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Geometric Simulation and Mapping of Holocene Relative Sea-Level Changes in Northern Norway

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ABSTRACT

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A simulated three-dimensional model of relative sea-level changes for northern Norway is presented. The model is based on the shoreline relation principle using a simple trend surface analysis of data from sixty raised sea-level indicators (SLI's). It represents an extension of the model presented by Møller (1987). Problems associated with constructing a reliable data base for the model are discussed. It is demonstrated how the model can be applied to raised sea-level problems, and used to generate maps and three-dimensional diagrams. Paleogeographic reconstructions may subsequently be tested against new field data in the area.

ADDITIONAL INDEX WORDS: *Geometric simulation, postglacial sea-level change, relative sea level, shoreline displacement.*

INTRODUCTION

Regional postglacial sea-level changes for northern Norway have traditionally been presented in the form of shoreline relation diagrams (TANNER, 1930; GRØNLIE, 1940, 1951; CORNER, 1980; MØLLER, 1987) and equidistant shoreline diagrams (UNDAS, 1938, MARTHINUSSEN, 1960, 1974; MØLLER and SOLLID, 1972; SOLLID *et al.*, 1973; RASMUSSEN, 1984; MØLLER, 1985). Local relative sea-level changes have been presented as shore-level displacement curves (MARTHINUSSEN 1962; CORNER 1980; RASMUSSEN 1981; HALD and VORREN 1983; MØLLER 1984, 1986).

Use of electronic data processing has facilitated development of paleogeographic models. KJENSTAD (1984) outlined principles for reconstructing glacier surfaces and raised sea-levels during the Late-glacial and Holocene time for selected areas of southern Norway. MØLLER (1987) presented a simulated model for Holocene sea-level changes in northern Norway, which was tested using ^{14}C-dated prehistoric settlement in the area. The computer programme used by MØLLER (1987) made it possible to present a three-dimensional model of sea-level changes for northern Norway in addition to traditional shoreline relation diagrams and local shore-level displacement curves.

The present paper represents a further development in constructing a model for Holocene sea-level changes in space and time for northern Norway. It discusses primarily (1) problems associated with establishing a reliable data base and (2) how the model can be tested against field data with a view both to improving the model and exposing errors or misinterpretations amongst the field data. Emphasis is placed on presenting the model, maps and diagrams in a clear and illustrative form for use in teaching and interdisciplinary research.

MODEL CONSTRUCTION

The simulated three-dimensional model of Holocene relative sea-level changes for northern Norway is based on the shoreline relation principle. The fundamental assumption in this principle is that there is a direct proportionality between the elevation of a certain raised

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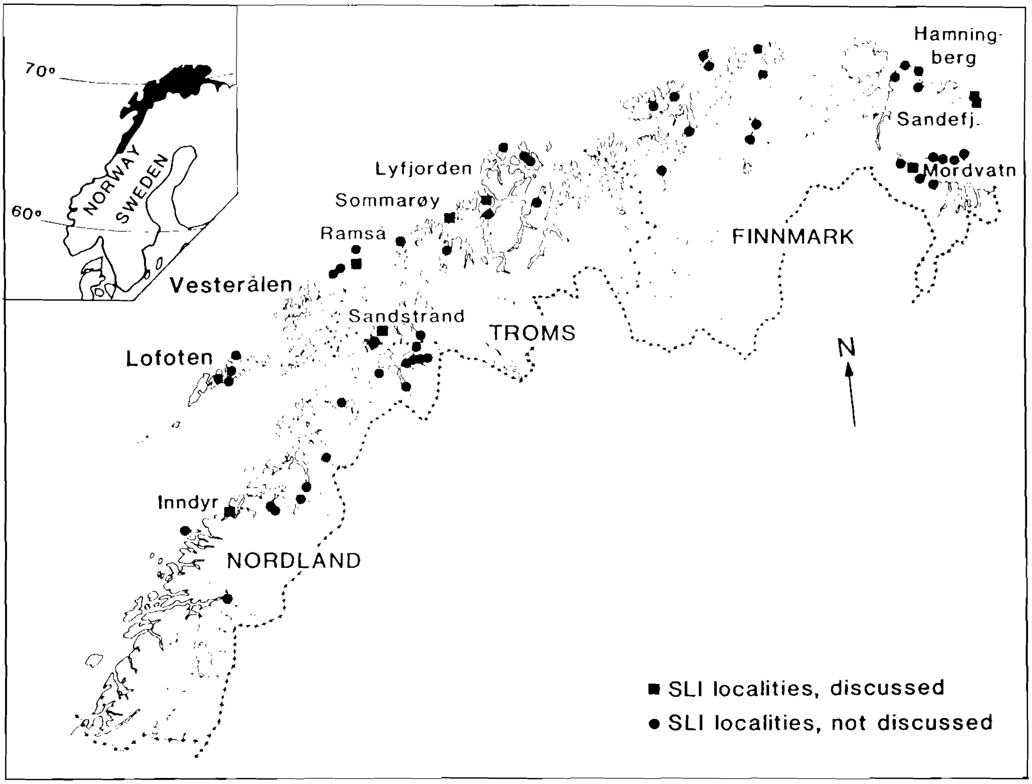

Figure 1. Location of sixty ^{14}C-dated raised sea-level indicators (SLI's) in northern Norway (Møller 1987), which provide the data base for the geometric simulation of Holocene relative sea-level changes in the area. The eight localities discussed more closely in this paper are indicated.

shoreline and the elevation of the other shorelines within a region (DONNER, 1965; ANDREWS, 1970). However, several uncertainties are involved. Local disturbances in glacio- and hydro-isostasy near ice margins, geoid changes and neotectonism may, theoretically, have caused differential sea-level changes.

The model combines geographic location, elevation and age. It represents a three-dimensional trend surface which is a best fit to data from sixty localities of raised sea-level indicators (SLI's) (MØLLER, 1987), three local shore-level displacement curves (DONNER, *et al.*, 1977; HALD and VORREN, 1983; MØLLER, 1986) and seven equidistant shoreline diagrams (MARTHINUSSEN, 1960, 1974; MØLLER and SOLLID, 1972; SOLLID, *et al.*, 1973).

Geographic Coordinates

Correlating field data from raised sea-level indicators from widely dispersed localities in northern Norway (Figure 1), requires a geographic coordinate system. The method of shoreline relation, on which this simulation is based, uses isobase coordinates. A geographic location is normally defined in two dimensions whereas, in this case, it is converted to one dimension, *viz* isobase elevation. This conversion represents a fundamental uncertainty factor in the method.

Figure 2 shows isobases for the Holocene transgression–maximum shoreline (Tapes), which in Vesteralen and Lofoten, is ^{14}C-dated to approximately 6000 BP (MØLLER, 1986). These isobases, compared with isobases for the

Table 1. *Geographic location, elevation, and dating of eight, raised sea-level indicators (SLI's) in northern Norway. UTM—Universal Transverse Mercator projection. Isobase—elevation of the Holocene transgression—maximum shoreline (Tapes).*

Loc. no.	Locality name	UTM ref.	Isobase in m above present m.t.l.	Beach morphology	Exposure	Beach stratigraphy	E_1 in m above present m.t.l.	E_2 in m above present m.t.l.	Material	Lab. no.	^{14}C-date years B.P.	References
1.	Inndyr	589376	26	tombola	S	high-tide	25	≥ 25	*Cerastoderma edule*	T-6895	5650 ± 60	Møller (1987)
2.	Ramsa	429748	9	terrace	S	high-tide	8.5	≤ 7	Peat	T-5287 A	6090 ± 100	Møller (1986)
3.	Sandstrand	725196	22	terrace	V	storm wash	16.5	≥ 12	*Artica islandica*	T-5635	4010 ± 80	Møller (1987)
4.	Sommarøy	845278	12	tombola	S	mean-tide	8	≥ 7	Whalebone	T-4196	3870 ± 90	Møller (1984)
5.	Lyfjorden	430140	12	terrace	E	high-tide	5	≤ 2	Twigs	T-4471	8350 ± 90	Hald & Vorran (1983)
6.	Mordvatn	758739	26	lake	E	high-tide	34.6	≤ 33	Gyttja	Hel-655	8780 ± 180	Donner et al. (1977)
7.	Hamningberg	114281	14	terrace	V	storm wash	14.7	≥ 9	*Mytilus edule*	Hel-747	4300 ± 130	Donner et al. (1977)
8.	Sandefjorden	094248	15	terrace	E	storm wash	13.0	≥ 10	*Mytilus edule*	Hel-749	4290 ± 120	Donner et al. (1977)

[a] Category of exposure is according to Møller (1985): V—very exposed, E—exposed and S—sheltered. E_1—elevation of the SLI's. E_2—elevation of the SLI's contemporaneous m.t.l.

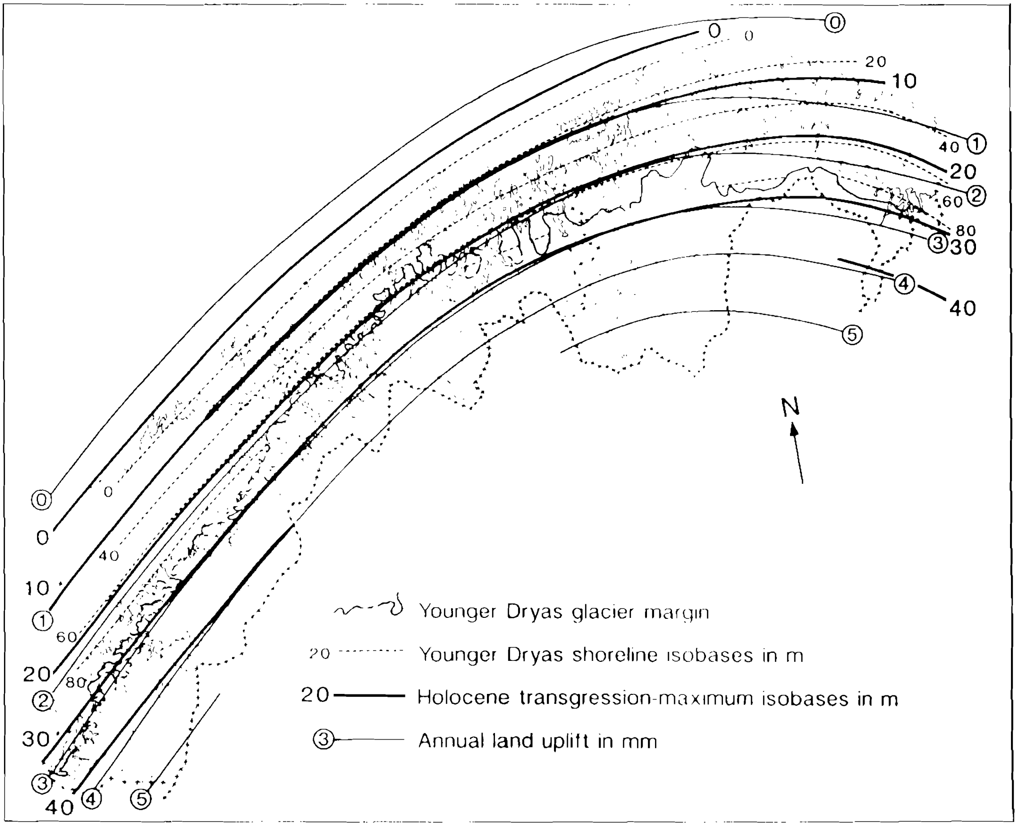

Figure 2. Isobases for the Main shoreline and the Younger Dryas glacier margin (Sørensen *et al.*, 1987), isobases for the Holocene Tapes shoreline (Møller, 1987), and isobases for the present land uplift (Bakkelid, 1979).

Younger Dryas main shoreline and for the present land uplift (BAKKELID 1979; SØRENSEN, *et al.*, 1987), correspond reasonably well for Nordland and Troms, but not so well for Finnmark. In Finnmark, there has probably been increasing differential sea-level changes from west to east during the early Holocene. For simulating Holocene relative sea-level changes in northern Norway, it is convenient to use isobases for the Tapes shoreline as geographic coordinates.

Elevation

Determining the elevation of raised SLI's, using morphological and sedimentological elements, is problematic, with regard to both datum-level and measured site (MØLLER and SOLLID, 1972; SOLLID, *et al.*, 1973; ROSE, 1978; MØLLER, 1985). Based on various sources, JARDINE (1986) presented a diagrammatic evaluation of different sea datum-levels at a location where the tidal cycle is not perfectly symmetrical. He recommended using mean sea-level as datum-level. However, all elevation determinations in this work refer to mean tide-level (m.t.l.) as datum-level except for localities from eastern Finnmark. These elevations have been determined using the level of *Balanus balanoides*, which corresponds approximately with the upper limit of the seaweed *Fucus vesiculosus*. Therefore, these elevation measurements have been adjusted (reduced) by 0.6 m, which is the mean deviation from m.t.l. according to SOLLID *et al.* (1973).

However, greater uncertainties are associated with a site's elevation in relation to the contemporaneous m.t.l. All elevations of the raised SLI's in Nordland and Troms are corrected according to criteria presented by

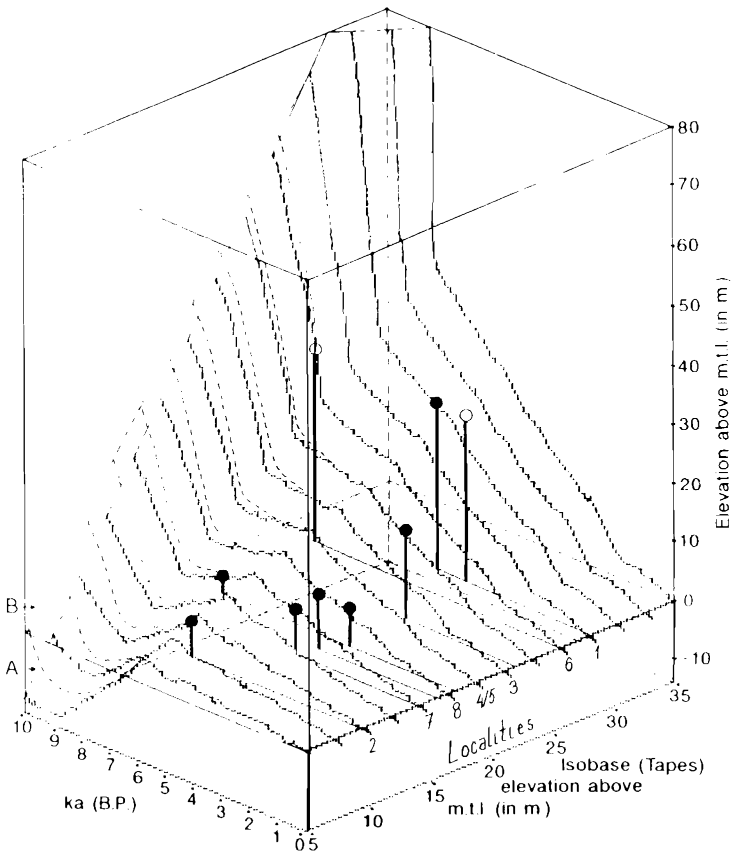

Figure 3. Simulated geometric model of Holocene relative sea-level changes for northern Norway presented as consecutive shore-level displacement curves indicating a trend surface in space and time which represents a best fit to sixty sea-level indicators (Møller, 1987). (A) represents Nordland and Troms and (B) the correction for eastern Finnmark (dotted lines). Geographic location (Tapes isobases), elevation, and datings are plotted for eight of the sixty SLI localities (Figure 1, Table 1). The plane of present sea-level is shaded. Shaded circles represent data which fit the sea-level trend surface within ± 1.0 m. Clear circles deviate by more than ± 1 m (+ 8 m for 4,390 ± 80 BP at Inndyr (locality 1) and − 8 m for 8,780 ± 180 BP at Mordvatn (locality 6).

MØLLER (1985) and for Finnmark by SOLLID *et al.* (1973).

^{14}C Dates

A fundamental problem associated with the absolute dating of raised SLI's, is the question of how closely the dating can be related to the contemporaneous m.t.l. and measured elevation. Ideally, the dating should indicate the age of the contemporaneous m.t.l. However, most dated material pertaining to raised SLI's in northern Norway is associated with various types of uncertainty (MØLLER, 1987) and needs a closer discussion and evaluation.

DISCUSSION OF THE DATA BASE

At present the data base is comprised of sixty SLI localities (Figure 1), of which twelve are from the author's own investigations and the remainder are taken from other studies (MØLLER, 1987). The quality of the data varies, and this represents an uncertainty factor in the data base as well as in the model. Eight localities have been selected and discussed more closely in order to illustrate this problem (Figure 1, Table 1).

At *Inndyr* (locality 1, Table 1), RASMUSSEN (1981) found seven different species of mollusc, 25 m above m.t.l. A fragment of *Ostrea edulis*

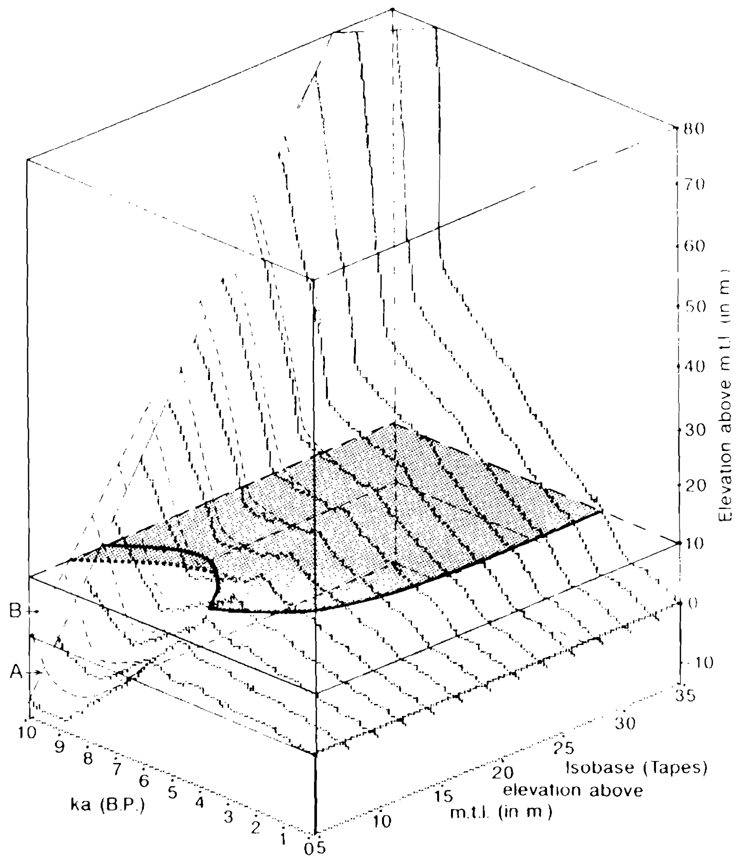

Figure 4. Age (^{14}C years) and regional location (isobases) for a relative sea-level having an elevation of 10 m above present m.t.l. in northern Norway (refer to Figure 3 for (A) and (B) definitions). The heavy line represents the intersection between the plane of 10 m elevation and the sea-level trend surface (dark shaded below and transparent above the sea-level trend surface). The heavy dotted lined represents the correction for eastern Finnmark.

was radiocarbon dated to 4390 ± 80 BP (T-3269). According to the model presented here, the shell was found approximately 8 m too high. On the other hand, assuming the date to be correct, this would imply a significant deviation in the isobases for the Tapes shoreline, as well as in relation to the isobases for the 6,500 years BP shoreline (SØRENSEN, 1984; SØRENSEN, *et al.*, 1987) and Holocene sea-level changes in the Trondheimfjord area (KJEMPERUD, 1986; SVEIAN and OLSEN, 1984), which lies to the south.

The locality was re-investigated in 1986, and shells of *Cerastoderma edule* were collected. The SLI locality, which is a tombola terrace about 200 m long and 300 m wide, lies 25 m above m.t.l. and is well protected from the sea.

The shells, collected from a 0.5 – 1 m thick upper bed of sand, were radiocarbon dated to 5,650 ± 60 BP (MØLLER, 1987), *i.e.* about 1,260 ^{14}C years older than RASMUSSEN's (1981) dating of *Ostrea edulis* from the same elevation. The new dating corresponds well with the model. Can stone age man's use of oysters for food have caused the error in this case?

The shelly sand layer is interpreted as a high-tide deposit formed from reworked low- and mean-tide deposits at the tombola. A recent fauna of *Cerastoderma edule* in sand is found in the littoral zone and down to depths of 8 – 10 m within the sublittoral

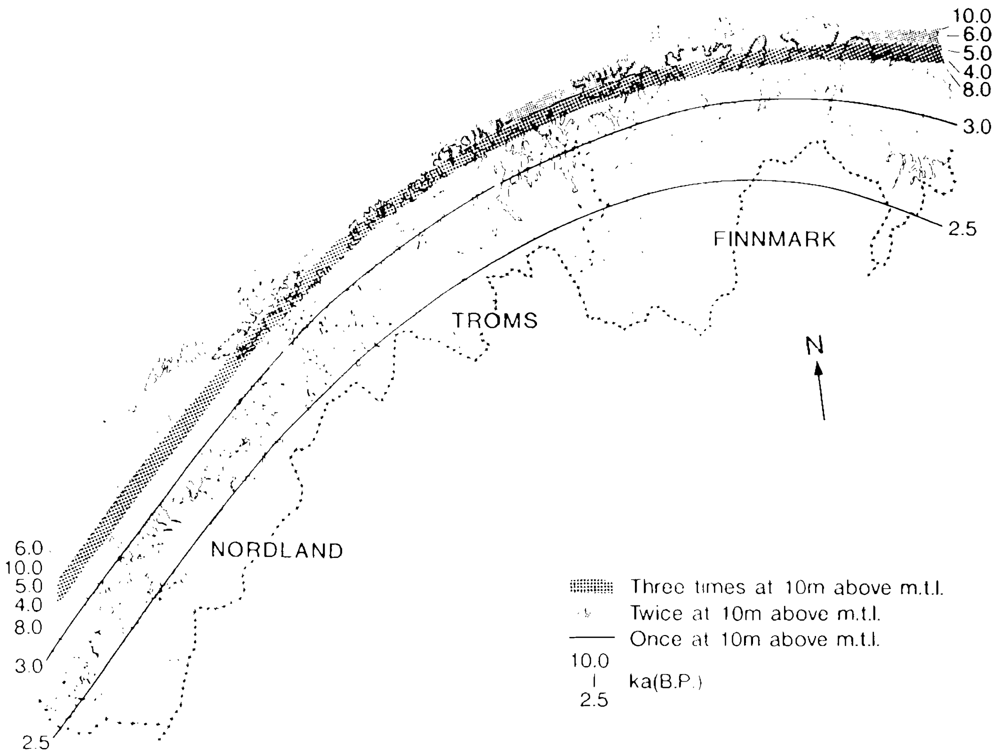

Figure 5. Age (^{14}C years) and regional position in northern Norway where Holocene relative sea-level had an altitude of 10 m above present m.t.l. The exact geographic location depends on the local coastal topography.

zone (PETERSEN, 1986). It is reasonable to assume that these shells lived at this locality when relative sea-level (m.t.l.) was at least 25 m above the present m.t.l. At this tombola, there are only two ^{14}C-dates and these deviate in age. Therefore, there are still uncertainties, connected with the data.

At *Ramsa* (locality 2, Table 1), Holocene sea-level changes have been investigated by several workers (MARTHINUSSEN, 1962; MØLLER, 1984, 1986; VORREN and MOE, 1986). The ^{14}C-dating of 6,090 ± 100 BP is from a peat lense in well sorted sand situated stratigraphically immediately below the Tapes beach ridge, 8.5 m above m.t.l. (MØLLER, 1986). Two other dates, 6,140 ± 50 and 6,290 ± 60 BP from a peat bed situated stratigraphically *c.* 0.5 m below the lense, provide additional evidence on the age of the sand bed. The sand bed with peat lense is interpreted as a high-tide deposit, formed when m.t.l. lay 7 m or less above present sea-level. The uncertainty at this locality is connected with the interpretation of the elevation.

Sandstrand (locality 3, Table 1), is a terrace situated in an exposed position. Shells of *Arctica islandica* from a 0.2 m thick shell bed in an uppermost bed of pebbly sand, have been dated to 4,010 ± 80 BP. The unit, lies 16.5 m above m.t.l., and is interpreted as a storm deposit. The shells have probably been washed up during extreme wave conditions. The contemporaneous m.t.l. for this type of locality is estimated to lie at least 4 – 5 m lower than the break of slope of the terrace (MØLLER, 1985). In the fjords of Finnmark, DONNER *et al.* (1977) found that *Arctica islandica* is common on the modern beach. The ^{14}C-dated shells at Sandstrand therefore probably correlate with a m.t.l. at least 12 m above present sea-level. Both the ^{14}C-date and the ele-

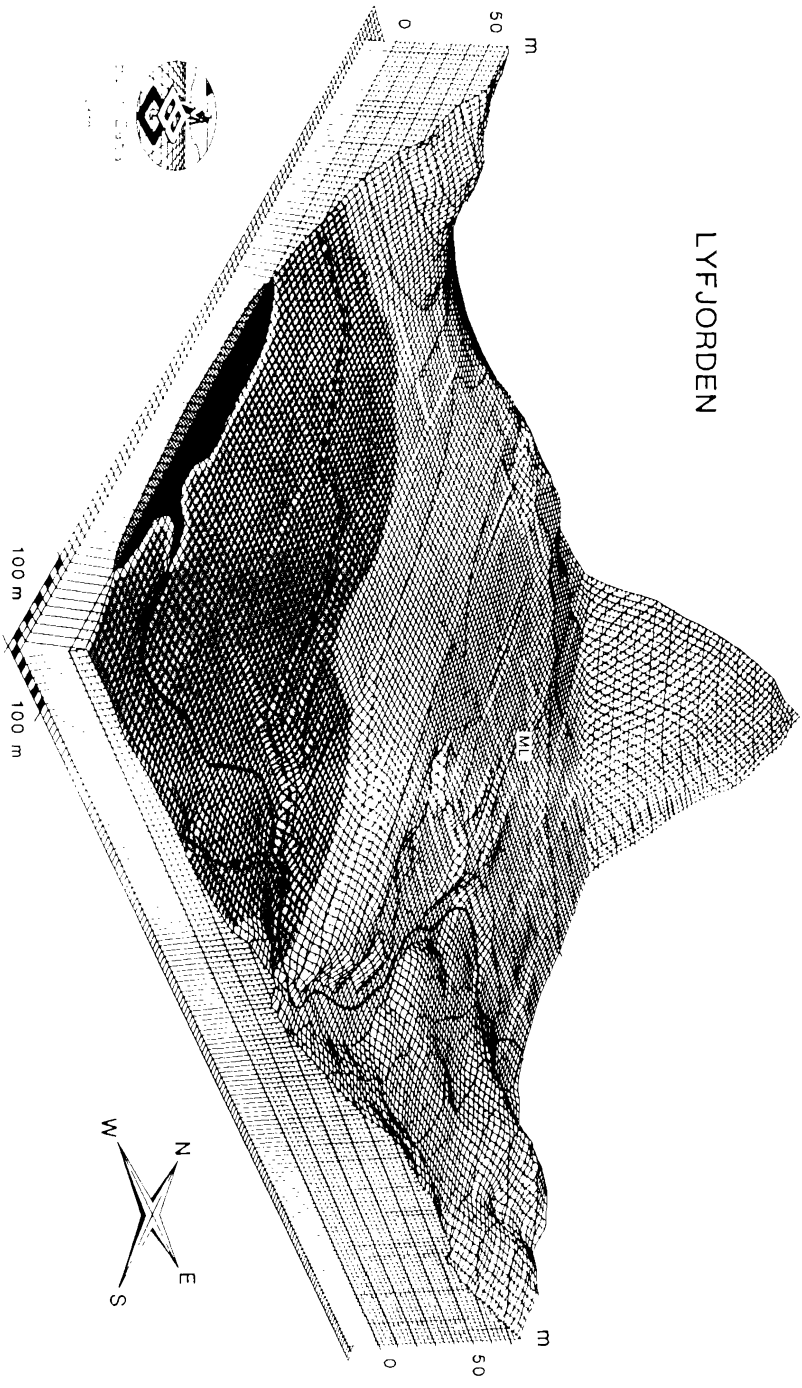

Figure 6. Computer drawn map model of Lyfjorden (locality 5) showing the zone affected by the Tapes transgression (dark shaded area) within which sea-level has been situated three different times during the Holocene. The dashed line shows the triple shoreline position at 10 m above m.t.l. The marine limit (ML) is 35 – 37 m above m.t.l.

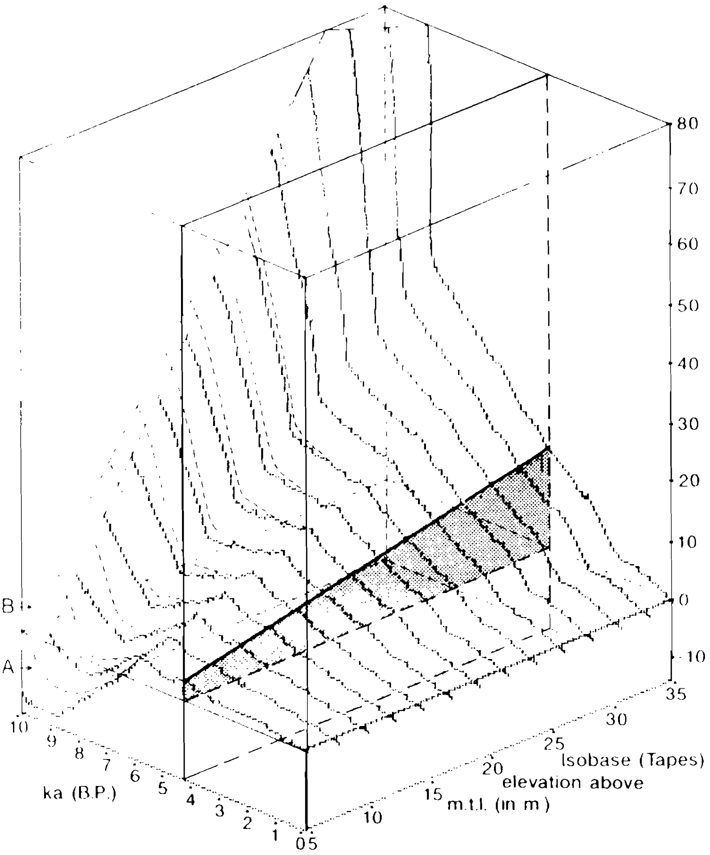

Figure 7. Elevation and regional location (i.e. isobases) of the 4,500 years BP shoreline in northern Norway (refer to Figure 3 for (A) and (B) definitions). The dark shaded area gives a perspective illustration of the increasing elevation (gradient) of the shoreline above present m.t.l.

vation interpretation are somewhat uncertain.

On *Sommarøy* (locality 4, Table 1), a whale skeleton was found during road excavations in 1980, in the uppermost bed of a tombola, 8 m above m.t.l. The locality is sheltered. It is reasonable to assume that a dying whale was stranded here between mean and high-tide sea-level, as occurs along the coast of northern Norway today. Sea-level corresponding to the dating of 3,870 ± 90 BP is therefore presumed to be at least 7 m above present m.t.l. Most of the uncertainty at this locality is connected with the ^{14}C-dating.

At *Lyfjorden* (locality 5, Table 1), HALD and VORREN (1983) investigated a section in a fluvial erosion scarp, 1 − 9 m above m.t.l. A twig-bearing sand layer, mostly less than 10 cm thick was found between a lower diamicton and an upper littoral gravel unit, 5 m above m.t.l. The twigs were identified as *Betula pubescens* and *Salix sp.*. A radiocarbon dating gave 8,350 ± 90 BP. HALD and VORREN (1983) interpreted the twig bed as having a littoral or fluvial origin. The overlying unit was interpreted as having been deposited during a transgression (Tapes). On this basis, it is reasonable to assume that the twig layer was deposited in a high-tide position, or close to a delta. The contemporaneous m.t.l. is placed at a maximum of 2 m above present m.t.l. At Lyfjorden the uncertainties in the data base are associated with the ^{14}C-dating and interpretation of the elevation.

At *Mordvatnet* (locality 6, Table 1), DONNER

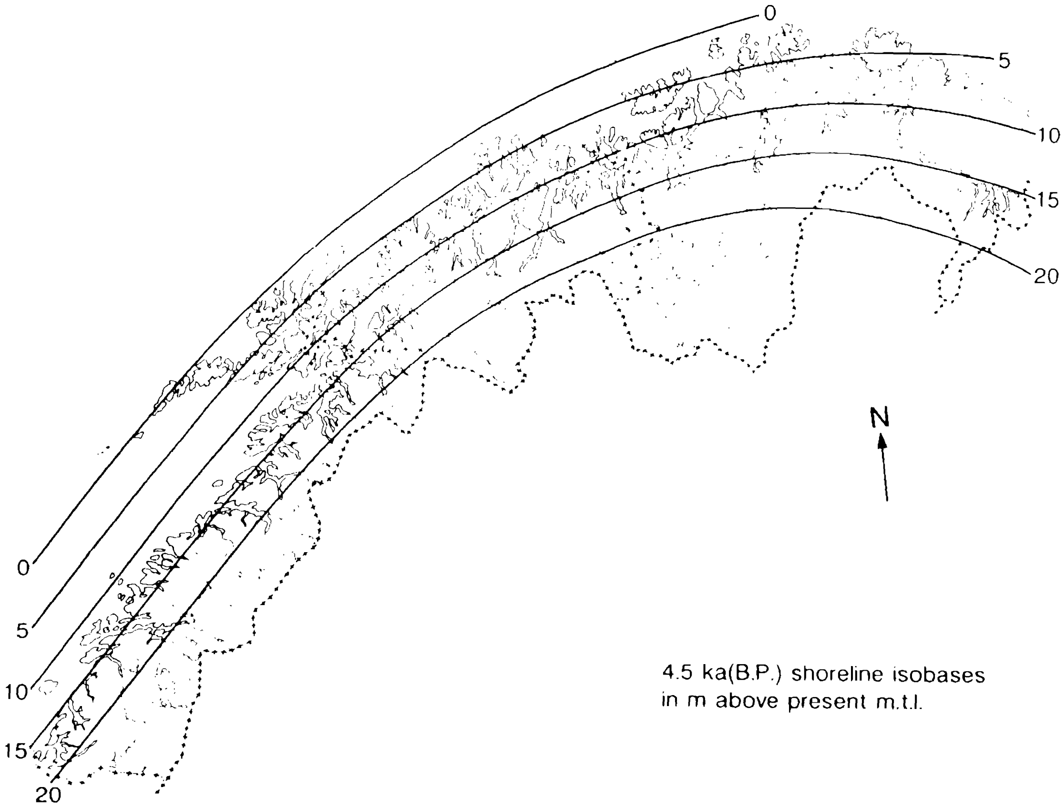

Figure 8. Elevation (isobases) of the sea-level trend surface at 4,500 years BP in northern Norway.

et al. (1977) obtained a ^{14}C-dating of the time when the basin became isolated from the sea, 8,780 ± 80 BP. The dating was carried out on the lowermost gyttja bed which contained a predominantly freshwater diatom flora. Mordvatnet has a threshold elevation of 34.6 m above present m.t.l. The dating refers to a high-tide position which, considering the exposure at this locality, may be related to a m.t.l. 33 m or less above present sea-level.

Compared with thirteen ^{14}C-dated SLI's in Varangerfjord (DONNER *et al.*, 1977), the dating of the isolation contact at Mordvatnet is too old in relation to the threshold level or, conversely, the elevation is too low by about 8 m in relation to the dating. However, a dating of 5,620 ± 190 BP for the isolation contact at Vaervatnet, a lake immediately west of Mordvatnet (DONNER *et al.*, 1977), corresponds well. It is possible that ^{14}C-dating of gyttja in such lakes may, in some cases, have been contaminated or affected by bioturbation. The data from Mordvatnet represents an example of the difficulties of fitting all the data from a limited area into a uniform trend. In this case, the greatest uncertainty is associated with the ^{14}C-dating of gyttja. The model is based on the other ^{14}C-datings in the area.

Hamningberg and *Sandefjorden* (localities 7 and 8, Table 1) are two localities from which DONNER *et al.* (1977) have obtained ^{14}C-dated shells of *Mytilus edulis* having approximately the same age (4,300 ± 130 and 4,290 ± 120 BP) but from two slightly different terrace levels (14.7 and 13.0 m above m.t.l.). The terraces are composed of shelly gravel and sand, and occur at strongly and medium exposed localities, respectively. *Mytilus edulis* is a species which is most common in the intertidal zone (DONNER, *et al.*, 1977). Based on this and the degree of exposure, it is reasonable to relate the datings to at least 9 and 10 m above present sea-

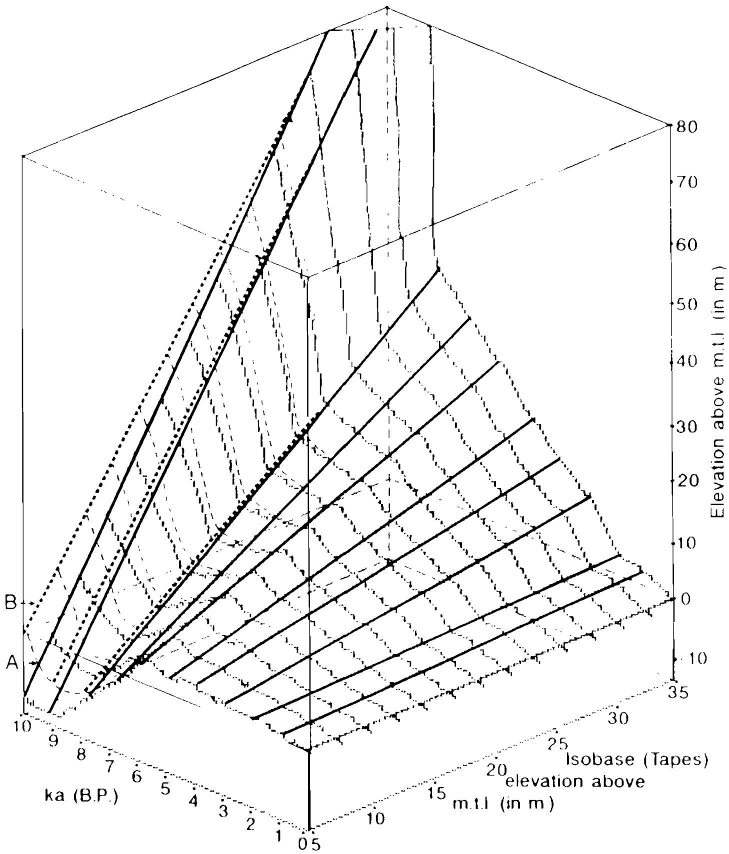

Figure 9. Holocene three-dimensional shoreline relation diagram for northern Norway (refer to Figure 3 for (A) and (B) definitions). Shorelines for each 1,000 years are drawn. The dotted shorelines represent the correction for eastern Finnmark.

level, respectively. The uncertainty factor connected with these two localities is found in the interpretation of the elevation.

SIMULATED THREE-DIMENSIONAL MODEL

The three-dimensional model (Figure 3) for Holocene relative sea-level changes for northern Norway must be adjusted for the early Holocene in Finnmark, based on investigations by MARTHINUSSEN (1960, 1974) and SOLLID *et al.* (1973). The cause of this is probably due to the increasing influence of the Barents Sea ice-cover (MØLLER, 1987). Data from eight of the SLI localities in the data base (Figure 1, Table 1) are plotted as examples in Figure 3.

The model provides a visual picture of sea-level changes in space and time. Sea-level regression is the dominant characteristic. The Holocene transgression (Tapes) in the outer coastal area, and the transition to syngression and regression in the intermediate and inner fjord areas is clearly apparent. A minor transgression (4,500 BP) in the outermost coastal area can also be discerned (MARTHINUSSEN, 1962; MØLLER, 1984). The computer programme provides calculated shoreline ages at a given geographic locality and elevation above m.t.l. If the sea-level indicator has been ^{14}C-dated, the programme can calculate elevation differences from the simulated contemporaneous m.t.l. On account of the uncertainties in both the principle of shoreline relation and SLI data base, the three-dimensional model presented should be considered as giving a rough

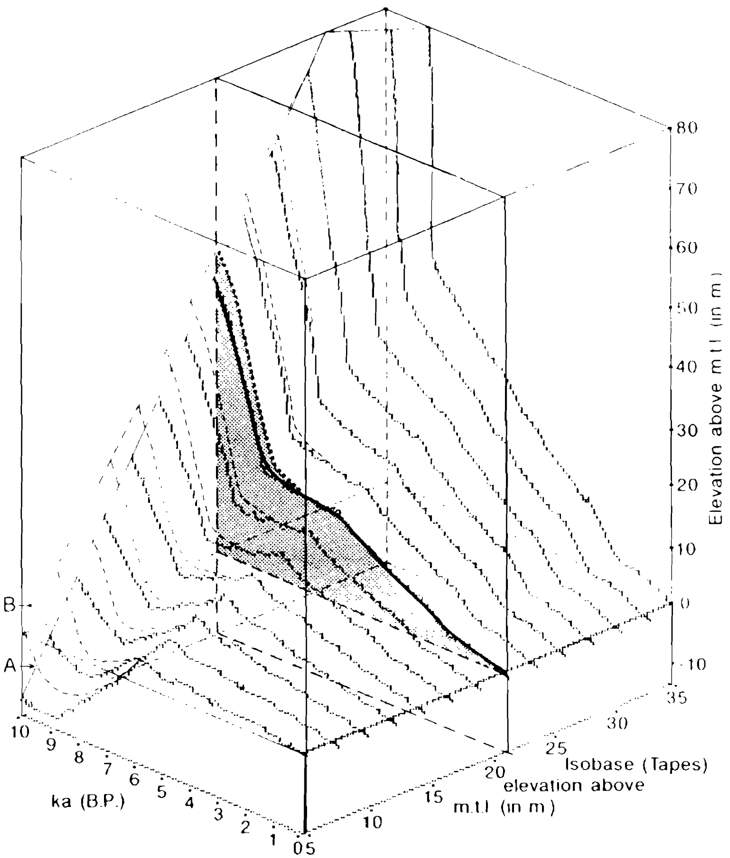

Figure 10. Shore-level displacement curve for a location at the 21 m (Tapes) isobase in northern Norway. The dotted line is the correction for Finnmark (Figure 3). The dark shaded area gives a perspective illustration of the altitudinal variation of Holocene sea-level changes with time.

approximation of the Holocene relative sea-level changes in the region.

MAP MODELS

Models of sea-level changes combined with computer programmes for digitalized areal photographs and maps further increase the possibilities for regional and local application (LEATHERMAN & CLOW, 1983).

At present, an accurate altitudinal base for digitalized maps only exists for limited areas in northern Norway for which three-dimensional map models can be computer drawn. The simulated three-dimensional model of Holocene relative sea-level changes for northern Norway (Figure 3) can be used for predictions and tests against new field data.

Age and Geographic Coordinates

If one would like to predict and test at which location and at which time, Holocene sea-level in northern Norway was situated at a *particular elevation*, this can be illustrated on the three-dimensional model (Figure 4) and presented on a regional map (Figure 5). In this example, a sea-level at an elevation of 10 m above m.t.l. has been chosen. As is apparent, the Tapes transgression (9,000 – 6,000 BP) has resulted in sea-level having been situated at this level, either two or three different times within the coastal zone indicated in Figure 5, but only once in the adjacent zone inside. Such predictions are important in archaeological research (ANDREASSEN, 1985; ANDREASSEN, in press; SANDMO, 1986), and may be

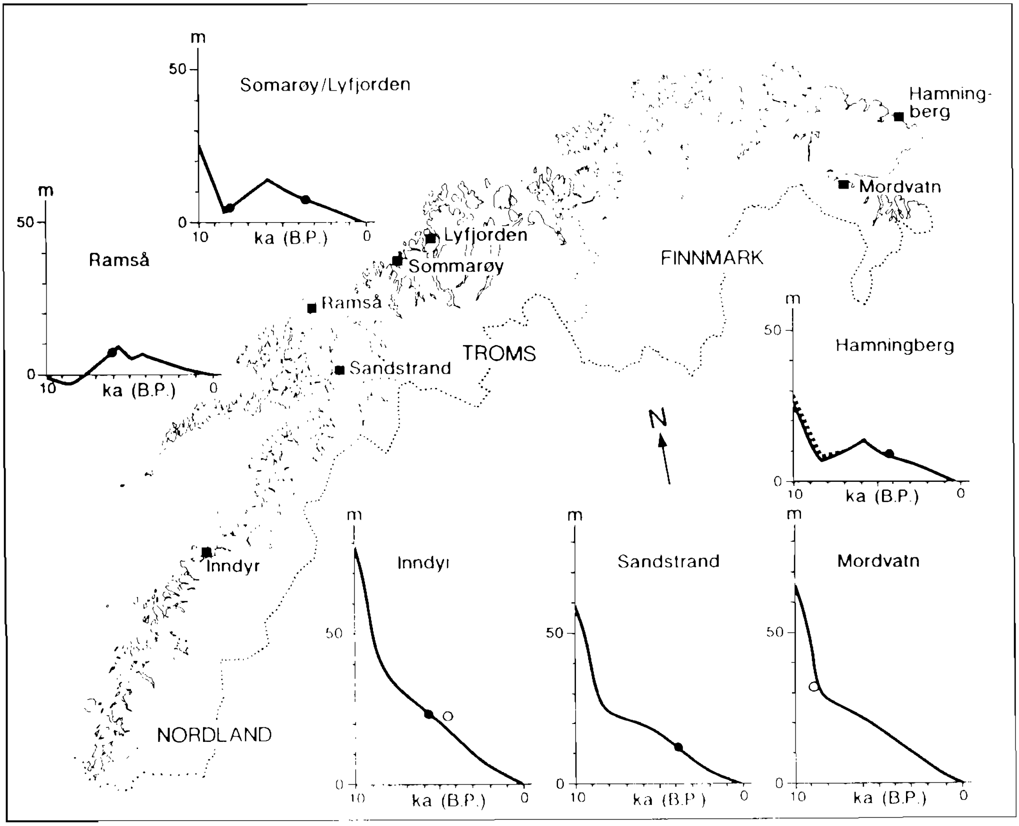

Figure 11. Shore-level displacement curves for seven of the eight localities shown in Table 1. See Figure 3 for the definition of shaded and clear circles. The dotted line for Hamningberg is the correction for eastern Finnmark.

defined and tested more accurately for limited areas and single localities on detailed three-dimensional, contoured map models (Figure 6). Application will be simpler and choices greater when digitalized computer drawn maps become available at different scales.

Elevation and Geographic Coordinates

Figure 7 shows how the three-dimensional model can be used to illustrate and test sea-level elevations at *particular times*. The example chosen is 4,500 years BP. The elevation of this shoreline, transferred to a map gives isobases (Figure 8) for northern Norway.

If the shorelines for each 1,000 years are drawn, this will give a three-dimensional shoreline relation diagram (Figure 9). Transferred to an isobase map, however, this will be too complicated and uninformative. As an example, a special testing programme could ask: are all Holocene shorelines in northern Norway really straight lines?

Elevation and Age

For a *particular geographic location*, the three-dimensional model gives a traditional shore-level displacement curve (Figure 10). Shore-level displacement curves for seven localities in Table 1 are shown in Figure 11.

New ^{14}C-dated SLI's at different localities and elevation in the area will provide the necessary basis for testing and improving the simulated geometric model of Holocene relative sea-level changes for northern Norway.

CONCLUSION

A simulated geometric model of Holocene relative sea-level changes for northern Norway is presented based on the shoreline relation principle. The model represents a simple best-fit trend surface for data defining geographic location, elevation, and age (^{14}C) of raised sea-level indicators (SLI's). Data from eight of sixty SLI localities (MØLLER, 1987) are discussed more closely. The accuracy of the model depends on reliability of the data base and the basic assumption of the shoreline relation principle. The model has been adjusted for the early Holocene in Finnmark. It is shown, in principle, how the model can be applied to raised sea-level problems and this is discussed in connection with maps for the whole region or three-dimensional map models for limited areas. Paleogeographic reconstructions may be tested against new field data.

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