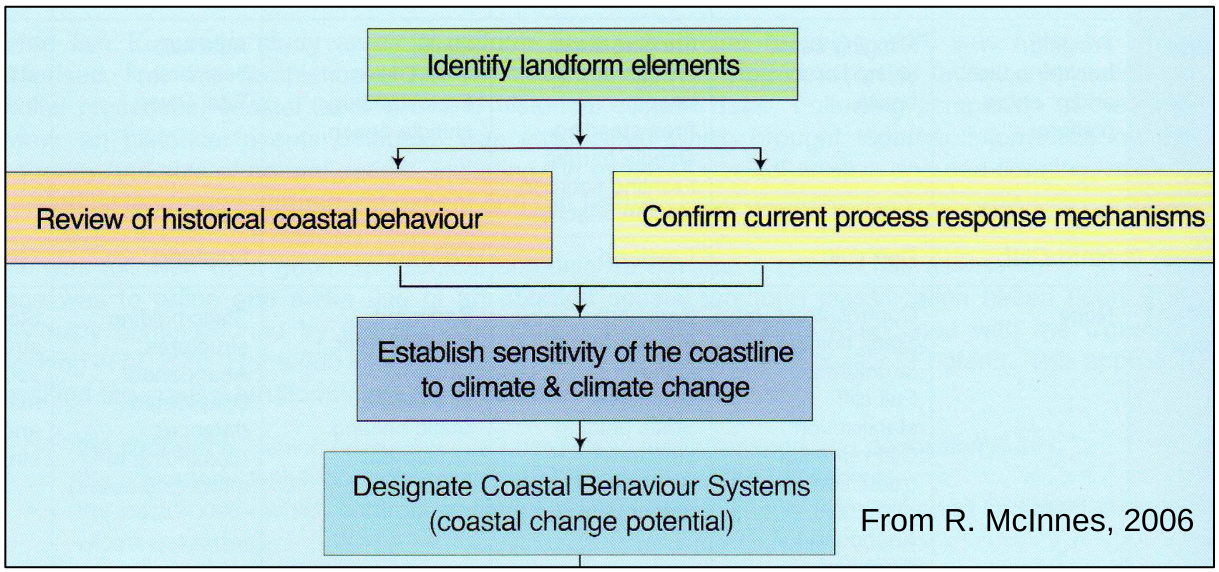
Slope instability responds to a combination of these factors. Predisposition factors change most times only gradually over time whereas the triggering factors are 'transient'.

For cliffs & 'coastal slopes', main influence of GWT fluctuations (rainfall) and sea erosion at the toe. These two main factors could be change following the climatic change scenarios.

Main predicted impacts of climate change

- **Methodology**

Great diversity of coastal landforms: shoreface, shoreline & backshore,
'**Coastal behaviour systems**' (**CBS**) have to be define according to:
- Interlinked landforms that control the system response to forcing events
- Connectivity of landforms cross-shore and longshore
- Changes in one landform can trigger adjustments to the others



From R. McInnes, 2006

'**Coastal behaviour systems**'

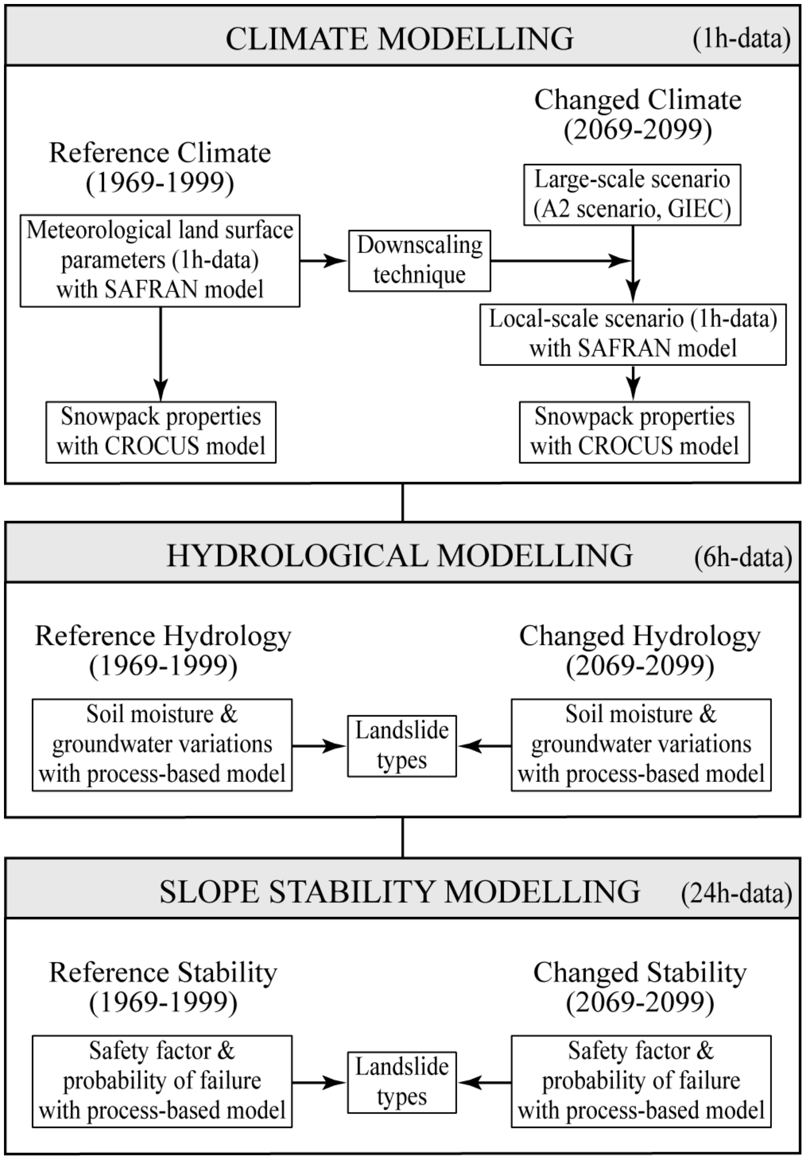
From the past to the future …
… via the present

Geomechanical & hydrological modelling:
(Fuzzy set, GIS-based & dynamic approach, …)

Establish **sensitivity** and **behaviour** of CBS to **actual climatic conditions'** and to **climate change**, based upon European regional climate models (by using climate variables downscaled from General Circulations Models as inputs conditions to the slope models) ➔ Assessment of the future predicted impacts,

Main predicted impacts of climate change

- **Good example of coupling modelling**



- **Methodology (applied in mountainous area):**

- Climate variables downscaled from GCMs are used as input conditions for the slope models

- Land surface meteorological parameters and snowpack properties are modelled for the reference climate and a ‘changed’ climate

- Hydrology and slope stability are modelled for the reference and ‘changed’ climate

From Malet et al., 2007

Main predicted impacts of climate change

Predicted impacts of future pressures on coastal zones include:

- Overtopping of coastal defences due to **sea level rise**;
- **Increased wave forces**
- **Increased cliff groundwater level** and **reduced toe support** for coastal landslide systems (by coastal erosion)
- change in longshore drift patterns
- tidal/fluvial flooding interaction
- potential for flash flooding
- Loss of fronting inter-tidal deposits

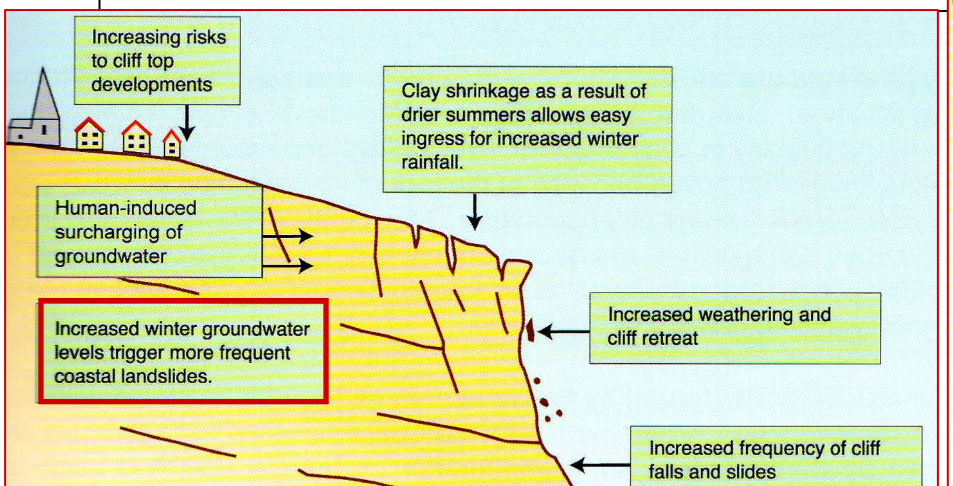
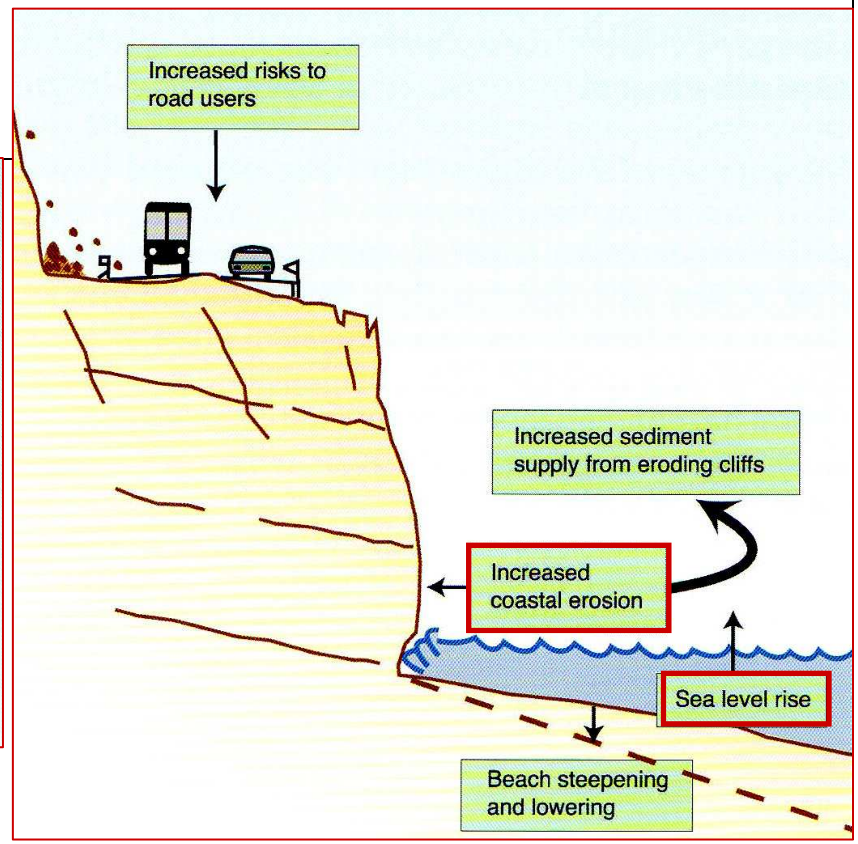


Figure 2.3: Some of the physical impacts of climate change on a developed coastal zone (McInnes 2006.)



Main predicted impacts of climate change

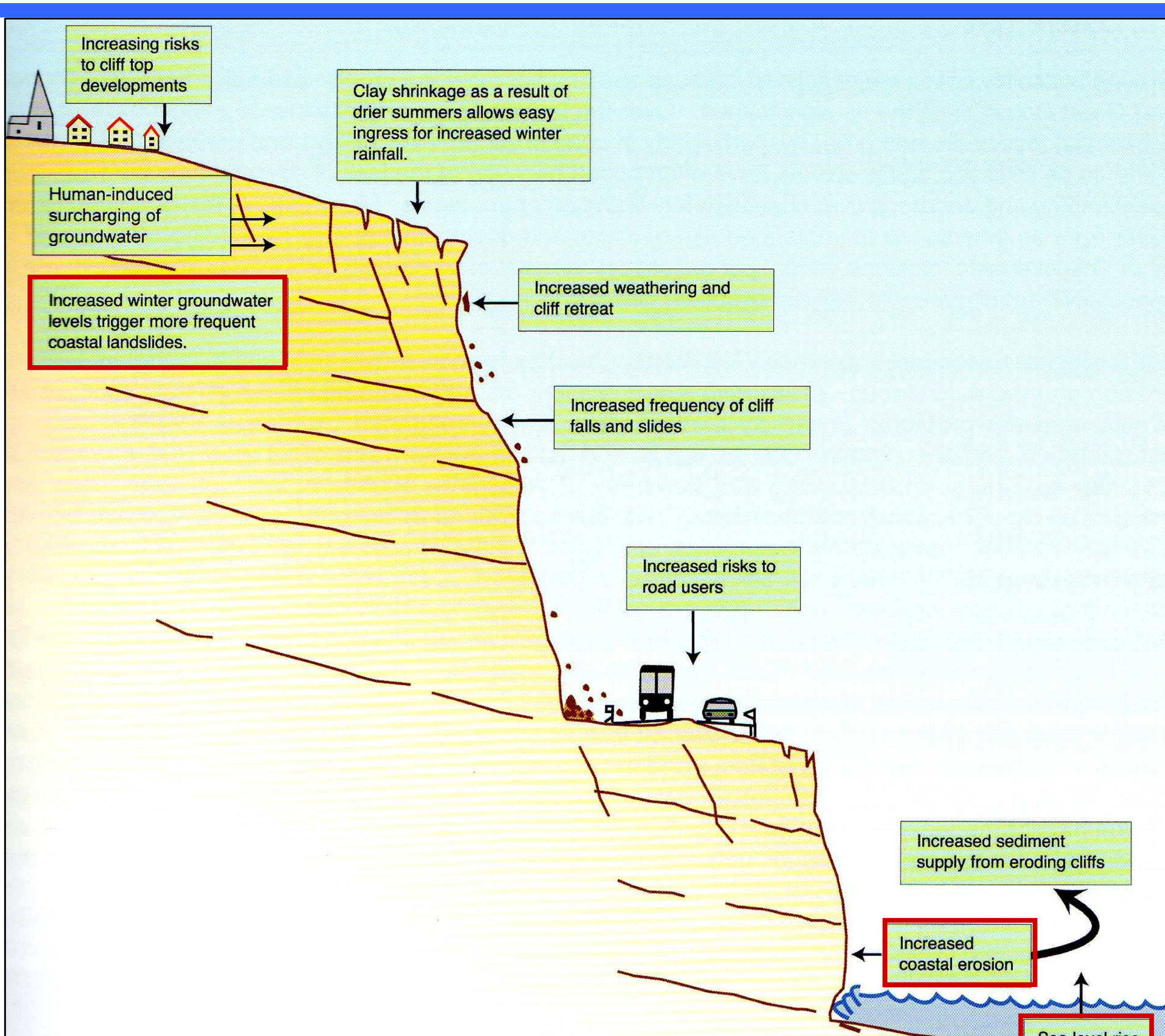
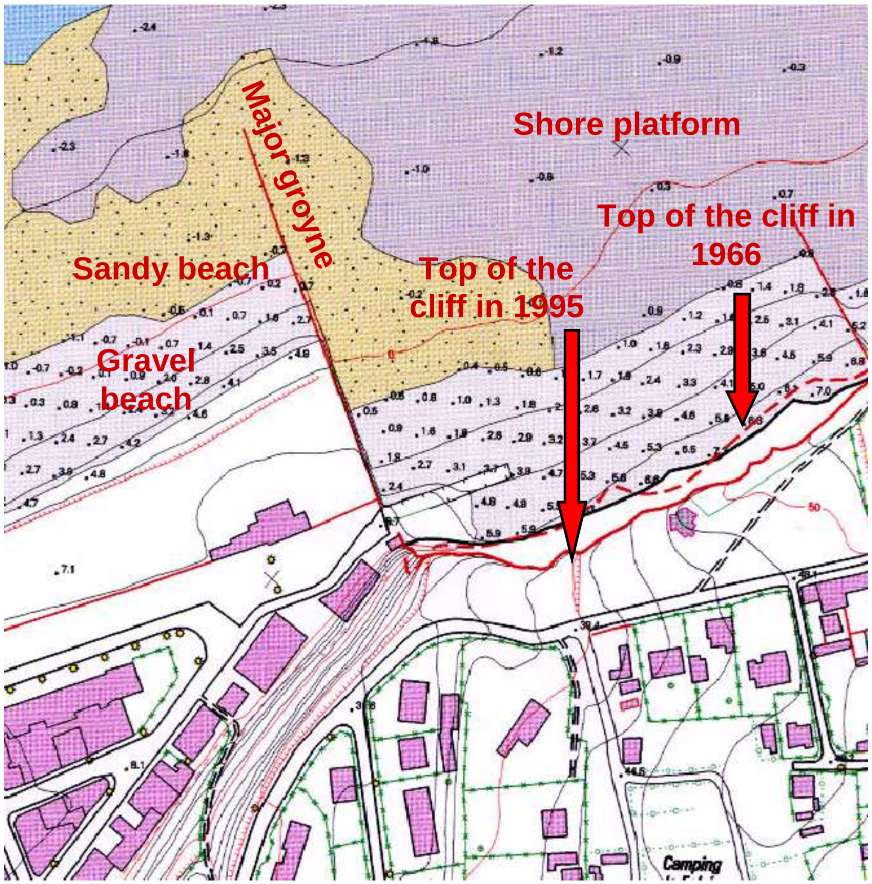


Figure 2.3: Some of the physical impacts of climate change on a developed coastal zone (McInnes 2006.)

From R. McInnes, 2006

Quantification of the shoreline and cliff retreat

Historical coastal behaviour



Eastern Part of Mers-les-Bains beach
(1/2 000 map; CPIBP)

Comparision of sereval types of documents: maps, cadastres, aerial photographies, …

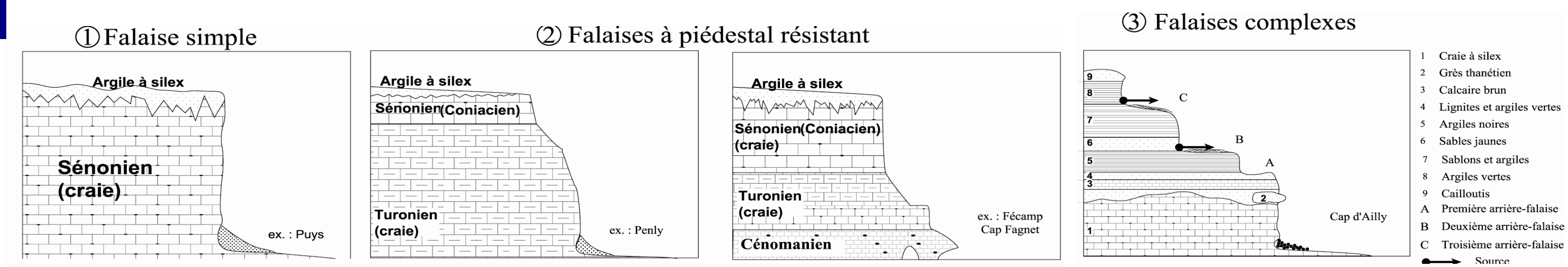
… by stereophotogrammetric analysis, …
under GIS environment (georeferenced data base, …

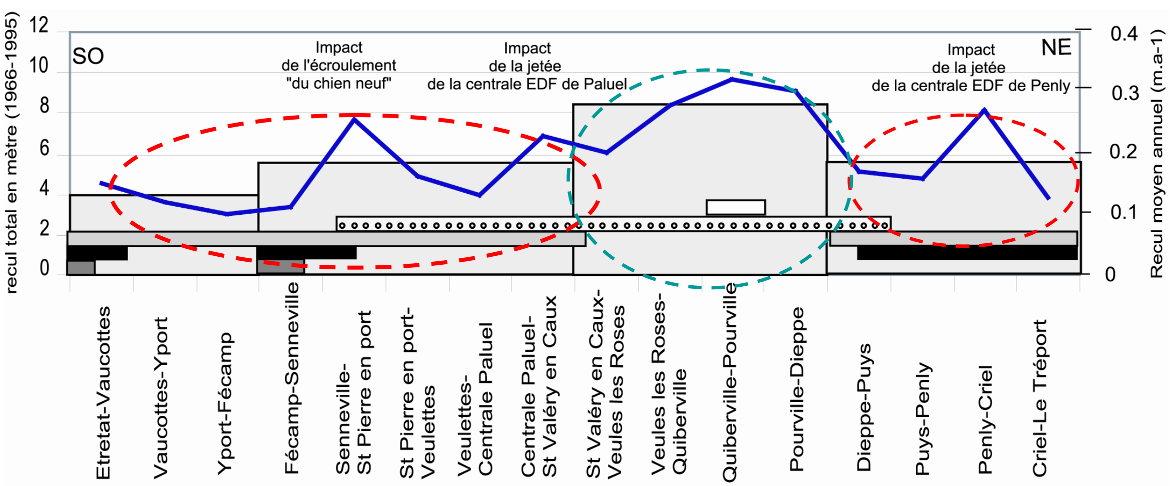
- Several dates

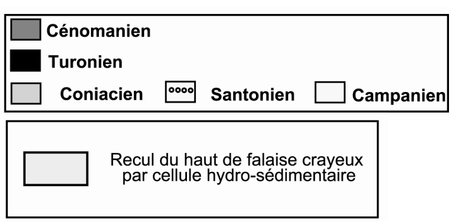
- **Accuracy** on the determination of the position of the top of the cliffs: ± 0.3 m to ± 0.8 m (quality & resolution of the documents)

Quantification of the shoreline and cliff retreat

- **Velocity of the retreat is controlled by hillslope morphology and lithology**

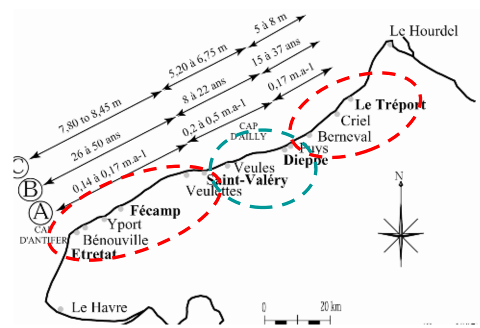






0.08 to 0.20 $m.yr^{-1}$

> 0.20 $m.yr^{-1}$

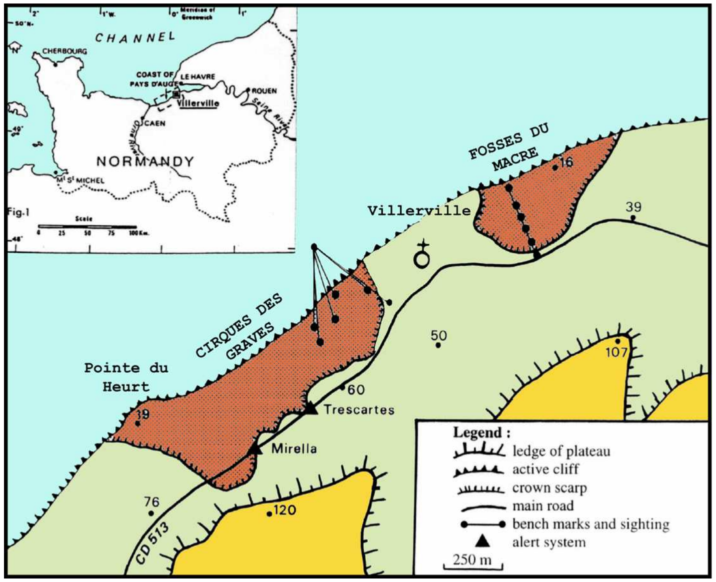


- **Low to moderate retreat**
- Turonian and Cenomanian lithologies

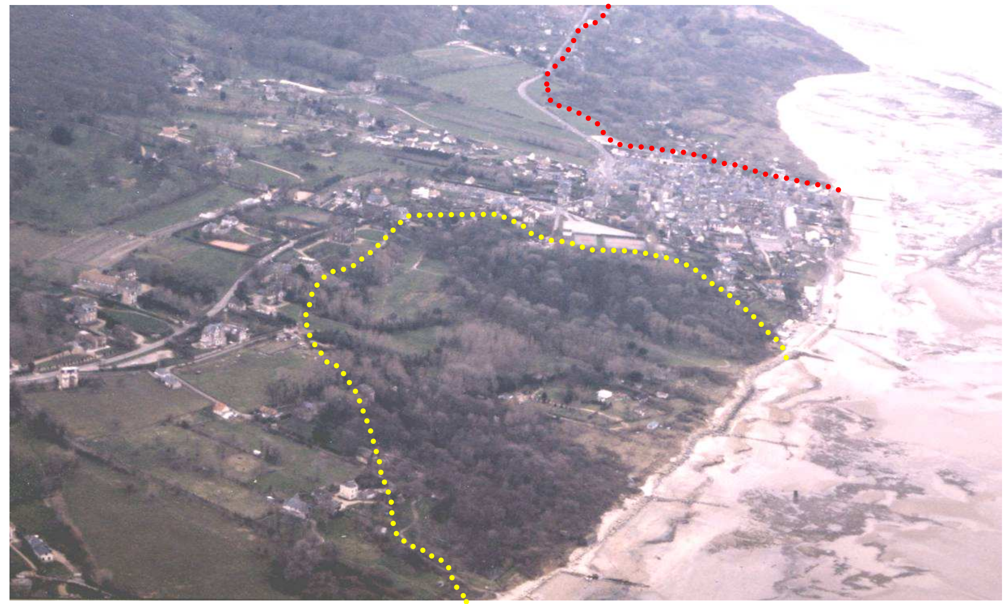
- **High retreat (St-Valéry to Dieppe)**
- upper part of the Senonian lithology
- high porosity and high micro-fracturation
- low shear strength

Study case: slides in soft-rocks coastal slope (marls)

- **Example of Villerville-Cricqueboeuf slide, Lower Normandy, France**



Location of the Villerville-Cricqueboeuf landslides and of the monitoring networks.



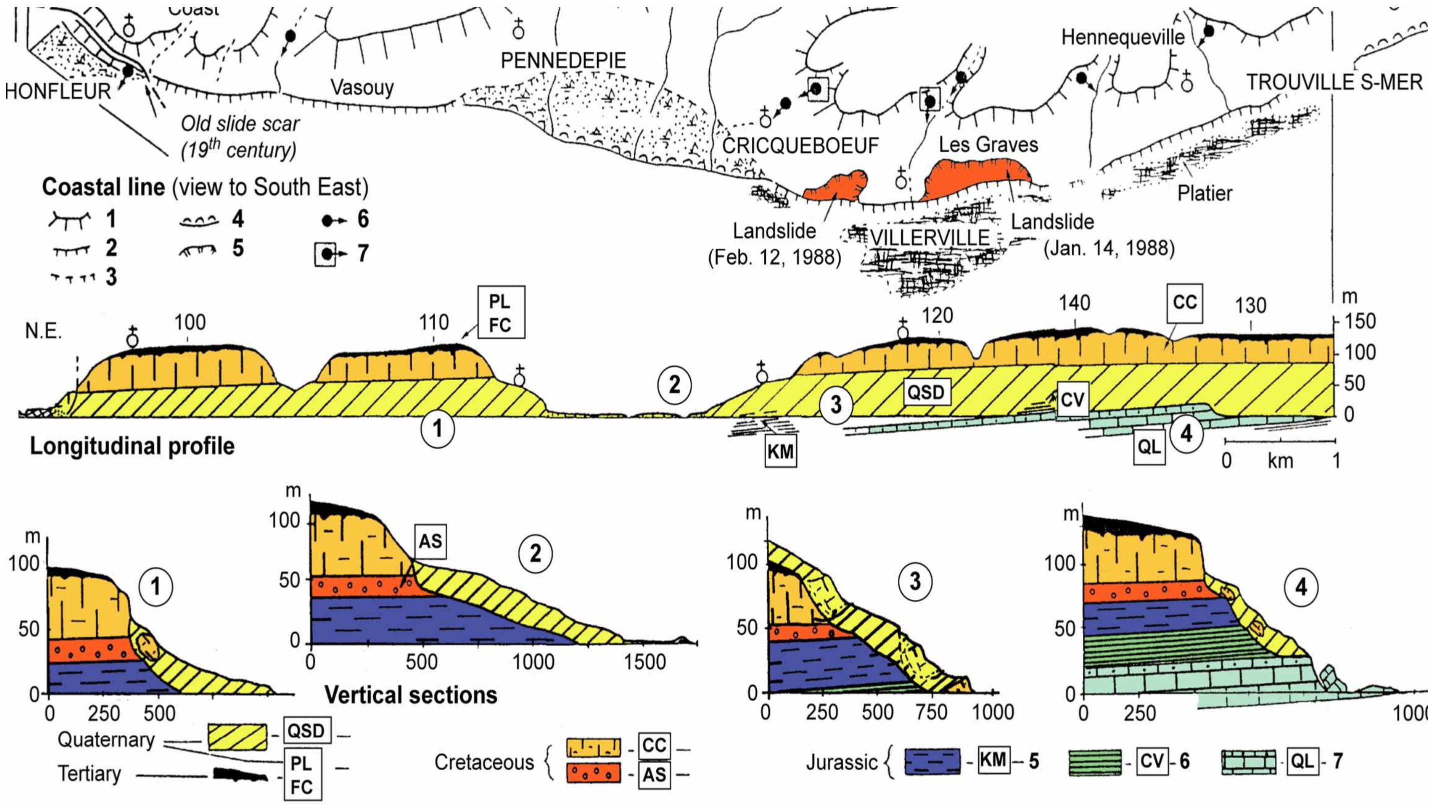
Aerial view of the Villerville-Cricqueboeuf landslide in 1988.

Pays d'Auge coast is periodically affected by landslides.

In January 1982, major landslides ➔ major damages (roads, destroyed houses): Cirque des Graves & Fosses du Macre.

Study case: slides in soft-rocks coastal slope (marls)

- **Example of Villerville-Cricqueboeuf slide, Lower Normandy, France**



Coastal line: 1. Ledge, 2. Active cliff, 3. Old cliff, 4. Sand bar,
5. Crown scarp, 6. Uncatched spring (Emergence), 7. Catched spring.

Longitudinal profile: 1. Quaternary surfical deposits, 2. Plateau loam and flint clay, 3. Cenomanian chalk,
4. Albian sands, 5. Kimmeridgian marls, 6. Villerville clays (Oxfordian), 7. Sandy limestones of Hennequeville.

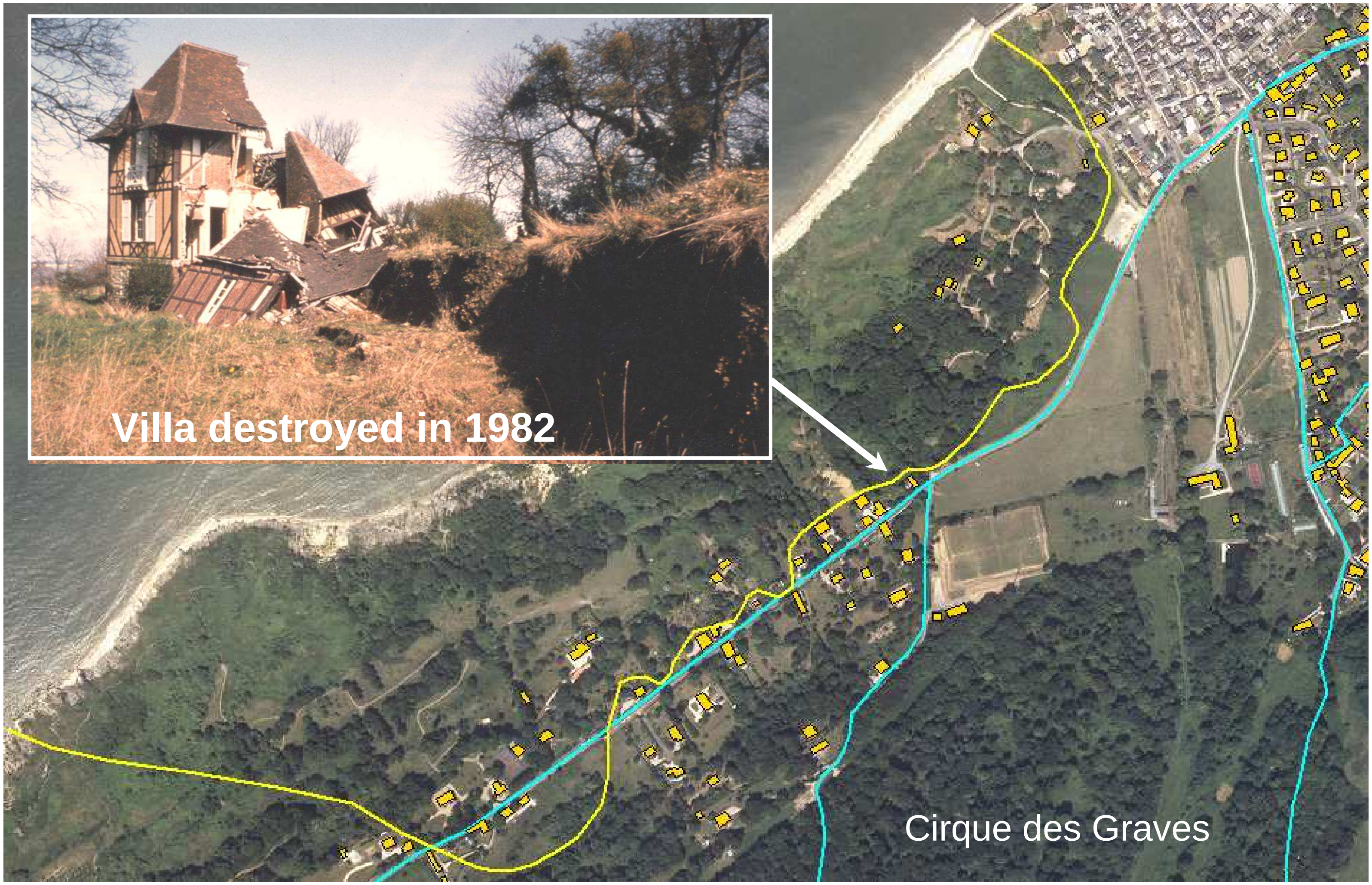
Morphological setting of Pays d'Auge cliffs (modified from Flageollet & Helluin, 1987) .

Main scarp is composed of Cenomanian **chalk** overlying **glauconitic sands**. Below, a thick layer of **marls** is on top of the **sandy limestone** of Hennequeville which shapes the cliff toe and constitutes a reef flat

Study case: slides in soft-rocks coastal slope (marls)

- **Example of Villerville-Cricqueboeuf slide, Lower Normandy, France**

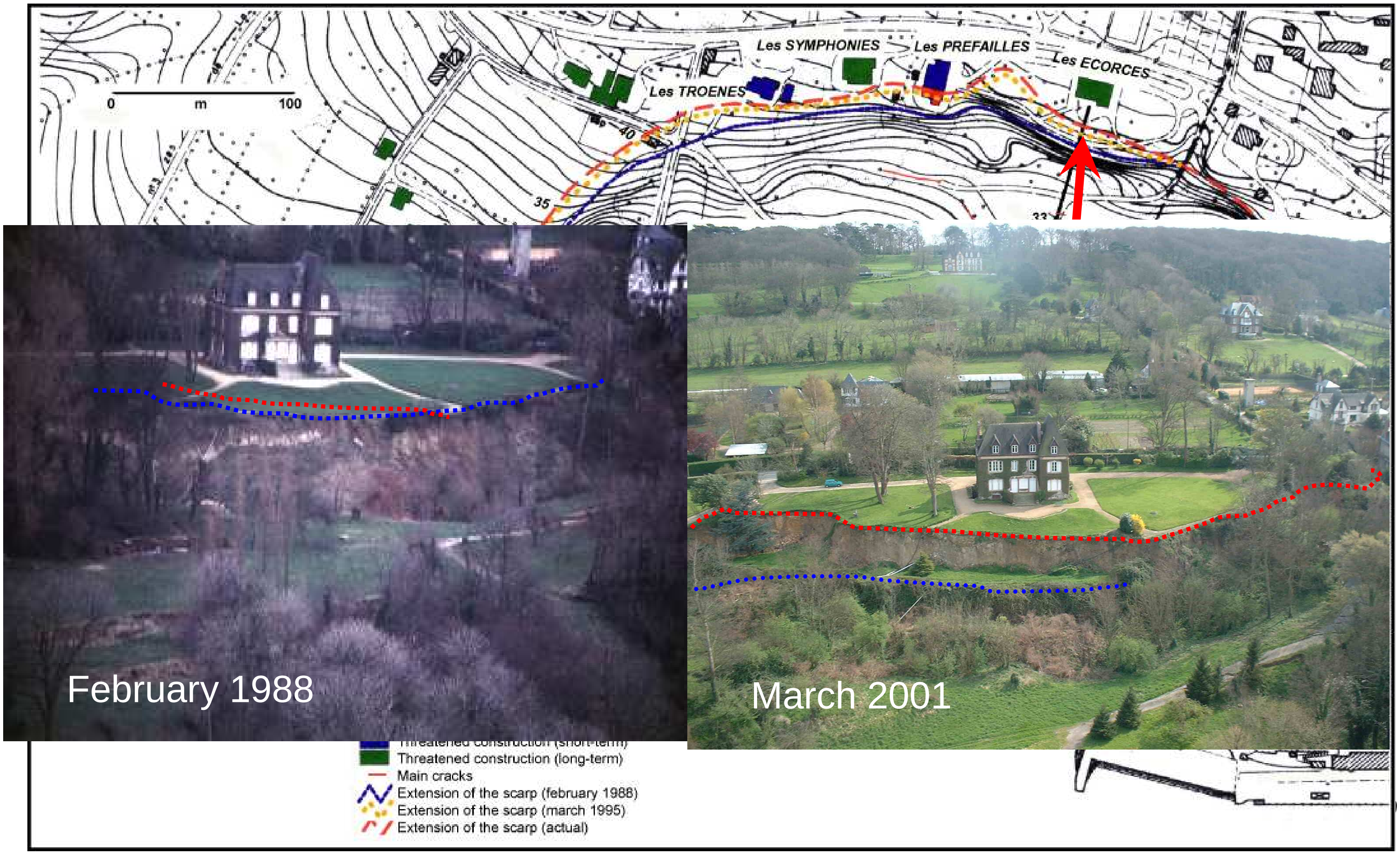
First time failure: on **10/11 January 1982,** a major landslide destroyed totally or partially some thirty houses and damaged the road in two places. At the top, crown of the landslide consists in a 3 m high scarp.



Study case: slides in soft-rocks coastal slope (marls)

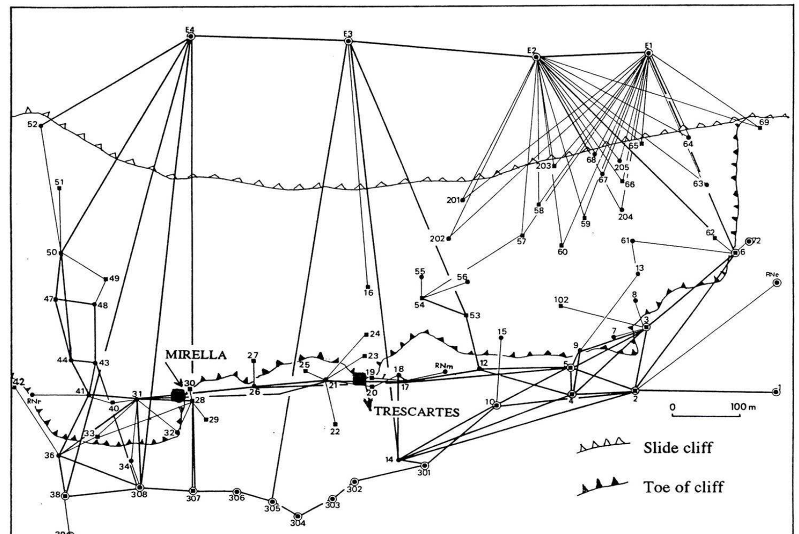
- **Example of Villerville-Cricqueboeuf slide, Lower Normandy, France**

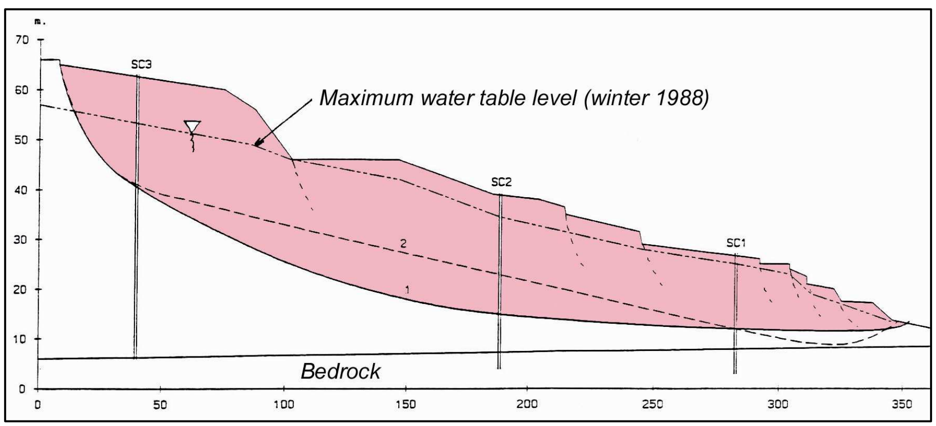
Reactivation: 1988, 1995, 2001 ➔ Recession of the main scarp and main damages:



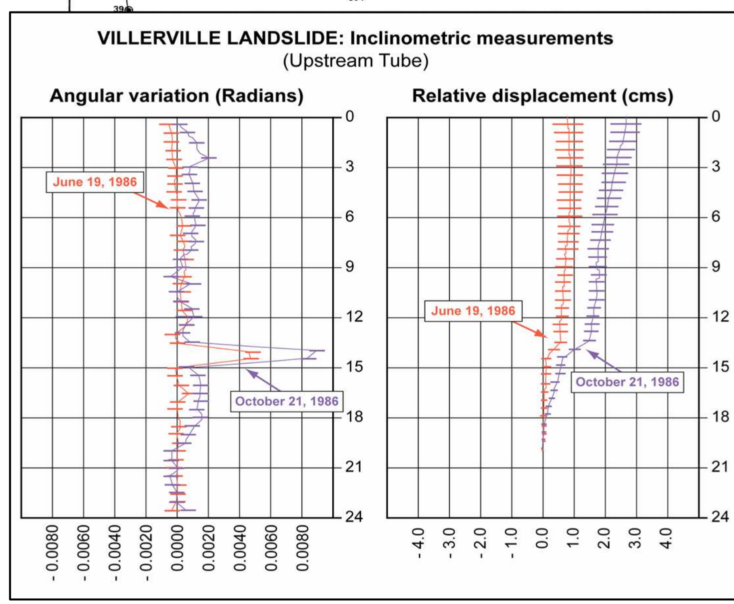
Study case: slides in soft-rocks coastal slope (marls)

- **Example of Villerville-Cricqueboeuf slide, Lower Normandy, France**
  - ➔ **Monitoring network:** surficial benchmarks, inclinometers, piezometers, climatic survey, …





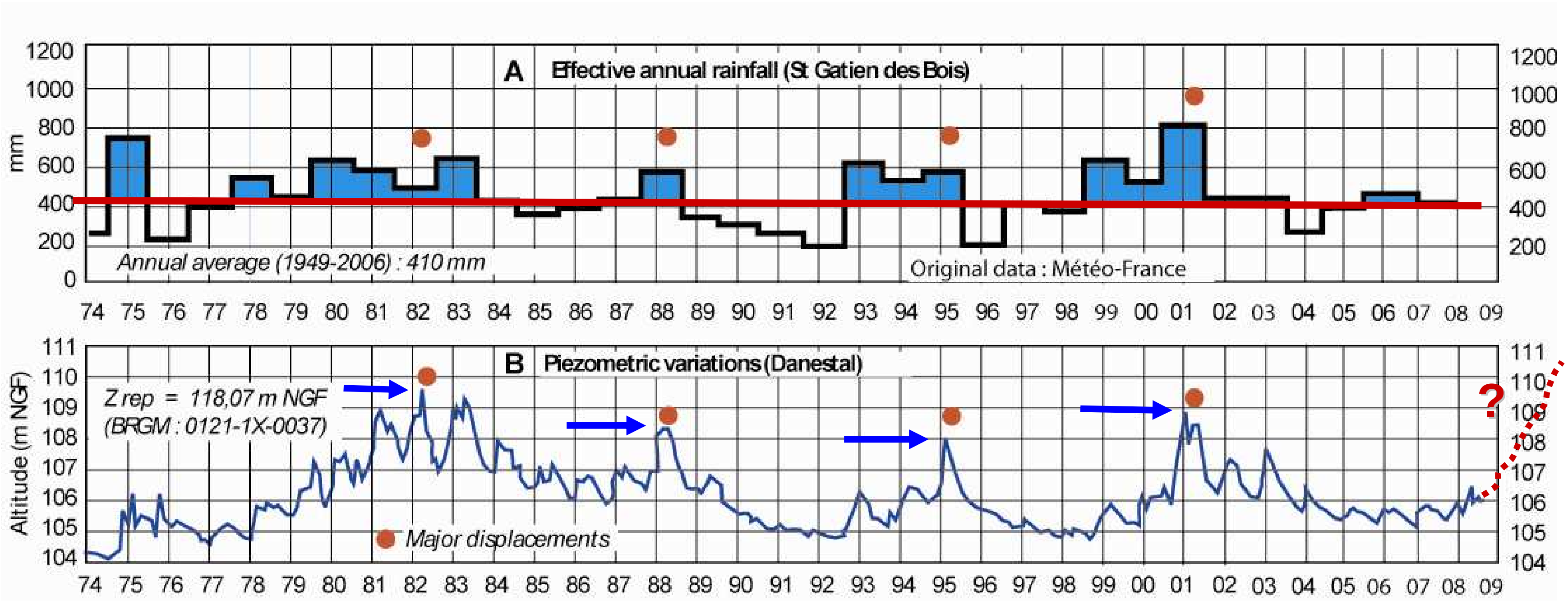
Location of inclinometers. Geometry of the 'Cirque des Graves' landslide with the location of the slip surface identified in the inclinometer.



Study case: slides in soft-rocks coastal slope (marls)

- **Example of Villerville-Cricqueboeuf slide, Lower Normandy, France**

• Acceleration triggered by GWT above a certain threshold



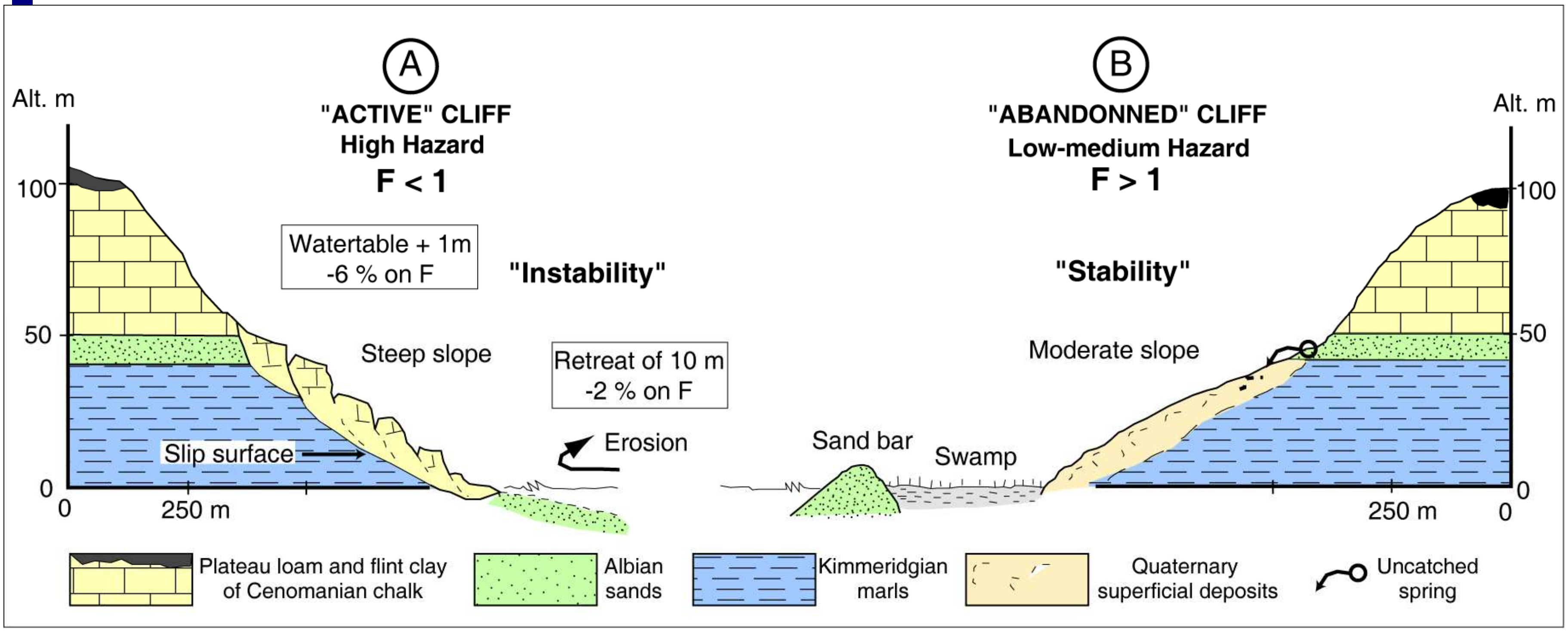
Development of the Villerville-Cricqueboeuf landslide in relation to the groundwater table and effective annual rainfall data (from Maquaire)

High groundwater level observed in 1982 is in phase with the onset of the major movement of January 1982. Same characteristics can be observed for the crises of February 1988 and 1995, and January 2001 which occurred after several hydrologic years of rainfall amounts higher than the average.

Thresholds were different at each crisis. GWT level in 2009 is very close to the lowest level (1975), but for the future with 'higher winter rain', the GWT will rise & trespass the previous thresholds (1982, …)

Study case: slides in soft-rocks coastal slope (marls)

- **Geomechanical slope stability analysis** (example of Villerville-Cricqueboeuf)



Main influence of:

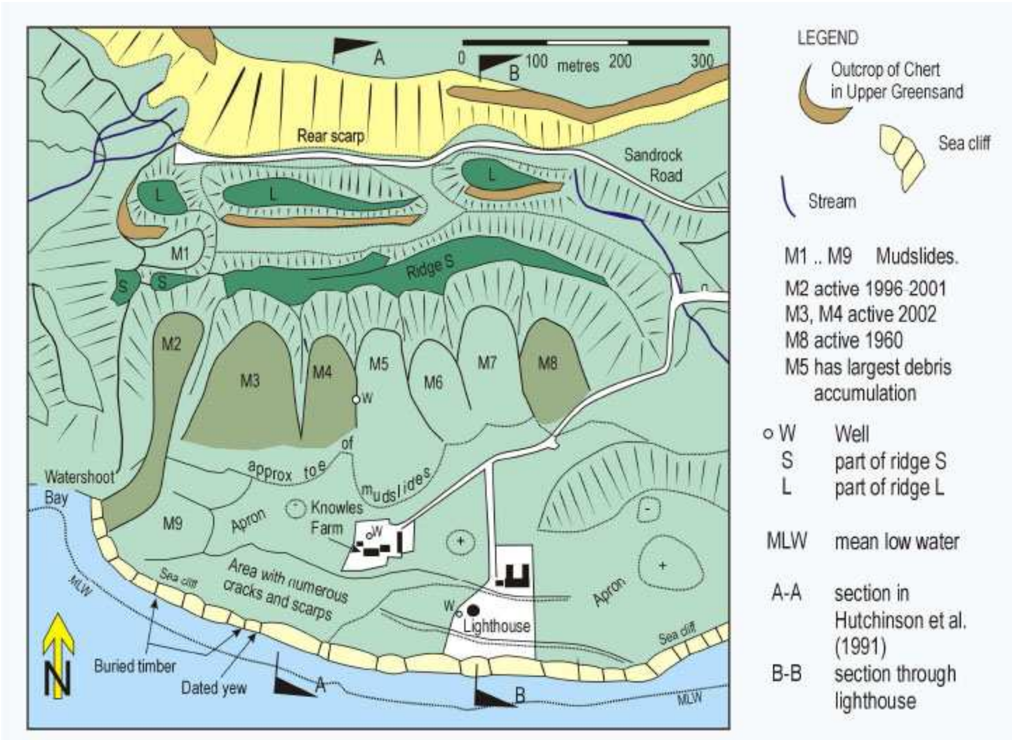
- **GWT variations**
- **sea erosion** at the base of the hillslope (toe unloading)

If slope activity is mainly controlled by climatic conditions & sea erosion, there are …

…. A lot of uncertainties ?, great variability of the F values following the portion of coastal slope analysed !!

Study case: slides in soft-rocks coastal slope (marls)

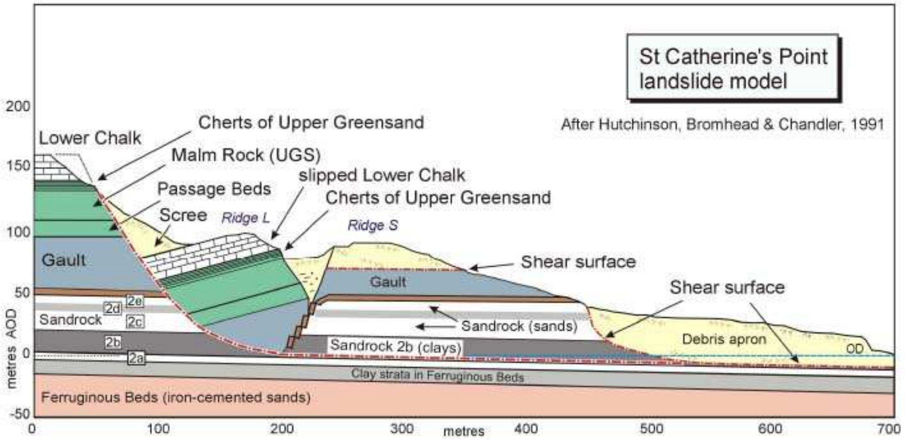
- **Slide of St Catherine's Point, Isle of Wight)**



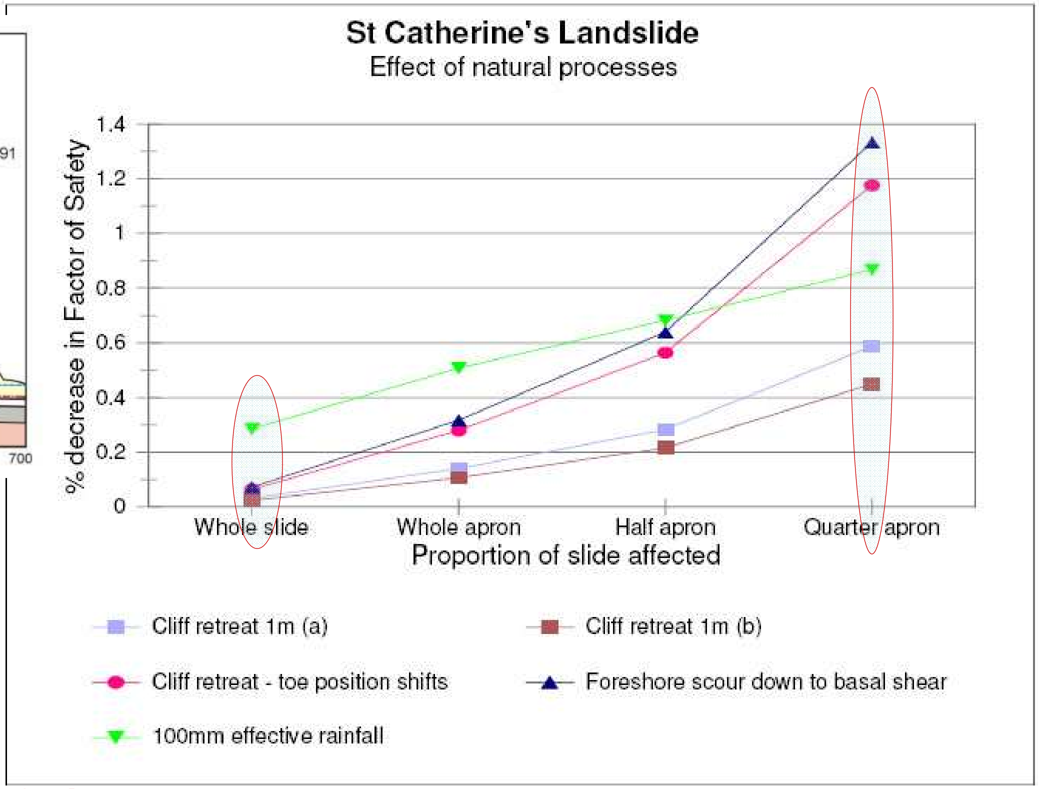
From E. Bromhead, Cliffs meeting, July 2006

Study case: slides in soft-rocks coastal slope (marls)

- **Geomechanical slope stability analysis** (example of St Catherine's Point, Isle of Wight)



From E. Bromhead, Cliffs meeting, July 2006



Main influence of:

- **GWT variations (i.e. effective rainfall)**
- **sea erosion** at the base of the hillslope (toe unloading)
- great variability of the F values following the analysed portion of coastal slope !!

A lot of uncertainties ?

For the future, possibility to assess the impact of climatic change, but **which scenario do we use?**

Choice of the realistic scenario?

- **Scenarios to assess the impact of climatic change**

Coastal sites could be destabilized by **several factors** (each have its own weight)

We well know that increased rainfall & sea erosion increases slide activity and cliff retreat

Climate change: Predictions are for increased rainfall overall, but more in winter, less in summer !!!, ….
….. Storm rainfall events will be intense (and frequent?) ➔ increased toe erosion

Likely Future Scenarios:

- Increased coastal erosion and cliff retreat?
- Higher winter rainfall, groundwater levels and coastal cliff instability?
- Reactivation of relict coastal landslide systems?

Key parameters:

- Historical recession rate
- Landslide event frequency
- Sea level rise
- Winter rainfall
- Sediment budget (beach)
- Shoreline protection

But, predictions are highly variable: Are these predictions realistic?
➔ We don't know the likelihood of each prediction

Choice of the realistic scenario?

Risk assessment & risk management: spatial occurrence

Potential reactivation of relict coastal landslide systems?

Choice of the realistic scenario?

Risk assessment & risk management: spatial occurrence

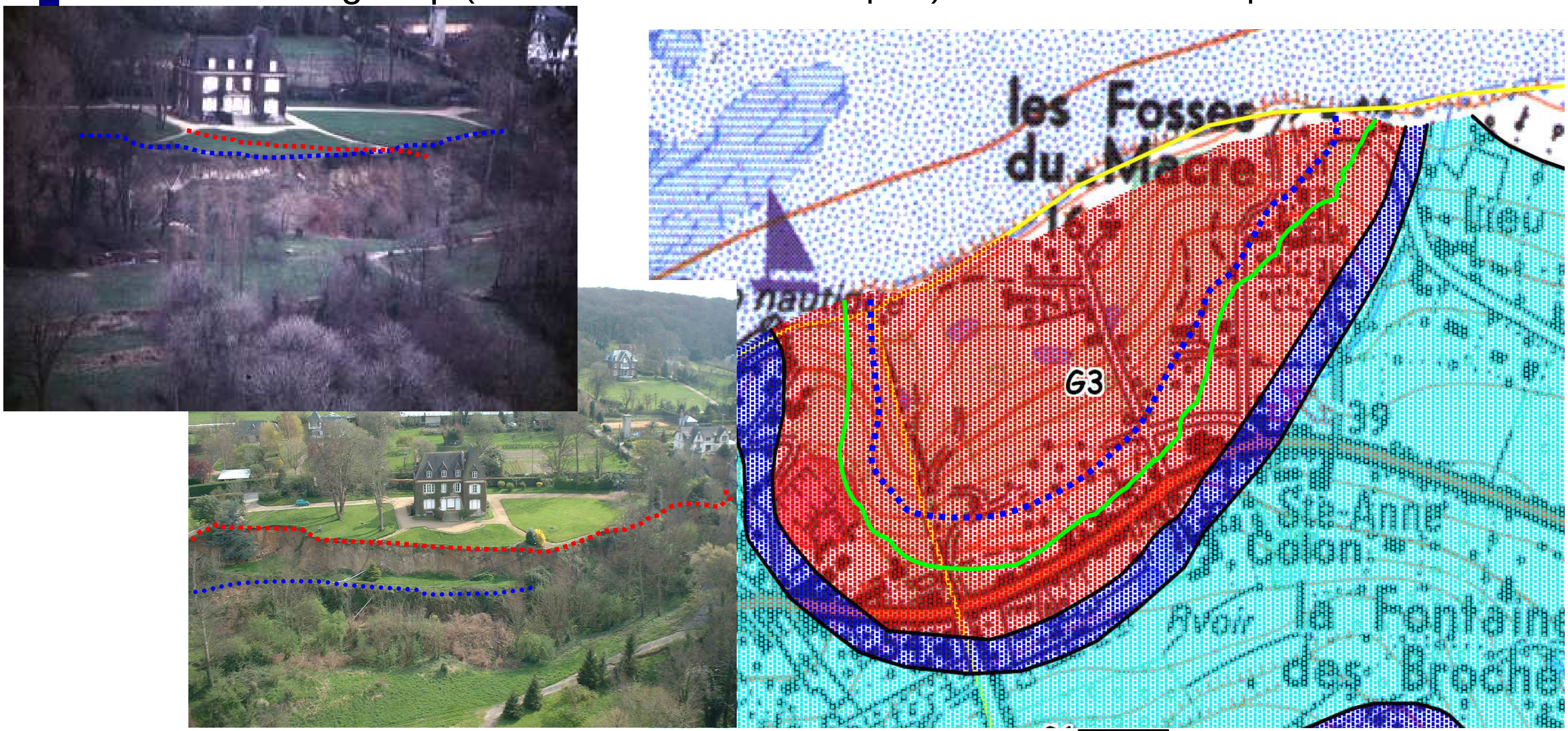
From McInnes, 2008

Cliff recession or slide progression prediction?

Choice of the realistic scenario?

Slide activity prediction? For Risk management

Hazard zoning map (Plan Prévention des Risques) of Villerville – Cricqueboeuf



Main scarp in 1980's

Main scarp in 2008 (limit of active zone)

G1: Low hazard.

G2: Medium hazard.

G3: High hazard.

Conclusion & Forthcoming steps

Great difficulties to assess the real impacts of climatic change on the coastal slopes & cliffs.

Following the '***evolution stage***' of the slope (value of its safety factor), the response to the natural forces will be very different following the:

- Thresholds (i.e. watertable position)
- Time of the each 'action' or process (rapid, transient, long, …)
- Temporal & spatial evolution and succession of the different processes,
- Stock of the inter-tidal deposits & its mobility: evacuation but deposition along the shoreline in the other places,
- Temporality of the 'adjustments' is not the same along the shoreline
- mitigation measures (adapted or not, sufficient or under-estimated, …)

➔ No always direct '**causes–effects**' relationships.

➔'**Transfer of knowledge**' to similar landform coasts is also very difficult (Need keys !!)

➔ Need to improve our knowledge on the '***chain (succession) of processes***' for different types of coast, different process, dynamic, …

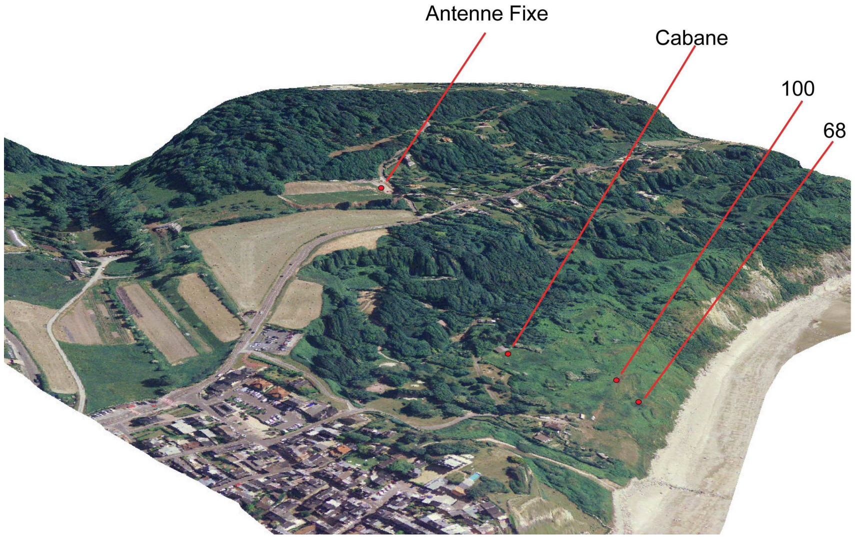
Conclusion & forthcoming steps

- **Towards QRA (Quantitative Risk Assessment)**

- **Better understanding of the process at the local scale**
  - implementation of high temporal resolution monitoring on selected sites (in **continuous**) i.e GPS, Inclinometer, …
  - identification of water circulation by geophysical techniques
  - Development of a 'chain of coupled models'
  - **Assessment of effects of climatic change**

- **Better understanding of the distribution of processes at the regional scale**
  - multi-date Lidar and hyperspectral survey
  - potential of VHR satellite imagery (quantification of cliff retreat, quantification of landslide displacement by image correlation)
  - probabilistic analysis of landslide susceptibility
  - **effects of Global Change** (climatic & human) on coastal hazards

- **Consequences and risks assessments**
  - identification of elements at risk, damages
  - vulnerability analysis (buildings, roads, protective works)
  - cost-benefits analysis, …



References

Bromhead, E. 2006. Some thoughts on climate change and its influence on slope stability. Cliffs project: meeting July.

Lissak C., Malet J.-Ph., Maquaire O., 2009. Hydrological concept of the Villerville-Cricqueboeuf landslides (Normandy coast, France): inferences from 20 years of groundwater observations and from geophysical investigation. European Geosciences Union, Vienna, April 2008. *Geophysical Research Abstracts*, Vol. 11, EGU2009-10389, 2009.

Malet, J.P., Remaître, A., Maquaire, O., Durand, Y., Déqué, M., Etchevers, P., Guyomarch, G., Van Beek L.P.H. 2007. Assessing the Influence of Climate Change on the Activity of Landslides in the Ubaye Valley. IWCCE Conference, Session 3: Advances in hazard modelling and prediction (short and long-term), May, 10p.

Maquaire, O. (1990), Les mouvements de terrain de la côte du Calvados. Recherches et prévention. *Documents du B.R.G.M.,* n°197. Editions du B.R.G.M., 430 p.

Maquaire, O., Malet, J.-P. Assessment of coastal landslide hazard: the Villerville-Cricqueboeuf landslides (Normandy coast, France). European Geosciences Union, Vienna, avril 2007. Poster.

McInnes, R. 2000. Managing ground instability in urban areas. A guide of best practice. September. Publications of ‘Centre for the Coastal Environment Isle of Wight Council United Kingdom. 80 p.

McInnes, R. 2006. Responding to the risks from climate change in coastal zones. A good practice guide. Publications of ‘Centre for the Coastal Environment Isle of Wight Council United Kingdom, 84 p. http://www.coastalwight.gov.uk

References

McInnes, R. 2008. Coastal Risk Management. A non-Technical Guide. Standing Conference on problems Associated with the Coastline (SCOPAC). October. Publications of ‘Centre for the Coastal Environment Isle of Wight Council United Kingdom 86 p. http://www.scopac.org.uk

McInnes, R. 2008. Risk management. General overview. Landuse control strategies. *Mountain-Risks Intensive course on Risk Assessment and Management. UPC, Barcelonna, 1-4 September 2008.*

Winter, M. 2006. Debris flow impacts on Scottish road infrastructure and the potential impacts of climate change. Cliffs project: meeting July.