Tsunami case studies and model analysis; Final GITEC-report.

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Preface

This manuscript is the contribution to the final GITEC progress report from the group at the Department of Mathematics, Mechanics Division, University of Oslo. The first two progress reports from the Oslo group are *Gjevik et al.* [1994,1995]. In the text these are referred to simply as the first and second progress report respectively.

GITEC (Genesis and Impact of Tsunamis on European Coasts) is an European project under the Environment Program. The project, that started in 1993 and will be completed within May 1995, has involved 9 different research groups; two from Italy (Bologna and Genoa), one from France (Paris), one from Portugal (Lisbon), two from Greece (Athens) and two from Norway (Bergen and Oslo). The responsible coordinator for the project has been Prof. S. Tinti from Bologna.

Summary.

Throughout the project period the GITEC group at the University of Oslo has included two scientist from the academic staff, one full time project assistant and one part time Post. Doc. assistant. Both the latter has been paid by the project. In addition, other scientists at the department have contributed through related, ongoing research activity.

In the project work the Oslo group has pursued two lines of scientific development, namely European case studies and general development and analysis of numerical methods. In addition the group has contributed to the tsunami catalogue by providing complete information on 23 Norwegian tsunami events.

Model activities.

The model work can be divided into four, partly overlapping, fields that are described below.

To assure a flexible, fast and reliable performance of the case studies we have developed an effective model based on the linear hydrostatic equations for gravity waves. Much effort has been put into attaining generality concerning the representation of topography and source mechanisms. Likewise, an integrated set of tools, mainly scripts, have been produced to assure a quick and correct description of the results.

We have especially emphasized a thorough testing of grid effects as well as importance of nonlinear and dispersive effects that are absent in, for instance, the hydrostatic linear model. As routine, all case studies have been run with a series of different grid-resolution and particular cases have been selected for nonlinear and dispersive simulations. The latter have been performed by an existing finite difference model for the Boussinesq equations, but a corresponding finite element model has been developed during the project. In order to study the actual physical effects separately we have also constructed a few "idealized" case studies that have been simulated with very high grid resolution and sometimes also with several different techniques. These investigations have led to the detection of spurious effects as well as providing a firmer basis for the general model development.

One of the key points of tsunami modeling is the calculation of the actual run-up at the shores. This is a difficult task in general, even though linear theory often produce remarkably good results. As a part of the project we have developed a 3-D finite difference model for a moving shoreline, based on Lagrangian coordinates. The model is still under development, but the preliminary results are promising.

Our experiences, both from case studies and numerical tests, indicate that the traditional finite difference approach to the description of waves in coastal regions is hampered with severe shortcoming. Consequently, we have undertaken the development of a finite element solver for the nonlinear and dispersive Boussinesq equations. This method, as all Boussinesq solvers, involves repeated solutions of large systems of linear equations. Thus, much attention has been devoted towards finding the optimal iterative methods for these systems. Another essential problem has been to obtain sufficient local grid refinement in coastal areas and over shoals (seamounts) while keeping the degree of grid distortion at an acceptable level.

Case studies.

The activity on case studies has mainly been directed towards the monstrous Storegga slide (7200 B.P. outside mid Norway) and the tsunamis in the Atlantic sea outside the Iberian peninsula. Among the latter we count the famous Lisbon event from 1755. In addition we have also carried out two investigations in the Eastern Mediterranean related to the Thera eruption (1640 B.C.) and the earthquake near Amorgos (1956).

In the Storegga study we have added further advances to a previous work in order to describe the wave motion in Norwegian coastal waters, with special emphasize on the responses in the fjords. The results produced so far are in good agreement with the Geological findings of the GITEC group from the University of Bergen.

Although we have done some preliminary studies of the 1755 event, our main efforts in the Atlantic sea have been devoted to the comparatively new and well documented tsunami of 1969 with origin in the Gorringe bank area. We have been through several series of simulations with different depth matrixes, source models and location. Even though the amplitudes have been of correct magnitude, it has not been straightforward to obtain systematic agreement between the simulations and the tide gauge measurements for the arrival time and shape of the leading pulse. However, in the last stage of the project there has been some very promising progress on the resolution of this discrepancy. The Atlantic studies have been carried out in cooperation with the French and Portuguese group and a joint journal article is in preparation.

Unfortunately, we have not been equally successful with the efforts in the eastern Mediterranean. Owing to lack of information on the detailed geological mechanisms of the Thera eruption, we have produced only a worst case analysis that indicated very high waves at, for instance, Crete. However, in their investigations at Crete the Coventry group has so far found no geological evidence of this tsunami. Likewise, employing a source model for the Amorgos case, provided by the GITEC participant from Athens, we severely underestimated the tsunami wave heights as compared to observations. However, we must note that some of the observations seemed somewhat unreliable.

Video production.

We also have been conscious to present the results of our research to a broader, non-scientific audience. In this context a considerable amount of work has been spent on the production of video animations of the Gorringe Bank and Storegga tsunamis, as well as idealized run-up simulations. The animations have been used extensively in scientific talks, at popular lectures, in education and some sequences have also been displayed in both Norwegian and British television.

1 Description of the group.

Throughout the project period the GITEC-group at University of Oslo has included the following scientists;

Dr.philos Bjørn Gjevik, professor, project leader

Dr.philos Geir Pedersen, professor

Dr.scient Carl B. Harbitz, associated scientist

Cand.scient Elen Dybesland, research assistent

Gjevik and Pedersen are working part time for the project, the costs being paid by the University. Harbitz has been working part time and Dybesland full-time both being paid by the project. During the last year of the project two other scientists at the department, Dr. Scient. Hans Petter Langtangen and Cand. Scient. Helge Johnsgard, have been partly associated to the project and contributed to the general model development.

2 Model activities.

2.1 Standard model.

During the project we have developed a linear hydrostatic model for simulation of tsunamis generated by bottom faulting or submarine slides.

The geometry is presented by a bottom matrix that is read from a file and may be refined or corrected by the program. Internally the program uses a stereographic map projection, but general routines for transformation to geographic coordinates are available for pre- and post-processing of data. We have also produced a general program for splicing a number of different depth matrixes described in different coordinates.

Sources are implemented by combination of a number of predefined shape functions or by reading digital data from a file followed by bilinear or spline interpolation.

The shore is implemented as a staircase boundary where a noflux condition is implemented. At the open seaward boundaries a sponge layer is introduced, in which the motion is damped by means of an artificial friction. Such layers turn out to be very efficient.

Interpretation of the results is done on basis of fields for the surface elevation and time series, at selected locations, for all field variables. To assure an effective and secure analysis of the data we have constructed a system of scripts, written in the standard UNIX tools, that automatically produces figures with correct labels and captions, extracts key data like times of first arrival, depicts the locations for time series, generates word-processor code describing the actual runs etc.

In order to estimate the importance of nonlinearity and dispersion we have imported a pre-existing Boussinesq solver into the same computational environment. Details on the use of this model are given in the first progress report.

2.2 Lagrangian model.

The run-up model may be regarded as an 3-D extension of the method in *Pedersen & Gjevik*[1983]. In order to trace the moving coastline automatically we formulate the equations in the Lagrangian enumeration coordinates, a and b. Moreover, curved coastlines are implemented through application of curvilinear coordinates. Expressed in terms of the unknowns x, y and η the continuity equation becomes:

$$H\frac{\partial(x,y)}{\partial(a,b)} = V, \tag{1}$$

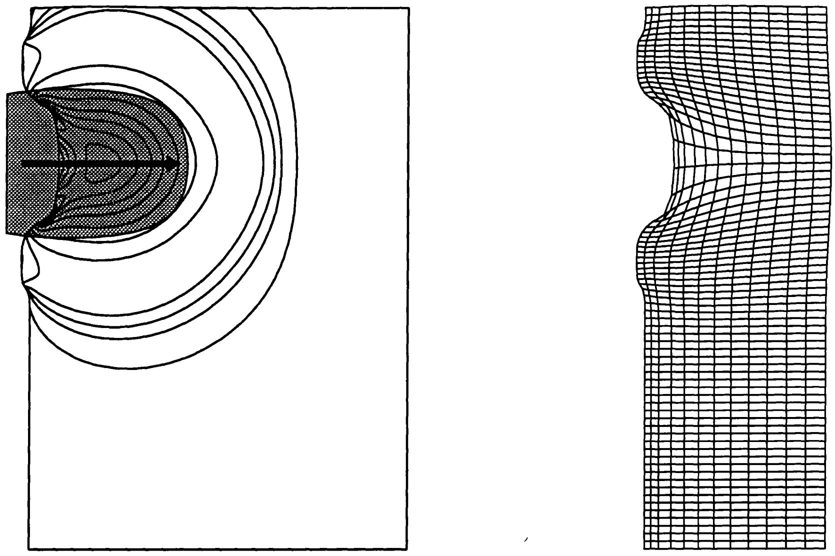

Figure 1: Slide in an idealized fjord. Left: Contour plot of the surface elevation; the slide body is marked by grey. Right: The horizontal displacement field of half the fjord width – one out of four nodes is depicted.

where $H \equiv h + \eta$, $\partial(,)/\partial(,)$ denotes the Jacoby determinant and V describes the initial distribution of fluid volume. For the momentum equation we have employed several, conservative as well as non-conservative, formulations. The simplest option reads:

$$\frac{\partial^2 x}{\partial t^2} = -g\frac{H}{V}\frac{\partial(\eta, y)}{\partial(a,b)} \quad ; \quad \frac{\partial^2 y}{\partial t^2} = -g\frac{H}{V}\frac{\partial(x,\eta)}{\partial(a,b)}, \tag{2}$$

For numerical solution the computational domain is divided into material fluid cells with a η node in the middle and x and y nodes at the corners. This arrangement, that is well suited for calculations of Jacobi determinants, is often referred to as an Arakawa B grid (*Mesinger & Arakawa*[1976]). The Jacoby determinants are represented by centered differences and a staggered temporal grid then leads to an explicit method. At the shoreline $H = 0$ is implemented explicitly as boundary condition. For some forms of the momentum equation we also invoke some extrapolation at the shore. Unless we experience waves that are close to breaking most methods tested seem robust and stable. Further details are given in the second progress report.

So far the method has been tested by comparison to simple analytical solutions (*Thacker*[1981]) and grid refinement tests in simplified three dimensional geometries. One of these tests described a slide, of prescribed shape and celerity, that penetrates the surface of an idealized fjord. An example is shown in figure 1. We note especially the large grid deformation experienced from the shoreline modification due to the slide. Such huge deformation will eventually call for regriding.

2.3 Element model.

In the vicinity of geometrically complicated coastlines or in cases with large depth variations it is generally convenient to apply the finite element method because of its flexibility in handling adaptive grids.

Our implementation of the element method for solution of long waves has been guided by previous experience with difference methods for Boussinesq- type equations, see for instance *Pedersen*[1988]. The Boussinesq equations employed are formulated with the velocity potential and surface elevation as primary unknowns. Applying a staggered temporal grid we then arrive at two separated, linear elliptic problems in each time cycle, which is discretized by a weak Galerkin formulation and linear or higher order elements. A vital part of the work has been to establish efficient methods for solving the sparse, but non-symmetric, algebraic equations arising from the discretization. So far we have found the favourable choice to be Krylov subspace methods in combination with suitable preconditioners, for example the BiCGSTEP scheme combined with a relaxed incomplete LU factorization preconditioner.

Tests on idealized cases have revealed that distorted grids in very shallow water may degrade the performance of the method severely. Hence, a key problem is to keep the number of nodes low while obtaining boundary fitted grids and local refinement near the shore, without introducing abrupt spatial changes in element size etc. An example that demonstrates the effects of higher order elements and local refinement is shown in figure 2. A plane wave interacting with a very shallow seamount is simulated with different elements and resolutions. In the mid panel of the figure we have depicted a coarse grid with local refinement at the seamount, yielding only 749 nodes when quadratic elements are used. As shown by the time series at the summit of the seamount, displayed in the lower panel, this resolution gives nearly as accurate results as much more refined bilinear or quadratic grids. The small, but noticeable, undershot before the main pulse is due to the grid distortions outside the seamount. On the other hand, a locally refined linear triangulation with 1083 nodes turns out to be much less effective.

2.4 Testing.

All techniques have been tested by reproduction of analytical solutions or comparison with results from another independent code.

For all case studies we have performed grid-refinement studies by means of the automatic refinement procedure for the bottom matrix, mentioned in section 2.1. The results of these studies are then applied to decide the allowable minimum depth for points at which time series may be extracted. We have also carried such studies one step further. To investigate the convergence and the performance of the methods in the shore zone we have performed a series of 2-D simulations with extremely high resolution and 3-D simulations in idealized geometries. One result is that staircase boundaries in very shallow water may give rise to crucial spurious effects. Another is that the convergence of waves spreading from seamounts are slow. For instance,

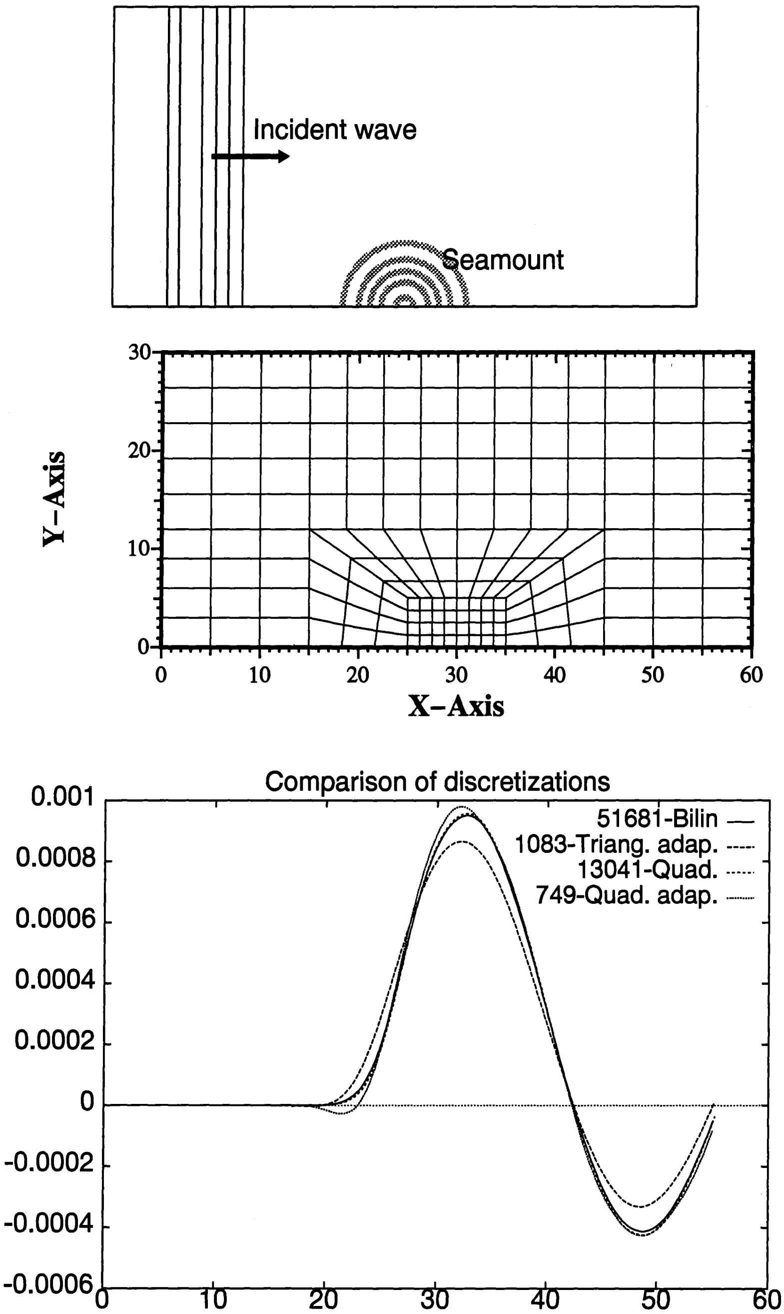

Figure 2: Wave interacting with seamount. Upper panel displays the incident wave and seamount. Only the upper half-plane of a symmetrical domain in shown. In the middle we have depicted a quadratic element grid, with 749 nodes, that is refined at the seamount. The lower panel displays time series at the summit of the seamount. We note that quadratic elements are superior to linear and that the adaptive grid with 749 nodes is efficient. (The noticable undershot before the main pulse is due to the grid distortions outside the seamount.)

when placing an initial elevation above the Gettysburg seamount (depth 25m), at the Gorringe ridge, a resolution of about 50m is needed to resolve the local motion in the standard difference schemes.

We have also investigated the effects of discretization errors on a moving underwater slide. For instance, it turns out that a simple linear interpolation applied to digital data for the slide-shape yields artificial oscillations with period well above the grid scale. This spurious effect may often dominate the solution. Spline interpolation, on the other hand, produce such features only for extremely coarse grids.

A few examples of tests are described in the first progress report, some more in the second progress report or, more completely, in *Pedersen*[1995]. The rest is documented in internal notes that can be made available at request.

3 Case studies.

3.1 The Storegga tsunami.

At the continental slope west of mid Norway, see figure 3, geological evidence has been found for several large submarine slides (*Bugge et al.* [1988]). The oldest event probably dates back to 30,000-50,000 years B.P. In the GITEC project the groups from Bergen and Oslo have been concerned with the Second Storegga Slide that occurred 7,200 years B.P. and presumably moved a total volume of 1700km^3. However, there is a considerable uncertainty regarding the actual slide incident, especially concerning the possibility of having a series of smaller slides as opposed to the whole involved mass being moved in a single event. A more complete description of the Storegga slides is found in the final report from the Bergen group.

The tsunami due to the second Storegga slide (7200 C14-years B.P.) has previously been simulated by *Harbitz*[1992] with a 12.5km$\times$12.5km resolution grid covering the Nordic Seas. In his paper Harbitz assumed a slab formed slide of horizontal extensions 150km$\times$85km, height 144m and a maximum speed of 35m/s. This is consistent with the idea of one major event. Harbitz found high waves, with amplitude of order 5m, along the western coast of Norway about 100 km east of the shelf break where the slide started. However, his grid resolution was far to coarse to resolve the complex geometry of these coastal areas with fjords and islands. Hence, it did not render any detailed information on the coastal response, which would be useful for the GITEC group from Bergen in their search for tsunami deposits.

As a first approach to a description of shore effects we employed a high resolution 500m$\times$500m depth matrix that covered a 290km$\times$270km section of the coastal waters in mid Norway. This matrix was already available from a previous project on modeling tidal and wind driven currents (*Gjevik et al.* [1992]). Surface displacements and current velocities from the large scale Storegga model were then used as input data along the seaward boundaries. The simulations revealed complex dynamics with wave amplification due to bottom topography and prevailing oscillations in the fjord systems. Predicted wave heights in the area southwest of Ålesund were consistent with possible evidence of tsunami run-up heights deduced from the coring samples of the Bergen group. However, the combination of two models was not very convenient for further studies and the results of the high resolution model were encumbered with false reflections from the open ocean boundaries of the model domain.

A more comprehensive study of the Storegga tsunami was carried out through two series of simulations. In the first series the automatic refinement technique, mentioned in section 2.1, was utilized to repeat the large scale simulations for the Nordic Seas with grid-increments ranging from 12.5km down to 2.08km. An improved local model for coastal effects was obtained through several steps. First we extended the high resolution depth matrix to cover a 380km×383km area. Secondly, based on this matrix and the large scale Nordic Seas matrix, the routines for nesting depth matrices (sec. 2.1) was employed. The product was a single 500m resolution matrix that covered the coastal domain and the main part of the continental shelf and deep sea basin that was affected by the slide (figure 3). At the open seaward boundary we implemented a flow relaxation scheme (FRS), to avoid spurious reflections. The orientation and position of the slide were slightly changed as compared to the original Storegga study. During the simulations we experienced a substantial production of noise that was removed by means of an improved interpolation routine for the slide body.

The solutions from the model were dominated by large scale longitudinal oscillations in the fjord basins. Due to their large length scales and the generally steep slopes at the Norwegian coast these waves will probably be rather insensitive to local run-up effects. However, we must note that most coring samples were taken from contemporary near-shore fresh water basins, in which the tsunami intruded by crossing a shallow sill. Consequently, the rise of the water level in the basin might be subjected to a substantial time lag that may reduce the maximum run-up height. Still, as shown in the table, the calculated run-up heights agree remarkably well with those deduced from possible tsunami deposits around Trondheimsfjorden, at Sunnmøre and in Hordaland by the GITEC group from Bergen.

Run-up heights (m)

Location	Deduced from deposits	Calculated
Sunnmøre	8-10	6
Bjugn, north of Trondheimsfjorden	7	6-8
Frosta, in Trondeheimsfjorden*	< 15	7
	> 12 (?)	
Bergen region, Hordaland	3-4	< 5

We note that in Frosta(*) there is no findings more than 15 m above contemporary sea level. One sediment core contains a possible tsunami deposit 12 m above contemporary sea level, but is still awaiting dating and further analysis.

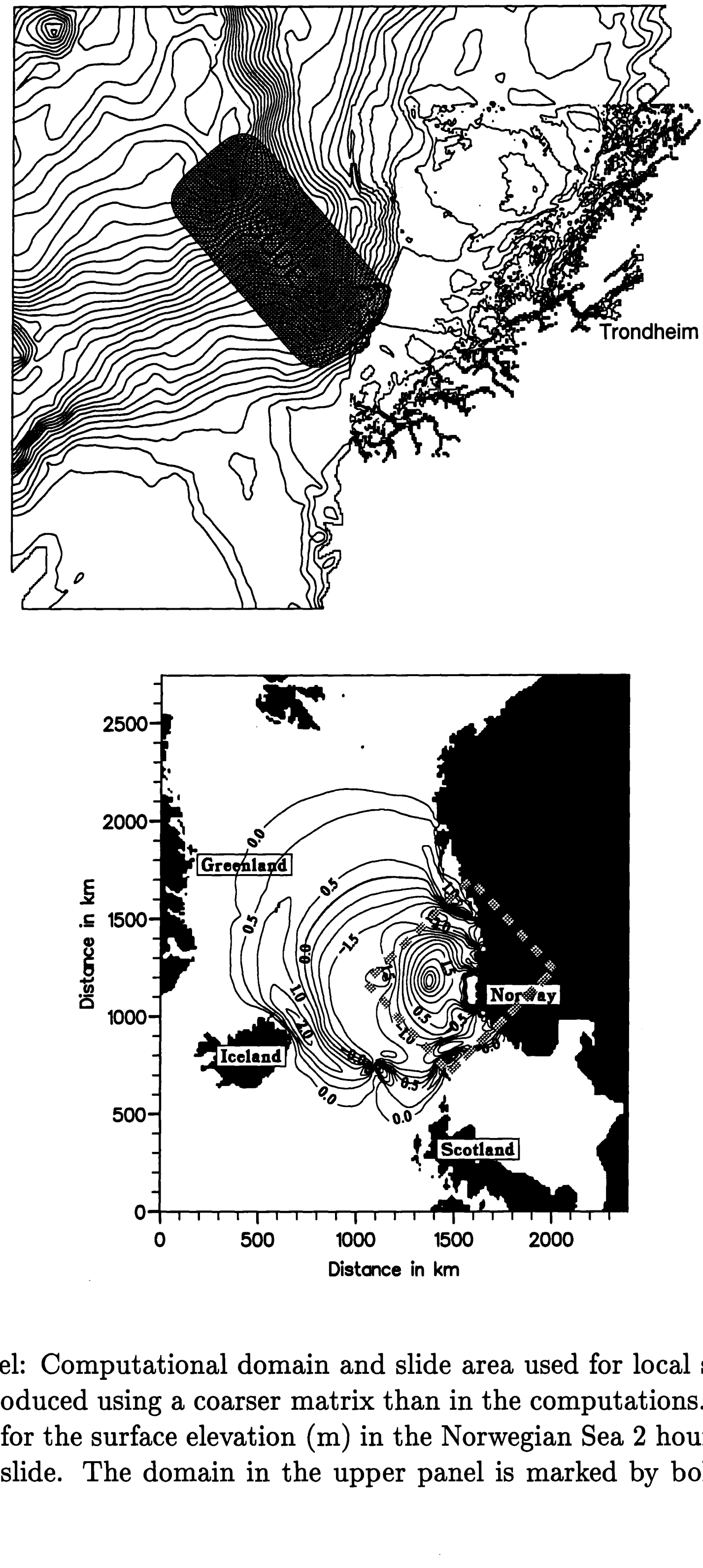

Figure 3: Upper panel: Computational domain and slide area used for local simulation. The figure is produced using a coarser matrix than in the computations. Lower panel: Contour lines for the surface elevation (m) in the Norwegian Sea 2 hours after the initiation of the slide. The domain in the upper panel is marked by bold grey dashes.

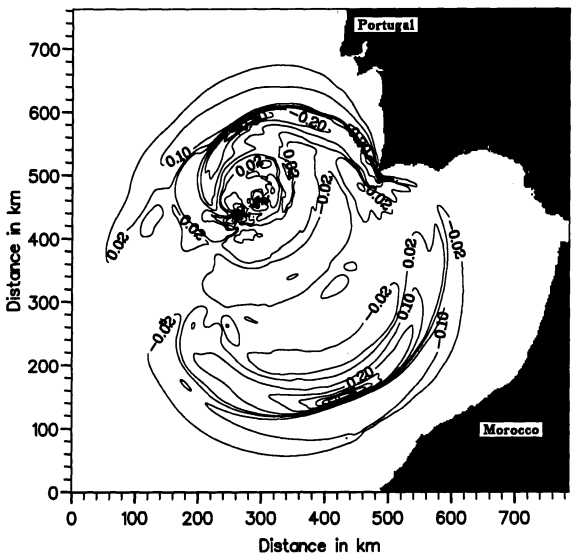

Figure 4: Contour plot of sea surface displacement with box shaped source, $\theta = 73^o$, centered at the epicenter position for the 1969 event. The displayed time is 20 minutes after start.

3.2 The 1969 Event near Gorringe Bank.

The Azores-Gibraltar fracture zone with the huge bathymetric reliefs in the area southwest of Portugal is believed to have been the source of large historic tsunami events. During the GITEC project we have focused on simulations of tsunami generation and propagation from sources near the Gorringe Bank. As a result of this work a joint journal article with the Lisbon and the Paris groups is in preparation. Preliminary results are also described in *Gjevik et al.* [1994] and in GITEC progress reports.

The large earthquake 28th February 1969 with epicenter on the seafloor southwest of Portugal, generated a small tsunami recorded at a number of tidal stations in Portugal, Spain, Morocco, Azores and Canary Islands. The existence of instrumental data for the 1969 event (*Baptista et al.* [1992]) provides a sound starting point for tsunami modeling in this area. The investigation will also shed light on the source position and mechanism for the 1755 event and contribute to future tsunami risk evaluation along the Iberian coasts.

The simulations are primarily done with linear hydrostatic shallow water models, but in order to check the validity of the approximation we have for comparison also performed simulations with the Boussinesq equations. This enables a discussion of the effects of non-linearity and wave dispersion. Discretization errors are estimated by means of grid refinement tests.

3.2.1 The tsunami source

We have modeled the sea bed motion due to an earthquake as an abrupt displacement which produces an instantaneous elevation of the sea surface of the same form.

The actual form of the sea bed deformation is obtained with source parameter reported by *Fukao*[1973] and the formulas given by *Okada*[1985]. An alternative box shaped source is introduced in order to be more flexible with respect to modeling the amplitude and extent of the areas with upward and downward motion of the sea bed. The alternative box shaped source has a similar dipole structure as the source obtained by Okada's formulas with the vertical displacement tapering off in the direction normal to the source axis. Sources with different spatial extent of the area of upward and downward displacements are obtained by combining shape functions with different horizontal length scales.

3.2.2 Simulations of wave generation and deep water propagation.

The linear hydrostatic model provides an effective method for studying how the wave generation depends on location, extent and structure of the source. We have therefore performed a large number of simulations in order to investigate how different choices of the source parameters influence the wave field. Finally we have attempted to determine a source location, size and strength which lead to wave travel time, period and amplitude consistent with observations from coastal stations for the 1969 event.

Three different source locations have been examined; (i) on the Gorringe Bank, (ii) south of the bank at (36.01° N, 10.57° W), reported by Fukao as the epicenter position for the 1969 event, and (iii) on the southeastern flank of the bank.

Simulations with the source centered on the Gorringe Bank and axis aligned with the ridge show strong effects of the bottom topography on the wave field. With a box shaped source with only upward displacement of the sea bed and spatial dimensions (50 km $\times$ 100 km) the wave field near the source is dominated by the initial upward motion of the sea surface followed by a large downward motion and a subsequent ringing with diminishing amplitude. With uniform depth one would expect as an effect of radial spreading a downward motion with amplitude of about one fifth of the initial. The topography of the Gorringe Bank dramatically increases this effect when the source is located on the bank (i). In this case a downward motion up to four times the initial upward amplitude is observed over the shallow Gettysburg seamount. It should be noted that even with a two-dimensional model an infinitely long ridge would produce a downward secondary motion. This effect is enhanced further by radial spreading in case of a finite ridge or seamount.

Also with the source located south of the bank the Gorringe ridge has a large influence on solution due to wave reflections.

The source deduced from Okada's formula, with a small area of downward displacement, fails to reproduce the large downward motion observed at Casablanca and also the first downward motion observed at S. Cruz, Tenerife.

A result of the simulation with the alternative box shaped source centered in the epicenter position (ii) for the 1969 event and with symmetry between the areas of upward and downward displacement is displayed in figure 4. A large primary wave of elevation propagates northwestwards followed by a downward wave and thereafter by a second wave of elevation. The distortion of the waves by Gorringe Bank is clearly seen. Similarly a large primary negative wave followed by a wave of elevation is propagating southeastward in the direction of Morocco. The wave amplitude varies dramatically along the circular wave front with small wave heights in the direction of the source axis which is pointing from SW to NE. Small changes in the direction of the source axis therefore have a large effect on the waves along the coast near Lagos and Faro.

Near shore wave refraction and amplification due to bottom topography are clearly seen when the waves approach the coast of Portugal, particularly near Cabo de São Vicente. This effect would be even more pronounced if the source was oriented such that the highest waves were impinging more perpendicular to the coastline at the cape.

3.2.3 Comparison with observations

A tsunami source with spatial length scale of the order 100 km in the Gorringe Bank area will generate a primary wave signal with period 10–15 minutes depending on the depth in the source area. The wave period is conserved while the wave length decreases when the wave propagates over shallower depths towards the coast. For relatively wide shelves, as along the coasts of Portugal, the wave length may decrease to a few km. In order to model properly wave reflection and interference near the coast a spatial grid resolution of the order 100 m is required. The results obtained with models with grid resolution 1 km can therefore only be used for direct comparison with observed travel time and the polarity of the initial part of the signal. Direct comparison with observed amplitude and phases for the later part of the signal may be uncertain due to local wave reflection and interference on sub-grid scale.

Bearing these limitations in mind we have attempted to compare the results from the hydrostatic model with 1 km grid resolution with the observations at coastal stations for the 1969 event.

The stations located on the coasts of Portugal and Spain, north and northeast of the possible source location, do not put a strong constraint on the exact location of the source. As a matter of fact, both the source location (ii) and (iii) lead to travel time consistent with observations within the relatively large error bounds which have to be anticipated. The first arrival at stations along the coast of Portugal north of Cabo de São Vicente are primarily upward while some stations east of Cabo de São Vicente indicate a weak downward primary wave followed by a large upward wave. These features may be reproduced reasonably well with the Fukao source parameters and Okada's formulas, but we are unable to fit the observed travel time at both Faro and Lagos with the same source configuration. Moreover, the two stations south of the source area, S. Cruz on Tenerife and Casablanca in Morocco, put further constraint to the location, shape and extent of the source. Particularly the fact that these stations show a clear downward motion for the first wave, which at Casablanca is peaking at about -0.8 m indicates that the source must have a rather large area of downward displacement on the southern side of the fault line. Also the relatively short travel time of about 50 minutes observed at Casablanca point to a more southern position of the source. These facts suggest the use of the alternative source although it cannot be justified by current seismic models based on the assumption of a single trust fault.

We obtain a good overall fit to travel times with the box shape source centered at the epicenter position (ii) as shown by the comparison of computed and observed time series (figure 5) and travel time readings. As noted above the modeled travel times for the station Lagos and Faro are sensitive to the orientation of the source axis as defined by the azimuth angle θ. It is interesting to observe the rather good fit of travel time both for Faro and Lagos with $\theta = 73^o$ while with $\theta = 55^o$, for the same source, the travel time is far from the observed.

3.2.4 Nonlinear and dispersive effects

To estimate nonlinear and dispersive effects we have compared predictions from the linear hydrostatic equations, the Airy equations and the Boussinesq equations at the Gorringe bank as well as in deep water. Nonlinear effects are very small, even on the summit of the Gettysburg seamount. Dispersive effects, on the other hand, have a noticeable influence on the wave system spreading out from the source. In addition to a marked change in the shape of the leading pulse, the dispersive effects produce a wave train in its wake.

3.2.5 Grid refinement studies

Applying bilinear, and to some extent, spline interpolation to the bathymetric data we have performed simulations with grid increments ranging from 5km down to 0.83km for the complete domain, and further down to below 100m corresponding to 2-D cross sections of the model bathymetry. In deep waters the coarsest grid yields an artificial dispersion comparable in magnitude to the real dispersion discussed above, while the results display very little grid dependence for $\Delta x < 2.5$km. In the shallow regions at the Gorringe ridge, on the other hand, the solution does not converge properly until Δx is reduced to 100m, say. However, this is not crucial since only very small influence of this local anomality can be traced in the far field solution.

We observe the same behaviour in very shallow near shore regions. As a rule of thumb we may state that, for the first few wave impacts at least, $\Delta x = 5$km yield good results for depths up to 100m, $\Delta x = 2.5$km up to 30m and $\Delta x = 0.83$km yields acceptable accuracy for depths larger than 4m. Generally, too coarse grids lead to an underestimation of the amplitude, sometimes even by a factor 2-3.

The coastal wave amplification is estimated by running the model successively with finer grid resolution. Basically the amplification follows Greens law, see for instance *Mei*[1989], but a fine grid is needed in order to resolve this effect near the shore.

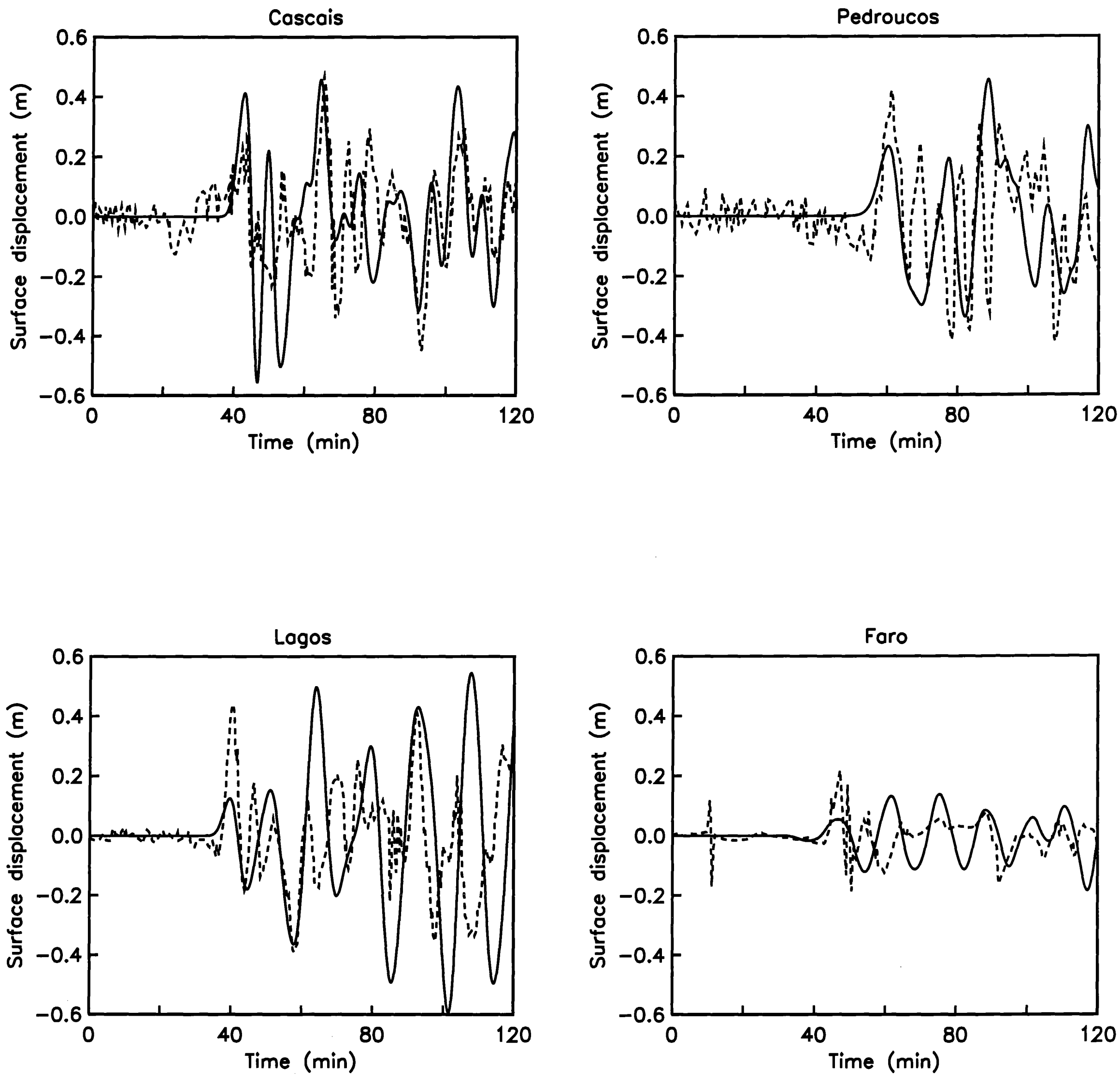

Figure 5: Time series of surface displacement. Observations from the 1969 event are marked by dashes while the solid lines represent model results with the source centered at the epicenter position (ii) and the source axis orientation $\theta = 73^o$. The depths at the locations for simulated time series vary between 3m and 16m.

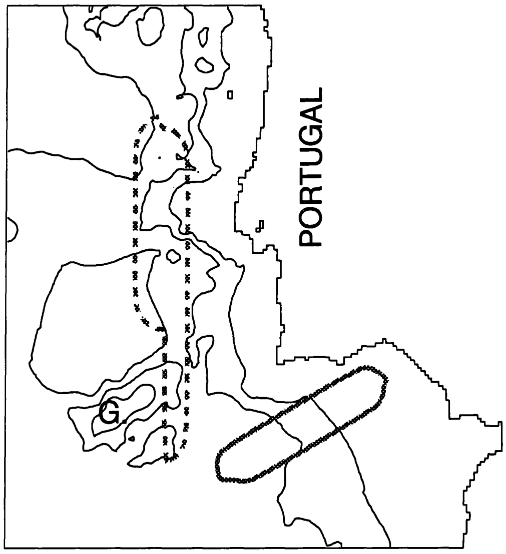

Figure 6: The 1755 event. Source locations are marked with shaded grey, the depth contours are depicted in black with 1500m increments. The capital G marks the position of the Gorringe ridge.

3.3 Lisbon 1755.

Most of our efforts in the Atlantic Ocean have been directed towards the relatively well documented 1969 event and the preparation of a corresponding article. Still, in the spring of 1994 we performed some preliminary studies of possible mechanisms for 1755 tsunamis.

Comparing the 1755 tsunami to the one in 1969 the most striking feature is the difference in magnitude. Naturally, one possible explanation is simply that the 1755 earthquake was much stronger, but otherwise very like the 1969 earthquake. To be able to explain the high amplitudes, observed over wide spread areas, of the 1755 tsunami we would then have to anticipate a bottom faulting of height 20 meters, or even more. Even though this by no means is impossible, it motivates the search for other explanations.

After personal communication with Prof. Ribeiro, University of Lisbon, we pursued the idea that the 1755 earthquake, even though originating at or near the Gorringe bank, may have involved two delayed secondary ruptures (see also *Ribeiro*[1982]). This is consistent with the observation of several very strong aftershocks. For the first we assumed a focal line running in the N-S direction outside the west coast of Portugal. The latter rupture zone was located roughly along the assumed direction of the Gibraltar–Azores fracture zone south of Algarve. The two source areas are depicted in figure 6.

For both sources we implemented box-like bottom deformations with an uplift area, of maximum height 2m, closest to the shore and a weaker depression area on the seaward side.

The source west of Portugal had a length of 340km and a width, of the uplift region, equal to 25km. Simulations performed with the standard model as well as additional plane simulations for a 2-D section (*Pedersen*[1995]) indicate much higher amplitudes at Cascais outside Lisbon than for the 1969 event. In fact, the plane simulations, that have been run with a very fine resolution, yield an amplification factor of nearly 5 and thereby a run-up height of order 10m. We also obtain high amplitudes at Cabo de Sao Vincente.

For the fault south of Algarve we have inferred an uplift domain of dimension 25×200km. With these assumptions we find high amplitudes, more than 5m, at Cabo de Sao Vincente and Lagos. The wave heights at Cadiz, on the other hand, are much smaller.

The preliminary investigations carried out for the 1755 case indicate that the large wave heights for the 1755 case may, at least partly, be explained by the source mechanism being more complex than a single fault in the Gorringe ridge area.

3.4 Aegean cases

The Aegean Sea and the Greek Archipelago have been the center of many large tsunami events as shown by the catalogue compiled by *Papadopoulos & al.* [1984].

One of the most famous geological events in the history are the eruption of the Thera (Santorini) volcano at 1640 B.C. It has been believed that this eruption, and the corresponding formation of the huge caldera, did generate tsunamis that has affected large parts of the eastern Mediterranean. In a preliminary investigation we assumed the volcano collapse to be the tsunami-genic geological event. As a worst case study we simulated the waves spreading from an abrupt mass defect, due to sinking of the sea bed, roughly corresponding to the whole underwater volume of the Santorini Caldera. The computations were performed in a rather coarse 5km×5km grid that was extracted from the world topographic matrix ETOPO. As result we obtained offshore wave heights of order 10m at the North coast of Crete as well as in the Northern Cycladis. At other locations, for instance Pelopponese and Rhodes, the waves had significantly lower amplitudes. Some more details are given in the first progress report. However, the generation mechanisms are uncertain. Moreover, since the Coventry group found no geological evidence of any tsunami impact on Crete, at the appropriate time, the study of a possible Thera tsunami was not carried any further.

A more recent and well documented tsunami in Greek waters is linked to the earthquake in the Amorgos basin in 1956. The observed wave heights displayed large local variations, the largest value of 30m being attained at the Amorgos Island itself *Ambraseys*[1960]. By the courtesy of Dr. A.C. Yalciner, Middle East Technical University (Ankara), we gained access to a 2.9km×2.9km depth matrix, covering the entire Aegean sea, that was automatically refined to 0.48km×0.48km. Focusing on time series at the Amorgos and Astypalaea Island, as well as Iraklion (Crete), we made two sets of simulations with different sources. The first was 75km×20km trough of maximum depth 3m, while the second had extensions 100km×15km and depth 1m as proposed by Dr. Papadopoulos. Both sources led to a fatal underestimation of wave heights as compared to observations. Even though the employed depth matrix was hampered with minor errors and the invoked hydrodynamic equations were linear and hydrostatic, the reason for the large discrepancies probably must be sought elsewhere, namely in the source mechanism and the compilation of the observations. At least some of the reported observations are apparently wrong or must be attributed to other origins than the Amorgos faulting. The source from Papadopoulos and a few selected time series are depicted in figure 7.

4 Video production

The classic way of presenting time evolution of wave fields is based on contour or 3-D plots at selected times, often combined with time series at particular spatial cites. The result is a display of fragmentary information in which important features may be overlooked or misinterpreted. Another problem is that the contents of a ingenious "collage" of different plots may be difficult to convey even to an audience of specialist in the field, let alone a non–scientific audience. Hence, there has been developed a number of graphic tools to aid scientists in effective production of video animation from computed data.

During the GITEC project we have employed the Iris Explorer system for computer animation of tsunamis. In addition to several minor "strips", we have so far produced three main sequences of animations for video. 1) The 1969 event near Gorringe Bank. 2) The Storegga slide event. 3) Wave run-up on an idealized headland.

This work has been carried out in close cooperation with the Computing Services at the University of Oslo (USIT). Their support has been essential for the success.

4.1 Methods

We have used the Explorer visualization system on Silicon Graphics work-stations. Explorer is a general tool including a number of modules (subroutines) which must be combined to yield the final graphic results. In order to satisfy the special requirements for our own applications we had to develop several new modules. Information on the Explorer system can, for instance, be found at NAG's IRIS Explorer WWW-site: <URL:http://www.nag.co.uk:70/1h/WelcomeIEC.html>.

In our applications the depth matrix and surface elevation matrix are manipulated and supplemented with special graphic items displaying compasses, simulation-time gauges etc. By means of special modules, sequences of pictures are then written to a Sony Laser-Videodisc machine that may be connected to a video-player. This enables us to edit the different animations to a VHS tape. The text pages shown

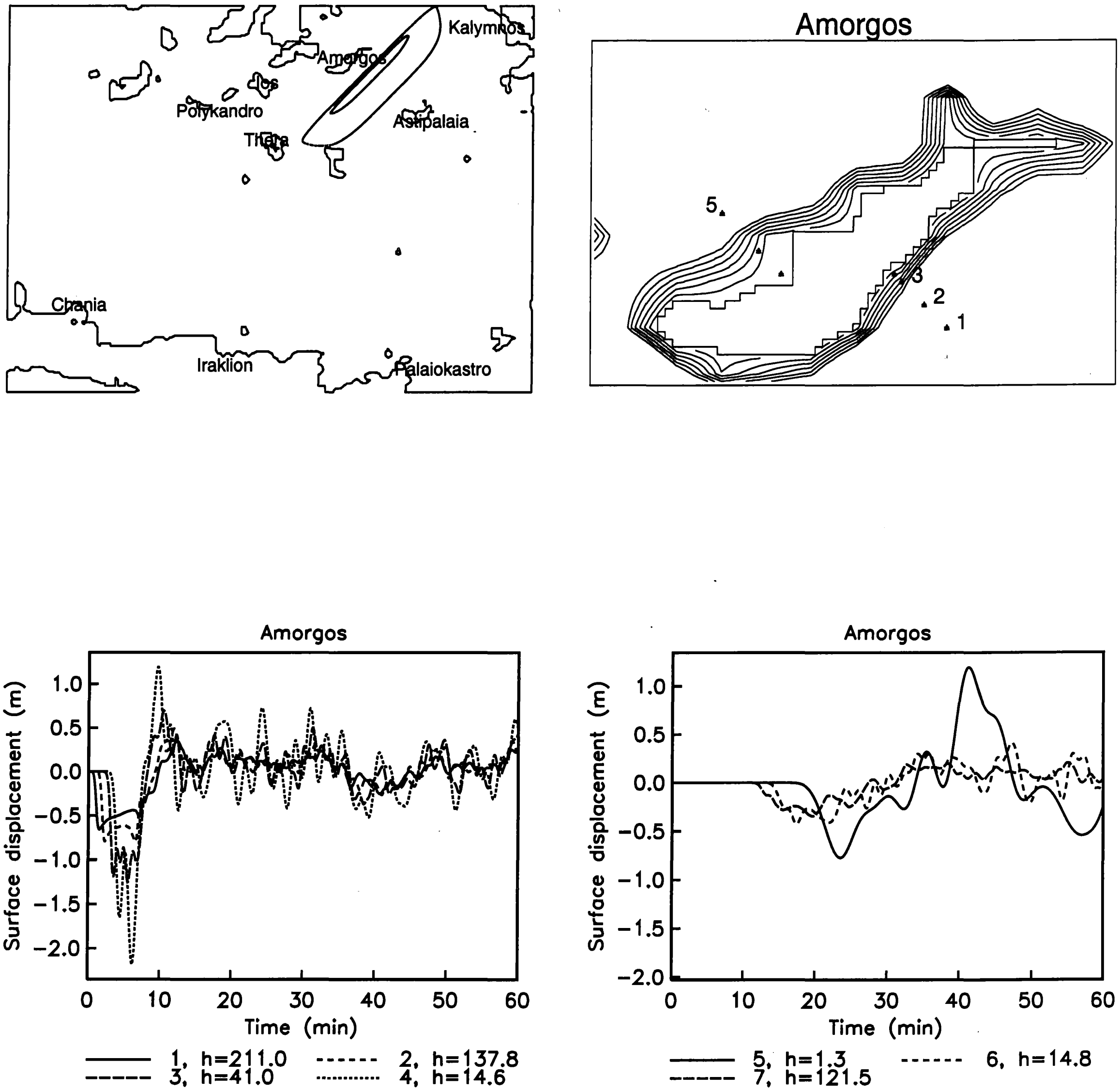

Figure 7: Upper panel: Source location (left), Amorgos Island in refined grid with locations for time series (right). Lower panel: Time series at different depths at the exposed (left) and shadow (right) side of Amorgos.

in the actual videos have been produced by combining Explorer made images with general presentation tools as Showcase and Photoshop.

The main bottlenecks of Explorer applications are the RAM and disc requirements. In addition the large CPU times easily become a constraint on the practical work. Much effort has been put into optimizing the matrix resolution in Explorer while retaining the CPU times at an acceptable level. Unfortunately, we can still present only subsections of the physical domains or work with a coarser resolution.

A graphic system like Explorer offer a lot of possibilities for rescaling and other manipulations to the original data. Naturally, such "tampering" has to be employed with the uttermost caution and our experience is that the selection of proper graphic parameters in relation to the physical parameters of the simulation is both a tricky and time consuming process. We have encountered this problem particularly in connection with run-up and the fjord response to the Storegga tsunami.

Our work with Explorer is documented in an internal report (manual). A short course in "Visualization with Explorer", based on our experiences, is planned to be held within the Division in May 1995.

4.2 Presentations and distributions

The video animations has been presented at several meetings: GITEC meetings in Grenoble 1994, Santorini 1994 and Rome 1995 , lectures for high school teacher at the University of Oslo in 1994 and 1995, the Morena-project meeting in Oslo, June 1994, undergraduate courses in geophysics at the University of Oslo, and at other informal meetings.

The sequence of animations showing the tsunami generated by the Storegga slide has been shown in the main Norwegian television channel (NRK), and in British television.

Still images have been produced for the GITEC brochure, in an article in the magazine: "Naturen" distributed by the University of Bergen, and in our WWW-site:
<URL:http://www.math.uio.no/gitec/>.

Copies of the video have been distributed to GITEC groups, NORSAR, Norway, Oceanographic Commission, UNESCO, Paris (Dr. Oliounine), Direccion General del Instituto Geografico Nacional, Madrid (Dr. Herrero), and the information office at the Norwegian Research Council.

A grant from the University of Oslo will enable us to make animation of the destructive, slide generated tsunami in Tafjord, Norway (1934). The work is scheduled to start in May this year.

5 Contribution to the Tsunami Catalogue.

The Oslo group has performed a thorough survey of the literature on Norwegain tsunamis and provided all information on a sample of 23 events for the tsunami catalogue of the GITEC project. The selection includes all the major recent events. In addition a number of smaller incidents are carefully chosen to give a representable overview of regional distribution, generating mechanisms and wave characteristics in lakes, fjords and open sea. Literature including detailed information on devastations, number of perished, geological aspects, slide modelling, numerical simulations and observations of tsunamis is extensively cited. Based on the experience gained when preparing the Norwegian contribution, the Oslo group has suggested amendments to the original catalogue format.

6 Publications and presentations.

6.1 Presentations.

Parts of the performed work have been presented at the EGS-meetings in 1993 and 1994; Proudman Oceanographic Laboratory, England 1993; Morena project meeting, Oslo 1994; and in several other seminars and open lectures.

6.2 Publications and forthcoming papers.

- Gjevik B., Pedersen G., Dybesland E. & Harbitz C.B. 1994 Numerical simulations of tsunami waves: Preliminary results of the Storegga, the Gorringe bank and the Thera case studies. *Preprint Ser. Dept of Maths, University of Oslo* **1-94**
- Gjevik B. & al. 1995 Modeling tsunamis from earthquakem sources near the Gorringe bank southwest of Portugal. *In progress – collaboration with the Portugues and French groups*
- Gjevik B. & Pedersen G. 1995 A numerical study of the tsunami from the Amorgos earthquake in 1956. *In progress.*
- Harbitz, C. B., Pedersen, G., and Gjevik, B., (1993) Numerical simulation of large water waves due to landslides. *J. Hydraulic Enginering*, **119**(12), 1325-1342.
- Harbitz, C. B. & al. 1995 The impact of the Storegga tsunami on the Norwegian coast. *In progress – collaboration with the Bergen group*
- Johnsgard, H. & Pedersen G. 1995 A numerical model for 3D run-up. *In progress.*
- Langtangen H.P. & Pedersen G. 1994 Simulation of Weakly Dispersive Nonlinear Water Waves. *Presented at the symposium "Waves and Nonlinear Processes in Hydrodynamics", Oslo, 17-19 November.*
- Langtangen H.P. & Pedersen G. 1995 Finite Element Methods for Weakly Dispersive Nonlinear Gravity Waves. *In progress.*

- Pedersen G. 1994 Nonlinear modulations of solitary waves. *J. Fluid Mech.* **267** 83-108
- Pedersen G. 1995 A note on nonlinear wave exitation in parabolic basins. *In progress*
- Pedersen G. 1995 Grid effects on tsunamis in nearshore regions *Preprint Ser. Dept of Maths, University of Oslo* **1-95**

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[7] Gjevik B., Pedersen G., Dybesland E., Harbitz C.B., Johnsgard H. & Langtangen H.P. 1995 Model development and simulation of tsunamis outside Portugal and Greece; Second GITEC status report. *Preprint Ser. Dept of Maths, University of Oslo* **3-95**

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