Applied Multidimensional Geological Modelling

A CONTRIBUTION FOR:--

SECTION 4 – CASE STUDIES

CHAPTER 24: Application Theme 2: Geohazard Identification

CASE STUDY #4: ROLE OF 3-D GEOLOGICAL MODELS IN EVALUATION OF COASTAL CHANGE, TRIMINGHAM, NORFOLK, UK

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OUTLINE

ROLE OF 3-D GEOLOGICAL MODELS IN EVALUATION OF COASTAL CHANGE, TRIMINGHAM, NORFOLK, UK

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1. INTRODUCTION

Coastal erosion was widespread around the United Kingdom during the 20th Century and is expected to become even more pervasive through the 21st Century due to sea-level rise and climate change. Erosion poses a direct hazard for coastal residents with potential risks of personal injuries or loss of life and damage or complete loss of property. Failure of natural and artificial defenses during storms increases the risk of coastal flooding. Erosion and flooding resulting from a specific coastal storm may be predicted accurately, but mesoscale predictions – encompassing 10-100 km (5-50 miles) and decades to centuries – are unreliable (Payo *et al.,* 2017). Yet these predictions are necessary to manage risks and make decisions on protective measures, or to evaluate responses to climate change impacts (Murray *et al.,* 2013; Nicholls, 2015). In response to this need, the National Environmental Research Council (NERC) established two projects: *Integrating Coastal Sediment Systems* (iCOASST) (www.icoasst.net), and *Improving our understanding of processes controlling the dynamics of our coastal systems* (BLUEcoast) (www.bluecoastuk.org).

The 4-year iCOASST project (2012-2016) involved a consortium of UK Universities, research laboratories (including the British Geological Survey, BGS), and engineering consultants, with the Environment Agency as a key embedded stakeholder. The project's task was to determine how best to predict mesoscale (i.e. decades to centuries) coastal morphological changes to guide long-term shoreline management and strategy studies (Nicholls *et al.,* 2012; 2015; van Maanen *et al.,* 2016). This is a difficult problem because the evolution of a coastal landform, such as a beach or cliff, is influenced by interactions with adjacent coastal landforms and by human interventions and because, coastal erosion is better understood and modelled than coastal recovery. The 4-year BLUEcoast project (2016-2020) is focused on both physical and biological dynamic processes and their role in coastal recovery after storm events. A principal BLUEcoast task is to produce a better representation of both transportable and source material within the coastal zone.

This case study illustrates how the sub-surface material can be represented and quantified as a bespoke-thickness model using Groundhog software (Wood *et al.*, 2017) and how this can be used to produce better coastal evolution assessment using the *Coastal Modelling Environment* (CoastalME) framework (Payo *et al.,* 2017). Geologists used Groundhog, a BGS software tool that utilizes a DTM, surface geological line work, downhole borehole information and geophysical data to produce a geological fence diagram that subsequently defined a 3-D geological framework model. Enhanced Groundhog capabilities supported the conversion of the 3-D geological framework model to a thickness grid model required by the numerical erosion model. CoastalME is a modeling platform which simulates decadal and longer coastal morphological changes. Developed as a proof-of-concept in iCOASST, it is being further developed within BLUECoast.

Because the Norfolk coast is subject to severe erosion threats, the EA Coastal Partnerships & Strategic Overview Team for the East Anglia Area contacted the British Geological Survey (BGS) in early 2017 to determine if erosion rates in that region could be more accurately assessed by combining BGS expertise in subsurface geological modeling and prior experience with the iCOASST/BLUEcoast projects. For an initial test case, a site near Trimingham was selected (Figure 24-CE1). The BGS organized a team of 11 staff-members with expertise on quaternary geology, landslide processes at the study area, subsurface geological modeling, and coastal morphodynamic modeling. This case study summarizes the experiences of this team in 2017 as they combined the capabilities of Groundhog and CoastalME.

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Figure 24-CE1 NEAR HERE

Figure 24-CE1. Location of Trimingham within Great Britain and 10m resolution DTM. The Trimingham project used a larger domain (black outline) to model coastal hydrodynamics and a smaller domain (red outline) to integrate 3-D geological information with CoastalME simulation of coastal change.

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2. COASTAL BEHAVIOR MODELING FRAMEWORK

Geomorphic coastal systems models combine understanding of hydraulics, waves, tides, sediment transport and sediment conservation that are captured as sets of logical arguments or conceptual models, mathematical formulations, physical scaled models or statistical relationships (Payo 2017). None of these models claim to represent reality in all its complexity, but instead provide a formal framework to explore, qualitatively and/or quantitatively, the behavior of coastal geomorphic systems that are too complex to analyze through reasoning. Rather than favoring one approach over another, the prospect of integrating the different modelling approaches has been identified as a way forward to develop a system-wide capability for assessing coastal geomorphological change (Nicholls *et al.,* 2015; Payo 2017). An innovative integration approach involves utilization of the essential characteristics of multiple landform-specific models using a common spatial representation within an appropriate software framework.

In the Coastal Modelling Environment (CoastalME) framework, change in coastal morphology is represented by means of dynamically linked raster and geometrical objects. A grid of raster cells provides the data structure for representing quasi-3-D spatial heterogeneity and sediment conservation. Other geometrical objects (lines, areas, and volumes) that are consistent with, and derived from, the raster structure represent a library of coastal elements required by different landform-specific models. Figure 24-CE2 illustrate how a real coastal morphology (upper panel) is conceptualized as shoreline, shoreface profiles, and estuary elements (middle panel). All elements can share sediment among them (double-headed arrows). The shoreface comprises both consolidated and non-consolidated material that forms the cliff, shore platform and beach respectively (bottom panel). At every time step the shoreline is delineated at the intersection of the sea level and the ground elevation. Shore face profiles are delineated perpendicular to the shoreline. Sea level and wave energy constrain the proportion of shoreface profiles that are morphologically active at each time step. Eroded sediment from the consolidated profile is added to the drift material to advance the shoreline, or is lost as suspended sediment. Gradients of the littoral drift further control the advance and retreat of the beach profile and the amount of sediment shared with nearby sections of the shoreline. Payo *et al.* (2017) provides additional details.

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Figure 24-CE2 NEAR HERE

Figure 24-CE2. Schematic diagram of the CoastalME approach (from Payo *et al.* 2017)

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CoastalME uses a simple representation of the ground elevation and sub-surface properties (Figure 24-CE3) which is well aligned with our current understanding and modelling capacity of the sub-surface. Ground elevation is characterized as a set of regular square blocks. Each block has a global coordinate x, y, z. As shown by Blocks detail in Figure 24-CE3, each block may be composed of six different sediment fractions defined as "coarse", "sand", and "fine sediment", with each size fraction further defined as "consolidated" (capitalized) or "unconsolidated" (lower case). Block types a, b, c and d illustrate blocks having the same total elevation but with different compositions. Integration with a 3-D geological subsurface model permitted improved definition of these CoastalME grid elevations and subsurface composition. This in turn resulted in better evaluations of responses of the cliff and shore base materials to waves and currents.

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Figure 24-CE3 NEAR HERE

Figure 24-CE3. CoastalME representation of ground elevation and sub-surface at different levels of detail (from Payo *et al.* 2017)

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3. CONDITIONS AT TRIMINGHAM

The Trimingham coast experiences periods of higher than usual rates of erosion followed by periods of relative stability. This makes prediction of erosion rates particularly difficult. Published reports suggest the cliff at Trimingham eroded between 1.5-2.5 m/year in the 1966-1985 period. Evaluation of historic maps suggests 50-60 m of erosion over a period of 100 years, or 0.5-0.6 m/year. The Shoreline Management Plan *Kelling Hard to Lowestoft Ness* (East Anglia Coastal Group, 2010) reports that erosion of 75-150 m can be expected over the next 100 years (0.75-1.5 m/year). Littoral sediment processes on the coast around Trimingham have been studied through observations and modeling (HR Wallingford, 2003a; 2003b). These reports provide estimates of potential net longshore sediment transport, changes in beach volume and steepness, cliff recession, and sediment yields.

The geology of the region consists of a thick layer of glacial deposits unconformably overlying marl and fossiliferous limestone of the Cretaceous Chalk Group. The rockhead surface dips gently to the east and is at or below sea-level along the coast, except for a few distinctive bedrock highs; one high occurs at Trimingham. Lee *et al.* (2011b) provide a detailed discussion of the glacial deposits; they consist of four recognized tills separated by sequences sand, silt and clay representing ice-marginal glaciolacustrine conditions, including large sand deltas and rhythmic, varved lake deposits.

The coastal cliffs between Trimingham and Overstrand offer a rare opportunity to examine the internal architecture these deposits (Figure 24-CE4). These cliffs form the eastern eroded extent of the Cromer Ridge, interpreted as a push moraine formed at the southern margins of the Middle Pleistocene ice sheet. The stratigraphy of Trimingham cliffs has presented something of a geological puzzle to many scientists due to their intense glacitectonic deformation (Hart, 1990; Hobbs *et al.,* 2008; Lee *et al.,* 2011b), and the frequent obscuring of exposures by large rotational landslides (Hutchinson, 1976). Lee *et al.* (2011a) reported on studies of coastal sections at Trimingham undertaken for 10 years (1996-2006). These studies took advantage of cliff and coastal erosion which created new, often temporary, exposures.

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Figure 24-CE4 NEAR HERE
Figure 24-CE4. Cross-sections of the Trimingham to Overstrand coastal sections showing the interpreted geology and landslides. (Lee *et al.,* 2011a; modified from Hart, 1990)
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4. EVALUATION OF CLIFF EROSION AT TRIMINGHAM

After reviewing existing information sources, the BGS team concluded that any analysis of cliff erosion at Trimingham must consider the following:

- Interactions between alongshore sediment transport and erodibility of the glacitectonic cliff material control the cliff recession rates;
- Future recession rates depend on variations in cliff height and presence/absence and condition of artificial coastal-defense structures; and
- Small beach volumes cause highly variable observed annual recession rates, ranging from 0-15 m/year between 1993-2001.

The limited resources available for this proof-of-concept initial project resulted in the BGS team integrating 3-D geology with CoastalME process modeling within a relatively small area at Trimingham. A larger "CoastalME domain" (entire rectangular area in Figure 24-CE1) was used to minimize boundary-condition influences on the CoastalME simulations of waves and alongshore currents. A much smaller domain (red outline on Figure 24-CE1) was used to build a 3-D subsurface geology model.

The BGS team created an integrated digital terrain model (DTM) for the larger CoastalMe domain by combining data from NextMap 5m-resolution DTM from the Ministry of Defence, EA 2m-resolution DTM of the shore areas obtained from 2016 Lidar surveys, and 10m-resolution bathymetry data from United Kingdom Hydrographic Office. These sources left an "information gap" along the shallow offshore; elevations in this zone were estimated by linear interpolation to proiduce an integrated 10m-resolution DTM.

The 3-D geological model was constructed according to standard BGS modeling procedures (Chapter 10) using borehole logs and geological maps to create a series of interlocking interpreted cross sections and ultimately a 3-D geological framework model (Figure 24-CE5) The completed model consisted of six geological units and extended from approximately 1.25 km behind the coast to 7 km offshore.

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Figure 24-CE5 NEAR HERE
Figure 24-CE5. Creating the 3-D Geological Model. A) User-defined network of interlocking cross sections (boreholes are red dots); B) Typical interpretive cross section; C) Typical digitized spatially-referenced cross section with borehole; (D) Completed 3-D geological model. (BGS)
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Groundhog Desktop (Wood *et al*., 2017) was used to manage the digital borehole and cross section data. Its capabilities were extended to support the export of 3-D material-property distributions as raster files to define material distributions and thicknesses in a form acceptable to CoastalME (Figure 24-CE6).

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Figure 24-CE6 NEAR HERE
Figure 24-CE6. Geological model horizons are grouped into material classes, forming CoastalMe layers; these are exported as thickness rasters for CoastalME simulations. (BGS)
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5. CONCLUSIONS

As a test case, the BGS team used CoastalME to simulate coastal recession at Trimingham for two scenarios by changing only the subsurface composition, with all other factors unchanged. Waves were assumed constant and propagating normal to the coastline with a 1 m significant wave height and an 8 second period. The simulations evaluated this wave regime for a period of 25 days. The first scenario assumed the cliff was composed of fine material that, when eroded, would be lost in suspension and not contribute to the nearshore sediment budget. The second scenario assumed a cliff made entirely of sand material that, when eroded, became part of the beach volume.

These two simulations illustrate how different subsurface material distributions are important influences on cliff recession rates at Trimingham (Figure 24-CE7). The cliff recession for a fine-grained muddy cliff was up to 950m greater than for a sandy cliff. These two scenarios indicate the sensitivity of shoreline evolution at Trimingham to cliff composition, and thus the importance of including accurate geological information in simulations.

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Figure 24-CE7 NEAR HERE
Figure 24-CE7. Results from two cliff erosion scenarios at Trimingham. Black line shows erosion assuming a sandy cliff; red line shows erosion assuming a fine-grained muddy cliff. Dashed line shows initial cliff location at start of simulation (PRESENTATION #48)
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Variations in cliff recession rates are due to influences of material contributed from the cliffs on beach volumes and how the characteristics of this material influence indirect morphodynamic conditions. The sediment yield per unit of eroded cliff is a function the cliff height and sediment characteristics. Large yields can increase beach width, resulting in an advancing shoreline. Subsequently, these wider and thicker beaches reduce the energy reaching cliff base, thus reducing the recession rate, and the energy reaching shore platform, thus reducing rate of shore face erosion.

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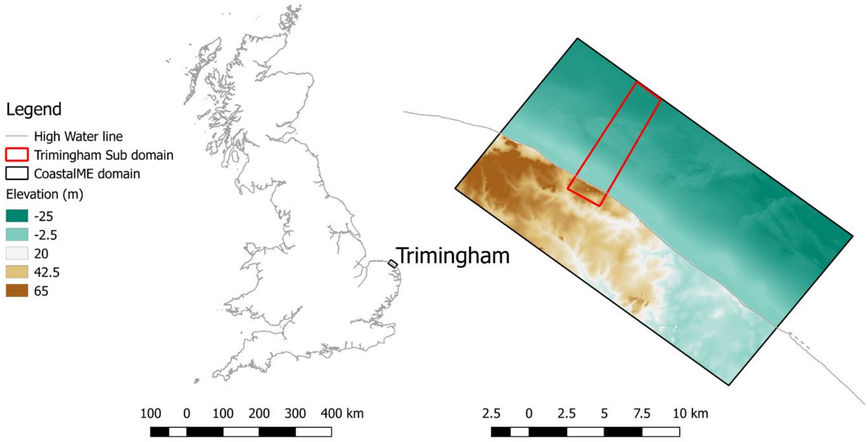

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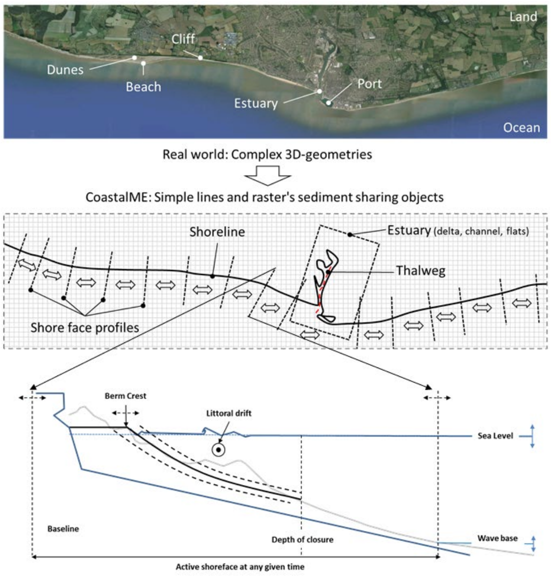


Figure 24-CE2. Schematic diagram of the CoastalME approach (from Payo et al. 2017)

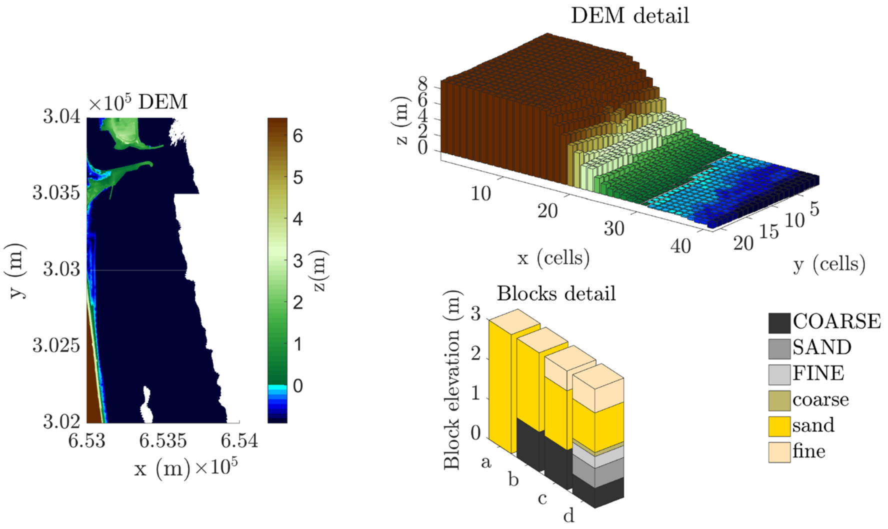
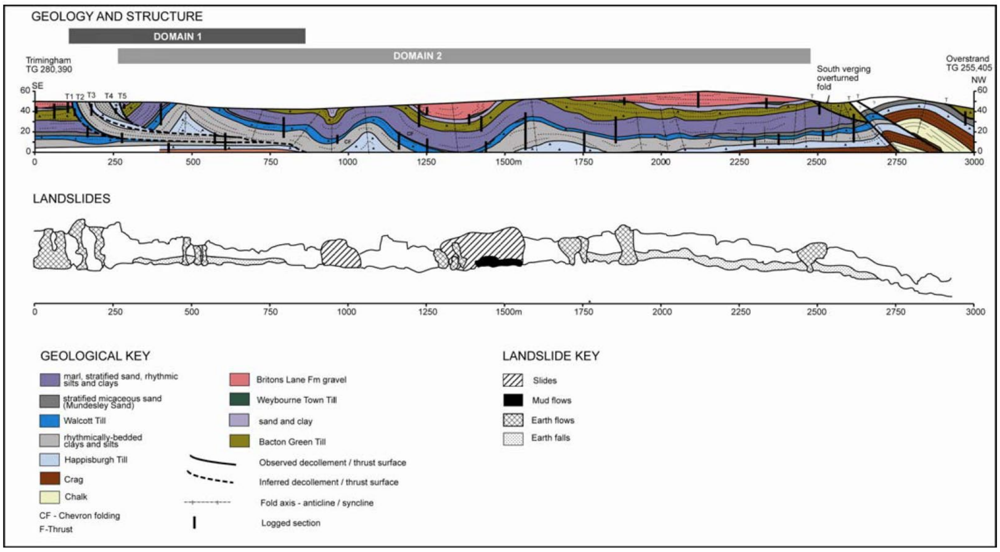


Figure 24-CE3. CoastalME representation of ground elevation and sub-surface at different levels of detail (from Payo et al. 2017)



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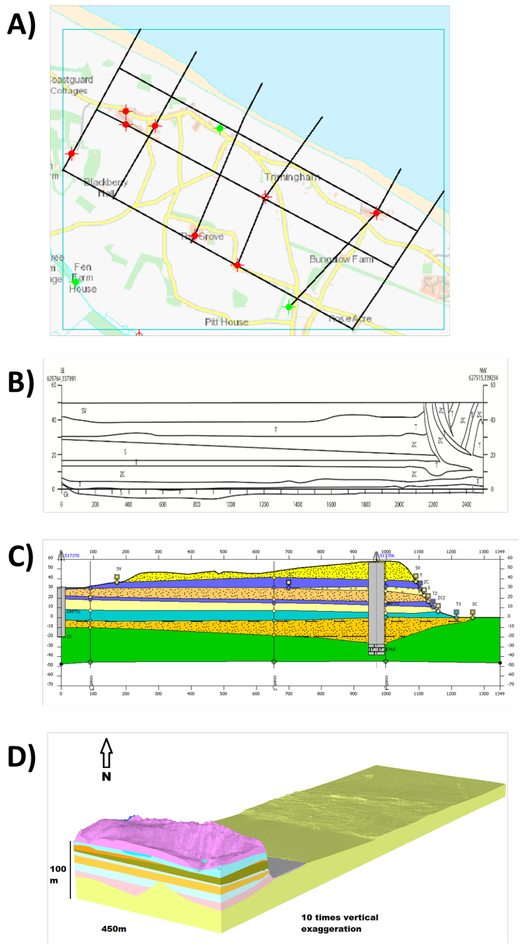

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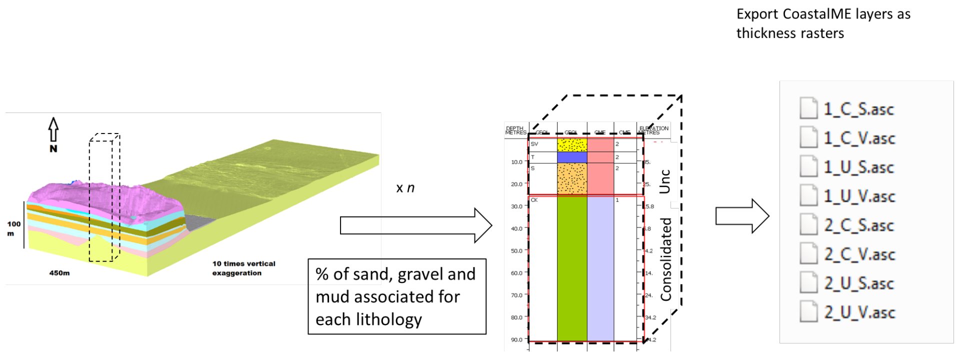

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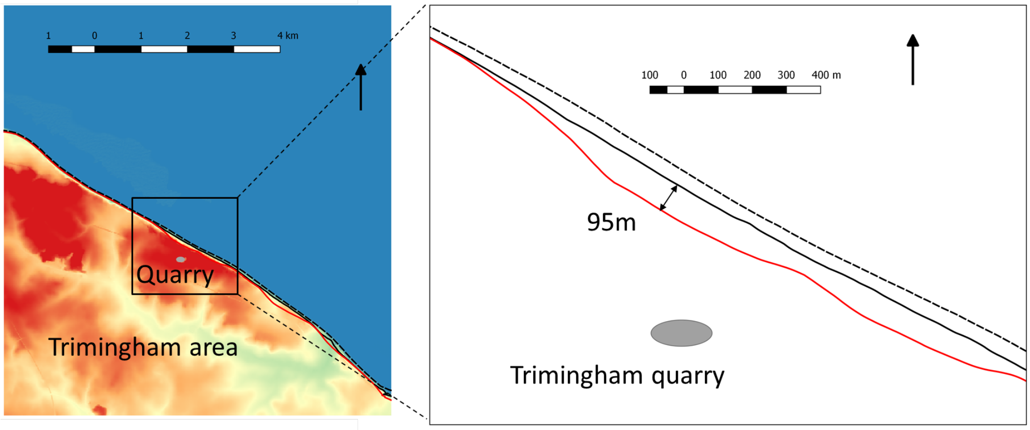

Figure 24-CE7. Results from two cliff erosion scenarios at Trimingham. Black line shows erosion assuming a sandy cliff; red line shows erosion assuming a fine-grained muddy cliff. Dashed line shows initial cliff location at start of simulation (BGS)