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Progress report

Sea levels: abrupt events and mechanisms of change

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International Geoscience Programme (IGCP) Project 495 'Quaternary Land-Ocean Interactions: Driving Mechanisms and Coastal Responses' commenced in 2004, three decades after the first project specifically concerned with sea levels began (Project 61: 1974–82). Over 30 years of coordinated international research have produced a detailed picture of the spatial variability inherent in sea-level change. Project 495 will undoubtedly refine this picture but, in addition, it seeks to develop a more detailed understanding of the mechanisms responsible for these patterns. This report reviews examples of recent research concerned with identifying underlying mechanisms, and concentrates on the role of studies examining abrupt events and rapid changes.

I Tsunamis

The last couple of years have seen a number of papers and special issues concerned with tsunamis (e.g., Tappin, 2004; Pelinovsky and Tinti, 2005). This subject has particular resonance in light of the tragic loss of life associated with the Indian Ocean tsunami of December 2004. The nature and extent of a tsunami's impact is related to the mechanism responsible for its generation (e.g., seismic event, mass movement, etc.). Consequently, this research naturally progresses from identification of deposits to an examination of the events responsible for them. This requires the linkage of terrestrial and marine records, and involves modern observations, palaeoenvironmental reconstructions and computer model simulations.

1 Modern observations

Tsunamis leave deposits that are 'out of place', such as marine sand layers within a terrestrial peat or freshwater lake (e.g., Dawson *et al.*, 1991; Bondevik *et al.*, 1997a; 1997b). In themselves, these attributes are not unique, since storm surges can also deposit marine sediments many metres above normal tidal levels (Dawson and Shi, 2000). Ongoing research is investigating the processes and impacts of modern tsunamis to develop a clearer picture of the distinctive anatomy of these events (e.g., Maramai *et al.*, 2005a; 2005b). Comparative studies examining both storm and tsunami deposits are particularly valuable in this respect (e.g., Nanayama *et al.*, 2000). A recent example is the study by Goff *et al.* (2004) in New Zealand, who examine sediments from a fifteenth-century tsunami and a large storm that occurred in 2002. The results show clear differences in their sedimentology, continuity and extent. This type of information enables the development of a set of diagnostic criteria

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for the identification of palaeotsunami deposits (e.g., Goff *et al.*, 2001; Smith *et al.*, 2004; Bondevik *et al.*, 2005a; Williams *et al.*, 2005).

In contrast to their sandy counterparts, rocky shorelines currently lack detailed sedimentary facies models describing the processes responsible for the formation of coarse deposits (Felton and Crook, 2003). Consequently, interpretations from these environments are more equivocal, relying on supporting evidence and argument (e.g., McMurty *et al.*, 2004; Scheffers, 2004). This situation is complicated by new data indicating that the influence of storm waves may be greater than previously thought. While attempts have been made to model the size of wave required to lift blocks of a given mass (e.g., Nott, 2003), recent studies of modern deposits suggest these significantly overestimate the size of the waves involved (e.g., Mastronuzzi and Sanso, 2004). For example, Williams and Hall (2004) graphically illustrate the power of storm waves in their description of megaclasts from clifftops along the Atlantic Irish coast. Here, boulders weighing several tonnes are recorded up to 50 m above sea level. It is likely that, as more data are collected, the power of storm waves will be reassessed, and this may prompt the reinterpretation of some purportedly tsunamigenic deposits.

2 Palaeoenvironmental reconstructions

The number, distribution and height of waves associated with a tsunami reflect the mechanism responsible for its formation. For example, in the case of a fault-related tsunami, runup height rarely exceeds twice the fault slip (Okal and Synolakis, 2004). Consequently, given maximum water levels of 25–30 m recorded in Sumatra, Stein and Okal (2005) suggest the recent Indian Ocean event was triggered by a fault displacement of between 12 and 15 m. Mass movements have the potential to produce even bigger waves, but at present these remain difficult to quantify, particularly when the slide or slump is submarine in nature (Pelinovsky and Tinti, 2005). This picture is further complicated when mass movements are triggered by seismic events. Investigations of past tsunamis can be used to develop and test models of tsunami generation, and identify regions at greatest risk of future events.

Smith *et al.* (2004) combine data from 32 sites in northern Britain to provide a comprehensive review of evidence for the Storegga Slide tsunami. This evidence predominantly takes the form of a widespread 'out of place' sand layer containing marine microfossils and radiocarbon dated to *c.* 8000 cal. yr BP. Sedimentological analysis of these deposits provides information on the anatomy of this intensively studied palaeotsunami. These results confirm that the slide was actually associated with more than one wave, supporting earlier evidence of multiple waves inferred from deposits on the Shetland Isles (Bondevik *et al.*, 2003). Tooley and Smith (2005) show that this signal is robust even within a high-energy setting, describing two fining-up sequences in coarse deposits of sand and gravel from Scotland.

Reconstructing runup height from a palaeotsunami requires information on the maximum altitude attained by the waves, and the altitude of sea level at the time of the event. Runup heights based on the inland limit of sand layers are treated as minimum estimates since water levels commonly exceed the height of sediment deposition (Dawson, 1999; Dawson and Shi, 2000). Many studies rely on estimates of former relative sea level derived from geophysical models of the glacial-isostatic adjustment process (e.g., Bondevik *et al.*, 2003). In an interesting development, Smith *et al.* (2004) use the tsunami deposits as a time horizon. By locating the inland limit of intertidal sediments capped by this marker, the shoreline position at the time of the tsunami can be reconstructed and subsequent patterns of land movement identified. A variable pattern of runup height is revealed which Smith *et al.* (2004) attribute to wave modification by the coastline, and differences in the state of the tide at the time of the event.

Accurate dating is central to all reconstructions and is particularly important where the timing of the event is considered a diagnostic feature. In common with many sea-level investigations, assigning a precise year to a tsunami deposit is complicated due to the difficulties associated with constructing precise chronologies from sedimentary sequences (Edwards, 2003). In the case of the Storegga Slide deposits, while there is no shortage of radiocarbon dates, the results show typical ranges of several hundred years due to a combination of problems such as erosion and the uncertainties inherent in the radiocarbon technique. Age estimates also vary depending on the dating method used, and Bondevik *et al.* (2003; 2005b) note that conventional 'bulk' radiocarbon dates are commonly too young due to contamination. While the precise year is uncertain, fish skeletons and plant macrofossils preserved within Storegga Slide deposits suggest that the tsunami occurred in late autumn (Bondevik *et al.*, 1997b; Dawson and Smith, 2000).

While dating sediments can constrain the timing of an undated event, it may also be used to identify a tsunami deposit by association with a known occurrence. Williams *et al.* (2005) attempt to fingerprint the sources of nine muddy sand layers preserved within a tidal marsh in Washington State, USA. They compare the ages of the layers with historical events and other dated tsunami deposits in the region. The authors conclude that four to six of the layers are probably the result of tsunamis, but that these are likely to have been generated by a variety of sources, involving both mass movements and seismic events from near- and far-field locations. Williams *et al.* (2005) note that this process is complicated by the fact that the uncertainties associated with their age data are of similar magnitude to the recurrence interval of events in this region.

3 Model simulation and marine data

As well as providing estimates of past relative sea levels, computer models are used to simulate the actual slides responsible for generating tsunamis and the patterns of wave propagation expected to result from different mechanisms of generation (McMurty *et al.*, 2004; Fryer *et al.*, 2004; Løvholt *et al.*, 2005). For example, Bondevik *et al.* (2005a) compare the extensive set of runup data from Norway, Scotland and the Shetland Islands, with numerical simulations of the Storegga Slide. Their best-fit model suggests that sea levels along the Norwegian coast fell by around 20 m during the first 30 minutes following the slide. The simulation also predicts the generation of multiple waves, matching the reconstructions based on sedimentological data. In an alternative application, Okal (2005) uses a model to fingerprint the source of the 1906 Pacific-wide tsunami. While the influence of the two candidate earthquakes is indistinguishable in terms of time (they occurred within 30 minutes of each other), the simulated tsunamis have distinctly different far-field characteristics, indicating that the Chilean event was in fact the most likely cause.

Additional information on tsunami source is provided by marine seismic data. The location, extent and architecture of the Storegga Slide is now well constrained by geophysical surveys (Haflidason *et al.*, 2004). The triggering mechanism is still under investigation, and Bryn *et al.* (2005) suggest a strong earthquake is a likely cause. This may have been facilitated by excess porewater pressure in the sediments brought about by high rates of deposition. Solheim *et al.* (2005) suggest that, immediately following deglaciation, rapid sedimentation coupled with glacio-isostatic seismicity could produce conditions favourable for slope failure. They report seven large pre-Holocene slides in the area that appear to form a complex of failures related to the glacial-interglacial cycle. The recent discovery on the Shetland Islands of two tsunami-like deposits postdating the Storegga Slide suggests that this instability persists throughout the Holocene (Bondevik *et al.*, 2005b). Hutton and Syvitski (2004) model sediment failures under changing sea levels, and note that, while most occur during sea-level falls or lowstands, the largest volume failures are associated with rising sea levels and highstands.

In fact, the nature of coastal sedimentation is increasingly being tied with tsunami risk. Using a catalogue of historic tsunamis in the Pacific Ocean, Gusiakov (2005) shows that sedimentation has a strong control on the likelihood that an earthquake will generate a tsunami. In this paper, written almost a year before the Indian Ocean tsunami of 2004, the extremely high efficiency of earthquakes in the western part of Indonesia is highlighted. In a recent paper, Syvitski *et al*. (2005) use a model to examine how the flux of sediment into the global coastal ocean has changed due to human activities. One of their results is that, in contrast to many other parts of the globe, Indonesian rivers now deliver much more sediment to their coastal waters than before. This research highlights the need for a greater understanding of land-ocean sediment fluxes and processes operating on the shelf (Long, 2003).

II Sea levels and seismic events

In addition to tsunamis, earthquakes are associated with relative sea-level changes driven by vertical land movement. Evidence for cycles of land uplift and subsidence have been known in coastal deposits from the Pacific coast of North America for some years (e.g., Atwater, 1987; Atwater and Hemphill-Haley, 1997). Of current interest is the observation that in some areas a period of preseismic subsidence occurs which could potentially be used as an indicator of forthcoming large earthquakes (Shennan *et al.*, 1999).

Distinguishing preseismic subsidence from coseismic change requires detailed investigations employing precise indicators of relative sea level. Quantitative palaeoenvironmental reconstructions employing microfossils have the potential to provide these records (e.g., Sawai *et al.*, 2004a). Zong *et al.* (2003) used diatoms and pollen to examine relative sea-level changes at two sites in Cook Inlet, Alaska, resulting from the 1964 earthquake. Their data, with a maximum precision of $\pm$ 0.06 m, indicate preseismic subsidence of around 0.15 m at both locations. In two related papers, Hamilton and Shennan (2005a; 2005b) also use a diatom-based transfer function for tide level to reconstruct changes associated with a series of seismic events in the area. Their results show evidence for preseismic subsidence of similar magnitude to that associated with the 1964 earthquake, although these subtle changes are at the upper limit of their transfer function's resolution.

Elsewhere Hayward *et al.* (2004) use a combination of foraminifera and diatoms to identify sudden elevation changes in three Holocene sedimentary sequences from Ohiwa Harbour, New Zealand. Their records indicate potential seismic-related subsidence of around 2 m, although the reconstructions are of lower precision than the transfer functions from North America. In Japan, Sawai *et al.* (2004b) use a diatom-based transfer function to reconstruct relative sea-level changes in eastern Hokkaido. Instrumental data from this area record recent land subsidence, while geological evidence, such as elevated marine terraces, indicates long-term net uplift. Sawai *et al.* (2004b) focus their attention on a large earthquake and tsunami that occurred in the seventeenth-century. Detailed analysis above and below the tsunami sand layer indicates gradual preseismic subsidence followed by postseismic uplift. Intriguingly, this postseismic uplift appears to have persisted for several decades rather than occurring abruptly. The authors conclude that a more detailed picture of earthquake deformation cycles in this area is necessary before the long-term balance between interseismic subsidence and postseismic uplift can be determined.

III Meltwater pulses

Abrupt changes in sea level have occurred during the Lateglacial and Holocene in response to injections of meltwater from terrestrial ice sheets. Work is ongoing to constrain the timing, magnitude and source of these meltwater pulses (MWP). In Ireland, Clark *et al.* (2004) present five AMS radiocarbon dates from foraminifera within stratified glaciomarine sediments which they use to support the idea of a rapid sea-level rise associated with a MWP around 19 000 cal. years BP. The existence of this pulse has been the subject of some debate since its earlier identification in marine sediments from Bonaparte Gulf, Australia (Yokoyama *et al.*, 2000; 2001; 2003; Clark and Mix, 2002; Lambeck *et al.*, 2002a; 2002b; Peltier, 2002a; 2002b; Milne *et al.*, 2002; Shennan and Milne, 2003). In fact, controversy also surrounds interpretations based on the reported glaciomarine sediments from the Irish Sea basin (see McCarroll *et al.*, 2001; Hiemstra *et al.*, 2005). McCabe *et al.* (2005) suggest that a series of Lateglacial relative sea-level changes are recorded by raised marine muds and boulder pavements in Ireland, reflecting the combination of eustatic sea level rise and isostatic adjustments to a dynamic, fluctuating ice sheet. These interpretations are incompatible with modelled relative sea levels (Lambeck and Purcell, 2001) and work in the Irish Sea basin and neighbouring areas continues to try to account for these important discrepancies.

While the existence of MWP 1a is less controversial, work continues to constrain its precise age (Shennan *et al.*, 2005) and the source of the water responsible for it. Peltier (2005) questions the suggestion by Clark *et al.* (2002) that the spatial pattern (or 'fingerprint') of reconstructed sea-level rise is indicative of an Antarctic source. He suggests that vertical uncertainties associated with critical sea-level data are too large to conclusively rule out a Northern Hemisphere source. Baroni and Hall (2004) present data from Terra Nova Bay, Antarctica, indicating that deglaciation of the Ross Sea took place comparatively late, with rapid retreat occurring sometime after 8000 cal. years BP. These authors suggest that the presence of large amounts of grounded ice in the Ross Sea around 8000 years ago makes a significant Antarctic contribution to the earlier MWP 1a less likely.

South America has recently received attention from sea-level modellers since the distinctive, differential pattern of relative sea-level change along its eastern coast provides a useful testing ground for their models. Peltier (2005) uses South American sea-level data compiled by Rostami *et al.* (2000) to test the accuracy of rotational effects as modelled by ICE-4G (VM2), concluding that these are 'rather accurate'. Milne *et al.* (2005) also analyse data from this area, but with the aim of constraining the Holocene highstand, and separating the contribution of eustatic and noneustatic components. Interestingly, they choose not to use the data of Rostami *et al.* (2000), suggesting it possesses some large observational uncertainties. Instead, they prefer a subset of data comprising the most reliable sea-level indicators, such as mangrove peats, vermitids and marine molluscs. Milne *et al.* (2005) suggest their best-fit model indicates a relatively fast eustatic rise in sea level of 7–8 mm/yr in the early Holocene, declining rapidly around 7000 BP.

IV Recent sea-level changes

Separating mass-related eustatic sea-level changes from those due to steric effects or the redistribution of water around the globe becomes increasingly difficult after the early-Holocene addition of meltwater diminishes. A classic example of this is the 'attribution problem': direct estimates of 'global' sea-level rise based on tide-gauge data indicate a rate of 1.5 to 2.0 mm/yr for the last century, but indirect estimates, based on modelling of mass and volume change, predict values much lower than this. The 'fingerprinting' approach can be employed to assist in deciphering the contrasting records provided by satellite altimetry, tide gauges and longer-term geological indicators (e.g., Clark *et al.*, 2003). Nakada and Inoue (2005) analyse seven long-duration tide-gauge records to estimate sea-level change over the last 140 to

200 years. After correction for land-level movements, their results reveal a spatial fingerprint consistent with a meltwater contribution from the Greenland ice sheet equivalent to 1 mm/yr, plus an additional 0.5 mm/yr from another source (e.g., thermal expansion and/or melting from Antarctica/mountain glaciers). The authors caution that their results are preliminary given the small number of stations and the fact that the use of data from a tectonically active area may violate an underlying assumption in their analysis.

Miller and Douglas (2004) evaluate the suggestion that tide-gauge estimates of sea-level rise are perhaps 2–3 times too high due to being located in areas of anomalous ocean warming (Cabanes *et al.*, 2001). They analyse tide-gauge data from the Atlantic and Pacific Oceans and compare them with average dynamic heights determined from oceanographic observations. They conclude that migration of the Gulf Stream introduced an error into the analysis of Cabanes *et al.* (2001) and that the new analysis indicates a discrepancy between tide gauges and steric effects of about 1.5 mm/yr. On this basis they suggest that more mass than previously thought may be being added to the oceans. Some support for this comes from Meehl *et al.* (2005) who publish the results of two global coupled climate models indicating that only 3–5 cm of the observed 15–20 cm rise in twentieth-century sea levels is due to steric change. They conclude that either the observations are wrong or melting from glaciers and ice sheets provides a more significant contribution to recent sea-level rise than currently thought. Intriguing new data from Antarctica, comprising over 2000 aerial photographs and 100 satellite images, charts charges in 244 marine glaciers from 1940 onwards, and shows 87% are in overall retreat (Cook *et al.*, 2005). While these have no direct influence on sea level (since they are floating) the authors speculate that melting may cause accelerations of the glaciers that feed them, resulting in an increased 'draining' of Antarctica.

Miller and Douglas (2004) do not rule out an alternative explanation for their results involving substantial mass redistribution, but they note that this would require sea-level falls during the twentieth-century over large areas of the central oceans (away from most of the tide gauges). Interestingly, Mörner *et al.* (2004) infer a recent fall in eustatic sea level in the central Indian Ocean based on observations from the Maldives.

A couple of recent papers point toward the possible detection of an acceleration in the long-term rate of sea-level rise. Donnelly *et al.* (2004) construct a high-precision relative sea-level curve from Connecticut, USA, covering the last 700 years. The curve is a composite derived from compaction-free AMS radiocarbon dated plant macrofossils and tide-gauge data. The authors suggest it indicates a nearly threefold increase in the rate of rise in the latter half of the nineteenth-century. Gehrels *et al.* (2005) use a precise foraminiferal transfer function in combination with a detailed chronology comprising AMS radiocarbon dates, pollen data and a suite of short-lived radionuclides to produce a high-resolution record of sea-level change for the past 1000 years from Nova Scotia. Their data indicate a doubling in the mean rate of relative sea-level rise to around 3.2 mm/yr between about AD 1900 and 1920. This paper highlights the importance of chronology construction, noting that erroneous fluctuations in relative sea-level records can be generated during the calibration of radiocarbon dates.

V Concluding remarks

Recent studies examining tsunamis and earthquake hazard provide an excellent example of how the combination of terrestrial and marine data, coupled with the integration of modern observations, palaeoenvironmental reconstructions and computer model simulations, can produce a detailed picture of the mechanisms responsible for an event. Well-dated abrupt events have played an important role in the hunt for the driving mechanisms of climate change, especially where these produce widespread signals that can be extracted from proxy records (e.g., the '8.2 kyr event'; Schmidt and LeGrande, 2005). Similarly, abrupt sea-level changes, such as those related to meltwater pulses, are beginning to cast light on the relationships among climate, ice sheets and ocean levels.

As geological records are probed at higher levels of resolution, the pattern of variability exhibited alters. In some instances, changes are greater than previously thought, such as the surprising amount of interglacial sea-level variability emerging from coral records (Thompson and Goldstein, 2005). In others, an apparently widespread abrupt event may be resolved into separate anomalies or more gradual changes, complicating the relationship between cause and effect (e.g., Rohling and Pälike, 2005). Sea-level research faces the particular challenge of linking satellite, tide-gauge and geological records together, each of which possess contrasting precisions, resolutions and apparent variability.

While satellite missions such as GRACE will provide new pictures of the global ocean, and feedback into the development of glacio-isostatic models (Peltier, 2004), a long-term perspective can only be provided by geological data. Consequently, attempts to link detailed, high-precision sea-level reconstructions with instrumental records are of critical importance (Gehrels *et al.*, 2002; 2005; Donnelly *et al.*, 2004). These will require continued improvement in the methods used to fix the age and altitude of past relative sea level. Age control is a particular challenge, and will require better methods of age interpolation (e.g., Gehrels *et al.*, 2005), a fuller understanding of radiocarbon ages derived from different organic components (e.g., van de Plassche *et al.*, 2005), and the adoption of alternative tools, such as luminescence dating (Duller, 2004). It also requires clear communication between disciplines of the errors and limitations associated with data. As Woodroffe and Horton (2005) observe in their recent review of sea-level data from the Indo-Pacific, correlations are compromised by the failure of many studies to account adequately for the vertical uncertainties associated with the sea-level indictors used. Hence, as Project 495 commences, it is evident that the guidelines developed during IGCP Project 61 are as relevant today as they were 30 years ago.

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